Impulsive loads on and water ingress in a landing craft: model tests and simulations

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ABSTRACT

This paper describes the use of two potential flow simulation tools, of varying degrees of non-linearity, for predicting landing craft motions, impulsive loads and water ingress. A comparison between experimental and simulation results for a landing craft hull form operating in irregular seas is provided. During the experiments, severe wave impacts against the bow door are recorded, with water ingress occurring through the bow door. Simulation results for these phenomena are compared with corresponding experimental results. The results from both non-linear and semi-linear versions of the simulation tool are discussed, together with measures adopted in the semi-linear method to yield results that approach the more representative non-linear results.

Keywords: *Model tests, Impulsive wave loads, Water ingress, Simulation methods.*

1. INTRODUCTION

For assessing the safety of ships in waves by means of simulations, advanced prediction methods are required. The advanced prediction method should be capable of handling six degrees of freedom, large motion amplitudes, non-linear waves, non-constant wetted geometry, water on deck effects, forward speed effects, impulsive wave loads and propulsion and steering.

Prediction methods that are capable of handling the above are in principle suited to simulate phenomena like resonant large roll motions, parametric roll, capsize due to loss of stability in waves, capsize after broaching and surf riding (van Walree and Carette 2011). Computational Fluid Dynamics (CFD) and fully non-linear potential flow methods require large amounts of computer time. For safety assessment purposes, many simulations are required to cover all combinations of speed, heading, loading condition and environmental conditions. This makes fully non-linear simulation tools (i.e. body-exact) less suitable for timely safety assessment purposes. As a compromise, simulation tools that are non-linear in only certain aspects of the hydrodynamic problem, such as wave excitation and restoring forces, are typically employed.

The Landing Craft (LLC) operating out of the Australian Defence Force (ADF) Landing Helicopter Dock (LHD) were procured as a Military off The Shelf (MoTS) vessel for performing a sea-shore connector role for the LHD. LLC seakeeping is influenced by a number of challenges associated with their operation within complex non-linear wave environments as well as their requirement for delivering large payloads at relatively high speed.

The Defence Science and Technology (DST) Group were requested by the ADF to assist with an examination of the operability of the LLC. Partnering with the Maritime Research Institute Netherlands (MARIN), a scope of work was established that combined a model scale test program with numerical simulation development. The objective of the MARIN/DST collaboration was to develop a validated numerical simulation capability. This capability could be used by the ADF for determining operational guidance for LLC operations via the development of operability guidance plots. These polar plots, presented in a format similar to the Ship Helicopter Operating Limit (SHOL) polar plots, can be used to depict LLC operability over a range of vessel speeds and headings, loading conditions and sea states using a variety of limiting criteria.

Capability improvements through enhanced understanding of LLC operability will provide a force multiplier for ADF amphibious forces and deliver important safeguards for embarked personnel and materiel. Together with the provision of significant improvements to the operating envelope of the existing LLC, the ability to evaluate the operability of future LLCs will facilitate the sustainment of Australia's amphibious assault capability into the foreseeable future.

The paper discusses the model test arrangement, the main test results and the use of the simulation tools to generate operational guidance.

2. MODEL TESTS

Seakeeping test facilities throughout the world are typically designed to test ship models at scale factors between 1/36 and 1/22. As a result, the wave makers in the test facility have been designed to generate moderate to large seaways at these scale ratios.

Unfortunately, small vessel model testing at the aforementioned range of scale factors would require small models which are too small for instrumentation and are subject to scale effects.

The model scale used for the present vessel (1/6.5) was dictated by the maximum wave height that can be generated in the seakeeping basin, space and weight considerations.

A carbon fibre model was constructed with main dimensions as given in Table 1. Propulsion and steering was by means of twin water jet units with steerable nozzles. Figure 1 shows a photo of the model.

Table 1: Main particulars

Item	Magnitude	
	Medium Load	Full Load
Lpp (m)	21.3	21.3
B-wl (m)	6.40	6.40
Tf (m)	1.19	1.29
Ta (m)	1.10	1.22
Vol (m^3)	117.7	131.9
GMt (m)	2.07	1.65
Tφ (s)	3.68	4.15

In order to measure global loads the model was segmented in four parts which were connected through an instrumented aluminium beam. At the three segment cuts the vertical shear force and torsional and vertical bending moments were calculated. The beam dimensions were chosen such that the natural frequencies for the one and two node mode shapes were approximately scaled.

Care has been taken to include the outer stiffener structure on the bow door since this was expected to affect the occurrence of water intake through the bow door louver openings, see Figure 2. Pressure gauges were used to record local pressures in the bow region.

Figure 1: Model photo

Figure 2: Bow door detail

The tests were performed in the Seakeeping and Manoeuvring Basin of MARIN. The basin measures 170 x 40 x 5 m in length, width and depth. Wave making is achieved using 331 flaps that are all individually driven by an electronic motor along the lengths of two sides of the basin. This facilitates generation of regular and long- and short-crested irregular waves from any direction. A main carriage (x-direction) and a sub-carriage (y-direction) follow the free-sailing model. An optical motion tracking system sends position information to the on-board autopilot.

Test conditions consisted of:

- Nominal speeds of 8 and 12 knots (Froude numbers 0.28 and 0.56);
- Moderate irregular waves with $H_{1/3}$=1.25 m and T_p=5.50 s (top SS3) and $H_{1/3}$=2.50 m and T_p=6.95 s (top SS4) with directions between and including head and following seas.
- Two load conditions: 119 tonnes (t) and 134 t, representing 50 and 65 t cargo payloads.

3. MODEL TEST RESULTS

Model testing was performed for various combinations of loading condition, sea state, wave direction and speed to examine the operability of the LLC in terms of motions, accelerations, slamming and water ingress onto the loading deck. Occasionally, nominal operational limits are reached in Sea State 3 and more frequently in Sea State 4. Relevant notable findings arising from the test program include:

- Roll angles in SS4 exceed generic NATO STANAG 4154 limits in beam seas;
- Loss of course control is not observed, however heavy use of the steering nozzles is required for course keeping at lower speeds in stern quartering seas (SS3 and SS4) indicating that in higher sea states course keeping will be problematic;
- Water ingress through the bow door occurs in head and bow quartering seas, especially for the higher speed conditions. However the amount of water ingress did not compromise the stability of the vessel as it was discharged quickly through the freeing ports;
- In bow quartering SS4 conditions the vessel may occasionally be subject to breaking waves spilling over the side on to the loading deck;
- Slamming occurs frequently at high speed in bow and bow quartering seas. Impact pressures up to 320 kPa (full scale value) have been measured which is equivalent to a head of water of 32 m;
- The wave loads acting on the vessel are substantial in head and bow quartering seas due to wave impacts on the blunt bow shape.

4. SIMULATION TOOLS

The time domain panel methods are used for predicting hydrodynamic loads and seakeeping behaviour of high speed craft operating in waves. Characteristics of these simulation methods include:

- 3D transient Green functions to account for linearized free surface effects, exact forward speed effects on radiation and diffraction forces and a Kutta condition at ventilated transom sterns;
- 3D panel method to account for Froude-Krylov forces on the instantaneous submerged body;
- Cross flow drag method for viscosity effects;
- Resistance (in waves) is obtained from pressure integration at each time step;
- Propulsion and steering using propeller open water characteristics, semi-empirical lifting-surface characteristics and propeller-rudder interaction coefficients. Also a semi-empirical water jet propulsion and steering method is incorporated;
- Empirical viscous roll damping by either the FDS or Ikeda methods;
- Autopilot steering.

There are two versions of the simulation tool: a linear (PanShip) and a nonlinear one (PanShipNL). In PanShip, it is assumed that the motions of the craft are small, i.e. the submerged geometry does not change in time. Furthermore, the speed and heading are assumed to be constant so that the Green functions can be computed *a priori* for use at each time step in the simulation. In effect, the radiation and diffraction problems are then solved in a linearised manner while the wave excitation and restoring forces are treated in a nonlinear way by using the actual submerged hull geometry under the disturbed incident wave. The disturbed wave is obtained from the pressure at waterline panels.

In PanShipNL the motions may be large while the speed and heading are not necessarily constant. The discretisation of the submerged geometry and the computation of the Green function convolution integrals are performed at each time step. This approach is still not fully nonlinear due to the use of the Green functions which satisfy the linearised free surface condition. By discretising the actual submerged hull form and using the submergence relative to the undisturbed incident wave surface rather than the calm water surface, a semi-nonlinear approach is obtained. More detailed information can be found in Van Walree et al (2016).

The hull form of MARIN model M10009 was discretised into a surface mesh consisting of 1400 panels below the still water level and 900 above the still water level panels. Figure 3 shows the mesh with a typical pressure distribution. The bow wave is clearly discernible.

During the simulations the ship was free running and self-propelled and kept on course using an autopilot. The impeller RPM was set such that the mean speed in waves was approximately equal to that of the model tests. The autopilot gains were the same as used for the model tests.

For all PanShip simulations the effect of forward speed on sinkage and trim was taken into account by determining the calm water equilibrium position a priori and adapting the hull mesh accordingly. For the PanShipNL simulations this was automatically achieved during the simulation since the mesh was adapted to the instantaneous motions and incident wave profile at each time step. The disturbed wave profile is not included in the adapted mesh; it is used for a hydrostatic correction of the pressure at each time step.

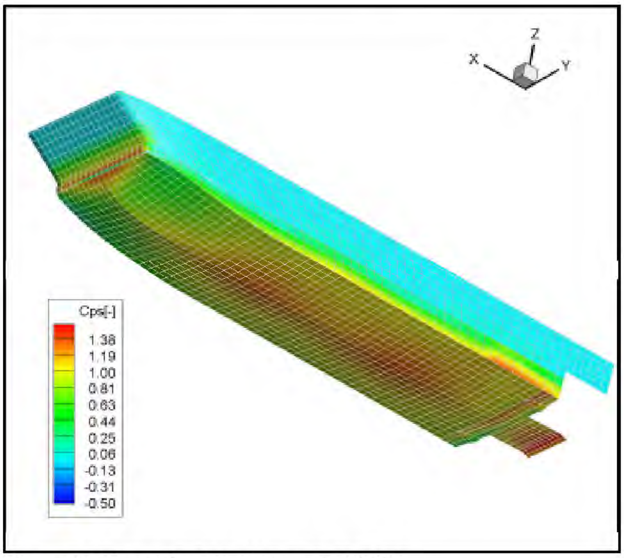

Figure 3: Discretised hull form M10009

Linear lift roll damping is included by means of the IHT method, see Ikeda (1978). For the Landing Craft model considered in this paper, quadratic roll damping was found to be well represented by the cross-flow drag method used to estimate viscosity effects in the horizontal plane for course keeping and manoeuvring.

5. SIMULATION RESULTS

Motions

Figures 4 through 7 show a comparison of motion responses for the 119 t load condition in SS4 at 8 knots speed for five wave directions where 180 deg is head seas. The response is defined here as the standard deviation of the motion divided by that of the wave height.

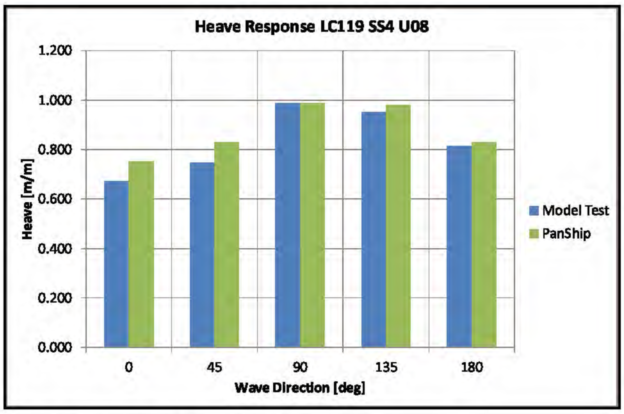

Figure 4: Comparison of heave

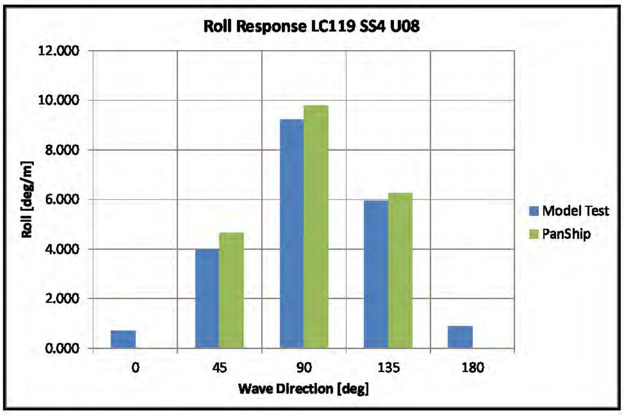

Figure 5: Comparison of roll

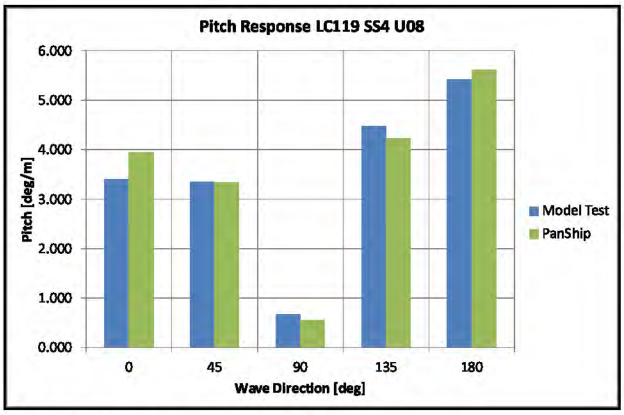

Figure 6: Comparison of pitch

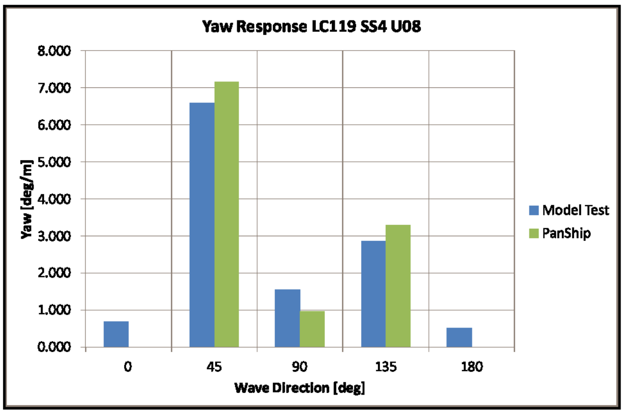

Figure 7: Comparison of yaw

The figures show that the motions are adequately predicted by the linear PanShip method. As a ship-to-shore connector for the LHD, the LLC is expected to be fully loaded on 0-90 deg headings most often as it transits from ship to shore, then most likely unladen on 180-90 deg headings on its way back to the LHD.

Wave loads

Although there are no criteria formulated for wave loads it can be an important aspect of the operability of landing craft. Figures 8 through 10 show a comparison of the mid-ship vertical shear force, torsion moment and vertical bending moment response. For this case the speed is 12 knots in SS3 and the 119 t loading condition. The uncertainty of the measurements is indicated by the error bars. It is seen that in bow seas the vertical shear force is overpredicted and the vertical bending moment is underpredicted by PanShip. This is unsurprising since the linear PanShip method cannot predict wave impact and hydro-elastic effects.

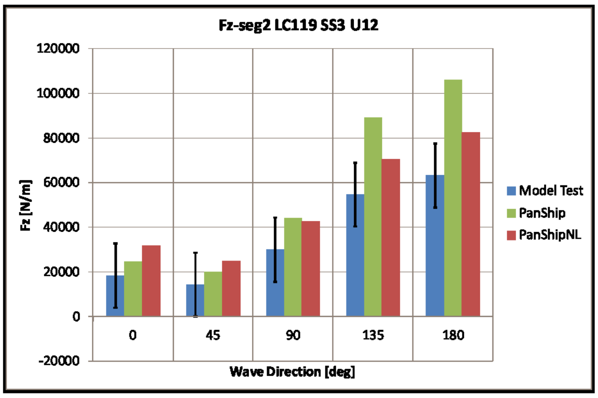

Figure 8: Comparison of vertical shear force

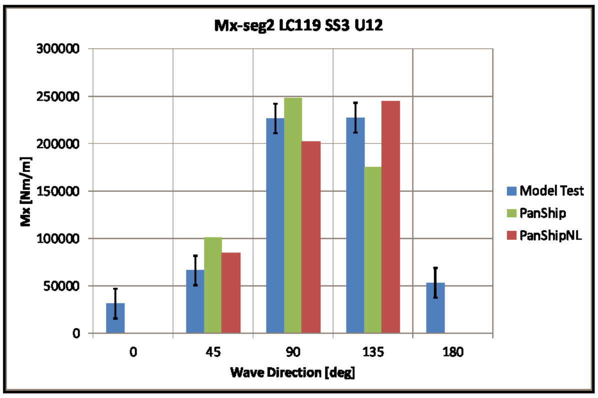

Figure 9: Comparison of torsion moment

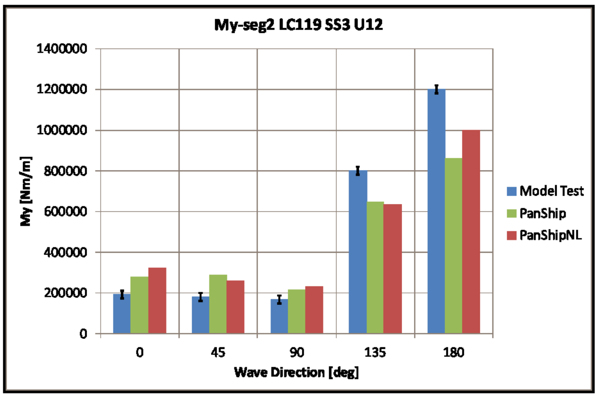

Figure 10: Comparison of vertical bending moment

The non-linear version PanShipNL does include wave impacts but still lacks hydro-elastic effects. Figures 8 through 10 show improved predictions using PanShipNL for some, but not all conditions. It is expected that the inclusion of hydro-elastic effects would improve the wave impacts prediction capabilities of PanShipNL.

Water entry

The next item of interest is water entry through the bow door louver openings. The model tests show that water may enter through these openings in head and bow quartering seas, especially at higher speeds and for heavier load conditions, see Figure 11. This phenomenon cannot be accurately predicted by PanShip due to the massive breaking bow wave and the flow blocking effect of the bow door stiffener structure. A CFD-based method is required here but would be too time consuming for generating operability information. The same is true for the non-linear PanShipNL method.

Figure 11: Model shipping water

As a compromise the following approach has been taken: depending on speed and wave direction, an additional factor (0.35 to 0.65 m) is added to the threshold relative wave height in PanShip (2.00 m above the water line) so that the predicted probability of water ingress better matches experimental observations. The probability is defined as the percentage of wave encounters that result in a water level on the deck of 0.10 m or more. Figure 12 shows a comparison between experimental, non-tuned and tuned water entry probabilities. The non-tuned simulation data are clearly much too conservative while the simple tuning does result in realistic water entry probabilities.

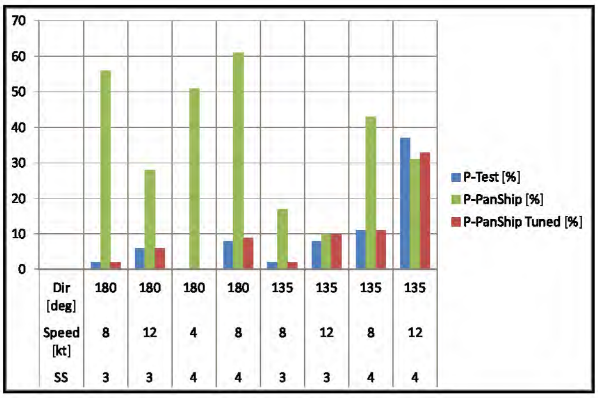

Figure 12: Water entry probabilities

Slamming

Figures 13 and 14 show the effect of a slam on the vertical acceleration and vertical bending moment. The condition is bow quartering seas SS4 at 12 knots for the 119 t loading condition. The wave frequent signal (WF) has been obtained by low-pass filtering of the measurement signal (HF). The whipping vibrations can be clearly seen in the HF signal.

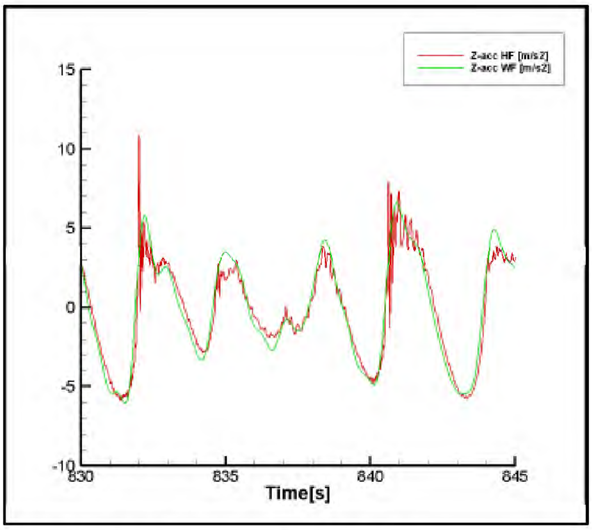

Figure 13: Vertical acceleration at the bow

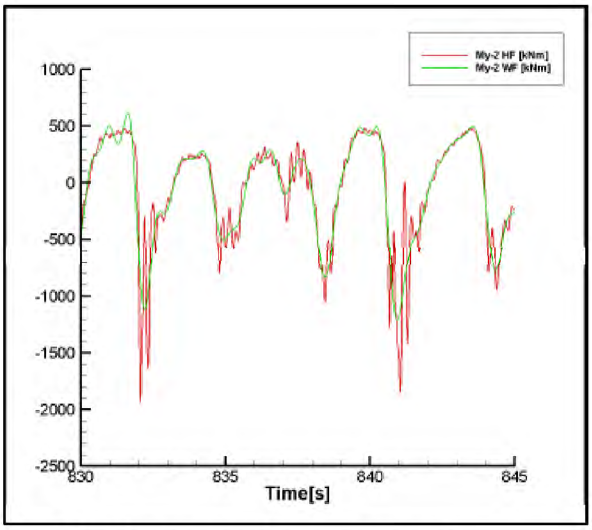

Figure 14: Midship vertical bending moment

For determining the effect of slamming on operability, one needs to define what a slam is and how much slamming can be allowed. To define a slam one can inspect time traces such as those shown in Figure 13-14 and declare an event with a significant peak followed by whipping response to be a slam. But what is significant in this respect? Another approach is to define a pressure recording above a certain threshold a slam. This approach has been adopted here, with a threshold value of 30 kPa (full scale value), related to the forebody impact pressure specified in the relevant Classification Society structural design documentation. Although not employed in this work, alternate slam identification approaches are available, see Thomas (2003) and Magoga et al. (2017) for details. The linear PanShip simulations have been tuned on the basis of the model test results with an Ochi-type approach, see Ochi (1973). An exceedance of a threshold value for the relative vertical velocity between the pressure gauge locations and the water surface is counted as a slam. The default Ochi threshold is $V_{rel} = C\sqrt{gL}$ with a value for C of 0.093 and where L is the length between perpendiculars. Figure 15 shows the experimental slamming probabilities and corresponding C-values which result in the same probability in PanShip. The C-values are seen to be fairly constant and higher than the default Ochi value.

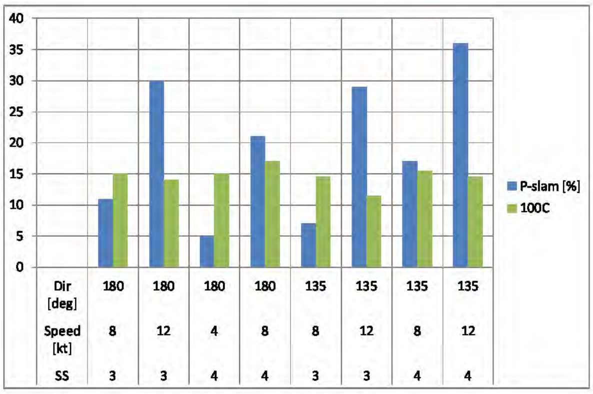

Figure 15: Slamming probabilities

The non-linear PanShipNL method can predict impact pressures. Using the same slam determination method as utilised on the model test data, the slamming probabilities predicted by PanShipNL are shown in Figure 16 for a selection of conditions. The correlation is considered to be satisfactory.

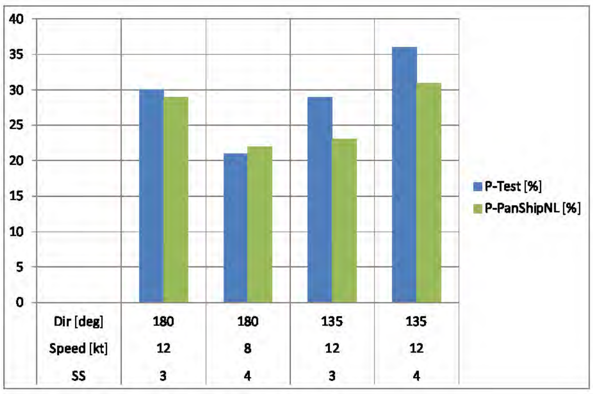

Figure 16: Slamming probabilities

6. OPERATIONAL GUIDANCE

The tuned linear PanShip method has been used to generate operability data for a large number of conditions. The conditions consisted of four sea states, three loading conditions, four speeds and thirteen wave directions, in total 624 conditions. For each condition half hour simulations were performed. The challenge is to define suitable operability criteria. In consultation with a range of stakeholders the following criteria are applied to the simulation results to generate the operational guidance plots:

- Standard deviation of roll 4-8 degrees;
- Probability of water ingress 5-10%;
- Probability of slamming 5-10%;
- Standard deviation of horizontal and vertical acceleration pilot house 1 and 2 m/s^2, respectively.

The operability guidance plots show three zones:

- Green: normal risk;
- Yellow: higher risk, consider additional controls;
- Red: urgent operational requirement only.

An example plot is shown in Figure 17.

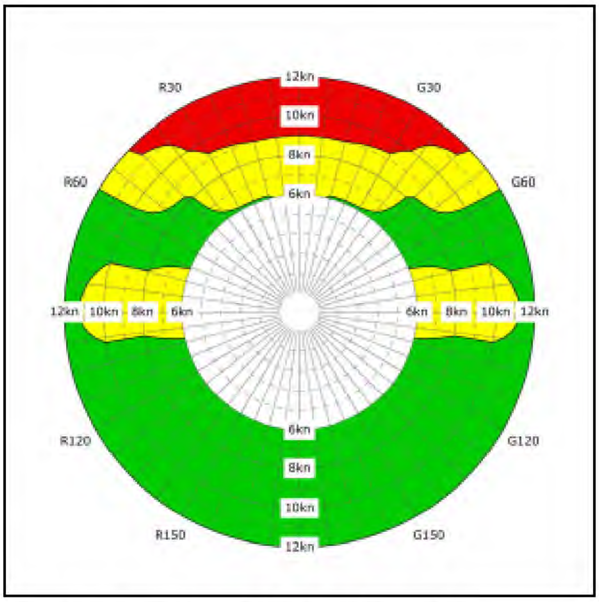

Figure 17: Example operability guidance plot

7. CONCLUDING REMARKS

The paper has addressed the use of the combination of model tests and simulation tools for generating operability data for a landing craft. The linear simulation tool PanShip can be used for the prediction of motions in waves. For predicting the occurrence of slamming and water entry through the bow door experimental data for tuning purposes is required. Predictions for wave loads are reasonable for conditions without slamming.

For improved wave load predictions in head seas the non-linear tool PanShipNL is required.

This tool can predict slamming loads without the need for tuning by using experimental results.

For the prediction of water entry through the bow door, experimental data for tuning purposes is required when using potential flow based simulation tools. CFD based tools would be better suited for this scenario, but are not presently practical for generating operability information due to lengthy simulation runtimes.

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