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Towards A Rational Intact Stability Criteria For Naval Ships

ABSTRACT Defining rational criteria and methodology for assessing ship intact stability poses a difficult problem. The survival of a ship in extreme sea and wind conditions is a dynamic and non-linear phenomena with many potential capsize scenarios. Naval ship criteria in use today do not attempt to represent actual capsize behavior in waves. Current criteria are based on the static righting arm curve, are largely empirical using WW II data, and do not explicitly consider many variables which can have a significant impact on dynamic intact stability. However, the current criteria are well accepted by the naval architecture community, and within the bounds of conventional hull forms, have proven to be a reliable, generally conservative, ordinal measure of intact stability. The US Navy and other navies continue to rely on these simple criteria until more sophisticated methods are developed and validated. This paper proposes an improved intact stability "weather" criteria which attempts to bridge the gap between the current empirical approach and future analytical methods. In order to maximize commonality with commercial specifications, the proposed criteria is modeled after the current IMO "weather" criteria, with refinements and modifications adapting it for naval ships. It considers the righting arm curve and other ship characteristics influencing roll motion. It also includes the effect of sea state and provides a more rational approach to wind effects including gusts. The proposed criteria is compared to model test results, US Navy criteria and IMO criteria as applied to four US Navy ships.

BACKGROUND

The current intact stability criteria used by the United States Navy were developed during and shortly after World War II (Sarchin and Goldberg, 1962; DDS 079-1, 1975). These criteria are based on the static righting arm curve, are largely empirical, and do not explicitly consider many variables which can have a major impact on dynamic intact stability. However, they are well-accepted by the naval architecture community, and within the bounds of conventional hull forms, have proven to be a reliable, generally conservative, ordinal measure of intact stability. Current international efforts for improving naval ship stability criteria are focused on time domain analysis including the capability to model a steered ship (Burton et al., 1996). Commercial ship intact stability is addressed in a number of International Maritime Organization (IMO) regulations. The IMO "weather" criteria considers wind with gusts and a roll-back angle which is dependent on the ship's static righting arm and other ship roll characteristics (IMO, 1985 and IMO, 1993). The US Navy and other navies have not kept pace with IMO developments. They continue to rely on the empirical World War II criteria until the more sophisticated methods are developed and validated. Validation and acceptance of these new methods may take some time. Current naval ship criteria can be greatly improved with a few small changes which maintain the integrity of their basic approach, and increase their commonality with the IMO criteria. These changes are worth making now, to support the design of new naval ships until more sophisticated methods are in place (Deybach, 1997).

Current Naval Ship Criteria

Before World War II, intact stability criteria were based primarily on GM, range of stability and maximum righting arm. Internationally and in the US these criteria were greatly influenced by Rahola (1935). This approach is still reflected in current international naval ship standards shown in Table 1 (DDS, 1975; NES, 1989; C-03, 1986; DCN).

The primary source of data for the current US Navy stability criteria was the typhoon of December 1944. The US Pacific Fleet was caught in a major tropical typhoon and many ships were lost (Calhoun). An extensive analysis was made of how the ships weathered the typhoon. The results were correlated with the characteristics of the ships to determine the relevant variables and their effect on survival. Three capsized destroyers and ships that only marginally survived provided particularly useful data. Some had heel angles up to 80°. One survived only because the loss of its stack reduced its sail area.

In 1946, the results of this analysis were summarized in an internal memo by Section 456 of the Bureau of Ships, and new ocean weather criteria were proposed. From the data gathered during the typhoon, a wind speed of 100 knots was chosen as a nominal value for modeling tropical storms (nominal value measured at 33 feet above the waterline). This wind speed was specified for new designs. The nominal wind speed specified for ships already in service was 90 knots.

TABLE 1

Current Naval Ship Intact Stability Criteria

CRITERIA	U.S.	France	Canada	U.K.
Conditions of loading	**Minimum Operating and Full Load**	**Minimum Operating**	**Operational Light Loading**	**Light Seagoing**
Criteria on righting arm curve (GZ):				
Area under GZ Curve with heel angle:				
• from 0° to 30°	NA	≥ 0.080 m.rad	NA	≥ 0.080 m.rad
• from 0° to 40°	NA	≥ 0.133 m.rad	NA	≥ 0.133 m.rad
• from 30° to 40°	NA	≥ 0.048 m.rad	NA	≥ 0.048 m.rad
Maximum righting arm (GZ max)	NA	≥ 0.3 m	0.3 m	≥ 0.3 m
Heel angle corresponding to maximum righting arm	NA	≥ 30°	NA	≥ 30°
GM with free-surface correction	NA	≥ 0.3 m	0.05 m	≥ 0.3 m
Capsizing angle	NA	≥ 60°	NA	≥ 60°
Beam wind combined with rolling:				
Wind heeling arm $\frac{0.0195\ V^2 Az \cos^2\theta}{1000\ \Delta}$ (m)				
V (knots), A (m^2), z (m), Δ(mton)	same	same	same	same
$\frac{GZ(\theta_0)}{GZ_{max}}$	≤ 0.6	≤ 0.6	≤ 0.6	≤ 0.6
Equilibrium heel angle θ_0: wind = 100 knts	NA	≤ 30°	≤ 30°	NA
wind = 90 knots	NA	NA	NA	≤ 30°
Windward roll-back angle (θ_1)	25°	25°	25°	25°
Ratio between capsizing and restoring energy $\left(\frac{A_2}{A_1}\right)$	≥ 1.4	≥ 1.4	≥ 1.4	≥ 1.4
Maximum angle for A_2 area	NA	NA	≤ 70°	≤ 70°

Wind heeling arm was calculated as follows :

$$HA = \frac{0.004V^2 AL \cos^2\theta}{2240\Delta}\ .\ \text{ft} \qquad (1)$$

where:

L = height of centroid of projected sail area above 1/2 the draft (ft)
A = projected sail area (ft^2)
V = nominal wind speed (knots)
θ = angle of heel (degrees)
Δ = ship displacement (lton)

The cosine square multiplication factor was intended to model the reduction due to heeling of the projected sail area above the waterline and the height of the centroid of the sail area above the center of lateral resistance.

Referring to Figure 1, the ratio of the righting arm at the intersection of the wind heeling arm and righting arm curves (Point C, θ_o) to the maximum righting arm, $GZ(\theta_o)/GZ_{max}$, was 0.67 and greater for the destroyers that capsized. Ships that survived had a ratio of 0.51 to 0.54. To provide a margin for gusts, the specified maximum ratio was 0.6.

The ability of a ship to right itself in a dynamic sea state was evaluated by comparing heeling and restoring energy. A2, the area under the righting arm curve between the angle of equilibrium (θ_o) and the extreme intersection between righting arm and wind heeling arm curves was compared with A1, the area under the righting arm curve between the roll back angle (θ_1) and the equilibrium heel angle (θ_o) as shown in Figure 1. The destroyers that capsized had less than a 15% margin. The surviving ships had an 80% to 110% margin. To provide for gusts and calculation inaccuracies, the specified margin was 40%. The roll back angle to windward was assumed to be 25°. No justification of this angle is found in the memo.

In 1948 the tentative criteria were included in a Design Data Sheet (DDS). In 1962 the criteria were refined and documented by Sarchin and Goldberg (1962). This version of the criteria was adopted by the US Navy in DDS 079-1 (1975), and in part by many of the world's navies.

International Maritime Organization (IMO) Criteria

The International Maritime Organization, IMO (formerly Inter-governmental Maritime Consultative Organization, IMCO) is an agency of the United Nations, and currently has over 130 member nations. Their charter is to create, improve and harmonize technical requirements for the

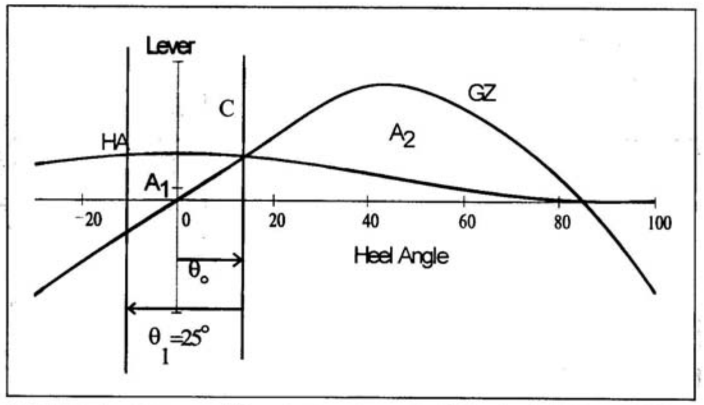

FIGURE 1. US Navy Stability Criteria

safety of ships from different countries. The IMO Subcommittee on Subdivision and Stability was formed in 1962, and the first international stability criteria was adopted in 1968 with Resolution A167 (IMO, 1968). This criteria applies to passenger and cargo ships under 100 meters in length, uses the righting arm curve, and is based on Rahola, (1935). This resolution was followed by Resolution A.562 (IMO, 1985) which applies to passenger and cargo ships over 24 meters in length, and includes criteria considering wind and the balance between capsizing and restoring energy. These resolutions were updated by Resolution A.749 (IMO, 1993) which combines the requirements of Resolutions A.167, A.206 (ships carrying deck cargo), A.168 (fishing vessels) and A.562 into a single intact stability code.

Resolution A.749 uses simplified equations and tables. It does not show its method of calculation from fundamental principles. Working papers presented at meetings of the Sub-Committee on Subdivision, Stability and Load Lines during the late 1970's and early 1980's were used to reconstruct the basis and history of A.749. Japan (1979) proposed a weather criteria to complement the righting arm criterion of Resolution A.167 which considers wind with gusts. The dynamic criteria proposed by Japan is illustrated in Figure 2. It considers the ship rolling in waves with an amplitude of θ_1 (roll-back angle), around an equilibrium heel angle (θ_0) due to a steady wind. The ship is subjected to a gust when at its maximum heel to windward. Dynamic stability must be sufficient to prevent the ship from heeling to leeward beyond the flooding angle θ_2. Sufficient dynamic stability is achieved when area A_2 is equal to or greater than area A_1.

The steady wind speed proposed by Japan is 26 m/s for ocean-going ships and 19 m/s for coastal ships. Gust speed is $\sqrt{1.5}$ times the steady wind speed (or 1.5 times the steady heeling moment). No justification for the choice of wind speed or gust speed is given in the working paper. Heeling moments are calculated using these wind speeds as in the US Navy criteria, but without the cosine square term. The heeling arm does not vary with heel angle.

The Japanese criteria specifies roll amplitude based on resonant roll amplitude in regular waves:

$$\vartheta = \sqrt{\frac{\pi \cdot r \cdot \theta_w}{2N}} \qquad (2)$$

where:

r = effective wave slope factor $= 0.73 + 0.6\frac{OG}{T}$

OG = vertical distance between G and water line (m)

T = ship draft (m)

s = wave steepness = wave height / wave length $= h/\lambda$

θ_w = wave slope $= 180{*}s$ (degrees)

N = Bertin's roll damping coefficient $= 0.02$

Based on this resonant amplitude, Japan proposed the following standard rolling amplitude in irregular waves (θ_1):

$$\theta_1 = 0.7\vartheta = \sqrt{\frac{138rs}{N}} \qquad (3)$$

Wave steepness is calculated using the relation between wave steepness and wave age developed by Sverdrup and Munk (1947). Wave age is represented by the wave speed / wind speed ratio. For a given wind speed (26 m/s in this case), wave steepness is given as a function of the wave period (T) by using the deep water wave relationship :

$$\text{WaveSpeed} = C = \sqrt{\frac{g}{2\pi}\lambda} = \frac{g}{2\pi}T \qquad (4)$$

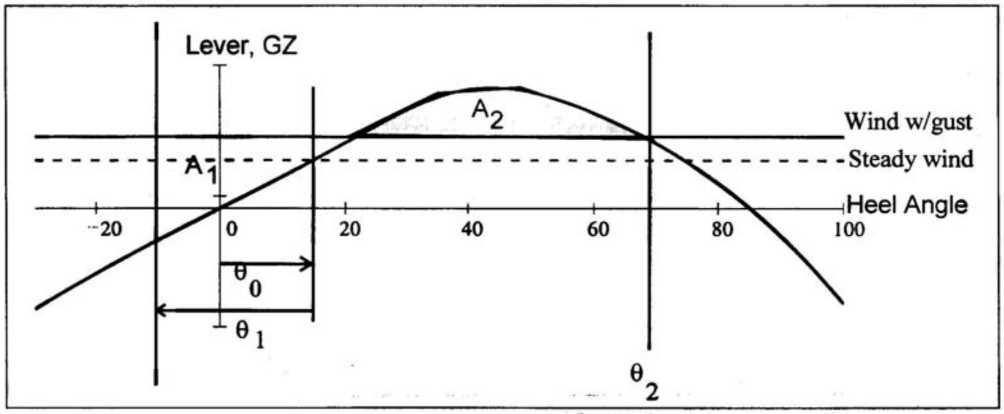

FIGURE 2. Japanese Stability Criteria

Japan proposed a linear approximation of the resulting curve with:

$$s = 0.151 - .0072\,T \tag{5}$$

Resonant roll amplitude occurs when the wave excitation period is equal to the natural roll period of the ship. The wave steepness is calculated at this roll period. Natural roll period is:

$$T = 2\pi \frac{k_x}{\sqrt{gGM}} \tag{6}$$

k_x = radius of gyration about the longitudinal axis

The USSR (1982) proposed an alternative method to calculate the amplitude of rolling. This method is derived from the "Rules of the Register of Shipping of the USSR," and it was obtained by approximation from calculations of rolling amplitudes in irregular seas for different types of ships. The calculations are based on the fundamental equations of motion with the coefficients obtained from experimental data. In contrast to the Japanese criteria, this method takes into account the dependence of the roll damping coefficient on the hull form and the effect of appendages.

The members of the Sub-committee completed calculations for a number of existing ships using the Japanese weather criteria, USSR criteria and Resolution A.167. The Japanese weather criteria was found to be more constraining than A.167 at low displacement.

A combination of these methods proposed by the Sub-committee resulted in the following expression for roll-back angle:

$$\theta_1 = \frac{kX_1X_2}{C}\,\theta_{1\,Japan} \tag{7}$$

where:

$\theta_{1\,Japan}$ = rolling amplitude calculated with the Japanese method

k, X_1, and X_2 = correction factors described in the USSR method and provided in A.749 Tables

C = coefficient from test calculations = 0.76

Resolution A.749 specifies a combination of the area requirement under the righting arm curve required by A.167, and a dynamic energy balance with a wind requirement or "weather criteria" based on Equation (7).

Time Domain Analysis

The Cooperative Research Navies (CRNav) project was established to develop dynamic stability criteria, and study the physics of extreme motion phenomena (Burton, 1996; DeKat et al., 1994). The project uses a time domain motion analysis program based on non-linear strip theory to predict capsizing and stern sea phenomena such as pure loss of transverse stability, parametric excitation, broaching with combination of successive overtaking waves, surf riding, and bow/trim submergence. This is an ambitious, but potentially very rewarding undertaking, and a great deal can be learned from the process. Strip theory codes are fast enough in the time domain to assess long-term statistics in extreme seas and provide faster than real time motion simulations. However, strip theory typically is not able to predict phenomena which are highly non-linear (steep waves), or sensitive to stern end / transom effects. Other methods such as the Rankine Panel Method are being developed to consider variable wetness of the ship hull, non-linear hydrostatic effects, radiation and diffraction wave disturbances, and transom viscous effects

(Kring et al., 1996). These new methods are still computationally demanding, and not yet fast enough for extended time domain analysis.

Although offering the potential for the "ultimate" prediction, complex models lack fundamental simplicity and transparency. After extensive calibration and fixes for nonlinear effects, excellent graphics and detailed results can often hide a composite of bad submodels and sometimes bad answers. Until extensive validation and critique of any complex model is completed, a simple model with the demonstrated ability to provide fast and reliable ordinal assessment is the preferred working tool.

Motivation for Improved Criteria

Ship dynamic models will ultimately replace static models and current criteria, but until they are thoroughly validated and critiqued they should not be accepted for working criteria. In the interim, current criteria can be improved while maintaining their basic integrity and simplicity.

Strengths of the current US Navy intact stability criteria are: 1) simple to understand, calculate and apply; 2) proven to be a consistent ordinal measure; and 3) conservative within limits. Weaknesses are: 1) fixed 25 degree roll-back angle; 2) arbitrary margin in the required dynamic stability ratio; 3) sea state and wind gusts are not explicitly considered; 4) the static model does not describe the true dynamic response of a ship; and 5) the criteria does not provide a cardinal measure of risk. The following recommends an improved criteria which seeks to build on the strengths of the current criteria, while addressing some of its weaknesses.

IMPROVED CRITERIA

The following changes to the current US Navy intact stability criteria are feasible, necessary and recommended: 1) provide a more rigorous approach to wind heeling arm with gusts similar to the IMO criteria; 2) calculate roll-back angle based on ship characteristics and sea state; 3) specify a dynamic stability ratio without margin – A2/A1 must be greater than or equal to one (vice 1.4); and 4) maximize commonality with the IMO "weather" criteria.

Revision to Wind Heeling Arm Calculation

The US Navy heeling arm varies as a cosine square function of the angle of heel. The theory behind this is that wind pressure acts on the projected sail area of the ship, and, as the ship is inclined, the projected area varies as a cosine function of the angle of heel. The same is true for the distance between the center of pressure and the center of lateral resistance. The combination of these effects results in the cosine square variation. This function reduces the moment to zero at 90°. This is appropriate for a two dimensional plate rotating around its waterline, but when a three dimensional ship heels, the projected area of the emerging hull increases with the angle as the deckhouse projected area decreases.

IMO resolution A.749 specifies a constant heeling arm through the full range of heel angles. The justification for this approach is that, for commercial vessels, the deckhouse is usually small and the projected area should be considered constant as the reduction in deckhouse projected area is compensated with the area of the emerging hull.

A more rational approach considers the projected area to decrease as a cosine function from the upright position to a minimum corresponding to the ship laying on its side with half its hull submerged:

$$A_{Proposed} = c_w \frac{L_{pp} B}{2} + \left(A - c_w \frac{L_{pp} B}{2}\right) \cos\theta \quad (8)$$

where:

B = Beam (m)
C_w = Waterplane coefficient
L_{pp} = Length between perpendiculars (m)

The lever arm (L) is calculated using a similar method. It decreases as a cosine function from the upright position to a minimum corresponding to the ship laying on its side with the centers of the above and the below water areas at one quarter of the beam:

$$L_{Proposed} = \frac{B}{2} + \left(L - \frac{B}{2}\right) \cos\theta \quad (9)$$

The proposed wind heeling arm is:

$$H_w = \frac{\frac{1}{2} C_D \rho V^2 \cdot \left[c_w \frac{L_{pp} B}{2} + \left(A - c_w \frac{L_{pp} B}{2}\right) \cos\theta\right]}{1000 \cdot g \cdot \Delta} \times \left[\frac{B}{2} + \left(L - \frac{B}{2}\right) \cos\theta\right] \quad (10)$$

where:

$C_D \doteq$ Drag coefficient = 1.12
g = 9.81 m/sec^2
ρ = Air density = 1.293 kg/m^3
V = Wind speed = 51.44 m/sec
Δ = Ship displacement (metric ton)
L = Lever arm = Height of centroid of projected sail area above 1/2 the draft (m)

The US Navy uses a wind speed of 100 knots (51.44 m/s) for new designs. Wind gust is not considered in the wind heeling calculation, but is included in the margin on dynamic stability ($A_2 \geq 1.4\, A_1$). In Resolution A.749, IMO specifies a steady wind speed of 26 m/s with gusts included explicitly as $\sqrt{1.5} \cdot 26 = 31.84$ m/s. A.749 includes no margin for wind gusts in the dynamic stability area ratio.

The proposed naval ship criteria uses a steady wind of 100 knots (51.44 m/s) with gusts to $\sqrt{1.5} \cdot 100 = 122.46$ knots (63 m/s), and no margin for gusts in the dynamic stability ratio, A_2/A_1.

Ship Dynamic Response and Roll-Back Angle

The second important aspect of the current criteria which requires improvement is the calculation of roll back angle and dynamic stability in random seas. The current criteria uses a constant roll-back angle of 25 degrees. A more rational approach is to calculate roll angle based on linear ship motion in waves (Beck et al., 1989). Simplifying assumptions made in this analysis include:

1. The ship has lateral symmetry—allows the six equations of motion to be uncoupled into two sets of three equations, three equations for longitudinal motion (surge, heave and pitch), and three equations for transverse motion (sway, roll and yaw).
2. The irregular beam sea is modeled as a linear superposition of sinusoidal incident waves, each with a sinusoidal response of the form:

$$\eta_j(t) = \bar{\eta}_j e^{i\omega t} \quad (11)$$

where:

$\bar{\eta}_j$ = complex amplitude of the response in the j direction

ω = incident frequency of the waves

3. Roll (η_4) is taken around the roll center. This ignores weak coupling of roll with sway and yaw around the roll center.
4. The equations of motion include an equivalent damping coefficient B^*_{44} and an equivalent restoring coefficient C^*_{44}. These coefficients are dependent on the amplitude of the response : $B^*_{44} = B^*_{44}(|\bar{\eta}_4|)$ and $C^*_{44} = C^*_{44}(|\bar{\eta}_4|)$. Nonlinearities become small for small amplitudes : when $|\bar{\eta}_4| \to 0$, $B^*_{44} \to B_{44}$ and $C^*_{44} \to C_{44} = g\Delta\overline{GM}_T$.

With these assumptions, the roll equation of motion becomes:

$$[-\omega^2(\hat{I}_{44} + \hat{A}_{44}) + i\omega B^*_{44} + C^*_{44}]\,\bar{\eta}_4 = \hat{F}_{EX4} \quad (12)$$

where:

I_{44} = Roll moment of inertia

A_{44} = Roll added moment of inertia

and where the excitation moment is:

$$\hat{F}_{EX4} = g\Delta\overline{GM}_T \frac{d\zeta}{dx} = g\Delta\overline{GM}_T\, i\frac{\omega^2}{g}\bar{\zeta} e^{i\omega t} \quad (13)$$

and: $\zeta(t) = \bar{\zeta} e^{i\omega t}$ = wave surface elevation

Or in non-dimensional form:

$$\left[-\left(\frac{\omega}{\omega_n}\right)^2 + 2i\frac{\omega}{\omega_n}\cdot\beta^* + \gamma^*\right]\bar{\eta}_4 = i\frac{\omega^2}{g}\bar{\zeta} \quad (14)$$

where:

$\frac{\omega}{\omega_n}$ = nondimensional wave frequency

$\omega_n = \sqrt{\frac{g\Delta\overline{GM}}{\hat{I}_{44} + \hat{A}_{44}}}$ = roll resonance frequency

$\beta^* = \beta^*(|\bar{\eta}_4|) = \frac{\omega_n \hat{B}^*_{44}}{2g\Delta\overline{GM}}$ = nondimensional damping factor

$\gamma^* = \gamma^*(|\bar{\eta}_4|) = \frac{C^*_{44}}{g\Delta\overline{GM}} = \frac{C^*_{44}}{C_{44}} \approx 1$ = nondimensional roll restoring term

The roll response amplitude operator (RAO), is then:

$$RAO\left(\frac{\omega}{\omega_n}\right) = \frac{|\bar{\eta}_4|}{|\bar{\zeta}|} = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\frac{\omega}{\omega_n}\cdot\beta^*\right)^2}}\cdot\frac{\omega^2}{g} \quad (15)$$

and the resonance frequency is:

$$\omega_n = \frac{2\pi}{T_n} = \sqrt{\frac{g\overline{GM}}{k}} \quad (16)$$

where: T_n = natural roll period

and: $k = \sqrt{\frac{\hat{I}_{44} + \hat{A}_{44}}{\Delta}}$ = radius of gyration

The radius of gyration, k, is estimated as $k = CB$, where B = beam of the ship. Various expressions to calculate C have been proposed. Beck et al. (1989) recommend $C = 0.3613$ for typical ships, but warn that the constant can vary by as much as 20 per cent. Resolution A.749 recommends:

$$C = 0.3725 + 0.0227\frac{B}{T} - 0.043\frac{L_{pp}}{100} \quad (17)$$

IMCO Stab/95 uses a factor for ships with inclined or flared side shell:

$$C = 0.3085 + 0.0227\frac{B}{T} - 0.043\frac{L_{pp}}{100} \quad (18)$$

Table 2 compares the results of these expressions for four naval ships and one ferry. Resolution A.749 provides the best results for these ships, and since it is also the current IMO standard, this expression is recommended in the proposed criteria.

TABLE 2.

Roll Natural Period Estimates

SHIP	MCM	FFG	DDG	DD	HOLYHEAD
Δ (t)	1261.	4182.8	8693.	8345.	4082.
L_{PP} (m)	62.6	124.4	142.	171.6	105.7
B (m)	11.9	13.7	18.9	16.8	16.78
T (m)	3.14	4.8	6.34	6.1	3.87
GM (m)	1.55	0.93	1.26	1.37	1.4
T_n (Measured)	8.	11.34	13.	12.	12.2
T_n (PNA)	6.93	10.3	12.2	10.4	10.3
T_n (A.749)	8.28	10.94	12.8	10.4	12.1
T_n (Stab/95)	7.05	9.11	10.6	8,5	10.3

The non-dimensional damping factor is estimated using the zero speed damping factor $\beta^{(0)}$ proposed by Miller et al. (1974):

$$\beta^{(0)} = \beta^{(0)}(|\bar{\eta}|) = 19.25 \cdot [A_k \sqrt{b_k} + 0.0024\, L\, B\sqrt{d}]\, \frac{d^2 \sqrt{d|\bar{\eta}|}}{C_B\, LB^3\, T} \quad (19)$$

where:

A_k = total area of the bilge keels (port + starboard)
b_k = width of the bilge keel
d = distance between the centerline at the waterline and the trace of the bilge keel
$|\bar{\eta}|$ = roll angle
C_B = block coefficient

Using the roll RAO, the response spectrum for angle of roll can be calculated from the sea state energy spectrum, SE(ω):

$$SR(\omega) = SE(\omega) \cdot (RAO(\omega))^2 \quad (20)$$

A Bretschneider wave spectrum is used for SE(ω):

$$SE(\omega) = \frac{5}{16}\left(\frac{\omega_m}{\omega}\right)^4 \frac{H^2}{\omega}\, e^{-1.25\left(\frac{\omega_m}{\omega}\right)^4} \quad (21)$$

where:

ω_m = most probable modal period (rad.s^{-1}) = .079(7.63 − ln H)
H = significant wave height (m)

The value of significant wave height is chosen to be consistent with the steady wind speed specified in the wind criteria.

Significant roll amplitude (mean value of the 1/3 highest roll amplitudes) is used to estimate the value of roll-back angle:

$$\theta_1 = 2\sqrt{m_0} \quad (22)$$

where:

$$m_0 = \mathrm{E} = \text{variance of the response} = \int_0^\infty SR(\omega)d\omega$$

A sample calculation is provided in the Appendix.

MODEL TESTS

Model test data are used to evaluate the roll angle calculations. Four ships were modeled in these tests: a DD, DDG, MCM and FFG. Tests for the first three ships were conducted in 1991 and 1992 by the Naval Surface Warfare Center, Carderock in support of the Naval Sea Systems Command (Jones, 1991, 1992, 1992). In these tests, each sea state is characterized by a wind speed, significant wave height and modal frequency. Long-crested irregular wave spectra similar to Bretschneider spectra are used for all test cases except Climatic, where a storm spectrum similar to that measured for hurricane Camille is used. The FFG test was conducted by the Hydromechanics Laboratory at the United States Naval Academy (Chong et al., 1993). It uses a nominal wind speed of approximately 100 knots and a Bretschneider spectra with modal period of 16.39 seconds and significant wave height of 11.52 meters. Calculations use Bretschneider spectra and the same wind speeds, significant wave heights and modal frequencies as the tests. Figures 3 through 5 and Table 3 compare roll angle test results with calculation results based on the method proposed in the previous section.

These comparisons indicate a good prediction of roll angle for all cases, with calculations generally predicting higher (more conservative) roll values. Calculations are simple and sensitive to hull form, loading and sea state characteristics. Predicted roll angle is particularly sensitive to damping, ship natural roll period and wave modal period. Test results also indicate a reduced roll angle in steady wind compared to zero wind cases (2-3 degrees), which accounts for some of the consistent difference compared to the calculated values. In all extreme (Sea State 8 and Climatic) cases, calculated roll angle provides a better estimate for roll back angle than the arbitrary value of 25 degrees assumed in the current criteria.

APPLICATION OF PROPOSED CRITERIA

The proposed changes are applied to the calculation of dynamic stability. The results of these calculations are compared to results using the current US Navy criteria and current IMO criteria. Results are presented in Tables 4 through 8.

Calculations are performed for design conditions as specified in the current US Navy criteria. Ships with compensated fuel systems are evaluated at the Full Load condition only. This is the more severe design condition. Based on the proposed criteria, the FFG has inadequate intact stability in both the Full Load and Minimum Operating (MinOp) design conditions (Table 7), although it has satisfactory stability based on the US Navy criteria. An additional FFG MinOp condition is calculated at a reduced wind speed sufficient to demonstrate adequate dynamic stability based on the proposed criteria. This speed is determined to be 71 knots (Table 8).

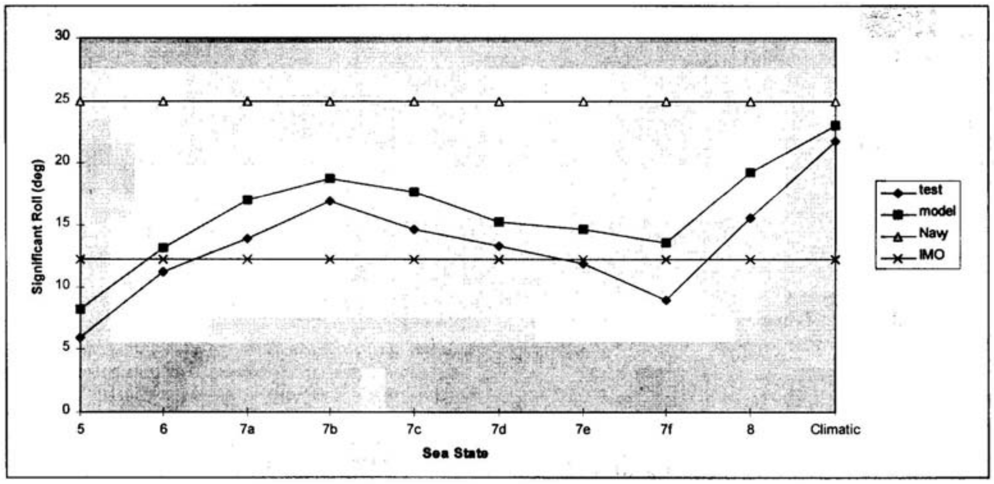

FIGURE 3. DD Predicted Roll Angle Comparison to Test

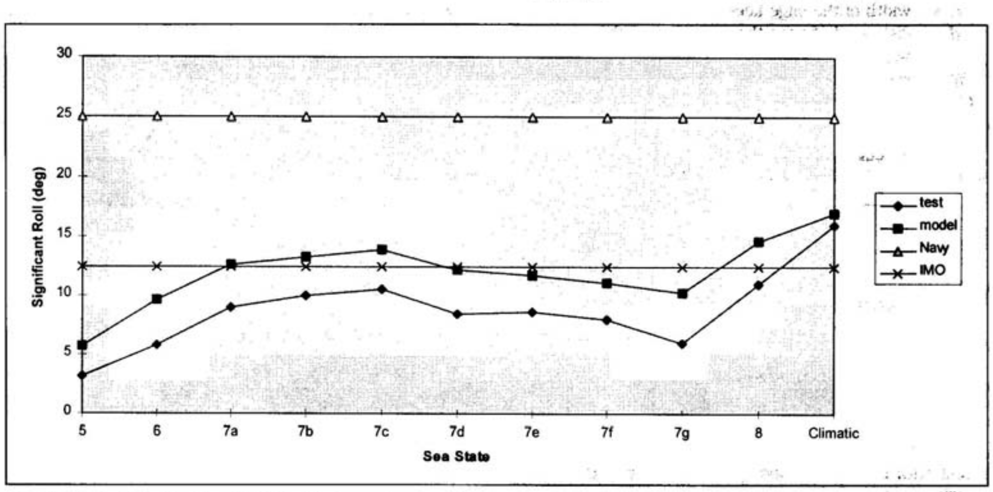

FIGURE 4. DDG Predicted Roll Angle Comparison to Test

DISCUSSION

Predicted roll angle comparisons shown in Figures 3 to 5 illustrate the utility of including a simple roll angle calculation in the improved criteria. This calculation provides conservative roll angle predictions for various sea states, and predicts extreme roll angles in cases of poor initial stability and/or roll damping. These predictions compare well to experimental results.

Roll angle calculated using the IMO formulation, Equation 7, is shown to provide a good average value for sea state 7 conditions, which is consistent with its derivation. The US Navy criteria of 25 degrees provides a conservative sea state 9 plus estimate for ships with good intact

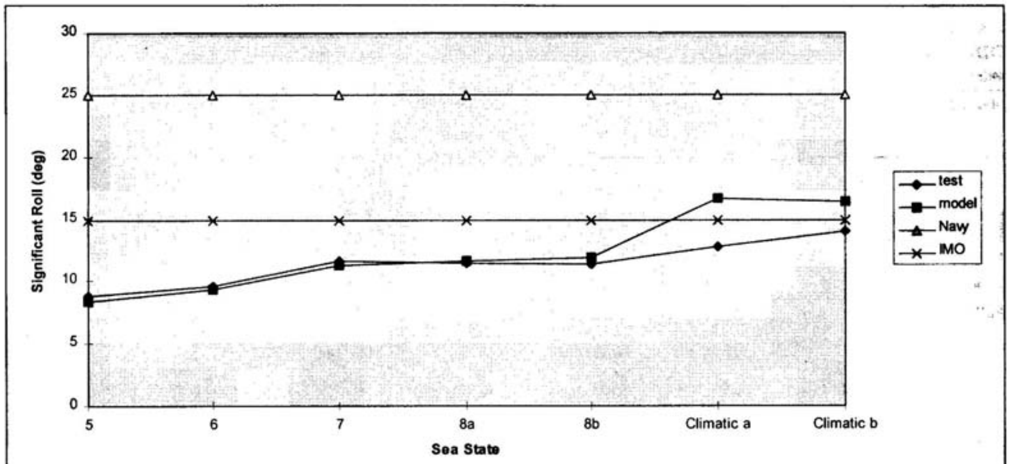

FIGURE 5. MCM Predicted Roll Angle Comparison to Test

stability. For ships with low initial stability and roll damping, as shown in the FFG Design Condition example, Tables 7 and 8, this estimate may be too low, and result in an overly favorable stability assessment. The FFG has the lowest GM of the four test ships, and also has relatively small bilge keel and skeg area. This causes low initial stability and low roll damping which results in a large roll amplitude. This ship is very dependent on active fin stabilization which is not considered in the proposed model.

Figures 6 illustrates the importance of a modified wind heeling arm (HA) formula. The IMO criteria assumes a very conservative constant wind HA represented by the upper HA curve in Figure 6. The US Navy uses a very liberal cosine square formula represented by the lower HA curve. The proposed formula takes a more rational approach to the derivation, and ends up a compromise between the two. Figure 6 demonstrates that these differences have a significant impact on the equilibrium heel angle, θ_o, and ultimately on the A2 area and resulting dynamic stability assessment.

Both the IMO and improved criteria explicitly consider wind gust. Figure 7 illustrates the significant impact of this effect, particularly in its application to a ship with large sail area such as the FFG. The IMO wind gust HA

TABLE 3.

FFG Predicted Roll Angle Comparison to Test

Wind Speed (knots)	Sea State	Significant Wave Height (m)	Most Probable Modal Period (s)	Test Significant Roll Amplitude (deg)	Calculated Significant Roll Amplitude (deg)	IMO Significant Roll Amplitude (deg)
100	8	11.52	16.21	14.36	14.91	14.13

TABLE 4.

DD—Full Load Design Condition

Wind	Sea State	Method	0(deg)	1(deg)	A_1(rad*m)	A_2(rad*m)	A_2/A_1
100 knts	8/9	Navy	21.48	25.00	0.119	0.511	4.31
	H = 14m	IMO	24.74	12.63	0.098	0.139	1.42
	ω_m = 15.9sec	Proposed	23.14	26.05	0.231	0.259	1.12

TABLE 5.

DDG—Full Load Design Condition

Wind	Sea State	Method	0(deg)	1(deg)	A_1(rad*m)	A_2(rad*m)	A_2/A_1
100 knts	8/9	Navy	11.13	25.00	0.163	0.901	5.53
	H = 14m	IMO	11.85	13.59	0.091	0.584	6.42
	ω_m = 15.9sec	Proposed	11.48	21.48	0.181	0.634	3.50

TABLE 6.

MCM—Design Conditions

Load	Wind	Sea State	Method	0(deg)	1(deg)	A_1(rad*m)	A_2(rad*m)	A_2/A_1
Full	80 knts	8/9	Navy	9.75	25.00	0.151	0.405	2.68
		H = 14m	IMO	10.38	16.04	0.105	0.155	1.48
		ω_m = 15.9sec	Proposed	10.00	17.01	0.121	0.195	1.62
MinOp	80 knts	8/9	Navy	10.50	25.00	0.148	0.335	2.26
		H = 14m	IMO	11.31	15.41	0.108	0.090	0.83
		ω_m = 15.9sec	Proposed	10.88	16.64	0.112	0.125	1.12

TABLE 7.

FFG—Design Conditions

Full	Wind	Sea State	Method	0(deg)	1(deg)	A_1(rad*m)	A_2(rad*m)	A_2/A_1
Full	100 knts	8.9	Navy	22.05	25.00	0.132	0.373	2.83
		H = 14m	IMO	29.02	14.09	0.144	0 000	0 00
		ω_m = 15.9sec	Proposed	27.63	30.49	0.346	0.096	0.28
MinOP	100 knts	8/9	Navy	29.46	25.00	0.127	0.264	2.08
		H = 14m	IMO	38.63	13.27	0.103	0	0
		ω_m = 15.9sec	Proposed	33.49	26.68	0.323	0.011	0.04

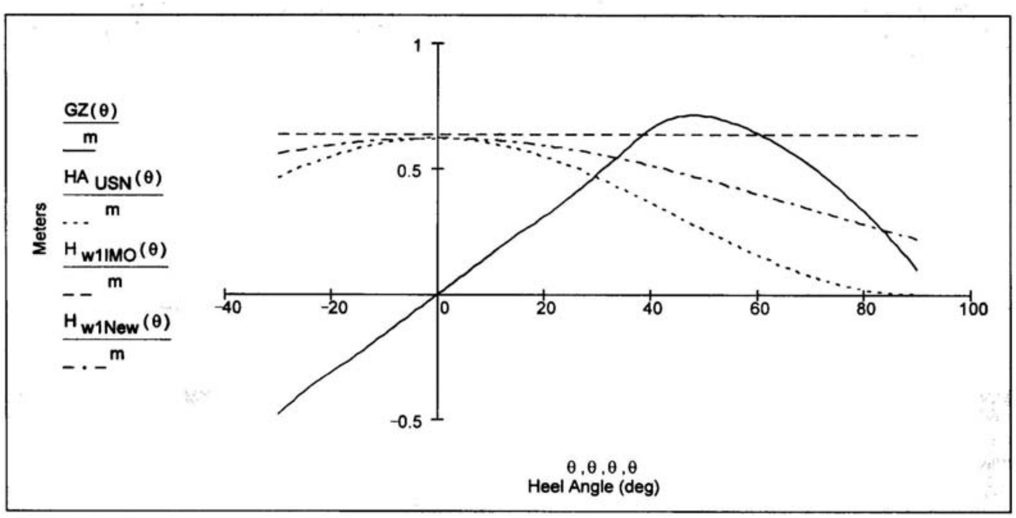

FIGURE 6. FFG MinOp θ_o Intercept

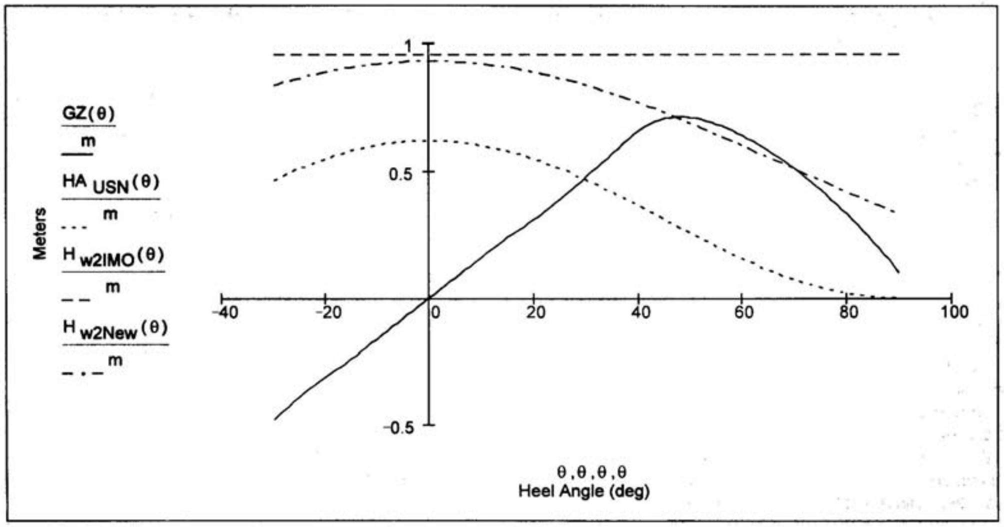

FIGURE 7. FFG MinOp Dynamic Stability Assessment

does not intersect the righting arm (GZ) curve. This predicts an immediate capsize in gusts independent of dynamic energy. This phenomena was observed and reported in the Naval Academy model test (Chong et al., 1993). The proposed wind gust HA does intersect the GZ curve, but A2 is very small, and the resulting dynamic stability is not satisfactory. The Navy HA curve follows the cosine square function and does not consider gusts. This results in an adequate dynamic stability prediction.

Assessments of dynamic stability for all three methods are consistent in their relative ranking of the four ships (DDG best, then DD, MCM and FFG). The proposed criteria discriminates more distinctly between ships. Both the IMO and proposed criteria find FFG dynamic stability to be unsatisfactory, and provide sufficient information to conclude that initial stability, roll damping and sail area are all problems in this ship. Only the proposed method is able to evaluate FFG at reduced sea and wind conditions to determine its limiting operating conditions.

FUTURE WORK

Future work in this area will focus on the following:

- Reduce roll-back angle calculation to tabular form similar to IMO criteria (IMO, 1993)
- Incorporate this methodology into a reliability-based approach similar to (Atua and Ayyub, 1997). The wave spectrum-based calculation of roll-back angle facilitates this approach.
- Review ocean wind and extreme wind gust literature and data to reassess wind speed and gust assumptions.

CONCLUSION

The proposed intact stability criteria has a number of important advantages relative to the current criteria:

- It incorporates a more rational, but still simple approach to dynamic stability within the traditional static righting arm framework.

TABLE 8.

FFG—Reduced Design Condition

Full	Wind	Sea State	Method	0(deg)	1(deg)	A_1(rad*m)	A_2(rad*m)	A_2/A_1
minOP	71 knts	8/9	Navy	18.01	25.00	0.091	0.379	4.18
		H = 14m	IMO	20.68	13.27	0.073	0.106	1.46
		ω_m = 15.9sec	Proposed	19.22	28.68	0.204	0.206	1.00

- It eliminates the empirical 40% safety factor in the A_2/A_1 area ratio.
- It corrects the overly simplistic and liberal cosine square approach to wind heeling.
- It explicitly considers wind gusts and the resulting added impact of sail area.
- It explicitly considers ship characteristics which influence roll amplitude including initial stability and damping.
- It explicitly considers sea state and can be adapted to different operational requirements.
- It is generally conservative relative to current criteria, but better able to distinguish between ships and identify excess or marginal stability.
- Roll and stability predictions based on the proposed criteria show excellent agreement with model tests.
- The proposed criteria is more in harmony with current commercial (IMO) standards.

Until more sophisticated methods are developed, validated, and streamlined for easy application by working engineers, the improved criteria provides a more rational and discriminating alternative to existing criteria. ✣

References

Beck, Robert F., Cummins, William E., Dalzell, John F., Mandel, Philip and Webster, William C., "Motions In Waves," Chapter 8, *Principles of Naval Architecture* (PNA), Society of Naval Architects and Marine Engineers, 1989.

Burton, D. et al., "Extreme Motion Analysis and Simulation for Ship Design and Operations," unpublished paper, 1996.

Calhoun, Raymond (Capt.), "Typhoon: The other enemy."

Chong, Keng Shin, Escamilla, Christopher R., and Compton, Roger H., "Experimental Studies of Ship Stability in Beam Wind and Waves," United States Naval Academy, Hydromechanics Laboratory, Division of Engineering and Weapons, Report EW-07-93, June 1993.

C-03-001-024 MS-002, "Stability and Buoyancy Requirements, Canadian Armed Forces Surface Ships," 5 June 1986.

DCN, IT 6014.

DDS 079-1, "Design Data Sheet : Stability and Buoyancy of U.S. Naval Surface Ships," Naval Ship Engineering Center, U.S. Department of the Navy, 1 August 1975.

De Kat, Brouwer, McTaggart and Thomas, "Intact Ship Survivability in Extreme Waves: New Criteria from a Research and Navy Perspective," Fifth International Conference on Stability of Ships and Ocean Vehicles, November 1994.

Deybach, F., *Intact Stability Criteria for Naval Ships*, Master of Science Thesis, MIT Department of Ocean Engineering, 1997.

IMO, Resolution A.167, "Recommendation on Intact Stability for Passenger and Cargo Ships under 100 meters in Length," International Maritime Organization, adopted 1968.

IMO, Resolution A.562, "Recommendations on a Severe Wind and Rolling Criterion for the Intact Stability of Passenger and Cargo Ships of 24 meters in Length and Over," International Maritime Organization, adopted 1985.

IMO, Resolution A.749(18), "Code on Intact Stability for All Types of Ships Covered by IMO Instruments," adopted 4 November 1993.

Kring, D.C., et al., "Non-Linear Ship Motions and Wave-Induced Loads by a Rankine Panel Method," 21st Symposium on Naval Hydrodynamics, Trondheim, 1996.

NES 109, "Stability Standards for Surface Ships," Issue 3, Sea Systems Controllerate, U.K. Ministry of Defence, August 1989.

Japan, "Intact Stability, Stability of Ships in Ballast Condition, Weather Criteria," IMCO - Sub-Committee on Subdivision, Stability and Load Lines - 24th session, STAB XXIV/4, 27 September 1979.

Jones, Harry D., "DD Intact and Damage Stability in Beam Waves and Wind," David Taylor Research Center, Ship Hydromechanics Department, Report DTRC/SHD-1360-01, September 1991.

Jones, Harry D., "DDG Intact and Damage Stability in Beam Waves and Wind," David Taylor Research Center, Ship Hydromechanics Department, Report DTRC/SHD-1360-03, January 1992.

Jones, Harry D., "MCM Intact and Damage Stability in Beam Waves and Wind," Carderock Division, Naval Surface Warfare Center, Ship Hydromechanics Department, Report CARDEROCKDIV/SHD-1360-04, September 1992.

Rahola, J., "The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability," Transactions, Institute of Naval Architects, 1935.

Sarchin, T.H. and L.L. Goldberg, "Stability and Buoyancy Criteria for U.S. Naval Surface Ships," SNAME Transactions, Vol. 70, 1962.

Sverdrup, H. U., and Munk, W. H., "Wind, Sea and Swell: Theory of Relations for Forecasting," US Hydrographic Office Pub. No. 601, March 1947.

USSR, IMCO - Sub-Committee on Subdivision, Stability and Load Lines - 27th session, STAB 27/5/3, 10 February 1982.

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APPENDIX—FFG FULL LOAD DESIGN ROLL CALCULATION

1. Ship characteristics:

$\Delta = 3.967 \cdot 10^3 \cdot \text{lton}$; $L := 124.4 \cdot m$; $B := 13.7 \cdot m$; $T := 4.83 \cdot m$; $GM := .99 \cdot m$; $C_B := .446$

Bilge keels: Height: $b_k := .91 \cdot m$; Area: $A_k := 64.672 \cdot m^2$; Distance to CL/DWL: $d := 5.66 \cdot m$

Roll period:

$C := \left(0.3725 + 0.0227 \cdot \frac{B}{T} - 0.043 \cdot \frac{L}{100 \cdot m}\right)$ $\quad C = 0.383 \quad T_n := \frac{2 \cdot \pi \cdot C \cdot B}{\sqrt{g \cdot GM}} \quad T_n = 10.592 \cdot \text{sec}$

Damping:

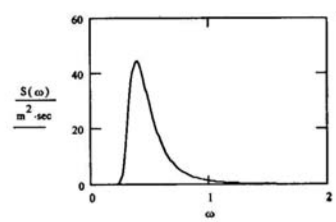
$\beta := 19.25 \cdot \left(A_k \cdot \sqrt{b_k} + .0024 \cdot L \cdot B \cdot \sqrt{d}\right) \cdot d^2 \cdot \frac{\sqrt{d \cdot \theta}}{C_B \cdot L \cdot B^3 \cdot T} \quad \beta = 0.111$

2. Sea characteristics:

$H_s := 14 \cdot m \quad \omega_m := .079 \cdot \left(7.63 - \ln\left(\frac{H_s}{m}\right)\right) \cdot \frac{rad}{sec} \quad T_m := \frac{2 \cdot \pi}{\omega_m} \quad T_m = 15.936 \cdot \text{sec}$

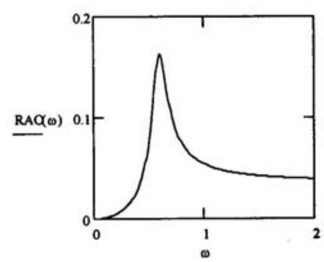
3. Sea spectra:

$$S(\omega) := \frac{5}{16} \cdot \left(\frac{\omega_m}{\omega}\right)^4 \cdot \frac{(H_s)^2}{\omega} \cdot e^{-1.25 \cdot \left(\frac{\omega_m}{\omega}\right)^4}$$



4. Response:

$$RAO(\omega) := \frac{\frac{\omega^2}{g}}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2 \cdot \beta \cdot \frac{\omega}{\omega_n}\right)^2}}$$



$SR(\omega) := (RAO(\omega))^2 \cdot S(\omega)$

$$m_0 := \int_{\frac{.01}{sec}}^{\frac{2}{sec}} SR(\omega)\, d\omega$$

$\theta 1 := 2 \cdot \sqrt{m_0} \quad \theta 1 = 30.489 \cdot \text{deg}$