Application of Parametric Roll Criteria to Naval Vessels

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ABSTRACT

Parametric roll has been a topic of interest for many years, particularly with the advent of hull form geometries such as containerships with large bow flare and stern overhang. With the recent interest in utilizing novel hull form geometries in naval ship design, there is an increased desire to assess the vulnerability of these naval designs to parametric roll resonance and to compare this vulnerability with more traditional hull forms.

This paper discusses the application of the ABS susceptibility and severity criteria for varying regular wave conditions to two naval ship designs, a tumblehome topside geometry and a more conventional flared topside geometry.

Comparisons of parametric roll predictions for a range of regular wave conditions using the ABS criteria, a single degree-of-freedom model, are made with results from a six degree-of-freedom ship motions simulation tool, *LAMP*, to assess the applicability of the simplified model. Limits of applicability of the simplified method to predict the susceptibility and severity of parametric roll for conventional and novel naval vessel designs are discussed.

KEYWORDS

parametric roll; susceptibility criteria; severity criteria; tumblehome; topside geometry

INTRODUCTION

Parametric roll has been a topic of interest for many years, particularly with the advent of new hull form geometries such as containerships with large bow flare and stern overhang. Accidents from parametric roll have resulted in injury to crew and significant damage to cargo and vessels.

There have been many studies of the physics of parametric roll, including Kerwin (1955), Paulling (1961), Spyrou (2000), Bulian et al. (2003), Umeda et al. (2003), Neves and Rodriguez (2004), and Shin et al. (2004). ABS developed criteria (2004) to assess containership designs for parametric roll susceptibility and severity vulnerabilities.

With the recent interest in departing from conventional hull form geometries for naval ship design, there is an increased desire to assess the vulnerability of these novel naval designs to stability failures, including parametric roll resonance. Comparison of stability vulnerabilities of these unconventional designs with more traditional hull form types have shown that topside geometry can significantly affect stability performance (Bishop et al., 2005, Bassler et al., 2007). McCue et al. (2007) using a single degree-of-freedom Mathieu equation type model, showed that parametric roll in longitudinal seas occurred at lower speeds for a tumblehome topside geometry than for more conventional wall-sided and flared geometries.

This paper discusses the application of the ABS susceptibility and severity criteria for varying regular wave conditions to two naval ship designs, a tumblehome topside geometry and a more conventional flared topside geometry. Predictions from the single degree-of-freedom model in the ABS criteria are then compared to results from numerical simulations, using both single degree-of-freedom and multiple degree-of-freedom models. An assessment of the influence of roll damping and wave height and speed criteria for parametric roll occurrence for naval vessels in longitudinal regular waves is also discussed.

SHIP GEOMETRY

The Office of Naval Research (ONR) Topside Series hull forms (Bishop et al., 2005) represent a modern naval combatant-type hull form, including varying topside geometry for conventional and novel topside designs. The hulls feature a common hull form below the design waterline. The above-waterline geometry consists of three topside configurations: wall-side (ONRWS), flared (ONRFL), and tumblehome (ONRTH).

For this investigation the ONRFL and ONRTH hulls (Figures 1 and 2) were used to examine the occurrence of parametric roll in regular waves for naval vessels. Ship particulars are given in Table 1.

Fig. 1: ONR Topside Series Hull Forms- ONRFL (top) and ONRTH (bottom).

REGULAR WAVES

This study examined the occurrence of parametric roll in longitudinal regular waves (Table 2), with wavelength, λ, equal to ship length, L. A range of ship speeds and regular wave heights, corresponding to the mean significant wave heights from the NATO Sea State Charts (Bales, 1982), were evaluated to assess the occurrence of parametric roll for the naval vessels.

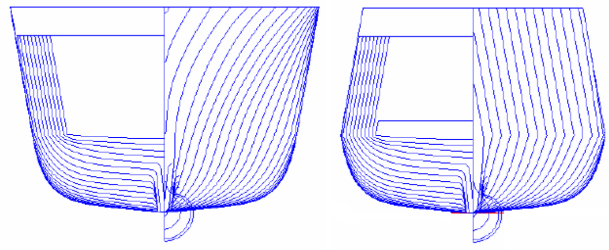

Fig. 2: Section View of ONRFL (left) and ONRTH (right).

Table 1: Ship Principle Dimensions for ONR Topside Series Hull Forms

Length, LBP	154 m
Beam, B	18.8 m
Draft, T	5.5 m
Displacement	8790 tonnes
LCB (aft of FP)	79.6 m
KM	9.74 m

Table 2: Regular Wave Parameters

NATO Sea State Mean H_s	Equivalent-Regular Wave Height (m)
SS2	0.298
SS3	0.880
SS4	1.879
SS5	3.247
SS6	4.995
SS7	7.495
SS8	11.491

NUMERICAL MODELS

Two numerical tools were used to assess the susceptibility of the ONRTH and ONRFL to parametric roll.

The first model is a simple, single degree-of-freedom model used in the ABS Guide for the Assessment of Parametric Roll Resonance in the Design of Container Carriers (2004). The second model used was the *Large Amplitude Motions Program (LAMP)* from SAIC (Lin and Yue, 1990, 1993) version 3.1.7. Two components of the assessment that were performed for the unappended hull forms: susceptibility criteria to determine the speed and encounter frequency where parametric roll is expected, and severity criteria to determine the resulting amplitude of parametric roll.

Susceptibility Criteria

A design wave, with the wave crest positioned at a number of stations, is applied to the ship to assess the stability of the vessel in waves. The metacentric height for each wave crest position is calculated and minimum and maximum GM are evaluated to then determine a mean metacentric height, GM_m and the amplitude of the GM change, GM_a. The mean frequency of encounter, ω_m, is then calculated.

$$\omega_m = \frac{7.854 \cdot \sqrt{GM_m}}{B},\ rad/s \qquad (1)$$

The frequency corresponding to the amplitude of excitation, ω_a, is defined by substituting ω_a for ω_m and GM_a for GM_m into **(1)**. The speed where parametric roll occurs, V_{pr}, is then calculated.

$$V_{pr} = \frac{19.06 \cdot (2\omega_m - \omega_w)}{\omega_w^{\ 2}},\ kn \qquad (2)$$

where ω_w is the wave frequency. A positive value for V_{pr}, indicates parametric roll occurs in head seas and a negative value indicates following seas. For conditions where the encounter frequency is twice a vessel's natural roll frequency, ω_0, parametric roll is likely to occur (Shin et al., 2004). The encounter frequency is defined by

$$\omega_e = \omega_w + V_{pr} \cdot k \qquad (3)$$

where k is the wave number. A linear roll damping coefficient, as a fraction of critical damping, is assumed, μ=0.03 (ABS, 2004).

Using the Mathieu equation,

$$\frac{d^2x}{d\tau^2} + (p + q\cos(\tau)) \cdot x = 0 \qquad (4)$$

where $\tau = \omega_e t$, the frequency parameter can be defined

$$p = \left(\frac{\omega_m}{\omega_e}\right)^2 - \left(\mu \cdot \frac{\omega_0}{\omega_e}\right)^2 \qquad (5)$$

the excitation parameter can be defined

$$q = \frac{\omega_a^{\ 2}}{\omega_e^{\ 2}} \qquad (6)$$

and then both are used to determine the boundaries of a solution to the Mathieu equation using an Ince-Strutt diagram (Shin et al., 2004).

Severity Criteria

After susceptibility to parametric roll has been determined for a vessel, the severity of parametric roll occurrence must be computed. The recommended numerical procedure (ABS, 2004) was used. The nonlinear roll equation

$$\ddot{\phi} + 2\mu\omega_0\dot{\phi} + \omega_0^{\ 2} f(\phi, t) = 0 \qquad (7)$$

is integrated with a nonlinear restoring term, including the stability change in waves. Computation of the GZ curve in waves can be performed using either the numerical code *EUREKA* (Paulling, 1961) or *LAMP* (Belenky and Weems, 2008).

The nonlinear restoring term, $f(\phi,t)$ is defined as

$$f(\phi,t)=\frac{sign(\phi)}{GM_0}\cdot GZ(|\phi|,x) \qquad (8)$$

where GM_0 is the calm water GM. $sign(\phi)$ is a function defined as 1 for positive roll angles and -1 for negative roll angles, and x is

$$x=V\cdot t-L\cdot floor\left(\frac{V\cdot t}{\lambda}\right) \qquad (9)$$

where V is the speed of encounter and V_s is the speed of the vessel.

$$V=V_s+c \qquad (10)$$

where c is the wave celerity. The function *floor* produces the greatest integer less than the ratio of distance the ship has travel in a given time and the wavelength, $(V\cdot t/\lambda)$. For this study, a range of roll damping coefficients was examined and will be discussed with the results.

LAMP Simulations

LAMP is a three-dimensional time-domain potential flow panel method that can predict ship motions in all six degrees-of-freedom.

For this study, motions were computed in *LAMP-0*, using only non-linear hydrostatics, for both unconstrained single degree-of-freedom (1DOF) roll and three degree-of-freedom (3DOF), heave, pitch, and roll, computations. Single degree-of-freedom models are often employed in analytical treatments or used as an initial analysis to determine system characteristics (McCue et al., 2007).

Accurate predictions using a numerical tool with a 1DOF model may be limited to only small and moderate wave heights. By definition, a 1 DOF roll model does not include heave and a vessel fixed in the vertical direction may be completely submerged or come completely out of the water if the wave height is large enough relative to the ship. 1DOF results are shown in this study only to enable a more direct comparison to the susceptibility and severity criteria which also employ a 1DOF model to analyze roll motion.

A series of simulations with the vessel free to sink and trim, as well as fixed, and with the model fully appended (bilge keels, skeg, and rudder), appended with rudders only (no bilge keels or skeg), and completely unappended (barehull), were performed to assess the impact of the motion constraints and inclusion of appendages on the roll amplitude. An initial heel angle of five degrees was used for the simulations to provide an initial perturbation of the system, but at a small enough roll angle not to bias the results.

Roll Damping in LAMP

LAMP has a number of options for viscous roll damping models to correct the potential flow solution. For this study, a model with both linear roll damping and quadratic roll damping was used. The roll moment, M_{roll}, is calculated

$$M_{roll}=-\mu\cdot V_{roll}-\mu_2\cdot V_{roll}\cdot|V_{roll}| \qquad (11)$$

where μ is the linear hull roll damping coefficient, μ_2 is the quadratic hull roll damping coefficient, and V_{roll} is the roll velocity (Lin et al., 2007). In addition to the standard assumed roll damping coefficients, μ=0.03 and μ2=0 (ABS, 2004), a range of linear and quadratic coefficients were examined to assess the effect of the specified damping on the amplitude of parametric roll in regular waves (Table 3).

For the 3DOF computations, damping for heave and pitch was also included. The damping used was derived from heave and pitch decay tests for the ONRTH and ONRFL hulls in *LAMP* (Lin et al., 2007).

Table 3: Roll Damping Coefficients

Linear roll damping coefficient, μ	Quadratic Damping Coefficient, μ_2
0.01	$2.00*10^7$
0.015	$1.00*10^7$
0.025	$2.00*10^5$
0.03	$2.00*10^3$
0.10	0.00
0.15	
0.20	
0.25	

RESULTS

Susceptibility Criteria

The ABS susceptibility criteria predicted parametric roll occurrence at various speeds for both the ONRTH and ONRFL (Tables 4 and 5). The speeds where parametric roll was expected for the ONRFL varied from 10-12 m/s in head seas. For the ONRTH, with increasing wave height, the speed to expect parametric roll in head seas decreased from 11.181 m/s to 4.783 m/s. For the largest wave height, 11.491m, the speed to expect parametric roll was 1.535 m/s in following seas.

Severity Criteria

For both the ONRTH and ONRFL hulls, parametric roll did not occur for the equivalent mean Sea State 3 significant wave height conditions and smaller. Severity criteria calculations with ship unbalanced-fixed at the calm water draft, as recommended by the ABS criteria, are shown (Tables 6 and 7). All severity calculations for both topside geometries were made for the ship without any appendages.

LAMP-0 Simulations

The removal of appendages led to an increase in the amplitude of parametric roll, as expected, shown in the 1DOF and 3DOF *LAMP-0* computations for both topside geometries (Tables 6 and 7). For the two smallest wave heights, parametric roll was not observed at any speed, for either topside geometry (Tables 6 and 7).

ONRTH

The 3DOF *LAMP-0* calculations for the unappended hull showed decreased parametric roll amplitudes for the 1.879-4.995m wave heights compared to the 1DOF simulations. For the 7.495m and 11.491m wave heights, the 3DOF parametric roll amplitudes computed were larger than the amplitudes computed by the 1DOF simulations.

The severity criteria, with the ship fixed at the calm water draft, consistently overpredicted the amplitude of parametric roll compared to both the *LAMP-0* 1DOF and 3DOF calculations, with ship free to sink and trim. The predictions from the 3DOF results and the severity criteria agreed for the 7.495m wave height.

The *LAMP-0* 1DOF results also predicted an increased amplitude of parametric roll compared to the 3DOF simulations. However, for the 11.491m wave height, the *LAMP-0* 3DOF simulations resulted in capsize, defined in this study as a roll angle event > 90 degrees, of the vessel (Table 6). Because of the large wave height condition and the occurrence of capsize early on in the motion time-history, the chosen wave initialization process in the simulation might have produced an unrealistic capsize event. Further investigation of wave ramp-up time is needed.

For the ONRTH, parametric roll occurred in the 5-11 knot range for the varying head sea wave conditions, except for the largest wave height, where parametric roll occurred in following seas.

ONRFL

The calculated amplitude of parametric roll for the unappended ship was larger for 3DOF than 1DOF *LAMP-0* simulations for the 1.879m wave height and larger.

The severity criteria consistently overpredicted the amplitude of parametric roll when compared to the 1DOF simulations by about 3-4 degrees. For the largest wave height, there was a large discrepancy between the predicted parametric roll amplitude from the 1DOF simulations and the severity criteria (Table 7).

3DOF simulations predicted an increase in parametric roll amplitude, compared to the severity criteria, by approximately 3 degrees for the 1.879m and 3.247m wave heights. The 3DOF and severity criteria predictions for both the 4.995m and 7.495m wave heights closely agreed. For the largest wave height, the amplitude of parametric roll predicted using the severity criteria was about 12 deg, or 30%, less than the computed 3DOF *LAMP-0* amplitude.

Parametric roll for the ONRFL occurred in the 15-21 knot range for the varying head seas wave conditions, and only at larger wave height conditions.

Parametric roll for the tumblehome topside occurred at smaller wave heights and lower speeds than for the flared topside geometry.

Roll Damping

The influence of both the linear and quadratic roll damping coefficients on *LAMP-0* results was examined for a fixed speed and single wave height (Tables 8 and 9). Reductions from the nominal linear damping coefficient of 3%, as specified in the ABS criteria, did not greatly affect the predicted amplitude of parametric roll, as can be expected in regular waves. Increased linear damping resulted in reduced roll amplitude, and linear damping coefficients greater than 10% resulted in a drastic decrease in roll amplitude for the severity criteria. For coefficients greater than 10%, roll was completely damped out for the 3DOF computations. For coefficients greater than 15%, roll motion was completely damped out for both the 1DOF computations and the severity criteria.

Although not included in the parametric roll analysis for multiple wave conditions, additional computations to examine the significance of the quadratic roll damping coefficient on the predicted parametric roll amplitude predictions from *LAMP-0* were made. Increasing the quadratic roll damping coefficient, from nothing to $2.00*10^3$ resulted in no major change in the *LAMP-0* predictions. A further one hundred-fold increase, resulted in a decrease in the simulation predictions and further increases damped out the roll amplitude completely.

Selected Analysis

Selected results for computations of the ABS susceptibility criteria (Figures 2 and 3), severity criteria (Figures 4 and 7-10), and *LAMP-0* (Figures 5, 6, 11, and 12) are shown. These representative cases show the unappended ONRTH at the 4.995m wave height with a linear damping coefficient of 3%.

Figure 2 shows the change of GM in waves, calculated from the susceptibility criteria. For this condition, a fifty-meter longitudinal difference in position of the wave crest, relative to midships, resulted in a decrease in GM, from nearly two meters to less than a third of a meter. The ONR tumblehome topside has been shown to be more likely to result in stability failure than the flared topside, at a given GM that would be considered acceptable for the flared topside (Bassler et al., 2007). Thus, a significantly reduced GM is more problematic for the tumblehome configuration than for the flared geometry.

The Ince-Strutt diagram (Figure 3) is a useful tool to examine the stability boundaries for the necessary frequency condition where parametric roll will occur. For a given condition where the frequency and excitation parameters are within the stability boundary, the onset of parametric roll can be predicted.

Because the Ince-Strutt diagram is obtained from a linear equation, parametric resonance of a nonlinear system is not confined to the stability boundaries (Spyrou, 2004) but it can still provide a useful tool for identifying possible conditions for parametric resonance.

Righting arm curves were plotted for each wave position for a given speed and wave height. The righting arm curve in Figure 4 was calculated with *EUREKA*, using ship balancing about calm water equilibrium and can be considered a quasi-static approach. The righting arm curves (Figures 5 and 6) were calculated using the post-processing capabilities of *LAMP* with balancing relative to the instantaneous ship position on the wave (Belenky and Weems, 2008).

The difference in predicted amplitude of parametric roll can be explained by the examination of predictions made using a quasi-static (Figure 4) or instantaneous GZ curve in waves (Figure 5 and 6) approach. A larger variation in the righting arm curves occurred in the severity criteria and *LAMP-0* 1DOF calculations. The *LAMP-0* 3DOF calculations show a strong clustering of righting arm curves around two peaks, close to the calm water righting arm curve peak heel angle of 20 and a heel angle of 40 degrees. 3-D representation of the GM change in waves, and the GZ change in waves as a function of roll angle and time are also shown (Figures 7 and 8). The instantaneous GZ curves in waves for the 3DOF results do not change as much as for the 1DOF results. The inclusion of heave and pitch motions reduced the overall change in stability in waves. The influence of heave and pitch on reducing the change of stability in waves shown using the dynamic model agrees with previous results using the quasi-static model (Shin et al., 2004).

Roll time-histories for parametric roll, predicted using the severity criteria (Figure 9) and a phase trajectory plot are shown. The phase trajectory plot of roll vs roll velocity provides a helpful illustration of the stability of the system. A circular "orbit" indicates system stability, in this case identifying the occurrence of parametric roll for the tumblehome topside (Figure 10). Calculations of roll time-histories from both *LAMP-0* 1DOF and 3DOF simulations are also shown (Figures 11 and 12).

Susceptibility Criteria

Table 4: ONRTH Susceptibility Results

Regular Wave Height (m)	Speed to Expect Parametric Roll, m/s (knots)	Encounter Frequency, ω_s, rad/s
0.298	11.181 (21.74)	1.094
0.880	9.969 (19.38)	1.044
1.879	8.571 (16.66)	0.987
3.247	7.131 (13.86)	0.928
4.995	5.882 (11.43)	0.876
7.495	4.783 (9.30)	0.831
11.491	-1.535 (-2.98)	0.572

Table 5: ONRFL Susceptibility Results

Regular Wave Height (m)	Speed to Expect Parametric Roll, m/s (knots)	Encounter Frequency, ω_s, rad/s
0.298	11.627 (22.60)	1.108
0.880	11.150 (21.68)	1.089
1.879	10.661 (20.73)	1.069
3.247	10.638 (20.68)	1.068
4.995	11.186 (21.75)	1.090
7.495	12.489 (24.28)	1.143
11.491	12.100 (23.52)	1.127

Table 6: Comparison of Severity and LAMP Results for ONRTH

Regular Wave Height (m)	Speed Examined for Parametric Roll, m/s (knots)	Amplitude of Parametric Roll, deg					
		Severity Criteria	LAMP Results				
			1DOF (Fully Appended)	1DOF (appended-rudders only)	1DOF (barehull)	3DOF (appended-rudders only)	3DOF (barehull)
0.298	All	None	None	None	None	None	None
0.880	All	None	None	None	None	None	None
1.879	5.673 (11.03)	14.398	None	4.248	15.51	None	10.35
3.247	4.630 (9.00)	24.683	15.88	19.99	21.03	11.59	15.51
4.995	3.630 (7.06)	28.964	22.87	24.72	24.83	21.1	21.54
7.495	3.086 (6.00)	27.422		19.28	19.60	24.59	27.29
11.491	-1.183 (-2.30)	30.868		17.38	17.91	Capsize	Capsize

Table 7: Comparison of Severity and LAMP Results for ONRFL

Regular Wave Height (m)	Speed Examined for Parametric Roll, m/s (knots)	Amplitude of Parametric Roll, deg					
		Severity Criteria	LAMP Results				
			1DOF (Fully Appended)	1DOF (appended-rudders only)	1DOF (barehull)	3DOF (appended-rudders only)	3DOF (barehull)
0.298	All	None	None	None	None	None	None
0.880	All	None	None	None	None	None	None
1.879	8.745 (17.00)	24.676	None	None	20.535	None	28.00
3.247	9.259 (18.00)	30.363	None	None	26.91	None	34.56
4.995	8.288 (16.11)	23.338	None	11.33	20.03	17.88	22.49
7.495	9.789 (19.03)	27.777	None	16.11	23.50	27.45	26.89
11.491	10.802 (21.0)	36.991	None	None	17.10	47.49	48.31

Table 8: Linear Roll Damping Influence on Severity and LAMP Results for ONRTH

Regular Wave Height (m)	Speed Examined for Parametric Roll, m/s (knots)	Linear roll damping coefficient, μ	Amplitude of Parametric Roll, deg		
			Severity Criteria	LAMP Results	
				1DOF (barehull)	3DOF (barehull)
7.495	3.086 (6.00)	0.01	**27.201**	**19.48**	**27.08**
		0.015	**27.19**	**19.76**	**27.09**
		0.025	**27.369**	**19.59**	**27.20**
		0.03	**27.422**	**19.60**	**27.29**
		0.10	**26.555**	**16.28**	**22.96**
		0.15	**22.692**	**3.97**	**None**
		0.20	**None**	**None**	**None**
		0.25	**None**	**None**	**None**

Table 9: Quadratic Roll Damping Influence on Severity and LAMP Results for ONRTH

Regular Wave Height (m)	Speed Examined for Parametric Roll, m/s	Linear roll damping coefficient, μ	Quadratic Roll Damping	Amplitude of Parametric Roll, deg	
				LAMP Results	
				1DOF (barehull)	3DOF (barehull)
7.495	3.086 (6.00)	0.03	$2.00*10^7$	**None**	**None**
		0.03	$1.00*10^7$	**None**	**None**
		0.03	$2.00*10^5$	**18.28**	**24.92**
		0.03	$2.00*10^3$	**19.55**	**27.34**
		0.03	0.00	**19.60**	**27.29**

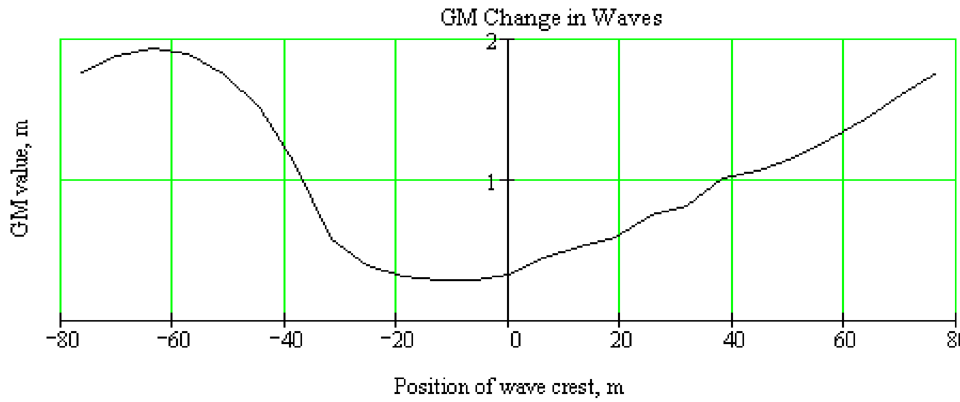

Fig. 2: Susceptibility Criteria: GM change in waves calculated for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0, Wave crest position zero at midships, positive toward the bow

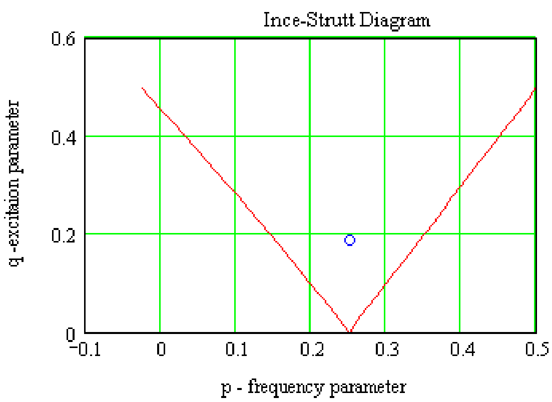

Fig. 3: Susceptibility Criteria: Ince-Strutt diagram calculated for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

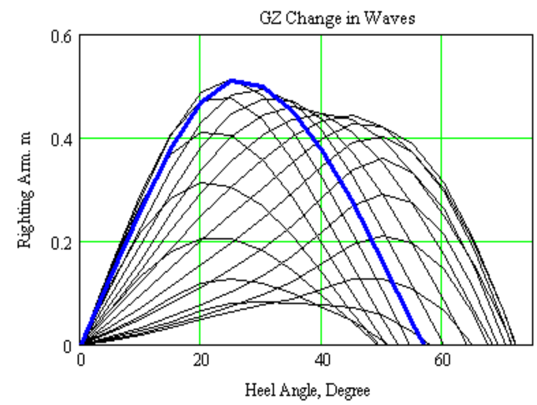

Fig. 4: GM Change in waves calculated using quasi-static method in *EUREKA* for ONRTH V_s= 3.630 m/s, in 4.995m head seas, λ/L=1.0

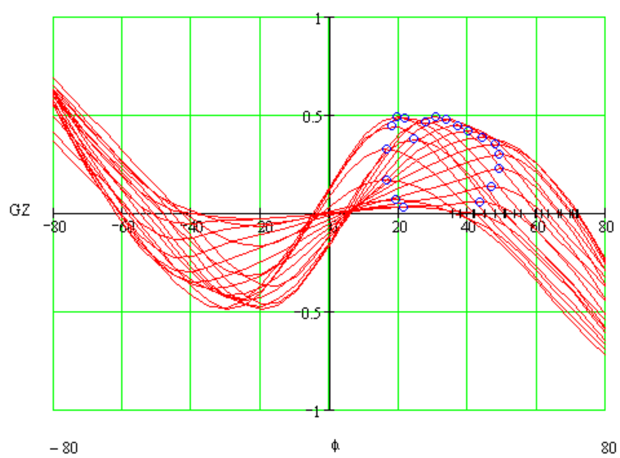

Fig. 5: LAMP-0 1DOF: Instantaneous GZ curve in waves calculated for unappended ONRTH Vs= 3.630 m/s , in 4.995m head seas, λ/L=1.0

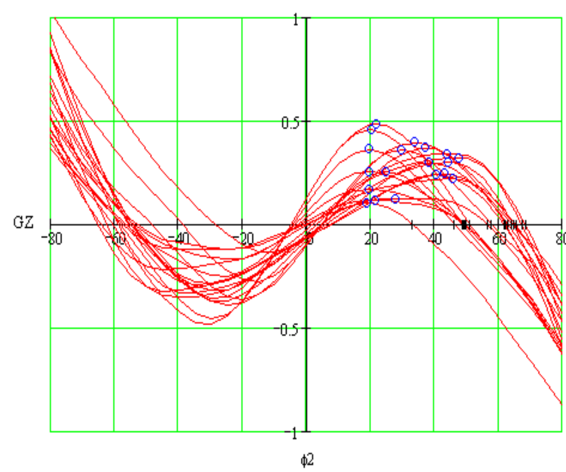

Fig. 6: LAMP-0 3DOF: Instantaneous GZ curve in waves calculated for unappended ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

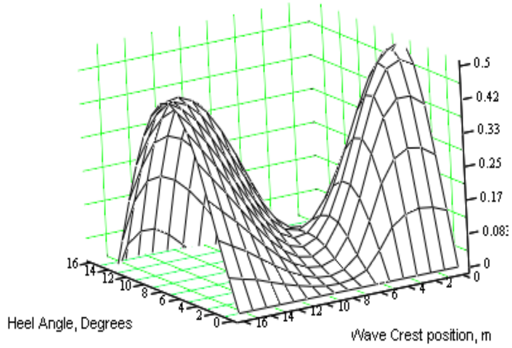

Fig. 7: Severity Criteria: 3-D View of GM change in waves calculated for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

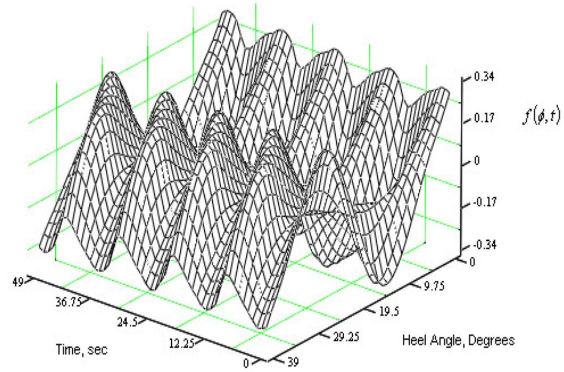

Fig. 8: Severity Criteria: GZ change in waves, as a function of roll angle and time, for ONRTH Vs= 3.630 m/s , in 4.995m head seas, λ/L=1.0

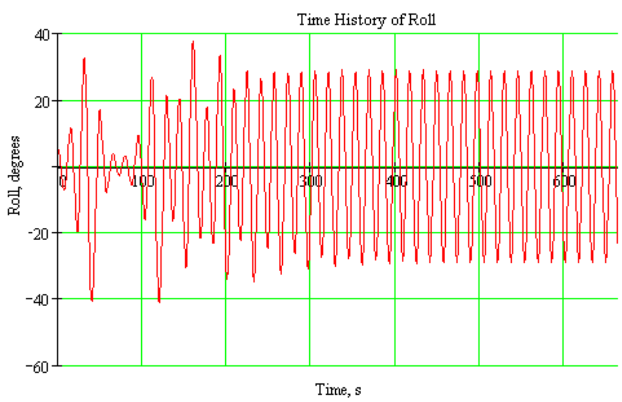

Fig. 9: Severity Criteria: Roll time-history computed for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

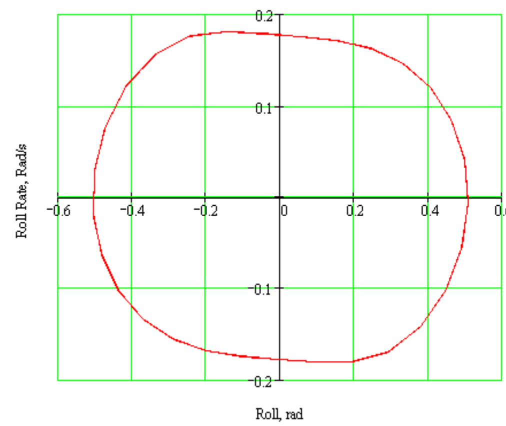

Fig. 10: Severity Criteria: Phase trajectory of roll velocity vs roll computed for ONRTH Vs= 3.630 m/s , in 4.995m head seas, λ/L=1.0

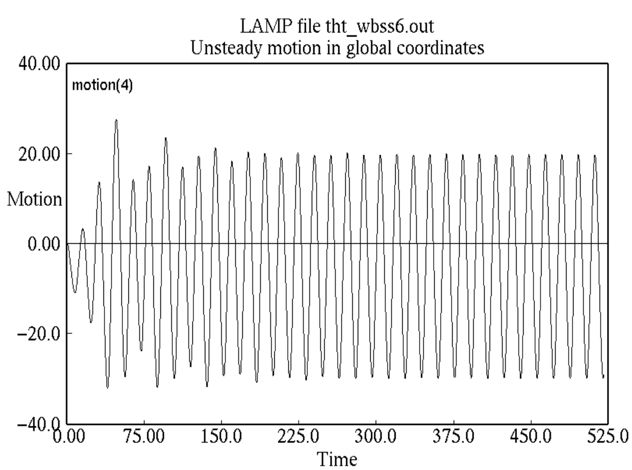

Fig. 11: *LAMP-0* 1DOF, unappended: Roll time-history computed for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

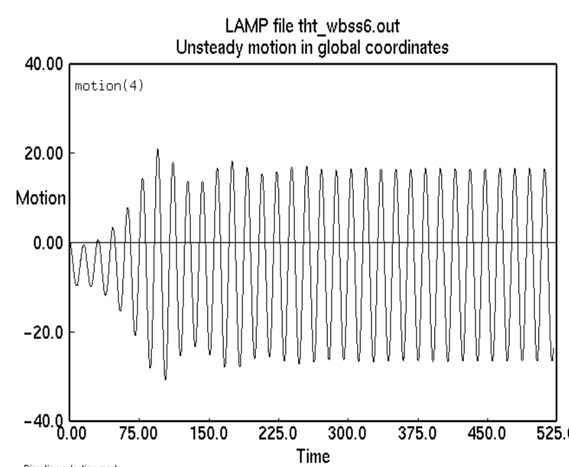

Fig. 12: *LAMP-0* 3DOF, unappended: Roll time-history computed for ONRTH V_s= 3.630 m/s , in 4.995m head seas, λ/L=1.0

CONCLUSIONS AND FUTURE WORK

The development of novel naval hull form geometries has led to a renewed interest in methods to assess stability vulnerabilities, including parametric roll. Methods which enable comparison of unconventional designs to more traditional naval hull forms are of great importance to allow for better understanding of the stability implications of drastic changes in hull form geometry.

This study examines the applicability of the industry standard for parametric roll assessment, originally developed for containerships, to assess parametric roll for naval vessels. The ABS susceptibility and severity criteria both predicted parametric roll occurrence and provided a conservative estimate of the amplitude of parametric roll, when compared to *LAMP* simulation predictions.

From the ABS criteria predictions and simulation results, topside geometry was shown to affect the amplitude of parametric roll for specific speed and wave height conditions and the speed where parametric roll would occur. Parametric roll for the tumblehome topside occurred at smaller wave heights and lower speeds than for the flared topside geometry. For the tumblehome topside hull, parametric roll occurred in the 5-11 knot range for the varying head sea regular wave conditions, except for the largest wave height, where parametric roll occurred in following seas. For the flared topside hull, parametric roll occurred in the 15-21 knot range for the varying head seas wave conditions, and only at the larger wave heights.

Ship speed conditions where parametric roll was observed for both topside geometries were less than typical service speeds for naval vessels. However, due to varied mission requirements, survivability for ship damaged conditions, and close-to-shore or return-to-port operations, a naval vessel must still be able to operate in a wide range speeds for various wave height conditions.

Only a limited scope of calculations was performed for this study to predict parametric roll of naval vessels in regular waves of wavelength equal to ship length. Using this data, a series of observations can be made concerning the operating speed under the examined wave conditions. To avoid parametric roll, the flared topside hull should travel at less than 15 knots or greater than 21 knots in wave heights greater than 4.995m. To avoid parametric roll, the tumblehome topside hull should increase speed with increasing wave heights, and not travel at less than 12 knots in wave heights greater than 4.995m. Although conditions where wavelength is equal to ship length typically represent worst-case scenarios, analyses of additional wavelength to ship length ratios are needed to confirm the maximum severity of parametric roll amplitude experienced by the ship in regular waves.

As expected, linear and quadratic roll damping coefficients did not have a notable impact on the predicted amplitude of parametric roll in regular waves. However, roll damping of a ship in irregular seas can influence the amplitude of parametric roll and should be examined in a future study.

The methodology presented in this paper also provides a demonstration of the current approach in the development of the International Maritime Organization's (IMO) *Framework for New Generation Intact Stability*. As defined in the IMO framework, vulnerability criteria can be used for an initial assessment of partial or total stability failure modes. Vulnerability criteria can also be used to differentiate between conventional hull forms, where traditional or simplified predictions for various modes of stability failure are satisfactory, and to identify unconventional hull forms where additional analysis must be performed.

The ABS assessment criteria provide an adequate and conservative initial analysis to identify susceptibility conditions and a prediction of the severity of parametric roll amplitude for naval vessels. Once speed and wave height conditions are identified where parametric roll can occur, further analysis can be carried out to verify the amplitude of parametric roll.

Additional computations including radiation and diffraction forces and a body-nonlinear formulation, such as with *LAMP-2*, are needed to evaluate the fidelity of the numerical model for realistic prediction of ship motions.

For *LAMP-0* 3DOF computations of the largest wave height condition, where capsize of the ship was observed, additional investigation of the wave initialization process is needed to verify whether capsize occurred because of suspected numerical instability or ship instability. Additional verification of both the ABS and *LAMP* predictions with model test data would also enable a better understanding of the fidelity of the predictions from both models.

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