Dynamic Stability Assessment of Naval Ships in Early-Stage Design

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ABSTRACT

A method is currently under development at the International Maritime Organization (IMO) to assess dynamic stability susceptibility during early-stage ship design. The method is intended to provide a physics-based, preliminary analysis of relative risk for ship designs to dynamic stability phenomena, including parametric roll and surf-riding and broaching, with only minimal information about the ship design of interest for evaluation. The method uses a two-stage approach to determine the susceptibility to dynamic intact stability failure modes. This approach can be used to identify designs with increased susceptibility to dynamic stability behavior, which will then require a more detailed analysis and possibly the development of ship-specific operator guidance. Using the mature method developed specifically to assess parametric roll and surf-riding, and to demonstrate the robustness of the method, results for eight naval ship types are presented and discussed. These results were also used to establish an estimate of the criteria corresponding to the second threshold for a sample population of eight notional naval vessels.

Keywords: *Early-stage design, Dynamic Stability, Parametric Roll, Surf-riding / Broaching-to*

1. INTRODUCTION

The International Maritime Organization (IMO) is currently developing the second generation intact stability criteria - SGISC (IMO SDC 2/WP.4). The new criteria are focused on dynamic stability and have a multi-tiered structure. The first two tiers are susceptibility checks that are suitable for early stage ship design (Peters, et al. 2011). In early stage ship design many detailed parameters of a ship design are unknown. The method to evaluate these criteria relies on basic hull geometry defined by a table of offsets, design speed, and basic dimensions such as length, beam, and draft. The results of dynamic stability assessment provide additional information to the ship designer to aid in decision making for either down selection or design modification.

The criteria are being developed for ships covered by IMO instruments. The complex designs typically associated with naval ships differ from typical commercial vessels. To demonstrate the robustness of the criteria and the applicability to naval vessels, a notional naval fleet of eight ships was assessed using the susceptibility criteria from IMO SGISC. The benefits of early identification of dynamic stability failure susceptibilities in naval ship design are discussed. Further discussion of the mathematical models and criteria can be found in the references, and are discussed only briefly here.

Other IMO efforts on dynamic stability criteria include failures related to pure loss of stability, dead ship conditions and excessive accelerations. A study of methods for early-stage design evaluation of pure loss of stability of notional navy ships has been performed earlier by Belenky and Bassler (2010). This paper can be seen as a continuation of those efforts.

2. PARAMETRIC ROLL

2.1 Physical Description

Periodic stability changes at certain frequencies resulting from the changing hull submergence while operating in waves causes the development of parametric roll. Increased stability from roll on the wave trough increases the restoring moment causing greater angles and increased roll rate. With stability decreasing as the ship is restored to upright, the ship rolls further to the opposite side due to the increased roll rate, see Figure 1 (SLF 54/3/3). The roll period during this phenomenon is generally about two times the wave period.

2.2 Sample Notional Naval Ship Calculations

The level 1 susceptibility check uses the Mathieu equation to check if both the frequency is within the necessary range and the magnitude of the stability change is above the threshold (Belenky, et al. 2011). The level 1 assessment accounts for bilge keels. The calculations were done following the requirement identified in Annex 2 of SDC 2.WP.4.

The level 2 susceptibility check increases the fidelity by accounting for certain aspects of irregular waves. The first check accounts for the possibility of encountering waves of different lengths. The second check accounts for roll damping and maximum roll angle during parametric roll. The standard for the criterion used in the level 2 calculations was 0.06 (Annex 2 of SDC 2/WP.4).

Calculations generally follow Annex 3 of SDC 1/INF.8. A wave scatter diagram from IACS Recommendation 34 was used as a data source for wave cases. Representative wave characteristics were calculated using Grimm Effective Wave as described in the document referred to above. As a result, the length of the representative wave equals to ship length. The height of the representative wave depends on spectral characteristics and roughly reflects the likelihood of encountering a wave of that length in a given sea conditions. Roll damping was calculated with a simplified Ikeda method as described in Annex 3 SDC 1/INF.8.

Three options to apply the second check of the level 2 criteria are considered in the calculations:

- Option 1. Numerical solution of a 1 degree of freedom (DOF) for the equation of roll motion, using the interpolated GZ curve defined by the user (as in Annex 22 of SDC-2/INF.10)
- Option 2. The *GZ* curve is fitted with a 5th order polynomial, then the maximum roll angle is evaluated by the averaging method as described in paragraph 2.6 of Annex 3 of SDC 1/INF.8.
- Option 3. The *GZ* curve is fitted with a 5th order polynomial, but the maximum roll angle is found by numerical solution of 1 DOF for the equation of roll motion (the result is expected to be close to the result in option 2)

Results are shown in Table 1. All calculations assume the ship is at the storm draft loading condition.

2.3 Discussion of Results

Several of the results are consistent with expected results. Where the second level shows susceptibility, the first level does as well. The level 1 criterion indicates susceptibility for more ships. This provides a conservative filtering method to identify ships with potential susceptibility to this dynamic stability failure mode. Some inconsistencies among the methods are discussed below.

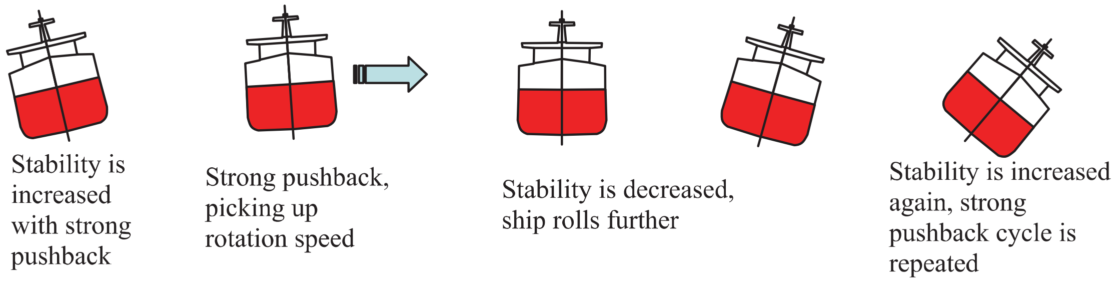

Figure 1. Development of Parametric Roll Resonance (Parametric Roll)

Table 1 Results of Susceptibility Check on Notional Navy Ships for Parametric Roll

				Level 1			Level 2				
Notional Ship	L, m	GM	Vs, kts	Criterion	Standard	Y/N	Criterion Check 1	Criterion Check 2 Option 1	Criterion Check 2 Option 2	Criterion Check 2 Option 3	Y/N
Amphib	200	4.6	20	0.390	0.297	Y	0	0	0.1385	0	N
Carrier	317	3.0	30	0.287	0.334	N	0	0.0224	0.1031	0	N
Cruiser	161	0.8	30	0.401	0.386	Y	0	0.0015	0.0008	0.0011	N
Destroyer	142	1.4	30	0.599	0.378	Y	0	0.0007	0.0003	0.0004	N
Frigate	127	1.1	30	0.459	0.378	Y	0	0.0003	0.0003	0.0003	N
Minehunter	53	4.9	20	0.125	0.474	N	0	0	0	0	N
Patrol Craft	48	1.2	20	0.312	0.578	N	0	0	0	0	N
Small Combatant	98	1.5	30	0.696	0.170	Y	0.5634	0	0	0	Y

Two of the options to check parametric roll susceptibility rely on an approximated GZ curve, so the approximation method should match well with the calculated curve. Two examples are shown below where the approximated curve closely mimics the calculated curve past the useful range to 25~30 degrees of heel before deviating substantially (see Figures 2, 3). Because the offsets of the ship must be known for the calculation the preferred method for naval ship designs is to use actual GZ curve, due to the sensitivity of the hull forms the fitted curve may not always be accurate.

Additionally for the amphibious ship and the carrier, ship specific data indicates that the two ships would not be susceptible to parametric roll. The geometry of these ships indicates that the change in stability would not be significant enough along the length of the ship to produce parametric roll. The simplified Ikeda method for predicting roll damping may be under-predicting the damping. Similarly, the small combatant indicates a very low standard on the level 1 check. Hard chines on the small combatant may provide greater damping than estimated. The under-predicted damping indicates a susceptibility that isn't supported by the specific information of the ships. Consideration to the applicability of the Ikeda method for roll damping should be made by the designer. Additional research for a more accurate prediction of damping in naval ships is still needed.

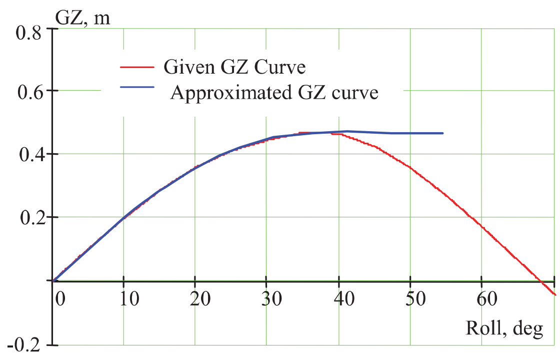

Figure 2. GZ Curve of a Notional Cruiser

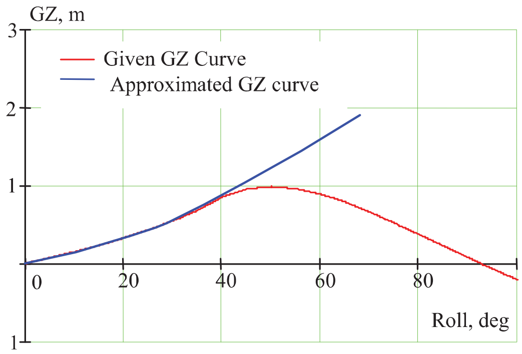

Figure 3. GZ Curve of a Notional Patrol Craft

3. SURF-RIDING AND BROACHING-TO

3.1 Physical Description of Broaching-to

Broaching-to is an operational phenomenon, which results in an uncontrolled turn, which is associated with unsuccessful efforts to reverse direction with maximum steering to the opposite direction. The result of a broaching-to event is often an excessive heel angle resulting from the sharp turn. This excessive heeling of the ship may cause a ship to sustain damage or even capsize. Surf-riding precedes the most common case of broaching-to. As the calculation of likelihood of surf-riding in early stages of design is easier than broaching-to, the susceptibility criteria use probability of surf-riding (Belenky, et al. 2011).

3.2 Sample Naval Ship Calculations

The level 1 susceptibility check assumes the possibility of surf-riding occurs when Froude number is greater than or equal to 0.3, while ship length is less than 200 m. If the length of the ship more than 200 m, then the ship is not considered susceptible even if Froude number exceeds 0.3 (Annex 3 of SDC 2/WP.4). Length is considered due to surf-riding being caused by steep waves with the length equal to about ship length. Encountering a long and steep wave is not very likely.

The level 2 criterion is based on the critical Froude number. If the critical Froude number is exceeded, surf-riding occurs from any location on the wave and with any initial speed. Melnikov's method is applied to calculate the critical Froude number as described in Annex 35 of SDC 2/INF.10; theoretical background can be found in (Spyrou, 2006). Melnikov's analysis is applied to a single wave; the probability of encounter of the wave where the critical Froude number is exceeded by the service Froude number is associated with the probability of the ship surf-riding. The standard criterion used in the level 2 calculations was 0.005 (Annex 3 of SDC 2/WP.4).

Two options for the method of calculation were used in determining the probability surf-riding. Option 1 uses a cubic polynomial fit for resistance in calm water, while option 2 uses a 5th degree polynomial fit.

Results are shown in Table 2. All calculations assume the ship is at the storm draft loading condition.

3.3 Discussion of Results

There was consistency among the criterion. Additionally, the calculations were consistent with what a designer would expect. Relatively short, fast ships are most susceptible to surf-riding and broaching-to. Short steep waves are more likely to occur naturally than long steep waves. Because surf-riding and broaching-to is most likely to occur on steep waves where the ship is similar in speed and length to the wave, shorter ships with significant speed are intuitively more susceptible to surf-riding.

Table 2 Results of Susceptibility Check on Notional Navy Ships on Surf-riding /Broaching-to

Notional Ship	L, m	Vs, kts	Fn	Criterion, option 1	Criterion, option 2	Y/N
Amphib	200	20	0.23	0	0	N
Carrier	317	30	0.28	0.0005	0	N
Cruiser	161	30	0.39	0.0186	0.0183	Y
Destroyer	142	30	0.41	0.0278	0.0276	Y
Frigate	127	30	0.44	0.0386	0.0386	Y
Minehunter	53	20	0.45	0.1094	0.1094	Y
Patrol Craft	48	20	0.47	0.1090	0.1090	Y
Small Combatant	98	30	0.50	0.0640	0.0640	Y

4. DESIGN CHANGES OR OPERATIONAL GUIDANCE

As with all early stage design calculations, the accuracy of the susceptibility assessments here are not significantly high, because of the minimal information available to make the assessment. The ship designer must take into account the limited accuracy of the calculation when making decisions to modify hull geometry or make recommendations for operational limitations guidance.

The information gained from the above calculations in early stage design can lead the ship designer to either modify the hull geometry design to reduce the susceptibility to parametric roll or broaching, or develop operational guidance to avoid parametric roll or broaching events. In some cases other ship design requirements may outweigh the risk of stability failure events and the hull geometry is not able to be changed. Other considerations for hull geometry can be signature, hydrodynamic, or weapons systems related. In the case that signature reduction or speed will be compromised to reduce the risk of dynamic stability failure, often the ship designer will assume the risk in favor of a more capable warship in the safe operating environment. If the risk of dynamic stability is identified but the hull geometry is unable to be modified the early stage design calculations still provide significant value to the ship designer.

The ship designer is able to identify early on an operational limitation of the ship in certain seaways. From a naval fleet perspective, the early identification of operational limitation offers a gap which may be filled by several other ships in the fleet already.

If greater operational area is a higher priority for a certain class of naval ship than speed or signature reduction, the susceptibility assessment allows the designer to modify geometry early in the design when modifications are most cost effective. In cases where these susceptibilities may not be identified until much later in the design process through computational fluid dynamics modelling or model testing, the design may be too mature to allow for significant modifications. Later designs changes in hull geometry can lead to changes in other aspects of the design leading to schedule delays.

5. CONCLUSIONS

Not all methods used in commercial ship designs are viable for assessing naval ship designs. Use of actual GZ curve is preferable over the fitted GZ curve, unless, there are some substantial benefits like use of closed-form solutions. The simplified Ikeda method for roll damping is also may be not applicable to all types of Naval ships.

While there are some limitations, the sample calculations shown indicate that provide a realistic susceptibility checks for naval ship designs. The accuracy of the assessment should be considered in relation to the accuracy and fidelity of the available information to be input to the models. The assessments discussed provide an advantage of additional decision making information to early stage naval ship designers.

6. ACKNOWLEDMENTS

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