Thoughts on Integrating Stability into Risk Based Methods for Naval Ship Design

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ABSTRACT

Design for Safety (DFS), Goal Based Standards (GBS) and Formal Safety Assessment (FSA) are powerful tools which establish a framework for integrating stability into a risk based design process. They provide a foundation for the development of novel designs which can provide insight that is not attainable through any other means. Naval ships are complex systems, sometimes operating in an environment defined by risk acceptance and risk taking beyond those of their commercial counterparts. The hazards seen by a naval ship in its service life may not be foreseen during design. The development of a design for safety process for naval ships should be capable of reflecting the nature of the military mission. Concurrently, there is certain fidelity inherent in the process that should be carefully defined. Three cases to categorize the risk assessment 'fidelity' are defined and discussed. These highlight the dangers of overstating and understating risk. Lastly the challenges of defining intact and damage stability risk in light of the sensitivity to the state of knowledge for naval ships are discussed.

KEYWORDS

Dynamic Stability, Risk Management, Formal Safety Assessment, Design for Safety, Goal Based Standards, Dynamic Stability, Static Stability, Probabilistic Methodology

INTRODUCTION

The maritime world and especially naval engineering has always dealt in the currency of risk management. Even the origins of the word Risk – *Riscum* (Greek/Latin) has a maritime origin, referring to a difficulty or reef to be avoided as sea. (Ayyub, 2003) The defining difference between the commercial and naval world is in the acceptance and management of risk. In the commercial maritime world risks are to be managed and balanced against economic goals and increased risk is to be avoided if it results in reduced safety. While the approach to risk management in the naval maritime world is the same as in the commercial world, there are times when increase risk acceptance is doctrine brought on by necessity, and the balance is weighed not against economic benefit and measures of safety but against policy and strategic objectives. This is the challenge for naval ship stability where the key is to provide a ship with a robust stability capability sufficient to survive in an unpredictable environment.

*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.

DEFINITIONS

Hazard	a phenomenon or 'event' of potential harm
Reliability	Ability of system or component to fulfill a design function
Consequence	Degree of damage or loss due to some 'failure' or hazard
Risk	Potential of loss associated with exposure to an event.

Risk = ***Probability*** x ***Consequence***

Risk is defined in terms of a probability of an *'event'* or *'hazard'* and a consequence. The risk assessment is the tool by which all of the anticipated hazards are assembled and ranked according to their relative risk. The fidelity of the risk assessment is based on the accurate definition of the hazards, rigorous calculation of the probabilities and correct determination of the consequences at any given point in time. As the environment changes, so do the hazards and the risks. (Papanikolaou, 2009), (Ayyub, 2003)

If done properly the use of risk assessment as a tool can provide a great deal of insight into inherent weakness associated with a particular design or its operation. (Shaw CDR USCG, 2001) But if not done properly, or done in a haphazard manner, the results can be misleading and actually overlook hazards that may prove fatal. The term "unintended consequences" has become almost cliché but is really evocative of an outcome of a process, policy, or system where the risks were not properly or thoroughly defined.

RISK MANAGEMENT PROCESSES APPLICABLE TO NAVAL SHIP SAFETY

Risk management processes can be applied to any aspect of acquisition, design development or operation. Within the marine industry, several approaches have been approaches have been developed to address ship safety. These include:

1. Design for Safety (DFS)
2. Formal Safety Assessment (FSA)
3. Safety Case
4. Goals Based Design

The concept of design for safety is an overarching risk based process which includes safety as an objective of the design. In broad terms this is characterized as Risk Based Design and Approval:

Design

- Safety Performance/Mission Capability
- Prediction Tools
- Risk Models
- Optimization

Approval

- Approval Procedures
- Risk Evaluation and Acceptance Criteria
- Framework for Risk Approval

$$\textbf{Risk}_{\textbf{design}} \leq \textbf{Risk}_{\textbf{Acceptable}}$$

In principle a formal safety assessment is a decision tool providing a systematic process for assessing the effectiveness of regulations at the International Maritime Organization (IMO). The FSA approach is based on five steps:

1. Hazard Identification
2. Assessment of Risk
3. Mitigation Options
4. Cost/Benefit
5. Recommendations (Papanikolaou, 2009)

The concept of the formal risk assessment or design for safety approach has been embraced by IMO in MSC/Circ. 1023 as "Guidelines for Formal Safety Assessment (FSA) for Use in the Rulemaking Process". (IMO, 2002) NATO has followed a similar course in adopting Goal Based Standards (GBS) as a basis for the "Naval Ship Code" ANEP-77. (NATO, 2010) Goal based standards outlines a process a goal or 'safety objective' is defined through a series of tiers or a framework for verification through design construction and operation.

In ANEP-77, the goal based standards approach is anchored on five 'tier's which are outlined to be:

- Tier 0 - Aim (Philosophies and Principles)
- Tier 1 – Goal
- Tier 2 – Functional Areas
- Tier 3 – Performance Requirements
- Tier 4 – Verification Methods
- Tier 5 – Justification

The "Goal Based" approach provides a systematic framework for certification of a ship to meet the aims of ANEP-77. Performance requirements are defined based on the Concept of Operations "CONOPS" and verified using appropriate criteria. Although the Goal Based approach contained in ANEP-77 provides for implementation of FSA approaches, it is not the same as an overarching "Design for Safety" approach in that ANEP-77 allows a Naval Administration to apply describes FSA in the Tier 4 verification of specific performance requirements associated with defined functional areas. Prescriptive standards can still be used to verify the 'goals'. (NATO, 2010)

INTEGRATING STABILITY INTO RISK MANAGEMENT PROCESS

The integration of Naval Ship stability into a risk based process requires the ability to articulate a risk based on a probability and a hazard. This can include a wide range of tools which can encompass many levels of technical maturity. For stability these may include heuristics, static design criteria, and model test simulation of a failure event probability. (Alman/NSSWG, 2010) Each provides a level of information as to what the risk might be for a stability failure for a particular ship design.

The goal based approach in ANEP-77 can be satisfied using existing design criteria, but Tier 4 does provide for inclusion of a FSA process. The FSA process outlined in ANEP-77 does not provide details as to how the hazards should be formulated, or the probabilities of failure and risk determined. It is left to the Naval Administration to establish the acceptable level. Implicit is how is an acceptable risk defined. Within the Goal Based (GB) approach, it is possible that risk levels will not get truly balanced across the design, depending on how the FSA is addressed over the functional areas. Consequently, with increasing use of the risk management processes, it will become increasingly necessary to develop probabilistic metrics for intact and damage stability.

If an overarching "design for safety" process is to be conducted for a Naval Ship, it must be applied form the top down, and Across the Tier 3 functional areas of which stability is one. Hazards must be identified accurately and completely.

A set of safety goals driven by design considerations for a commercial ship has been outlined as follows:

- No Accidents leading to total ship loss
- No loss of human life related to accidents
- Minimal environmental impact from Operation
- Minimal environmental impact from accident
- Vessel to remain afloat and upright in all loading conditions
- Vessel to remain afloat in case of water ingress and flooding
- Ship structure to withstand all foreseeable loads
- High passenger comfort (motions) (Papanikolaou, 2009)

Similar safety objectives could be developed for major naval combatant but with considerations recognizing the nature of the hazards.

- Operations
  - No Accidents leading to total ship loss
  - No loss of human life due to ship related accidents
  - Minimal environmental impact in operation
  - Minimal environmental impact from accident
  - Vessel to remain afloat and upright within NA limits in all operational conditions including extreme seaways environments
  - Vessel to remain afloat and upright in case of flooding due to accident
  - Maintain structural integrity over lifetime
- Battle Damage
  - Vessel to remain afloat and upright in case of battle damage
  - Residual Structural Strength after battle damage
  - Other considerations

THE CHALLENGE OF THE NAVAL SHIP ENVIRONMENT

Past experience is a powerful tool to facilitate the process of hazard identification, but over reliance on past experience and historical data is may be misleading if the knowledge base is derived from experience gained from a class of ships or operating environment that is not reflective of the new design. This paradigm is captured in the cliché of "designing for the last war" in which the design of a weapons system is based on missions and hazards and doctrine from the last war (comfort zone of the experts) the result being that the weapons system may be unsuitable for the required missions of the next war in which it is actually fielded. Generally engineers like to focus on known data and feel uncomfortable when speculating on the unknowns. (Ayyub, 2003)

Dealing with ignorance of the future is a critical aspect of the naval risk management process. Although risk is always minimized as much as possible there are times in the Naval Environment when risk avoidance is not a 'constant' and in fact at times risk 'acceptance' may be doctrine. In other words in the naval environment safety may not always be paramount and may sometimes be supplanted by overarching tactical or strategic goals.

The decision by ADM Halsey to sail through the 1944 Pacific Typhoon rather than accept delay caused by weather routing is an example of the perceived strategic necessity overtaking strict adherence to safety. (Alman, et al 1999) Rather than viewing heavy weather as a hazard to be avoided, in the pacific theater of operations during World War II, storm fronts were sometimes deliberately used as coverage to obscure fleet maneuvers in advance of attack or as a means to provide a haven during a withdrawal. (Orville CAPT USN, 1945)

The merchant marine was also impacted. On August 9, 1941, President Roosevelt unilaterally suspended the International Load Line Convention, due to "changing circumstances created by the war in Europe". (Whiteman, 1970) While it is not known what impact suspension of the Convention might have had on ship safety, in theory it would be possible to load to deeper drafts if needed without violating international law. Transportation of supplies and equipment across the Atlantic to support the allies in Europe was absolutely vital. The greatest risk to safety faced by the allied merchant marine at that time came from enemy action. During the Battle of the Atlantic 1939-1945, approximately 2,177 ships were lost along with 30,132 personnel. (Horodysky, 2007)

Nothing embodies risk acceptance better than two quotes from John Paul Jones:

"I wish to have no connection with any ship that does not sail fast; for I intend to go in harm's way."

"It seems to be a law of nature, inflexible and inexorable, that those who will not risk cannot win." (Morison, 1959)

If we deconstruct his statement in terms of a goal based approach, John Paul Jones doctrine might be expressed as follows:

- Tier 0 Aim – "Win"
- Tier 1 Goals – A ship to "Get into Harm's Way"
- Tier 2 Functional Requirements -

  Speed

  - Tier 3 Performance Requirement – Faster than the enemy

  Armament

  - Tier 3 Performance Requirement – Superior fighting capability

  All other functional requirements as necessary to support tier 0, and 1.

Note; he did not say the following:

"I want to have no connection with any ship that is not safe for I intend to keep out of harm's way".

Although we live in a complex modern world, is it unreasonable to think that his doctrine will still be paramount during wartime? If so, finding the right balance of safety and capability is the challenge faced by the naval ship community.

In this context risk management or Risk Based Design can eventually help to provide the tools to follow an equitable process but must acknowledge the complexity of conflicting requirements and should be based on a very clear and realistic understanding of the nature of risk acceptance in the naval community. There are times when mission requirements may force increased risk acceptance and consideration of hazards that were not planned for. In this context lies the challenge of defining the hazard environment for a naval ship. The hazards are changing with time over the life of a ship and are frequently unpredictable. This is especially true when ships have projected service lives of perhaps 40-50 years. The ship designer may be completely ignorant of how missions and threats will evolve in the future. (Cavas, 2011) This can perhaps be illustrated as a Venn diagram depicting Commercial shipping and Naval Shipping Hazards. Generally both have an overlap or set intersection of common hazards, but there may be times when there is a necessity for increased risk acceptance brought on by new hazards and an increased willingness to acknowledge the possibility of loss so that the hazard space for a naval ship increases as illustrated in Figure 1 below.

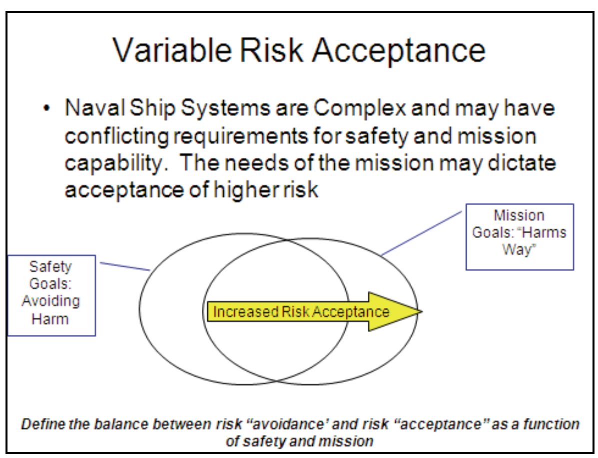

Fig. 1 - Variable Risk Acceptance

NAVAL SHIP HAZARD SPACE

If we allow that naval ships have a unique set of changing hazards resulting from doctrine, mission or wartime employment; it is also true that there is a subset that is the same for all ships whether naval or commercial. The total naval ship hazard space can be thought of as those hazards which are common to all ships plus those hazards which reflect the unique military nature of the ship mission as shown in figure 2. Some common hazards are outlined in figure 3 below.

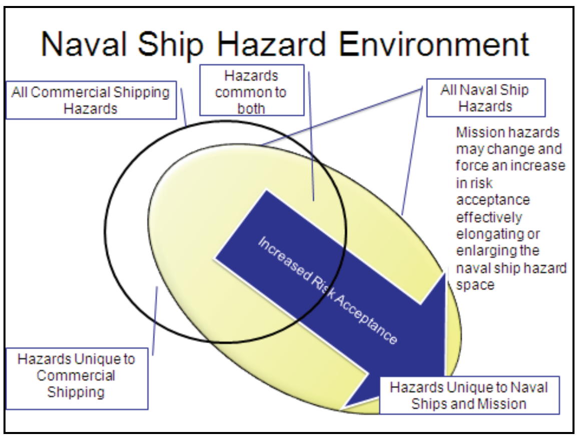

Fig. 2 - Effect of Increased Risk Acceptance on Hazard Space

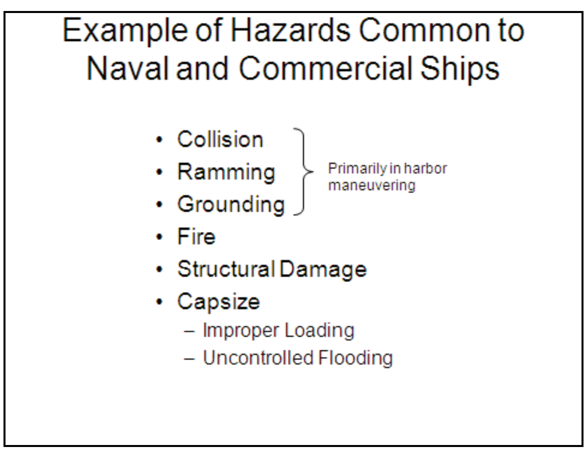

Fig. 3 - Example common hazards for commercial and naval ships

The hazard space can be further refined by looking at an existing ship class with similar mission capability. But while this can help to further refinement of the hazards, it may not be sufficient to adequately address the entire hazard space. At this point it may be necessary to do scenario development and some amount of crystal ball gazing. All this though ultimately means that there is an "ideal" set of hazards that can be imagined with a degree of realism or fidelity, and then there is the actual set of hazards, which include those things that can't be envisioned. The goal is to minimize the later.

The principle safety elements outlined in the DDS-079 are an articulation of basic naval ship stability hazards.

Principal Safety Elements in DDS-079 Criteria

<u>Intact Ship</u>

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

<u>Damaged Ship</u>

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

<u>Flooded Ship</u>

- Beam Winds Combined With Rolling
- Progressive Flooding

THE "UNKNOWN" RISK: ASSESSMENT FIDELITY

"Risk is a characteristic of an uncertain future and is neither characteristic of the present nor the past". (Ayyub, 2003) The risk assessment can be thought of as an approximation or simulation of the true ship risk that exists in the real world. This concept has been characterized as the state Knowledge and Ignorance. At any snapshot in time there is a state of knowledge about a complex system that is a measure of truth and fallacy or ignorance. Some hazards, characteristics of performance, probabilities, and consequences we may know as truth from experience. Others we may mistakenly believe as significant or not; still others we may be completely ignorant and unaware because we have limited or no experience. (Ayyub, 2003) The degree to which the risk assessment approaches truth can be thought of as 'fidelity'. The fidelity of a risk assessment might be thought of as a characterization of how thoroughly the hazards are identified, the probabilities are calculated and the consequences understood. *It is not be possible to ever achieve 100% fidelity.* This would mean that every hazard has been identified, every probability exactly calculated and every consequence completely defined. There are going to be unknowns even in the most thorough process.

Hazards

How well is the system understood? How complex are the systems? Is this a conventional ship? Novel ships may not have much experience base. Areas of operation and potential environment. Is there an experience base to draw on?

Probabilities

All sorts of calculations or estimates can be made to develop a probability. What is the fidelity of the prediction or simulation tool? Is the event being modeled properly and with sufficient accuracy? *"They couldn't hit an elephant at this distance…"*[4] (McMahan, 1884)

Consequences

Is the severity correctly understood? Have undesirable events been adequately developed and by the right people?

For a formal safety assessment for a naval ship, each of these questions must be addressed across systems so that the final risks can be properly ranked. If not properly ranked, the resources may not get applied to the highest risk. In this context, a great challenge for stability is the development of a correct representation of hazards and associated probabilities as well as a realistic portrayal of the cost/benefit of mitigations. A great deal of work has been done to look at probability of damage from collision, ramming and groundings and the characterization of extent and penetration for flooding. However, if the impact of seaway dynamics is to be considered in damage stability the stochastic nature of the environment and motions must be appropriately modeled to attain a realistic fidelity. The stability community is just starting to address flooding dynamics and intact dynamic stability.

In MSC/Circ. 1023 "Guidelines for Formal Safety Assessment" The International Maritime Organization advocates a screening approach based on the progressive employment of more refined tools and increased detail as a means to scope the requirements for the risk assessment. This is an important step as is similar to the approach advocated by the (Alman/NSSWG, 2010) for assessing dynamic stability tool fidelity in an iterative process evolving through a team collaborative process as shown in figure 4.

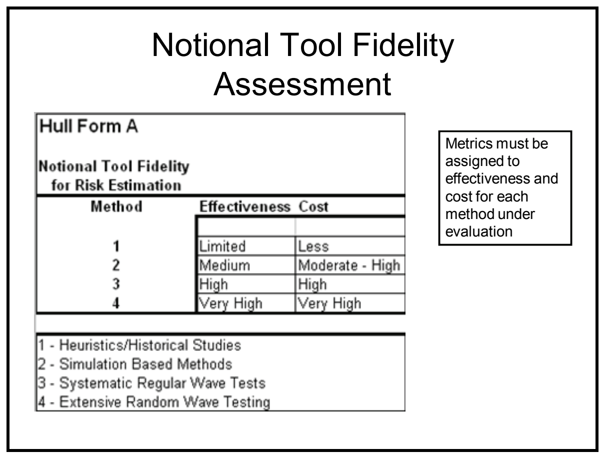

Fig. 4: Notional Tool Fidelity

RISK FIDELITY: CASE I, CASE II, CASE III

One way to think of the maturity of the process is as a 'fidelity' meaning how closely the risk model represents the real life risks of the ship. This is a challenging prospect in the application of risk assessment to naval ship design due to the vast complexity of the systems. Of course in development of a FSA process one always assumes that the process yields results of realistic fidelity. When critical decisions weighing the balance between capability, performance and safety are being made, how do we know this is true? Certainly this applies to the statistical methodology used to estimate probabilities, but it also affects the definition of hazards as well as the consequences. The effect of risk fidelity is shown in figure 5 below. In this case there is a region in which the risk model and actual risks coincide.

[4] Last words of General Sedgwick, USA, - Spoken after rebuking his subordinates for taking cover, shortly before being killed by Confederate sharpshooter at Spotsylvania Courthouse. One could say he incorrectly assessed his probability of being hit as nil; perhaps the result of ignorance of the sharpshooter's true likelihood of hitting the target. Other "experts" around had disagreed and took steps to mitigate the risk – which the General adamantly felt were unnecessary. Unfortunately he couldn't revise his estimate later.

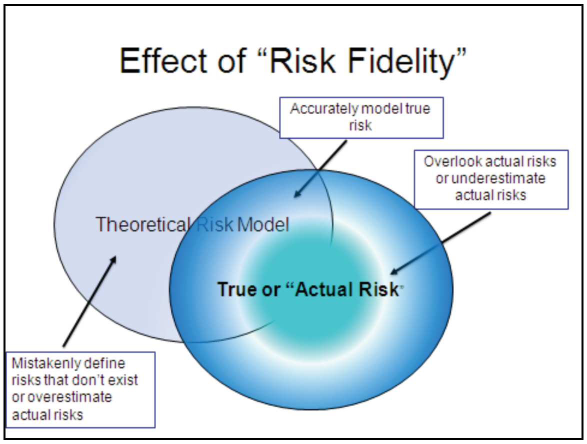

Fig.5: - Risk Assessment Fidelity

It is possible to define the potential outcomes of a risk assessment in terms of cases. In this context there are three possible cases for defining the fidelity of the model:

- **Case I:** The risk model predicts the real risks accurately
  - *Hazards are correctly envisioned and*
  - *Consequences are correctly understood and*
  - *Probabilities are correctly modeled*
- **Case II:** The risk model over predicts actual risks
  - *Hazards are mistakenly defined and/or*
  - *Consequences are over estimated and/or*
  - *Probabilities modeled are too high for the hazard*
- **Case III:** Risk model under predicts actual risks
  - *Hazards are not identified or are minimized and/or*
  - *Consequences are not identified or are minimized and/or*
  - *Probabilities modeled are under estimated*

We would like to think that the process is confined to Case I, but clearly there are always varying degrees of all three cases present. Additionally, personalities and institutional pressure may weigh into leaning to Case II or Case III results. Clearly the challenge is to develop Case I, minimize Case II and avoid Case III altogether.

For example, for intact dynamic stability the risk estimate can be greatly influenced by the probabilistic model used, the technical tool used to develop events, and the environmental model which defines the exposure. These are subject to technological maturity, and expert opinion. A risk assessment team process could be as shown in the figure 6. (Alman/NSSWG, 2010)

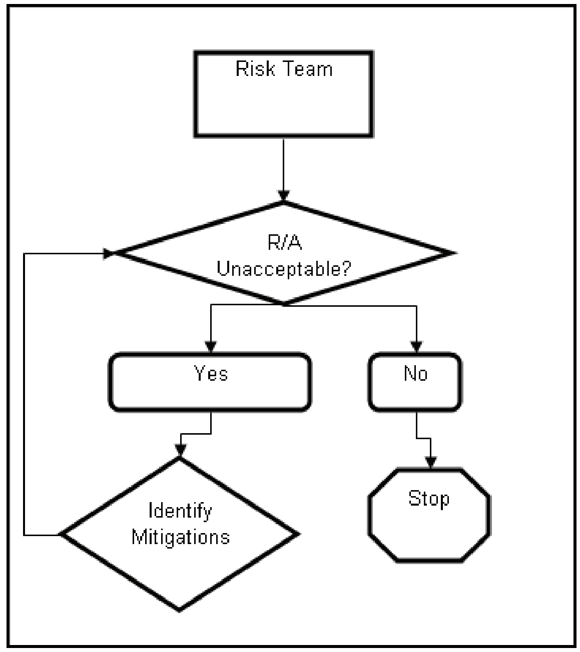

Fig. 6: - Risk Assessment Team Process

If there is a great deal of experience with a specific ship design or class, the associated hazards for the most part might be pretty well understood by those with experience. Consequently it is more likely with a conventional hull form fall into Case I. However, for a naval vessel with novel design characteristics, new technologies, unique missions, the need to use a formal safety assessment as a tool becomes greater. At the same time, the likelihood of a Case II and Case III fidelity occurring during the process also increases. It may be possible to employ strategies to attempt to head off Case II and Case III from dominating results.

These could include:

- Identification of Scenarios to explore possible failure events
- Evaluation against a baseline design
- Examining Factors of Safety in Criteria

Figure 7 below provides an example case showing how a team might assess technological maturity to address Case II and Case III.

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

Fig. 7 - Technological Maturity Effectiveness and Cost

LEVERAGING EXPERIENCE

The application of a formal safety assessment for a naval ship design could follow an iterative or screening process as a means to leverage experience. The use of a screening process can allow informed judgment to be the basis for deciding where in the assessment it is necessary to increase risk fidelity in critical areas. (IMO, 2002) Three basic design categories can be identified. These are equally applicable to naval ship design: (Papanikolaou, 2009)

1. Partial risk-based design using safety equivalence of one function
2. Partial risk based design using safety equivalence and safety balance addressing several functions
3. Complete risk based design

In development towards a complete risk based design it may be possible to develop similar approaches as a stepping stone or tuning process for a novel or alternative design using techniques such as benchmarking or design enhancement.

Benchmarking – Conduct a risk assessment on a benchmark design and the new design as an over arching total system process. Establish a relative risk of system areas based on prior knowledge of the performance of a similar system with a safe history. This would require an assessment of risk for a benchmark ship. The new design then follows an equivalent Risk Assessment process and uses the benchmark risk level as a target. Figure 8 process an example flow diagram to illustrate how this process might look.

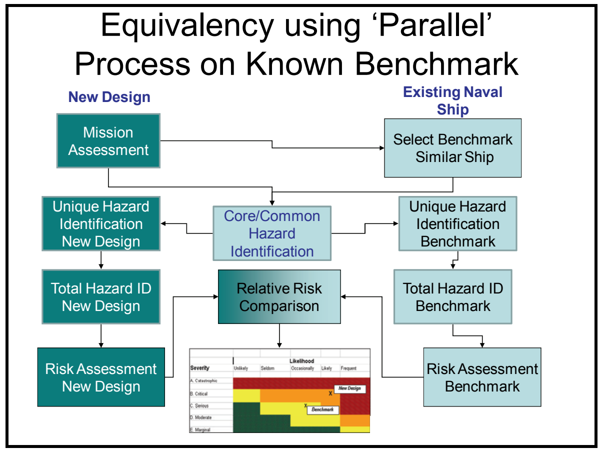

Fig. 8: Risk Assessment Benchmark Process

Safety Design Enhancement – Conduct a risk assessment a new design which complies with existing criteria. Use the results to identify specific system design weaknesses that should be enhanced. A flow diagram for this might look as in figure 9.

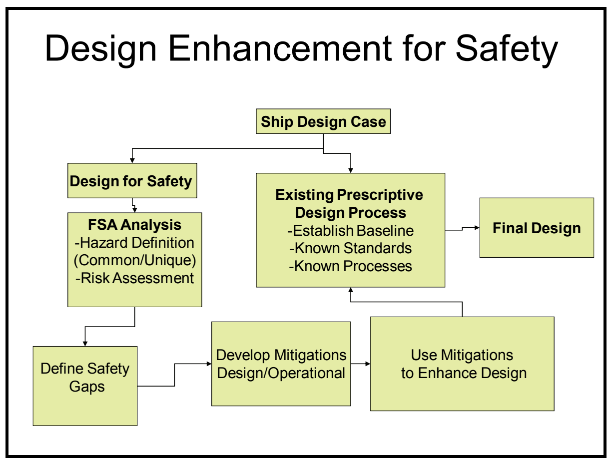

Fig. 9 - Design Enhancement for Safety

STABILITY – INTEGRATING DYNAMIC STABILITY INTO ACQUISITION DISCUSSION

Successful integration of stability into an FSA process requires the ability to characterize a risk. It may be a risk associated with maintaining Naval Architecture limits, and managing mass properties during design and service life (Tellet, 2011). The risk can be qualitative as in a probability of a stability failure, or it can start as a subjective process based on heuristics associated with a particular hull form. The process might start with assembling a 'tool' kit defining available resources for developing measures of risk. (Alman/NSSWG, 2010)

An iterative process to allow 'screening' should be used to identify areas of concern early on and allow employment of focused resources.

A multi tiered approach to identify dynamic stability hazards in heavy weather might follow an approach as shown in figure 10 and 11 below. (Belenky, et al 2008) (Alman/NSSWG, 2010)

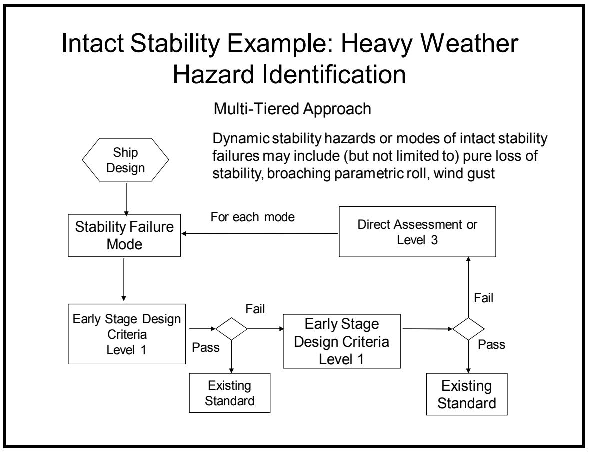

Fig.10: Heavy Weather Hazard Identification

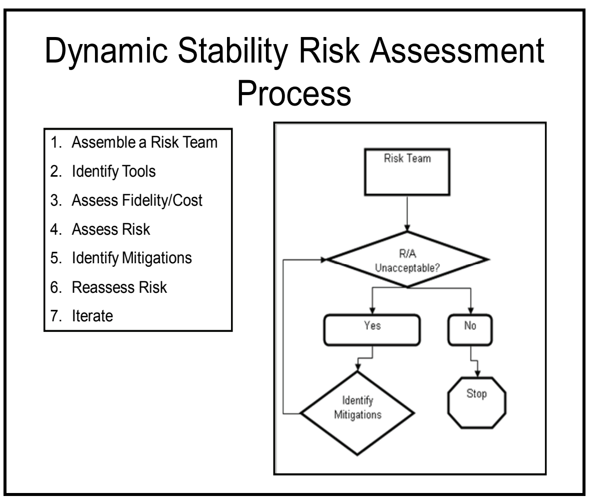

Fig. 11: Dynamic Stability Risk Assessment Process

Since a stability failure could be a catastrophic event resulting in loss of ship and or life, the goal within the risk assessment process should be focused on attaining Case I fidelity. Also important to stability is the ability to address what might be unknown about the performance or operation of the design. If we consider that Case III (failure to recognize or under predict risk) can in part be attributed to lack of knowledge, then this is an important task in the process.

DEALING WITH THE "UNKNOWN" IN STABILITY

As discussed earlier, one of the chief faced in applying risk assessment processes to naval ships is addressing the unknown. It may be a prudent exercise as part of a stability risk assessment to include an assessment of potential 'unknowns' about vessel performance, operational environment, and mission requirements that might significantly change the risks or hazards. It may be a useful exercise with any new design to try to characterize the state of knowledge about the design, hull form characteristics, CONOPs, environment, special geographic areas of operation.

Categorization of the "knowns" and "unknowns" for the stability system and larger ship system as a whole may provide valuable information. A series of 'what if" exercises using a team of experts to define potential scenarios could be drawn together, collated and evaluated by the risk assessment team (Alman, et al, 1999). Methodologies such as development of Bayesian networks can also be used as a tool to help define the probabilistic relationship between uncertain or unknown actions or decisions. (Ayyub, 2003) A detailed discussion of the use of such a process is presented in (Papanikolaou, 2009). Known "facts" about the hazards and risks for a specific design such as operational doctrine, mission, environment etc could be categorized and ranked against the "unknowns". This process could include an evaluation of "Tool" fidelity, criteria etc. A notional ranking is shown in figure 12 below.

Hull Form A

Notional Unknown Evaluation for Risk Estimation

Ranking	Known	Unknown
1	Limited	High
2	Medium	Moderate - High
3	High	Moderate- Low
4	Very High	Low

Fig. 12 - Tabulation of "Knowns" and Unknowns"

Information such as this can be used subjectively to "adjust" the risk during the screening process to aid in defining critical areas for further risk development. The goal is to progressively increase the 'Known" domain while continuously decreasing the "Unknown" domain.

Risk sensitivity could be developed based on changing requirements, 'what if' exercises, scenarios as an aid to judge the robustness of a new design. This may be useful in highlighting potential design weaknesses arising from unique stability failure modes. In figure 13 below, the initial risk estimate is displayed as an 'X' indicating in this case a dynamic stability failure risk. The effect of a sensitivity study may indicate that there is a region which actually may encompass some possible frequent and catastrophic events. The conditions, assumptions, operational environment etc, under which those events occurred should be examined in greater detail to determine if they are really indicative of potential high risk for the design.

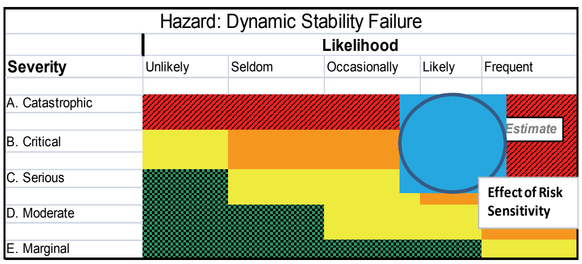

Fig. 13- Notional Dynamic Stability Risk Sensitivity

CONCLUSIONS

Risk assessment processes can yield valuable information on the safety and capabilities of a design. The maritime community is developing techniques to incorporate risk assessment to develop informed safety decisions regarding design, regulations and criteria. All have benefits, but must be applied consistently across systems in developing risks. A risk assessment process to assess safety for a naval ship should recognize from the onset that there are significant unknowns associated with risk acceptance that affect potential hazards and acceptable probability levels. This impacts the "fidelity" of the risk assessment. Even so, by acknowledging this, it should be possible to develop processes that recognize and isolate those unknown factors and improve or understand the "fidelity" of the risks identified.

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