On parametric roll predictions

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ABSTRACT

Experiments have been carried out with a model of the KCS container vessel. The model tests focussed on three out of five stability failure modes of the Second Generation Intact Stability Criteria that are currently being developed by the IMO. This paper focusses on two aspects of the prediction of the risk on parametric roll in regular waves. The first aspect is a check on the assumption of the IMO that simulation programs exist that properly can predict the risk on parametric roll; the second aspect is the effect of the roll damping model on the predicted parametric roll amplitudes.

The first aspect has been investigated by asking members of the CRS community[1] to do simulations using proprietary programs. Five members responded to this request. The paper shows that a prediction of the roll damping based on exclusively geometrical information results in quite different answers. If the coefficients of a quadratic damping model are fixed in the input, the predictions of parametric roll angles in regular waves as a function of the wave amplitude are quite close for the different simulation programs. However, there is a significant discrepancy between simulations and experimental results with respect to the threshold wave amplitude at which the parametric roll phenomenon starts. An investigation in the modelling of the damping shows that this has some effect, but it does not explain the large difference. A final conclusion is, that the studied simulation programs will benefit from further improvements to predict all aspects of parametric roll events accurately. A good understanding of these aspects is considered important for a reliable Direct Stability Assessment.

Keywords: *Parametric roll, roll damping, simulation, direct stability assessment.*

1. INTRODUCTION

As the Second Generation Intact Stability Criteria (SGISC) are now in the final phase, it is now the appropriate time to verify if the existing simulation tools are indeed ready for the Level 3 Direct Stability Assessment. Work has been done in the Cooperative Research Ships consortium that focused on three out of five failure modes: parametric roll, loss of stability and dead ship. This paper focusses on parametric roll in regular waves only. Results of different simulation programs are compared to results of experiments. The hull form chosen for this study is the Korean Container Ship (KCS) since this is a public hull form.

This work adds to existing benchmark cases like those published by France *et al.* (2003), Spanos and Papanikolaou (2009) and Reed (2011). The added value of this work is the effort put in accurately determining the roll damping, also for larger amplitudes, and in the availability of results both in regular waves (one wave length and increasing amplitude) and irregular seas (not presented here).

2. NOMENCLATURE

Symbol	unit	Description
$A_{\varphi\varphi}$	ton.m^2	Roll added moment of inertia
B_1	kNms	Linear comp. of roll damping
B_2	kNms^2	Quadr. comp. of roll damping
B_3	kNms^3	Cubic comp. or roll damping

[1] CRS – Cooperative Research Ships, www.crships.org

Symbol	unit	Description
B_{eq}	kNms	Equivalent roll damping
B_{cr}	kNms	Critical roll damping
$C_{\varphi\varphi}$	kNm	Roll restoring moment
g	m/s^2	Acceleration due to gravity
GM	m	Metacentric height
$I_{\varphi\varphi}$	$ton.m^2$	Roll moment of inertia
KG	m	Height CoG above keel
T	m	Draft
T_e	s	Wave encounter period
T_φ	s	Roll natural period
k_{xx}	m	Roll gyradius
k_{xx}^*	m	Roll gyradius incl. added mass
Vs	kn	Ship speed
Vs av	kn	Average ship speed
Δ	ton	Displacement
φ	rad	Roll angle
φ_a	rad	Roll angle – amplitude
ζ_a	m	Wave amplitude
ω_0	rad/s	Earth fixed wave frequency
ω_e	rad/s	Wave encounter frequency

3. SUBJECT VESSEL

The subject vessel is the KCS hull form. The main dimensions and loading condition are given in Table 1, the hull form is fully specified on the SIMMAN2008 website, SIMMAN (2008).

A model was constructed at scale 1:37.89. the model was equipped with bilge keels, height 0.40 m, length 68.82 m (St 6 – 14) and a rudder (span 9.90 m, mean chord 5.54 m). An autopilot kept the model on course.

Table 1: Main dimensions and loading conditions of the KCS for the parametric roll experiments.

Parameter	symbol	LC-1	units
Length perp.	Lpp	230.00	m
Beam	B	32.20	m
Draft	T	10.80	m
Displacement	Δ	53389	ton
Vertical CoG	KG	13.67	m
Metacentric height	GM	1.22	m
Roll nat. period	Tφ	23.6	s
Roll gyradius	k_{XX}	11.90	m
Pitch gyradius	k_{YY}	57.50	m
Yaw gyradius	k_{ZZ}	57.50	m

4. SIMULATION PROGRAMS

Five different simulation programs have been used in this paper, the programs are owned by the companies of the respective authors. The programs have identical basics: the hydrodynamics are calculated by a linear potential flow theory and the linear restoring and excitation due to the incoming wave are replaced by non-linear Froude-Krylov and restoring forces. Specifics about the programs used are detailed in Table 2.

Table 2: Characteristics of the simulation programs used in this study.

	Sim-1	Sim-2	Sim-3	Sim-4	Sim-5
Wave model	S5	L	L	L	L
Hydrodynamics	R	ZG	R	S	ZG
Rel. motion	I	I	I	I	I
Pressure for z>0	H	H	H	HW	HW
Pressure integration	M	M	M	M	M
Course control	SD	F	R	R	R
Speed control	S	C	S	C	C
DoF	6	6	6	6	6

Key to Table 2:

Wave model: most programs use linear waves (L), one program uses Stokes 5th order (S5).

Hydrodynamics: The hydrodynamics are based on Rankine source panels (R), Green functions for zero speed with an encounter frequency correction (ZG) or on strip theory (S).

Rel. motion: To determine the wetted surface, the relative motion is based on the incoming wave only (I) or incoming + diffracted wave (ID).

Pressure for z>0: The pressure above the calm water surface is usually determined by the hydrostatic pressure only (H). In two cases Wheeler stretching is added for the dynamic pressure (HW).

Pressure integration: the pressure integration is in all cases performed over a mesh (M), also in case the dynamics are calculated by a strip method.

Course control: Course control can be realized by springs and dampers (SD), by freezing the yaw degree of freedom (F) or by a rudder controlled by an auto-pilot (R).

Speed control: For these simulations, the speed is kept constant (C) or first order surge motions are allowed by means of a soft spring system (S).

DoF: The number of degrees of freedom that are solved by the equations of motion. For all cases all 6 DoF are solved, but the average speed is fixed.

A critical aspect is the determination of the roll damping. Usually this is an input value for the simulation program determined either by Ikeda's method or by CFD. One program uses a translation of the Ikeda method to the time domain to better capture non-linear effects.

5. ROLL DAMPING – CALCULATED

Calculations of the roll decay in calm water were made before doing experiments. The predictions were made by the various programs on basis of just the geometrical parameters. Not all programs have a procedure to estimate the damping of the rudder and bilge keels. In particular program 'Sim-3' uses only the potential flow damping of the naked hull. In general damping from CFD calculations would be added, but this was not done for this case.

Results of roll decay tests at Vs = 0 and 10 kn are given in Figure 1 and Figure 2 respectively. Especially at speed Sim-3, with only potential flow damping, is an outlier, but there is also a great variety in the roll damping for the other programs.

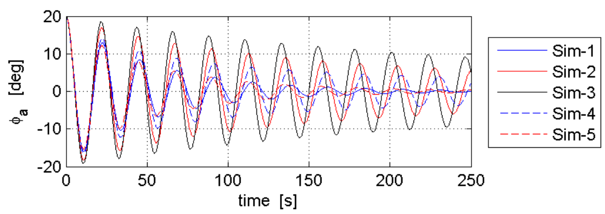

Figure 1: Result of the blind roll damping simulations. Initial angle 20 deg, Vs = 0 kn.

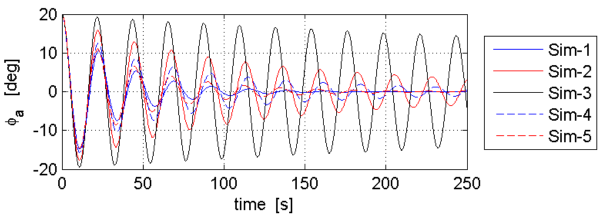

Figure 2: Result of the blind roll damping simulations. Initial angle 20 deg, Vs = 10 kn.

6. THE EXPERIMENTS

Experiments were carried out in the Seakeeping and Manoeuvring Basin of MARIN, measuring 170*40*5 meters. Tests were carried out with a target speed of 8 kn. This speed was considered to be the minimum speed to maintain course in large waves. The required thrust to achieve this speed in varying wave heights was estimated based on added resistance. The vessel was propelled by an electrical motor and a propeller. To avoid any influence of varying propeller RPM on the results, this was kept constant during each run. It was found that with the onset of parametric rolling, the added resistance increased significantly and the speed dropped from 8 to 5.5 knots. It was tried to increase the initial RPM to achieve a speed of 8 knots during parametric rolling. However, in these cases the initial speed was too high for parametric rolling to start due to a too large difference between roll period and twice the encounter frequency and a higher roll damping.

7. ROLL DAMPING - EXPERIMENTAL

Quite some effort was spent on measuring the roll damping since this is a critical parameter in most of the SGISC failure modes. Roll decay experiments were carried out at different speeds and different initial angles, repeat experiments were done for critical cases and forced roll experiments were done. This latter experiment was carried out by fitting an electrical motor with a flywheel inside the model. This motor was mounted on a 6 DoF force balance. The motor has the rotation axis in the longitudinal direction of the model and was forced in a harmonically changing RPM. The rotational acceleration of the flywheel provides the roll moment. Experiments were done with various amplitudes, all at the natural roll frequency.

The roll decay's were done for different initial angles: 6, 12 and 15 deg and several repeat tests were done. They were analysed using a fitting procedure for a 2nd order, 1 DoF roll damping model, eq. (1), as proposed by Lewandowski (2011). Note that the restoring moment in eq. (1) is defined by just the linear (hydrostatic) coefficient.

The forced roll tests were done with different values of the roll moment, all at the roll resonance frequency. The experiments were analysed using the measured roll moment by the 6 DoF force balance and using the phase angle between roll motion and moment produced by the motor.

$$\left(A_{\varphi\varphi}+I_{\varphi\varphi}\right)\ddot{\varphi}+B_1\dot{\varphi}+B_2\dot{\varphi}\left|\dot{\varphi}\right|+C_{\varphi\varphi}\varphi=0 \qquad (1)$$

The linear and nonlinear damping coefficient were combined to arrive at an amplitude dependent equivalent damping coefficient, eq. (2).

$$B_{eq} = B_1 + \frac{16}{3} B_2 \frac{\varphi_a}{T_\varphi} \qquad (2)$$

Often the damping parameters B_1 and B_2 are expressed in non-dimensional coefficients p and q. These coefficients are defined in eq. (3). These definitions make use of the critical roll damping B_{cr} that is defined in eq. (4).

$$p = 2\pi \frac{B_1}{B_{cr}}, \quad q = \frac{32\pi}{3T_\varphi} \frac{B_2}{B_{cr}} \qquad (3)$$

$$B_{cr} = 2\Delta k_{xx}^{*} \sqrt{g\,GM} \qquad (4)$$

The results of the roll damping experiments at Vs = 8 kn are shown in Figure 3. This figure shows the results of the roll decay tests over the range of roll angles that were used in the analysis of that particular test. It appeared not to be possible to have results at large roll amplitudes, but such results could be obtained from the forced roll tests. It appears that the results of the two methods give consistent results, but for large roll angles the forced roll experiment is the way to go.

Figure 3 also demonstrates a fundamental problem; it is not possible to accurately model the roll damping with just a quadratic model. The plot shows the equivalent linear damping as a function of the roll amplitude, so a quadratic roll damping model as defined in eq. (1) is displayed as a straight line following from eq. (2) and illustrated in Figure 4.

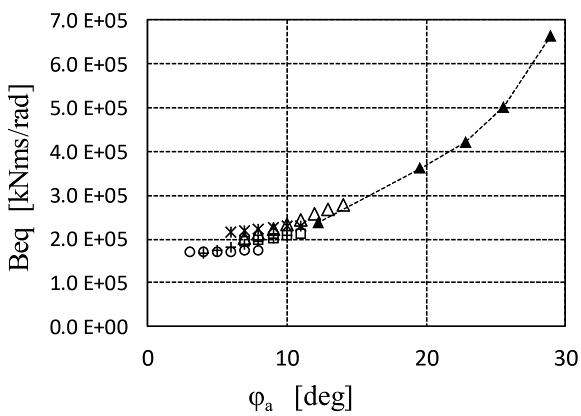

Figure 3: Roll damping at ω_φ = 0.273 rad/s and Vs = 8 kn. Results of forced roll tests (filled triangles connected by dashed line) and of roll decay tests (other symbols).

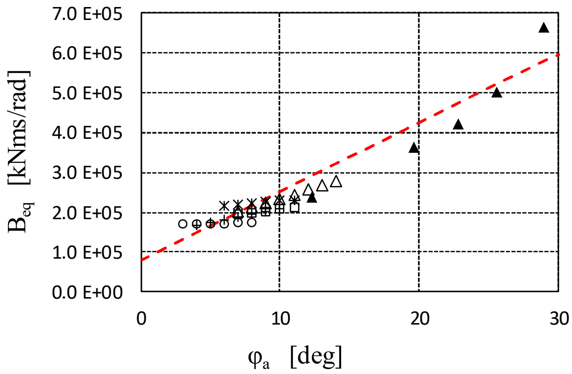

Figure 4: Roll damping at ω_φ = 0.273 rad/s and Vs = 8 kn. Experimental data (symbols), 2nd order model (red dashed line).

8. PARAMETRIC ROLL IN REGULAR HEAD WAVES

Experiments

The experiments in head seas were carried out at a speed that was selected as a minimum value to keep the vessel under (heading) control in a severe sea state: Vs = 8 kn. The wave condition was based on simulations to maximize the probability of parametric roll. This resulted in a wave length of λ/L=1.07. Together with a speed of 8 kn this results in an encounter period of Tφ/Te=2.2, which is slightly higher than the 'ideal' ratio Tφ/Te=2.0. An explanation might be, that the speed reduces when parametric roll occurs and hence the encounter period increases. This reduces the Tφ/Te ratio to a value of 2.1 for the last two cases given in Table 3.

Table 3: Results from the experiments in regular head waves, KCS – LC1.

ω_0 [rad/s]	ζ_a [m]	φ_a [deg]	Vs av [kn]	ω_e [rad/s]
	1.0	0.3	7.9	0.60
	1.5	0.2	8.2	0.61
0.50	2.0	0.2	8.4	0.61
	2.5	25.8	5.6	0.57
	3.0	26.9	5.5	0.57

The wave amplitude was increased such that the two highest waves showed large parametric roll angles. It was noticed that in the experiments the cross-over from no parametric roll to significant parametric rolling was very abrupt.

Results of the simulation programs

The choice was made to derive a linear and a quadratic damping coefficient from the experimental results. Since roll decay and forced roll results were available for 0 and 8 kn speed, p and q values were chosen for these speeds and it was agreed to use linear interpolation for intermediate speeds. The values used by all programs are listed in Table 4. The result of the p, q model for Vs = 8 kn is plotted in Figure 4 (the red dashed line) together with the results of the experiments.

A comparison of the various programs with the experiments is shown in Figure 5. It is apparent that all programs can model parametric roll. However, the calculations seem to onset parametric roll at lower wave heights than the experiments. This could be due to more idealized conditions in the calculations. For some programs the onset is significantly delayed at the lower wave heights and require a very long time to develop.

Table 4: Choice of p and q coefficients for the parametric roll simulations in LC-1.

Vs [kn]	p [-]	q [1/deg]
0	0	0.0235
8	0.107	0.0230

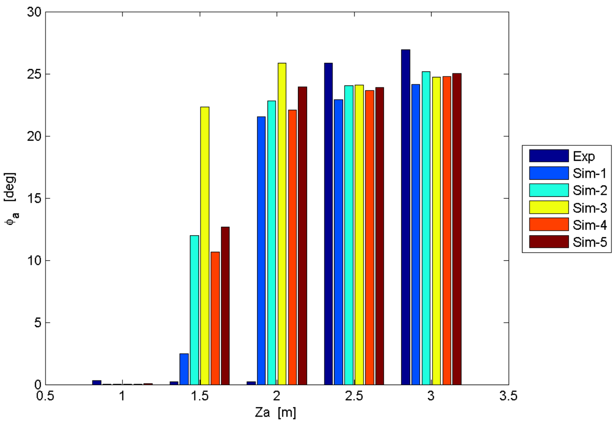

Figure 5: Comparison of roll amplitudes in regular head waves.

The results of the simulations and experiments are compared in Figure 5. Parametric roll occurred in the experiments only for a wave amplitude of 2.5m and higher, most programs predict the phenomenon to start at a wave amplitude of 1.5m.

The experiments in 1.5 and 2.0m wave amplitude showed no signs of parametric roll, although the length of the run was 540 s full scale. The measured wave and roll motion of the run in 2m waves are shown in Figure 6, the roll motion is very low, the roll period is the same as the wave period and there is no sign of any build-up of the amplitude. In a wave with a little higher amplitude, ζa=2.5m, there is however a significant amount of parametric roll with the characteristic factor 2 between the roll and the wave encounter periods, Figure 7.

For these simulations, it appeared that a 'water on deck' module in the programs needed to be switched off. Although in hydrostatic conditions there is a considerable amount of water on deck, the experiments showed that even at a speed of 5.5 kn and in a wave of 3.0m amplitude this was hardly the case for these dynamic conditions, Figure 8.

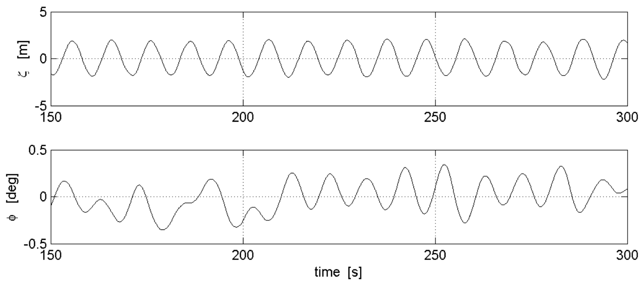

Figure 6: Measured roll motion in regular head waves, ζa = 2.0 m, ω = 0.50 rad/s. Vs = 8.4 kn.

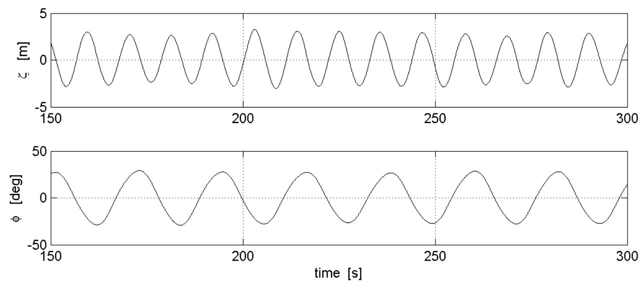

Figure 7: Measured roll motion in regular head waves, ζa = 2.5 m, ω = 0.50 rad/s. Vs = 5.6 kn.

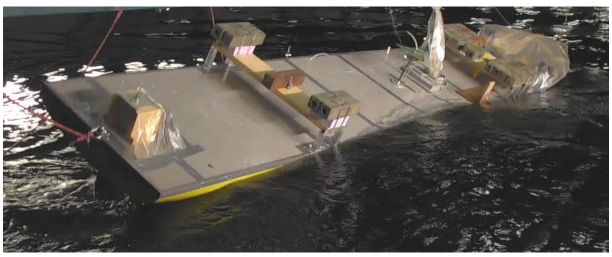

Figure 8: Still from the experiment in regular head waves at maximum roll angle: ζa = 3.0 m, ω = 0.50 rad/s. Vs = 5.5 kn.

9. VARIATION OF THE DAMPING MODEL

The comparison between the different simulation programs has been made with a medium fit, Figure 4, of the experimental damping data. This means that the damping is good for φ_a around 10 deg, but it is too low for both $\varphi_a < 5$ and $\varphi_a > 25$ deg. This might mean that the predicted wave amplitude for which the phenomenon starts might be too low and also that the final amplitude of the parametric roll motion in higher waves might be too low. Both are bad aspects for a prediction method.

In order to check the effect of the choice of the roll damping model and the value of the coefficients, two variants were tested:

1. Fit a 2nd order model on the roll damping at low amplitudes
2. Fit a 3rd order model on the full range of damping values.

The third order model is defined in eq. (5), the B_3 coefficient is usually presented as a non-dimensional factor r, eq. (6). The fits are illustrated in Figure 9 for Vs = 8 kn.

$$B_{eq} = B_1 + \frac{16}{3} B_2 \frac{\varphi_a}{T_\varphi} + 3\pi^2 B_3 \left(\frac{\varphi_a}{T_\varphi}\right)^2 \tag{5}$$

$$r = \frac{6\pi^2}{T_\varphi^2} \frac{B_3}{B_{cr}} \tag{6}$$

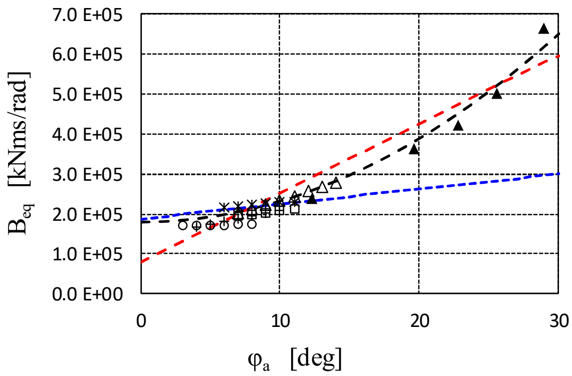

Figure 9: Roll damping of the KCS at Vs = 8 kn. Experimental data (symbols), 2nd order model based on all data (red dashed line), 2nd order model fitted on values at low amplitudes (blue dotted line) and 3rd order damping model (black dashed line).

Simulations with the Sim-4 program were carried out for these 3 models for the roll damping. Since initial results were surprising, small steps on the wave amplitude axis were made. The results are given in Figure 10. The figure shows that indeed the value of the roll damping at $\varphi_a = 0$ has some effect on the threshold wave amplitude at which parametric roll starts. Secondly, the figure shows that a lower roll damping at large roll angles results in larger parametric roll amplitudes. Both effects are however smaller than expected and the large discrepancy with the experimental results is not explained by any of these variations. The third order model blends the two second order models as expected.

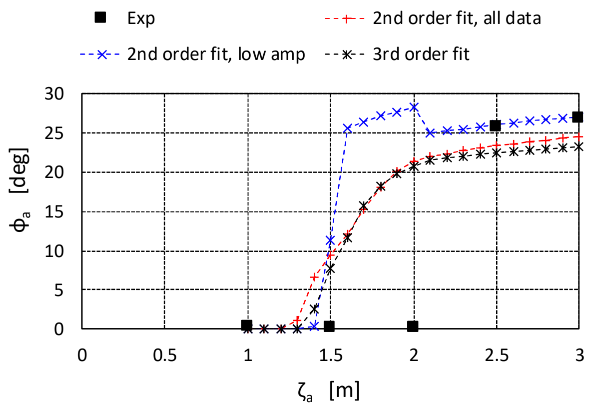

Figure 10: Results of simulations using a 2nd order damping model based on all data points (red dashed line), a 2nd order model fitted on values at low amplitudes (blue dotted line) and 3rd order damping model (black dashed line). Experimental data are indicated by black square markers.

10. DISCUSSION AND CONCLUSIONS

The IMO has published qualitative and quantitative criteria for simulation programs in document SDC 6/WP.6 dated 7 Feb 2019. It has been verified that the programs used in this study satisfy these criteria. Noted is, that these criteria specify limits for under-prediction of the roll angle, not for over-prediction. This means that only the results for wave amplitudes 2.5 and 3.0 m are relevant in this respect.

It can be argued that this work is not relevant for the SGISC since this vessel in this loading condition did not suffer from parametric roll using the criterion of a roll angle larger than 40 deg (in this case a lower angle would be applicable since the edge of the deck submerges at $\varphi > 22$ deg). However, large roll angles were measured and are also predicted. It is the opinion of the authors that these predictions should also be accurate in order to predict parametric roll angles of more than 40 deg.

The prediction of the roll damping inside the simulation programs appears to be very unreliable, this is a matter of concern. However, when this problem is avoided by using measured values for the roll damping, the predictions of five different simulation programs show little variation. It appeared that, although roll angles were larger than the angle at which there is water on deck in static conditions, the effect of water on deck should be ignored in simulations for this vessel at this speed.

The prediction of the threshold wave amplitude at which the parametric roll phenomenon starts appeared to be severely underestimated. Large roll angles were predicted for wave amplitudes in the range 1.5 – 2.0m while no parametric roll was measured in the wave basin. On the other hand, predictions appeared to be accurate for waves that showed parametric roll in the basin.

The roll damping is taken from experiments in calm water. Although there might be differences to the damping in waves, it is suggested that the problem in predicting the threshold wave amplitude correctly is mainly due to shortcomings in the mathematical model for the excitation of parametric roll. This problem is fundamental, it is present in all simulation programs.

A final conclusion is therefore that the studied simulation programs will benefit from further improvements to predict all aspects of parametric roll events accurately. A good understanding of these aspects is considered important for a reliable Direct Stability Assessment.

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REFERENCES

Lewandowski E.M., “Comparison of Some Analysis Methods for Ship Roll Decay Data”, 12th Int. Ship Stability Workshop, (STAB2011), 12-15 Jun 2011, Washington DC, USA.

SIMMAN (2008), MOERI Container Ship (KCS), geometry http://www.simman2008.dk/KCS/kcs_geometry.htm

France W., Levadou M., Treakle T.W., Paulling J.R., Michel R.K., and Moore C., “An investigation of head-sea parametric rolling and its influence on container lashing systems”, Marine Techn., Vol 40, No 1, pp1-19, Jan 2003.

Hashimoto, H., Umeda, N., Matsuda, A. and Nakamura, S., “Experimental and Numerical Studies on Parametric Roll of a Post-Panamax Container Ship in Irregular Waves”, Proc. of the 9th Int. Conf. on Stability of Ships and Ocean Vehicles, (STAB2006), 25-29 Sep 2006, Rio de Janeiro, Brazil.

IMO, Report of the Experts' Group on Intact Stability, Finalization Of Second Generation Intact Stability Criteria, IMO document SDC 6/WP.6, 7 Feb 2019.

Reed A.M., “26th ITTC Parametric Roll Benchmark Study”, 12th Int. Ship Stability Workshop, (STAB2011), 12-15 Jun 2011, Washington DC, USA.

Spanos, D. and Papanikolaou, A., 2009, “Benchmark Study on Numerical Simulation Methods for the Prediction of Parametric Roll of Ships in Waves”, Proc. of the 10th Int. Conf. on Stability of Ships and Ocean Vehicles, (STAB2009), 22 - 26 Jun, St. Petersburg, Russia.