### ABSTRACT

The paper describes the validation of two time domain methods to simulate the behaviour of a destroyer operating in steep, stern-quartering seas. The significance of deck-edge immersion and water on deck on the capsize risk is shown as well as the necessity to account for the wave disturbances caused by the ship. A method is described to reconstruct experimental wave trains and finally two deterministic validation cases are shown.

**KEY WORDS:** Model test; Simulation; Stern-quartering seas; Water on deck; Deterministic validation.

### INTRODUCTION

The operability and safety of a ship depends on its behaviour in waves. At higher speed in steep waves from after directions dynamic stability risks may exist. These risks can be investigated by means of model tests. Provided these tests are properly executed, they offer the most reliable information on dynamic stability.

Issues in the use of model testing are the costs, the limited statistical reliability of the required tests in irregular waves, the limited flexibility, some limitations in representation of the physics of ship behaviour in waves from the stern quarter and the fact that the test results are not always easy to understand. The limitations in the physical representation relate to viscous effects in the components of the hull resistance with an effect on the propeller loading, in some of the smaller components of the roll damping, in components of the manoeuvring reaction forces and in the (dynamic) stall of the rudders. The neglect of wind on the roll damping, the wind heel and on the propeller loading and related steerage has an effect. Issues that are modelled implicitly correctly are the natural peak-trough a-symmetry in steep waves, the presence of breaking waves, the wave induced forces on the propeller and rudder, rudder and propeller ventilation and down-stream effects of vortices from the bilges and bilge keels on the rudder.

In order to understand the physics of dynamic stability, numerical modelling has been pursued for some time. Although the latest CFD techniques have undoubtedly the largest potential, they have not met the expectations yet. This is partly due to the problems of modelling the generation, propagation and absorption of steep waves in a limited computational domain and partly to the local physical character of issues like spilling wave crests on deck, roll damping from bilge keels and rudder stall and ventilation and the role of the propeller herein. In combination with the required domain size, this yields an extreme computational effort.

In between the above two techniques are hybrid models, which combine the efficiency of potential flow theory with empirical modules covering the non-linear aspects of manoeuvring and roll damping. After validation, these models are particularly used in assessing capsize risk.

The present paper deals with validation of two such simulation methods for a destroyer hull form operating in steep stern-quartering seas. A brief description of the simulation methods is given first. Next, the experimental arrangement is described followed by a discussion on deck-edge immersion and a comparison of experimental and simulated motion responses. The last section deals with deterministic validation, including the method to reconstruct the experimental wave train in a simulation program.

### SIMULATION METHODS

Predicting the motion performance of ships operating in steep stern-quartering sea states is more complicated than that for beam or head seas. In steep stern-quartering seas motion amplitudes may be large and both vertical and horizontal plane motions (course keeping) are important. Ideally, prediction methods should be capable of accounting for:
Six degrees of freedom motions, especially the coupling between sway, yaw and roll,

- Large motion amplitudes,

- Non-linear waves: dynamic stability problems are generally most severe in steep waves for which non-linear effects are of importance,

- Time-varying wetted hull geometry and its effects on restoring forces, wave excitation, wave diffraction and wave radiation forces,

- Deck-edge immersion and dynamics of water on deck,

- Forward speed and the effects of friction and flow separation on hydrodynamic properties: in stern-quartering seas the wave encounter frequency is low so that potential flow damping is relatively low,

- Propulsion and steering: the speed variations in the horizontal plane should be predicted adequately, and course keeping is important with respect to broaching,

- The contribution of the wind to the roll damping and the roll excitation.

Prediction methods that are capable of handling the above are in principle capable to simulate phenomena like capsize due to loss of stability in waves, water on deck and surf riding and broaching. However, fully non-linear simulation methods are scarce and rather computationally intensive. When a large number of conditions needs to be investigated the required simulation times are impractical. Therefore, there is a need for fast(er) time simulation methods. These are based on partial linearisation of the hydrodynamic problem. Two of such methods are briefly described below.

FREDYN (De Kat et al., 2002), is a fast-time, blended, seakeeping-manoeuvring simulation method. It has been developed by the Cooperative Research Navies (CRN: US Navy/NSWC Carderock, UK-MoD/Qinetiq, DGA/BEC- France, US Coast Guard, DoDDSTO-Australia, DND/ DRDC Atlantic- Canada and Netherlands Navy/ MARIN). FREDYN is based on:

- Added mass and damping from strip theory in the frequency domain applied in the time domain through retardation functions, accounting for the wetted geometry at rest only, neglecting the effects of wave reflection and radiation in the relative wave elevation,

- Froude-Krylov forces through a 3D panel method using the undisturbed wave pressures on the instantaneous submerged body,

- Linear irregular, long and short crested waves,

- Deck-edge immersion and dynamics of water on deck,

- Forward speed and the effects of friction and flow separation on hydrodynamic properties: in stern-quartering seas the wave encounter frequency is low so that potential flow damping is relatively low,

- Propulsion and steering: the speed variations in the horizontal plane should be predicted adequately, and course keeping is important with respect to broaching,

- The contribution of the wind to the roll damping and the roll excitation.

FREDYN is a versatile tool that is used by CRN for the Naval Ship Stability Working Group (NSSSWG) to perform capsize risk assessments. Note that for a single ship and loading condition such a risk assessment requires about 20,000 half-hour simulations. Although FREDYN is a fast-time tool (about real time) it requires a powerful grid of workstations to keep the total simulation time within practical limits. FREDYN has been well validated for operational conditions, and to a lesser extent for more severe sea conditions (regular waves). In order to validate FREDYN for the larger temporal wave steepness occurring in irregular waves, and to validate the recent method to determine deck-edge immersion and water on deck effects in particular, a series of model tests have been performed for CRN at MARIN, see Section 3.

A separate development is PANSHIP (Van Walree, 2002 and De Jong and Van Walree, 2009), a time domain panel method characterised by:

- 3D transient Green function to account for linearised free surface effects, exact forward speed effects, mean wetted surface, mean, radiated and diffracted wave components along the hull and a Kutta condition at the stern,

- 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,

- FDS (Blok and Aalbers, 1991) viscous roll damping,

- Autopilot steering,

- Unsteady wind loading based on wind tunnel derived wind load coefficients.

PANSHIP is used at MARIN for seakeeping predictions for fast and unconventional ships. A more non-linear version accounting for the instantaneous wetted surface in the transient Green function approach is available as well, but this version is still too slow for practical use.

MODEL TESTS

Model tests have been performed on a European version of the well-known destroyer hull form DTMB-M5514 (Precontract DDG 51) in steep stern-quartering seas. The tests have been performed in MARIN's Seakeeping and Maneuvering Basin which measures 170x40x5m in length, width and depth respectively. Table 1 shows the main
particulars of the hull form and Figs. 1 and 2 show the hull form sections and the model during testing, respectively. The model was equipped with twin propellers, rudders and bilge keels. The model scale was 35.45.

Table 1 Main Particulars

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars (m)</td>
<td>142.25</td>
</tr>
<tr>
<td>Beam on waterline (m)</td>
<td>19.06</td>
</tr>
<tr>
<td>Draught forward (m)</td>
<td>6.15</td>
</tr>
<tr>
<td>Draught aft (m)</td>
<td>6.15</td>
</tr>
<tr>
<td>Displacement (ton)</td>
<td>8643</td>
</tr>
<tr>
<td>Metacentric height (m)</td>
<td>1.00</td>
</tr>
<tr>
<td>Natural roll period (sec)</td>
<td>16.10</td>
</tr>
</tbody>
</table>

Fig. 1 Hull form sections

Fig. 2 Model during free running test

Previous validation of FREDYN indicates that using the undisturbed wave height in combination with the instantaneous position of the ship in the wave field, to obtain deck-edge immersion and the amount of water on deck, leads to rather conservative capsize risk predictions. In order to improve this, FREDYN was extended with a more accurate method to determine deck-edge immersion. To validate this method two sets of experiments were conducted.

First, tests with a captive model in regular waves were performed to obtain information on deck-edge immersion and the amount of water on deck. Tests were performed for 10 and 20 degree heel angles and several wave frequencies, amplitudes and directions.

Second, free running, self-propelled and self-steered tests were performed in long crested irregular seas. The model was given a relatively low initial stability ($GM = 1.0m$) to have large amplitude roll motions, up to capsizing. The conditions for a selection of tests are shown in Table 2. These tests were performed for further validation of the deck-edge immersion method and more in general for validation of FREDYN for large amplitude motion conditions.

Table 2 Test conditions for free running tests.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Mean Speed $U$ (kts)</th>
<th>Heading $\Psi$ (deg)</th>
<th>Significant wave height $H_s$ (m)</th>
<th>Peak period $T_p$ (sec)</th>
<th>Test duration (sec)</th>
<th>Number of wave encounters</th>
<th>No. of capsizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>205</td>
<td>24.1</td>
<td>300</td>
<td>10.0</td>
<td>10.5</td>
<td>1800</td>
<td>130</td>
<td>1</td>
</tr>
<tr>
<td>216</td>
<td>23.8</td>
<td>330</td>
<td>10.0</td>
<td>10.5</td>
<td>1800</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>217</td>
<td>23.6</td>
<td>300</td>
<td>7.50</td>
<td>9.0</td>
<td>1800</td>
<td>130</td>
<td>1</td>
</tr>
<tr>
<td>218</td>
<td>24.3</td>
<td>330</td>
<td>7.50</td>
<td>9.0</td>
<td>1800</td>
<td>75</td>
<td>0</td>
</tr>
</tbody>
</table>

VALIDATION

Deck-edge immersion

The captive tests in regular waves showed that the steady wave due to forward speed was comparable in magnitude to the reflected wave. At moderate to high speed, the disturbance components result most times in a reduced wave amplitude aft of the bow. Fig. 3 shows the measured wave crest heights at six locations at the lower (starboard) side for a heel angle of 10deg. The undisturbed wave crests exceed the deck-edge aft of midship, while the disturbed wave only does so for the highest wave period ($T=11.5sec$). Fig. 4 shows that for a 20 deg heel angle the deck-edge is immersed.
for all wave periods, but again for the lower three wave periods the immersion is reduced relative to that for the undisturbed wave. The wave crest line for the highest wave period is seen to exceed those for the three lower wave periods significantly.

![Graph of measured maximum wave height along the hull for four wave periods. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 300 deg.](image1)

![Graph of measured maximum wave height along the hull for four wave periods. Speed 24 kts, heel 20 deg, wave amplitude 2.50 m, wave direction 300 deg.](image2)

Fig. 3 Measured maximum wave height along the hull for four wave periods. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 300 deg.

Fig. 4 Measured maximum wave height along the hull for four wave periods. Speed 24 kts, heel 20 deg, wave amplitude 2.50 m, wave direction 300 deg.

Figs. 5 and 6 show the measured and calculated maximum wave elevations along the hull, again for the lower side of the hull. It is seen that the linear (zero heel) FREDYN-Strip Theory prediction is less accurate than the non-linear (actual heel) PANSHIP prediction. Nevertheless, the FREDYN method with wave disturbance taken in to account can be expected to give better predictions for the amount of water on deck than without wave disturbance taken in to account, since the relative wave height reduces where the freeboard is low.

![Graph of comparison maximum wave height along the hull. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 330 deg., wave period 10.5 sec.](image3)

![Graph of comparison maximum wave height along the hull. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 330 deg., wave period 8.5 sec.](image4)

Fig. 5 Comparison maximum wave height along the hull. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 330 deg., wave period 10.5 sec.

Fig. 6 Comparison maximum wave height along the hull. Speed 24 kts, heel 10 deg, wave amplitude 2.50 m, wave direction 330 deg., wave period 8.5 sec.
The local width of the deck covered by water \( w \), is proportional to the heel angle \( \varphi \) and the local deck-edge immersion \( h \):

\[
w \sim h / \tan(\varphi) \quad w \sim h / \tan(\varphi)
\]

As shown in Fig. 7, the resemblance between the calculated (maximum) width according to equation (1), using the experimental deck-edge immersion \( h \) and heel angle \( \varphi \), and the experimentally observed width is quite good. This indicates that dynamic effects are small for the conditions considered here.

![Fig. 7 Calculated and observed maximum width of deck wetting. Test 217.](image)

The effect of accounting for the wave disturbance (Und: without; Dist: with) on the number of capsizes is shown in Table 3 below. This table shows the number of capsizes encountered during 1800 seconds of model testing and simulation. A capsize is assumed to occur when the roll angle exceeds 90 deg. The duration of the tests and simulations is too low for accurate predictions of the number of capsizes per half hour. Assuming a Poisson distribution of the number of capsizes per time interval, for Test 205 for instance the probability is 18% that the number of capsizes is two instead of one, when using another wave realisation. Nevertheless, the simulation results suggest that water on deck is a very significant factor and accounting for this reduces the overestimation of the number of capsizes in the simulation results.

![Fig. 8 Probability of exceedance for roll.](image)

Fig. 8 shows the probability of exceedance for roll for Test 205, with and without accounting for the wave disturbance. The effects of accounting for the wave disturbance are again very clear in the plot. For roll angles above 40 deg, the ship will almost always capsize, when not accounting for the disturbed wave. For roll angles below 40 deg, the probability of exceedance is higher when taking the disturbed wave into account than without taking this in account. PANSHIP results follow the experimental curve quite accurately while FREDYN results are not as close for low roll angles, but they are in close agreement with the experiments and PANSHIP for high roll angles. Fig. 9 finally shows the pressure distribution on the hull during a PANSHIP simulation, illustrating the effect of heel and the disturbed wave profile along the hull.

![Fig. 9 Pressure distribution on hull.](image)

### Table 3 Effect of accounting for disturbed wave on number of capsizes per half-hour.

<table>
<thead>
<tr>
<th>Test</th>
<th>Und</th>
<th>Dist</th>
<th>Und</th>
<th>Dist</th>
</tr>
</thead>
<tbody>
<tr>
<td>205</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>216</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>217</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>218</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

The local width of the deck covered by water \( w \), is proportional to the heel angle \( \varphi \) and the local deck-edge immersion \( h \):

\[
w \sim h / \tan(\varphi) \quad w \sim h / \tan(\varphi)
\]
Validation of motions

Both FREDYN and PANSHP runs have been performed for a number of test conditions in irregular waves. Autopilot gains in FREDYN and PANSHP were the same as used for the model tests. The duration of the simulations was the same as that of the model tests: 1800 sec. Although the wave trains in both sets of simulations satisfy the same wave spectrum as the experiments, the encountered wave sequences for the three sets of results are different. For runs 216 and 218 the number of encountered waves during the half hour test is 75 which is considered to be too low for reliable standard deviation of motions. Nevertheless, motion responses are provided in the Figs. 10 through 15 below. The responses are defined as the standard deviation of the motion divided by the standard deviation of the wave height. In both simulation methods, the disturbed wave height along the hull was taken in account. In all Figures, the left, centre and right bars denote Experimental, Panship and Fredyn results respectively.

Fig. 10 Comparison of experimental and simulated speed variation response.

Fig. 11 Comparison of experimental and simulated sway response.

Fig. 12 Comparison of experimental and simulated heave response.

Fig. 13 Comparison of experimental and simulated pitch response.

Fig. 14 Comparison of experimental and simulated roll response.
The figures above show that the speed variations tend to be under-predicted by both simulation methods, more so by FREDYN than by PANSHIP for Tests 216 and 217. The sway responses are fairly well predicted by both simulation methods, while heave is alright for PANSHIP and under predicted by FREDYN. The roll response is appreciable and is well predicted by PANSHIP and somewhat under-predicted by FREDYN. Pitch predictions are reasonably good, except for Test 216. The same is true for yaw.

Figs. 16 through 19 below show the variation in roll, sway and yaw response (standard deviation, left bar) and extremes (maximum and absolute minimum values, centre and right bars respectively) for 10 PANSHIP simulations for Test 217. Each simulation has again a duration of 1800 seconds, but for each simulation a different wave train realisation was generated from the wave spectrum by using a different initial random seed.

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**Fig. 15** Comparison of experimental and simulated yaw response.

**Fig. 16** Response and extremes for roll for 10 wave realisations.

**Fig. 17** Response and extremes for sway for 10 wave realisations.

**Fig. 18** Response and extremes for yaw for 10 wave realisations.

**Fig. 19** Response and extremes for speed for 10 wave realisations.
The variation in roll, sway yaw and speed responses is seen to be limited. Speed extremes show relatively little variation, however the variation in roll is larger while variations in sway and yaw extremes are substantial, in a relative sense. In absolute terms the variations in sway and yaw extreme values are still limited. The required test and simulation time to obtain reliable statistics of rare events like broaching and capsizing is currently under investigation by the NSSWG (Campbell and Belenky, 2010).

Deterministic validation of motions

A way to circumvent the need for lengthy model tests and simulations when validating ship motions in following and stern-quartering seas is to run the simulations in the same wave train as the experiments, i.e. deterministic validation.

The presently adopted procedure for deterministic validation starts with determining the wave spectrum components from the experimental wave train. During the model tests, the wave height was measured by wave probes attached to the carriage (following the model) at three locations. The mean position of the wave probes was:

- probe #1: 1.5 ship lengths in front of the model, at the centre line,
- probe #2: 0.25 ship lengths next (transverse direction) to the model, at midship,
- probe #3: 1.0 ship lengths next (transverse direction) to the model, at midship.

The wave spectral densities \( S \) are determined by means of spectral analysis of one of the wave trains that was measured while travelling at very low speed through the basin (without the model present). This yields an “average” wave spectrum valid anywhere in the basin. Next, the phase angles \( \varepsilon \) are determined by means of a non-linear minimisation procedure (IMSL routine RNLIN). In this procedure the difference between the measured and reconstructed wave trains, \( \zeta_m \) and \( \zeta_r \) respectively, is minimised at each time step by varying the phase angles. The measured wave train \( \zeta_m \) is that measured during the actual model tests. The object function \( F \) at time \( t \), and the reconstructed wave train at wave probe \( j \) are defined by:

\[
F_j(t) = \zeta_m(t) - \zeta_r(t) \\
\zeta_r(t) = \sum_{i=1}^{n} A_i \cos(k_i x_j - \omega_i t + \varepsilon_j)
\]

where \( A_i = \sqrt{2 \Delta \omega_i S_i} \) is the wave amplitude of spectral component \( i \), \( k_i = \omega_i^2 / g \) is the wave number, \( x_j = x_j(t) \cos(\psi) + y_j(t) \sin(\psi) \) is the position of wave probe \( j \) in the wave field, \( \omega \) is the wave frequency, \( (x_j, y_j) \) is the basin fixed position of the wave probe and \( \psi \) is the wave direction. The number of spectral components \( n \) is 240.

The object function is minimised using the observations (measurements) at the three wave probe positions sequentially, yielding the phase angles \( \varepsilon \). The length of the measurements signals is typically 300 seconds per wave probe, per run. The number of observations used per run is typically 500 per wave probe. The assumption is then that equation (3) is valid for arbitrary positions \( (x, y) \) in the neighbourhood of the ship. Fig. 20 shows a comparison between the measured wave train and the reconstructed wave train at wave probe #2 for test 205.

![Wave height comparison](image1)

![Comparison between measured (gray) and reconstructed (black) wave train.](image2)

Simulations in the reconstructed wave field were performed by means of PANSHP. In order to have the correct memory function in the initial stages of the run, the experimental velocities and positions were read in to PANSHIP during the first 15 seconds of the simulation. The rudder and propeller arrangements, including autopilot gains, in PANSHIP were the same as used for the model tests. Figs. 21 through 26 show a comparison between the measured and simulated ship motions, for the first run of Test 218 where relatively low waves were met. The black lines denote the simulated results while the grey lines denote the experimental results.

![Comparison speed](image3)
It is seen that initially (beyond 15 sec) the simulated motions follow the experimental motions reasonably well. However, position deviations are inevitable and after about 200 seconds of simulation, the simulated position of the ship in the wave field is different from the experimental one so that different waves are met and thereby different motions are resulting.

Figs. 27 through 32 show a comparison for Test 205 where waves are higher initially than for Test 218. Also, the wave encounter frequency is higher than for Test 218. Here, a start-up period of 30 sec was used. It is seen that significant deviations between the experiments and simulations start earlier in time than for Test 218, especially for yaw. Looking at heave, roll and pitch during the first 100 seconds, it seems that the reconstructed wave height is lower than the experimental wave height. However, Fig. 33 shows that the reconstructed wave (black) at the ship CoG is not lower than the experimental wave at probe # 2 (gray), 30m next to the model’s CoG.
Fig. 27 Comparison speed.

Fig. 28 Comparison sway.

Fig. 29 Comparison heave.

Fig. 30 Comparison roll.

Fig. 31 Comparison pitch.

Fig. 32 Comparison yaw.
CONCLUDING REMARKS

The paper has dealt with validation of two time domain simulation methods. The validation case consists of captive and free running model tests for a destroyer sailing in steep stern-quartering seas.

It is shown that taking the wave disturbance by the ship into account in simulation methods, and thereby determining deck-edge immersion and water on deck more accurately, reduces the number of capsizes significantly.

Motion responses based on standard deviations of motions and wave heights show in general a fairly good agreement between the experimental data and results from the two simulation methods. The variation of the roll, sway and yaw responses and extreme values with wave realisation in PANSHIP simulations is shown to be limited for one of the test cases with 130 wave encounters.

However, deterministic validation shows that experimental and simulated time traces start deviating sooner (high waves) or later (lower waves). This is deemed inevitable when using any simulation method. Nevertheless, it is believed that initial correspondence is good enough to investigate single events. In the near future a similar validation study will be performed for more non-linear versions of the simulation methods.

ACKNOWLEDGEMENT

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REFERENCES


