Validation of Simulation Tools for a RHIB Operating in Heavy Seas

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ABSTRACT

The paper describes model test experiments representing a Rigid Hulled Inflatable Boat (RHIB) in heavy seas. A numerical simulation tool is briefly described. Simulation and experimental results are compared in a deterministic way. The cases that are compared include regular and irregular waves from various directions.

Keywords: *Small boat, Heavy seas, Numerical Simulation, Validation.*

1. INTRODUCTION

The US Coast Guard has undertaken a project to develop a standard process to define operability limits for small boats supporting naval missions. Coast Guard boats are often operated in challenging sea conditions, requiring considerable operator skill to avoid swamping, capsizing, and broaching.

Analytical tools for small boat seakeeping predictions must be developed and validated for use in the definition of operating limits. Scale model testing was chosen as one means to provide validation data and identify nonlinear behaviors for a model representing a cutter boat.

2. MODEL AND TEST PROGRAM

Considerable efforts have been made in seakeeping model tests of conventional ships during the past century. Up to now, only limited research has been performed on small boat seakeeping.

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 boat 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 approach taken for this model test was to build a 1 meter light-weight model with full instrumentation and conduct tests in moderate and steep seaways. Concerns regarding scale effects in roll damping were dealt with by comparing model scale roll damping with roll decay tests performed full-scale. Trim as a function of speed was also verified by comparing model scale data with full scale.

A carbon fiber RHIB model was constructed with main dimensions given in Table 1. Propulsion and steering is by means of a single centerline water jet unit with steerable nozzle.

Table 1 Main particulars

Item	Magnitude	
	Design Load	Full Load
Lpp (m)	6.00	6.00
B-wl (m)	2.144	2.144
Tf (m)	0.446	0.547
Ta (m)	0.646	0.689
Vol (m^3)	3.762	4.559
GMt (m)	0.720	0.551
Tφ (s)	2.04	2.46

The model scale was dictated by maximum wave height that can be generated in the SMB of MARIN. The required significant wave height was 3.00 m yielding scale 6.7 model with a length of 1 m.

Due to high speed and large motions in the horizontal plane the carriage cannot always follow the model. The model needs therefore to be fully

[1] *The views expressed herein are those of the author and are not be construed as official or reflecting the views of the Commandant or of the US Coast Guard.*

free running with on-board position measurement system, autopilot computer, power supply, measurement instrumentation and data storage.

The instrumentation consisted of:

- Optical motion tracking system;
- XSENS inertia and rate gyros in 6 DoF at CoG;
- Accelerometers forward and aft;
- Propulsion motor RPM;
- Steering nozzle angle;
- Cockpit and collar water level sensors;
- Incident wave sensors at three locations around the model;
- Pressure transducers to record green water impacts against steering console;
- On-board mini camera;
- miniature PC with autopilot software and hard disk for data storage;
- system for transmission of measurement data to carriage via WiFi.

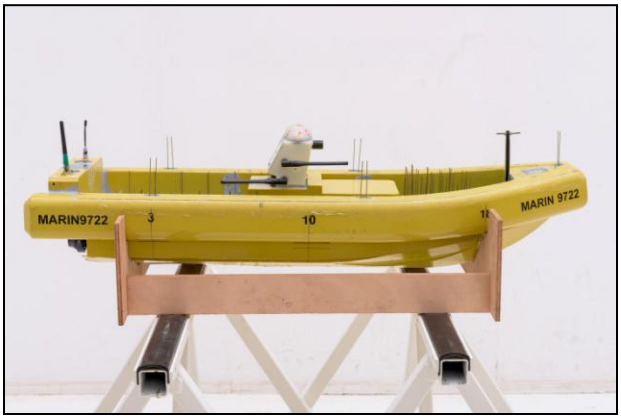

Figure 1 Model photo

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. It is equipped with wave makers along one long and one short side. The wave maker consists of 331 flaps that are all individually driven by an electronic engine. 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) attempt to follow the free-sailing model. The optical motion tracking system functions when the model is in the measurement window of the carriage. It sends position information to the on-board autopilot. When not in the measurement window the on-board inertia navigation system takes over.

Test conditions consisted of:

- Nominal speeds of 6 and 12 knots (Froude numbers 0.35 and 0.70) complemented with free drifting tests;
- Steep regular waves with steepness $H/\lambda=1/15$ and varying wave length, height and directions between and including head and following seas;
- Moderate irregular waves with $H_{1/3}=1.7$ m and $T_p=6.9$ s with directions between and including head and following seas;
- Steep (breaking) irregular waves with $H_{1/3}=2.5$ to 3.0 m and $T_p=5.2$ s with directions between and including head and following seas;

3. MODEL TEST RESULTS

The regular wave tests show that:

- Motion responses are typical for planing craft hull forms operating in the sub-planing speed ranges;
- High vertical accelerations and pitch angles are recorded in head waves, especially for the higher speeds. Transverse accelerations are substantial in beam seas;
- Some ingress of water occurred for the lower speeds in head waves;
- Impact pressures at the steering console occurred for a few head wave conditions only.

In irregular waves safe operation limits are reached occasionally in NATO Sea State 4 and more frequently in a steep Sea State 5:

- Excess horizontal and vertical accelerations occur for operation in head and bow quartering seas at 12 knots;
- Excess pitch angles are recorded prior to wave jumping, i.e. when the boat jumps out of a wave crest;
- Water ingress over the bow occurs in head and bow quartering seas, especially for the lower speed conditions;
- Surf riding occurs in Sea States 4 and 5 at 12 knots speed in stern quartering and following seas. Broaching after surf riding with accompanying high heel angles does not occur;
- Loss of course control is seen in Sea States 4 and 5 stern quartering seas;
- In stern quartering sea state 5 conditions at a 6 knots speed the boat is swamped due to breaking wave crests overtaking the boat. In

these conditions capsizing may also occur due to loss of course control resulting in beam-on breaking waves. One capsize has been observed for the design load condition and two for the full load condition for a half hour test duration for each loading condition. Figure 2 shows a swamping event.

Figure 2 Swamping event

4. SIMULATION TOOLS

The PanShip(NL) time domain panel methods are characterized by:

- 3D transient Green function 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 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 semi-linear (PanShip v2.4) and a semi-nonlinear one (PanShipNL v1.2). 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 linearized 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.

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 each time step. This approach is still not fully nonlinear due to the use of the Green functions which satisfy the linearized 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 De Jong (2011) and Van Walree and Turner (2013).

The hull form of MARIN model 9722 was discretized into a surface mesh consisting of some 1900 below water and 2100 above water panels. Figure 3 shows this mesh with segment boundaries in blue. The flow streaks on the hull bottom and transom flaps were not included in the mesh. The effects of these were included empirically in PanShip(NL).

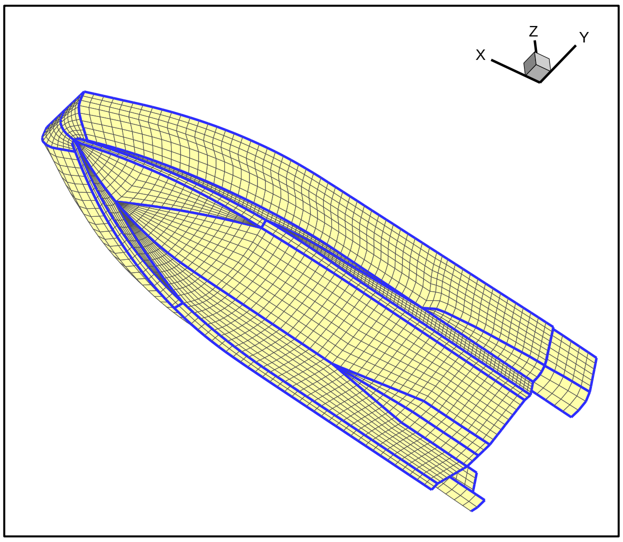

Figure 3 Discretized hull form m9722

During the simulations the ship was free running and self-propelled and kept on course through 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 each time step.

Viscous roll damping is included by means of the FDS method, see Blok and Aalbers (1991). No tuning of the roll damping on basis of model test data has been applied.

5. VALIDATION RESULTS

Validation is based on direct time trace comparison, whereby the input wave train was reconstructed in the simulations. For regular waves this is a simple procedure. For irregular wave the procedure is more elaborate as explained in Van Walree et al (2016).

5.1 Regular waves

In the steep regular waves considered here acceleration responses may be non-sinusoidal. It is noteworthy to mention that for the higher 12 knots speed the linear PanShip code could not deal with head sea conditions. In the simulation, the boat jumps out of the steep waves to reach pitch angles over 90 degrees. The non-linear PanShipNL code however can deal with these conditions. Figures 4 through 8 show comparisons between experimental and simulated time traces for a steep regular head wave with a frequency of 1.88 rad/s and an amplitude of 0.58 m, i.e. H/λ=1/15. The waterjet RPM was set for a calm water speed of 15 knots. Figure 4 shows that in waves the speed (X0d) varied between about 7 and 10 knots which is well predicted by PanShipNL.

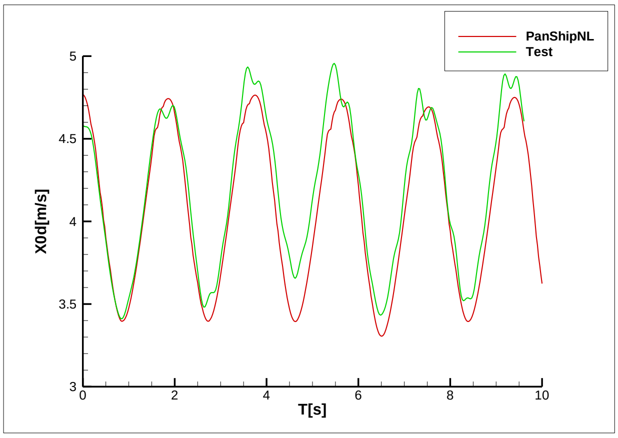

Figure 4 Comparison of forward speed

The heave (Z0) and pitch (Theta) time traces shown in Figures 5 and 6 show adequate predictions as well. Note the slight trochoidal character of the pitch motion.

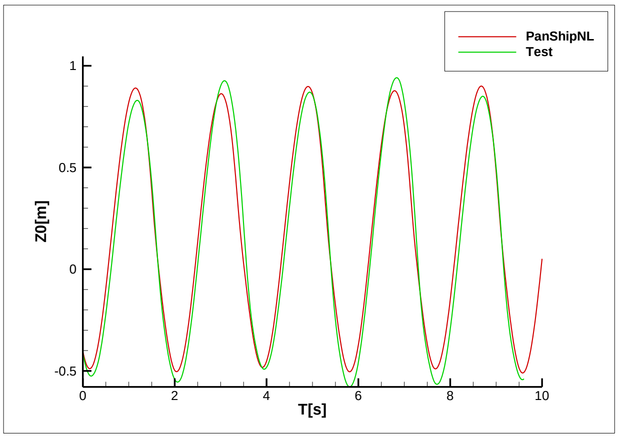

Figure 5 Comparison of heave

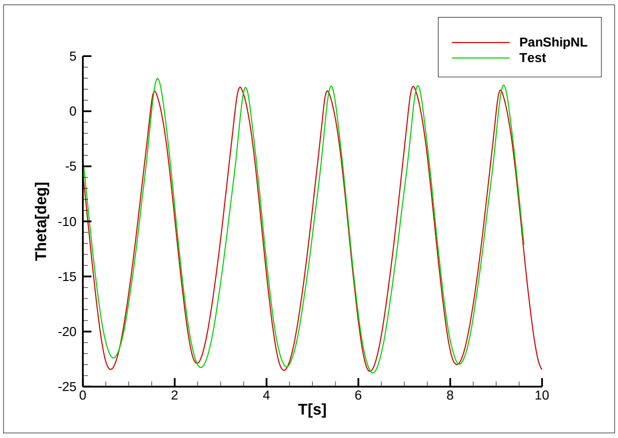

Figure 6 Comparison of pitch

The longitudinal (Acc-x04) and vertical (Acc-z04) acceleration components at the bow shown in Figures 7 and 8 show slamming peaks which are reasonably well predicted. The experimental time traces show the effect of a slight variation in wave amplitude which is due to non-linear wave propagation effects in the basin.

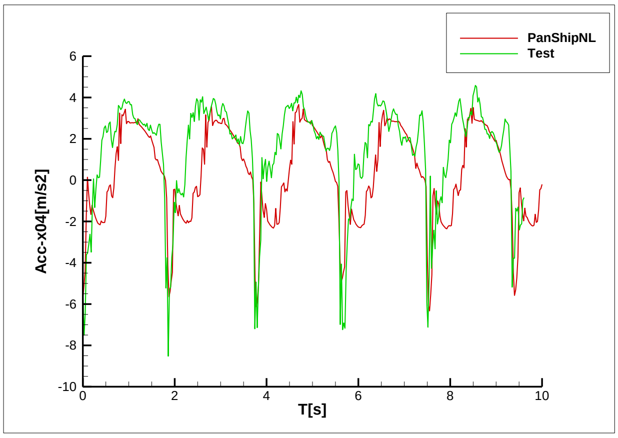

Figure 7 Comparison of x-acceleration

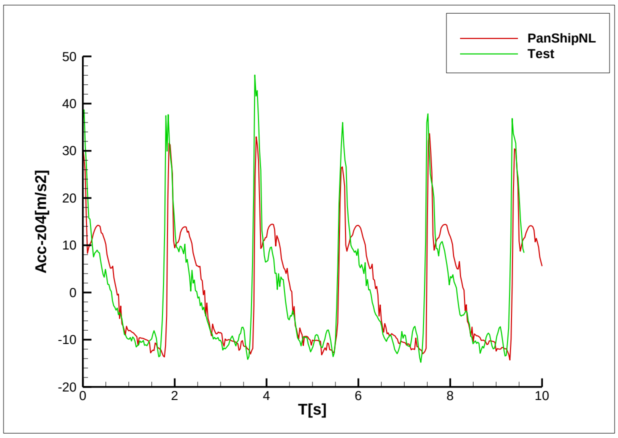

Figure 8 Comparison of z-acceleration

Figures 9 through 16 show a comparison of time traces for a near following seas condition with a wave direction of 15 degrees off the stern. The wave frequency is 1.88 rad/s and the wave amplitude is 0.45 m with H/λ=1/20. The waterjet RPM was set for a 6 knots calm water speed, yet the speed in waves varies between about 14 and 19 knots, when the model is captured and released by the wave crest, see Figure 9. This speed variation is well predicted by the linear PanShip code.

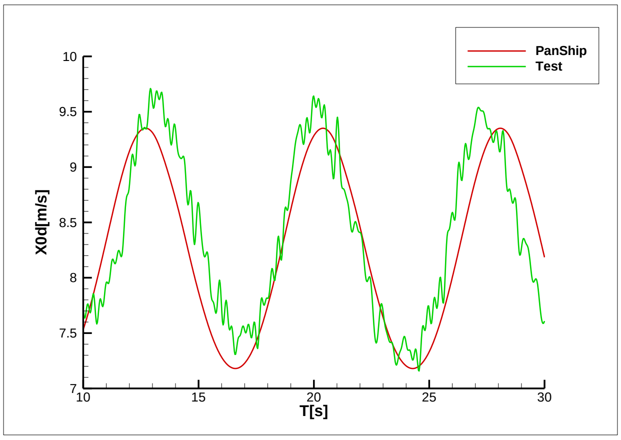

Figure 9 Comparison of forward speed

Figures 10 through 13 show that the motions are reasonably well predicted although the experimental roll and yaw motions are somewhat affected by wave reflections from the basin beaches.

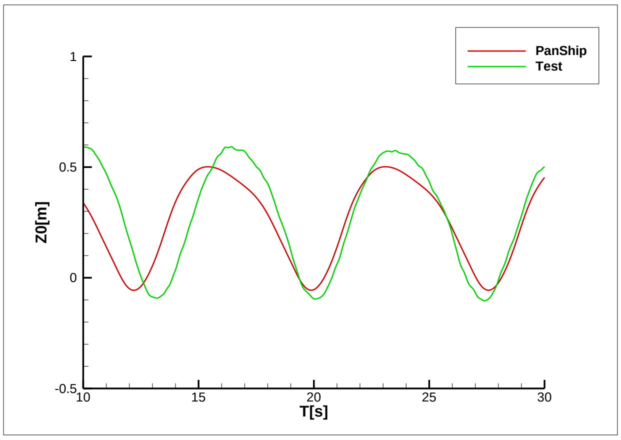

Figure 10 Comparison of heave

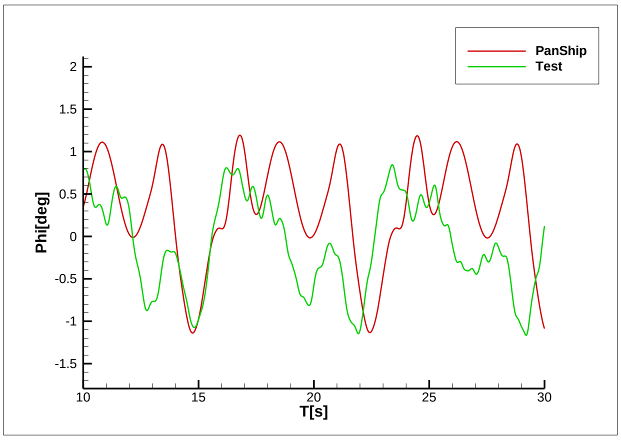

Figure 11 Comparison of roll

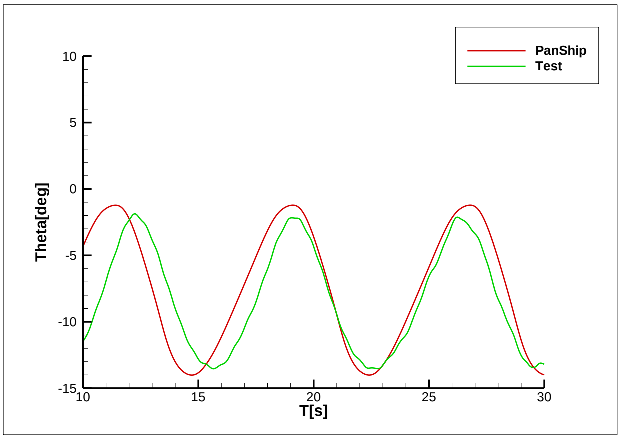

Figure 12 Comparison of pitch

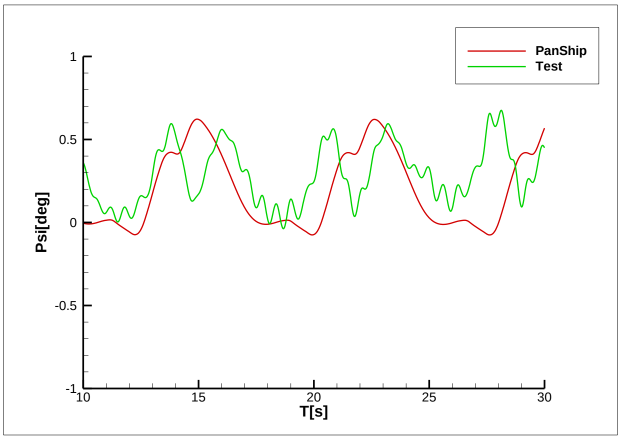

Figure 13 Comparison of yaw

The acceleration components are relatively low and the experimental signals show the noise due to the propulsion system, see Figures 14 , 15 and 16.

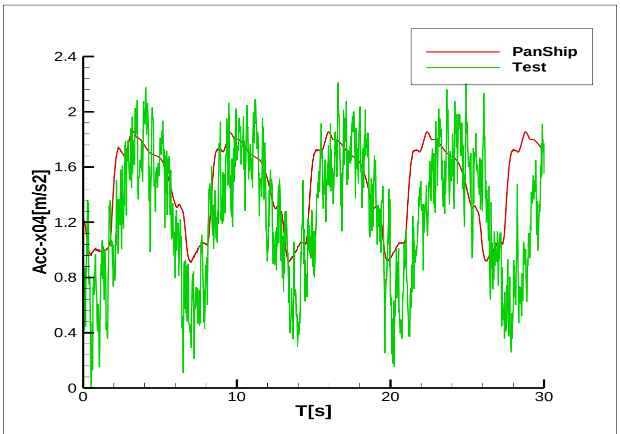

Figure 14 Comparison of x-acceleration

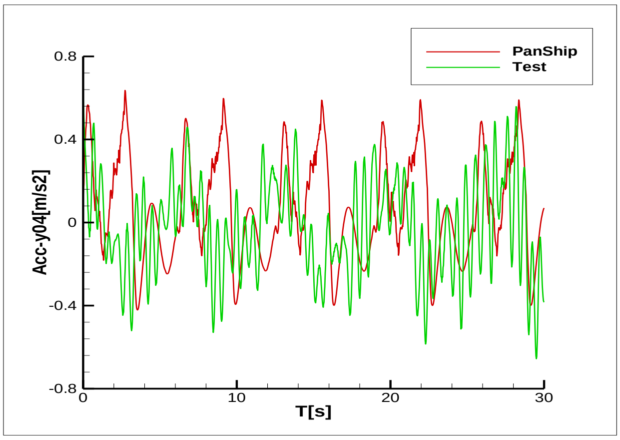

Figure 15 Comparison of y-acceleration

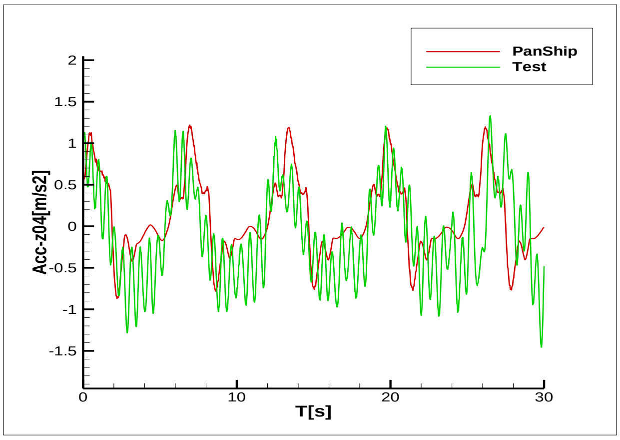

Figure 16 Comparison of z-acceleration

5.2 Irregular waves

The first case concerns a PanShipNL simulation for a steep irregular head sea with $H_{1/3}$ = 2.5 m and T_p = 5.2 s. The nominal forward speed is 12 knots (Fn=0.70). Figures 17 through 21 show a comparison of time traces for forward speed, heave, pitch, and acceleration components. It is seen that the comparison is not perfect, especially for the highest wave amplitudes. One reason for this is that wave reconstruction method cannot deal with breaking waves. This is illustrated in Figure 22 showing a comparison between the measured and reconstructed wave time traces for the time frame with the highest wave amplitudes. Figure 23 shows a detail of the pitch time traces for that time frame. The bow-up pitch amplitude is rather high: some 35 degrees causing the model to fly above water for a short while, see Figure 24. This event is reasonably well captured by PanShipNL. Even if the waves were perfectly reconstructed there would be differences because PanShipNL cannot deal with breaking waves and waterjet intake ventilation.

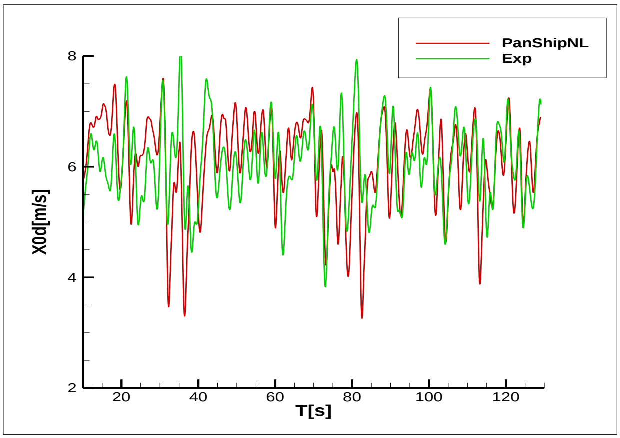

Figure 17 Comparison of velocity

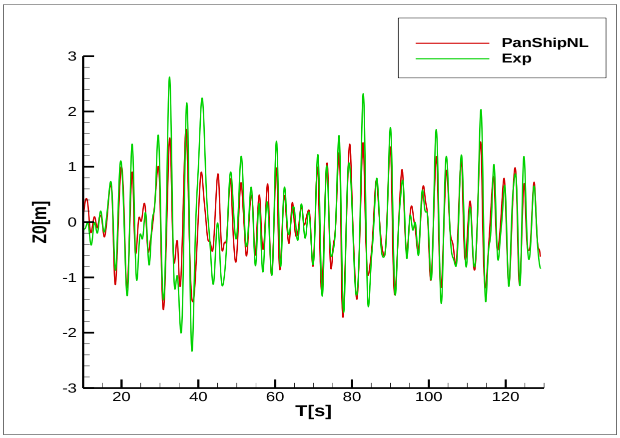

Figure 18 Comparison of heave

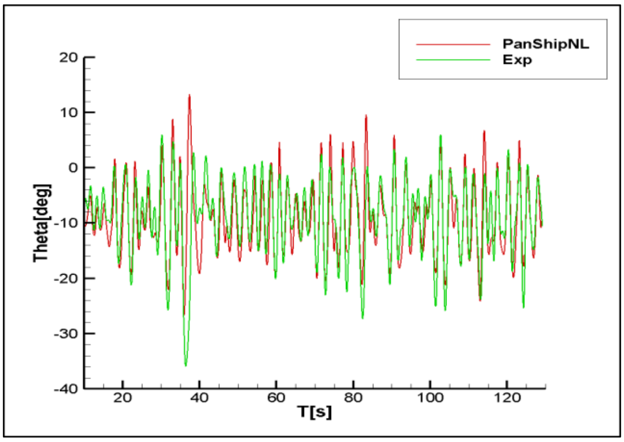

Figure 19 Comparison of pitch

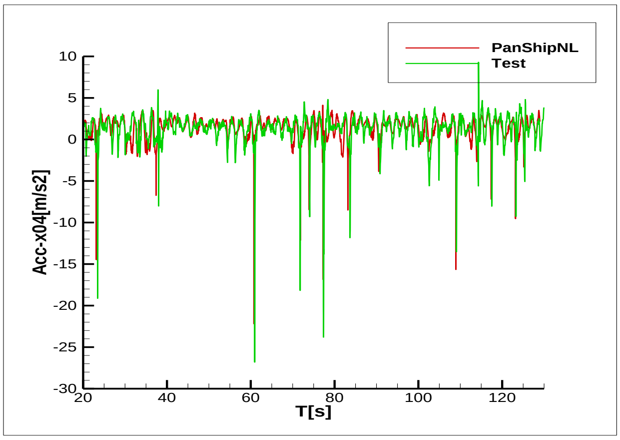

Figure 20 Comparison of x-acceleration

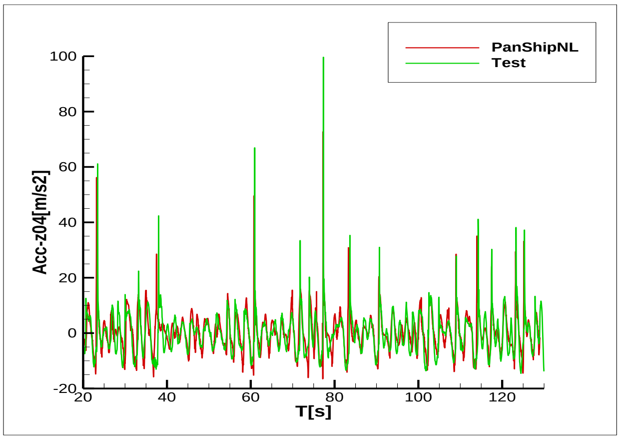

Figure 21 Comparison of z-acceleration

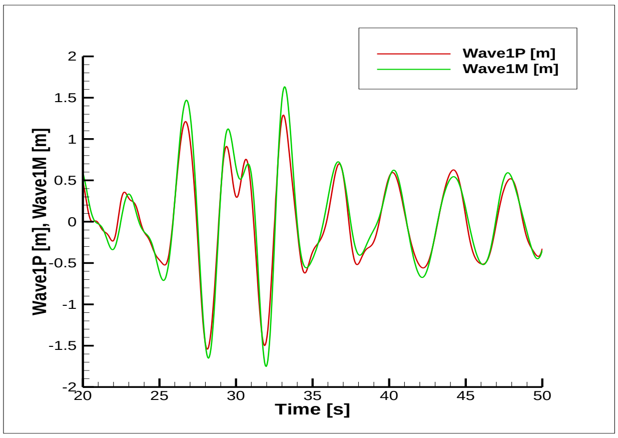

Figure 22 Comparison of reconstructed (Wave1P) and experimental (Wave1M) wave time trace

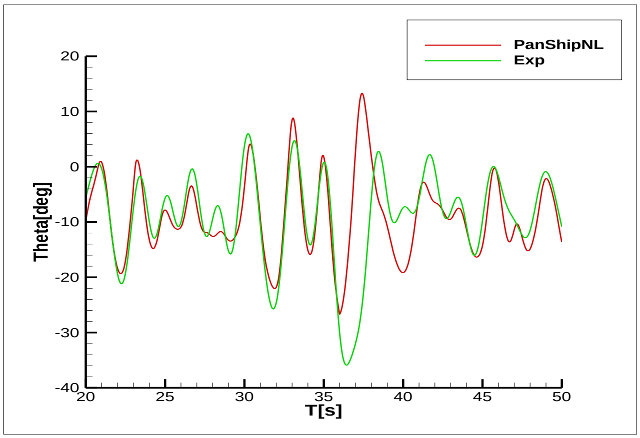

Figure 23 Comparison of pitch time trace detail

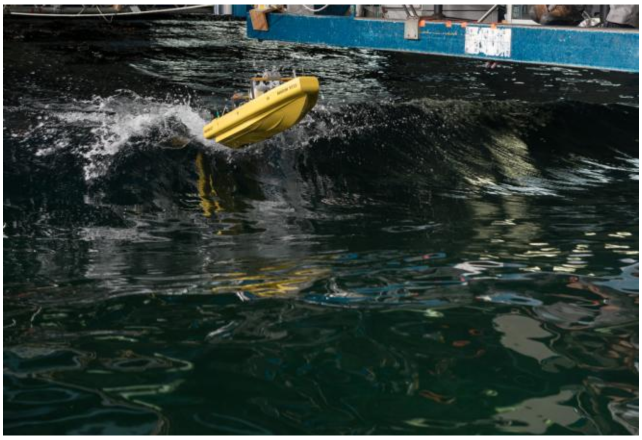

Figure 24 Flying model

Interestingly, the highest vertical accelerations do not occur during the event described above. Figures 25 and 26 show a detail of the acceleration time traces. The high peak values are reasonably well captured by PanShipNL.

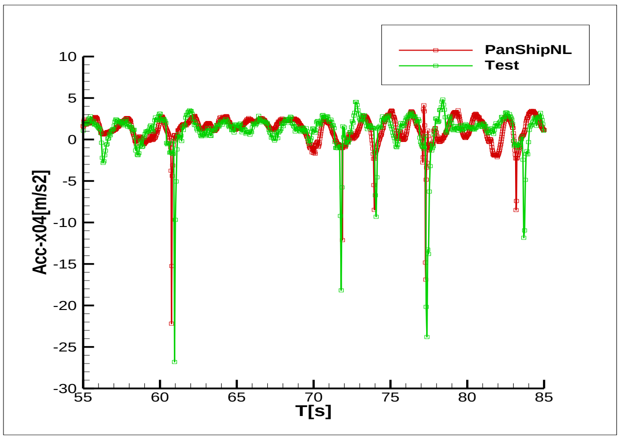

Figure 25 Comparison of x-acceleration (detail)

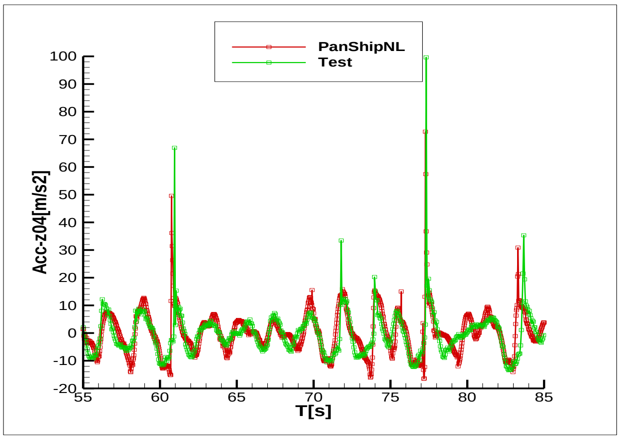

Figure 25 Comparison of z-acceleration (detail)

The second comparison concerns the same sea state ($H_{1/3}$=2.5 m, T_p=5.2 s) but now as a beam sea. The speed is 12 knots. Figures 26 through 31 show comparisons between experimental and simulated time traces. It is seen that the predicted yaw time traces deviate from the experimental result. This has an effect on the sway and pitch motions and forward speed as well. Heave and roll are reasonably well predicted. It is believed that the difficulty in predicting yaw is again partially due to the presence of breaking waves. Other reasons may be the use of a semi-empirical method for water jet steering in PanshipNL and the occurrence of waterjet intake ventilation.

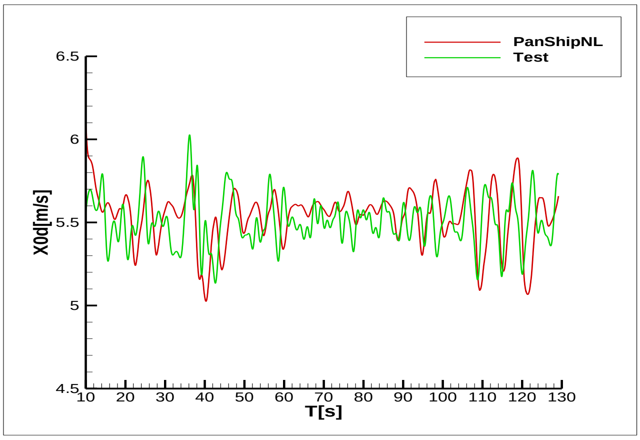

Figure 26 Comparison of velocity

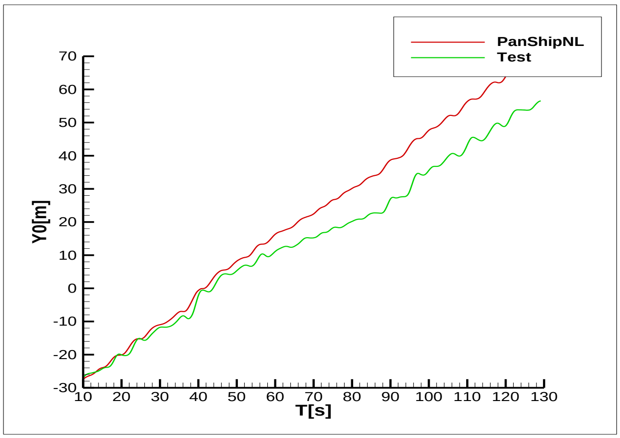

Figure 27 Comparison of sway

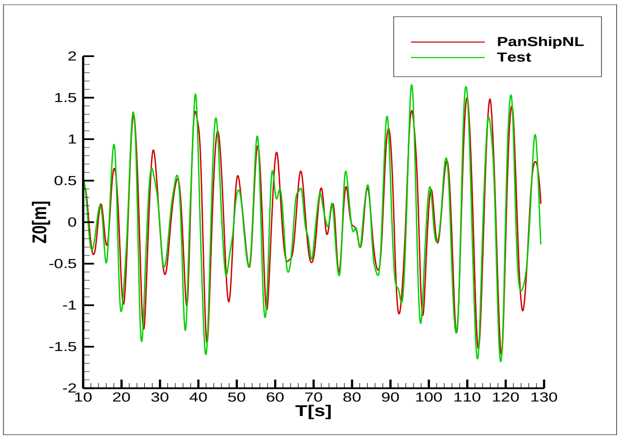

Figure 28 Comparison of heave

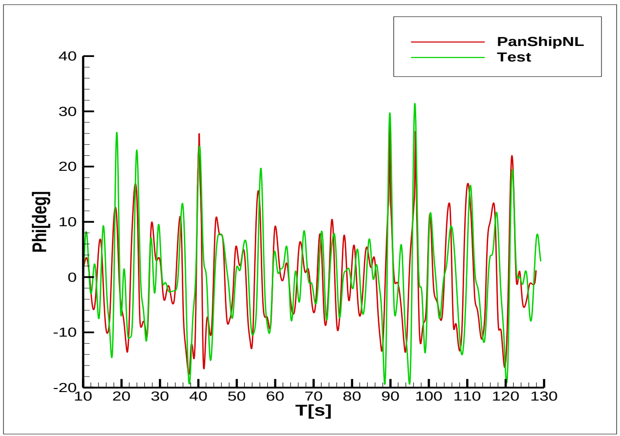

Figure 29 Comparison of roll

6. CONCLUDING REMARKS

The comparisons between experimental and simulated time traces shows that PanShip provides adequate predictions for low amplitude yet steep regular waves.

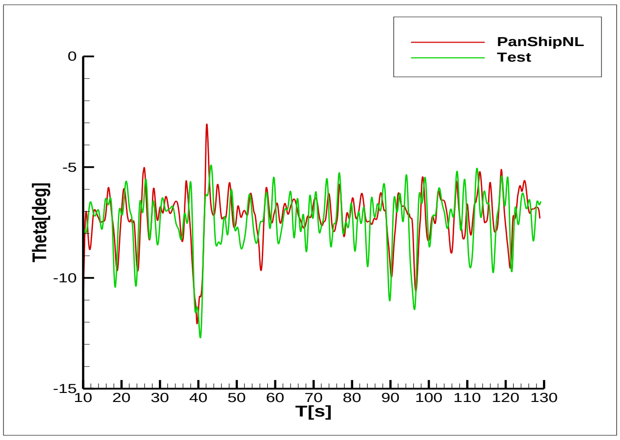

Figure 30 Comparison of pitch

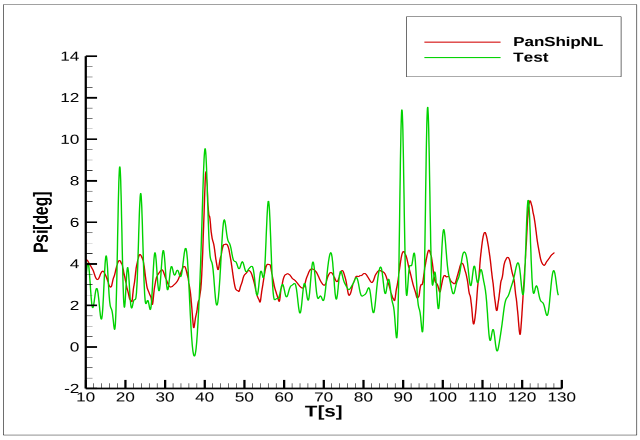

Figure 31 Comparison of yaw

Predictions for steep and heavy irregular seas show that non-linear events in head seas such as jumping out of wave crests and acceleration peaks are reasonably well predicted. In beam seas heave, roll and pitch are reasonably well predicted as well, however yaw and sway deviate. This is believed to be at least partially due to the effects of breaking waves and water jet intake ventilation. Such phenomena are not included in the simulation tools.

The tests in the steep irregular waves from a stern quartering direction showed the occurrence of swamping and capsizing in breaking waves. Such events occur about two to four times per hour. It would have been of interest to show deterministic validation results for such events. This has not been attempted because the simulation methods used cannot deal with breaking waves and the resulting water ingress leading to a capsize. This remains a challenge, even for CFD based tools.

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