

MANOEUVRING VALIDATION ANALYSIS OF THE M/F LANDEGODE

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ABSTRACT

A framework is described in which a manoeuvring simulator can be built up from model tests. It is applied to a modern LNG powered RORO ferry, the M/F Landegode, with model tests and computational results being used to make full-scale predictions. These predictions are tested against full-scale manoeuvring performance measurements, and are shown to be of a high quality.

NOMENCLATURE

- v Velocity of body relative to inertial frame, expressed in body frame.
 η Generalised position of body relative to inertial frame, expressed in inertial frame.
 $\mathbf{J}(\theta)$ Transformation matrix between body-fixed and inertial reference frame.
 \mathbf{M} Generalised mass matrix.
 \mathbf{A}_∞ Generalised added mass matrix at infinite frequency.
 \mathbf{M}_A Generalised added mass matrix.
 $\mathbf{D}(v)$ Generalised damping forces.
 $\mathbf{C}(v)$ Coriolis-centripetal matrix.
 $\mathbf{g}(\eta)$ Generalised restoring and gravity forces.
 $\mathbf{h}(\tau)$ Matrix of retardation functions.
 \mathbf{q} excitation function, described by its subscript and superscript, e.g. \mathbf{q}_{wind} is the generalised wind force.

A_{bcd} General form of hydrodynamic derivative, where the force is given by $A = A_{bcd}bcd$, e.g. $X = X_{uvv}u^2v$.

INTRODUCTION

The MAROFF funded KPN project, “Sea Trials and Model Tests for Validation of Shiphhandling Simulator Models” (“SIMVAL”), took place over the four year period 2013-2016. The project focused on ways in which ship specific manoeuvring models could be validated through advanced model testing, sea-trials, and effective simulation. Also participating in the project were international partners from Belgium, Singapore, Japan, and Brazil.

A key part of the project was to select several case-vessels, and focus extensively on data-gathering. This approach included high quality model scale tests, both captive and free-running, combined with sophisticated full-scale testing, allowing for more comprehensive analyses than would normally be practical.

This paper presents a manoeuvring analysis of the M/F Landegode, an LNG-powered coastal ferry, owned and operated by Torghatten Nord. The focus is on how the vessel, and indeed vessels in general, are tested, modelled, analysed, and integrated into SINTEF Ocean’s simulation framework.

The paper begins with a description of SINTEF Ocean’s vessel simulation package, VeSim, which is an in-house

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time-domain vessel simulation package, and offers a powerful framework in which to solve the relevant dynamic equations of motion for vessels, simultaneously taking care of both the seakeeping and manoeuvring problems.

Following the overview, the paper demonstrates how planar motion mechanism type model tests can be used as a data-source to generate manoeuvring models of a high accuracy, and in a form suitable for use within VeSim. The primary methodology is through the use of nonlinear regression to find the various resistance, lift, and drag terms necessary for a manoeuvring model. The approach is demonstrated using planar motion mechanism tests (PMM), in which many dynamic derivatives are shown to be evaluable from these non-static experiments.

With the manoeuvring model available, an approach is offered by which these low-frequency hydrodynamic derivatives can be integrated in a sound way with SINTEF Ocean's strip-theory based seakeeping code. Such considerations are highly important in performing simulations in which the models are sourced from both seakeeping and manoeuvring theories, and it is vital to take great care in ensuring that true physical effects are not modelled twice, and hence included twice, in a unified simulation model. The unified seakeeping and manoeuvring model of the M/F Landegode is further integrated with a high quality rudder-propeller model from Rolls-Royce, giving a comprehensive simulator for manoeuvring in waves.

With work completed on creating a high quality simulator model, several verification and validation tasks are performed to demonstrate the utility of both the final simulation model, and also of the process used to develop it.

Full-scale tests were performed in the project, and a calm-water subsection of these are used for validation of the simulation model. These tests consist of a variety of turning-circles and zig-zags, all of which show good correspondence with SINTEF Ocean's simulation model. Further to this, spiral tests are compared to simulation, also showing congruence. Finally, the rudder-propeller model is validated against model-scale propulsion data.

M/F Landegode

M/F Landegode is a modern LNG RORO ferry, operating between Bodø and Moskenes in northern Norway. The ferry is owned and operated by Torghatten Nord AS, a part of Torghatten ASA, and was built and delivered in 2012. Torghatten Nord runs a large fleet of express boats and ferries in the Norwegian counties of Nordland and Troms. The ferry is depicted in Figure 1.



FIGURE 1. THE M/F LANDEGODE.

VeSim

Vessel Simulator, or “VeSim” is SINTEF Ocean's in-house time-domain simulation tool for the simulation of ships in a seaway with variable heading and speed. The simulator functions in 6-DOF and solves manoeuvring and seakeeping problems simultaneously.

VeSim is essentially a tool which solves the rigid-body equations of motion in six degrees-of-freedom. In order to do this, it utilises a network of federates, each one of which forms a calculation module which can resolve calculations for a large variety of states, such as first-order wave forces, wind forces, actuator dynamics, autopilot commands, and so forth. The simulator is primarily designed to take care of surface hydrodynamic simulation tasks, and so is particularly capable of calculating and implementing hydrodynamic properties of a ship, such as added-mass and damping. In the seakeeping sense, these tasks are solved in the time-domain utilising retardation functions (see, for example, [1,2]), or more precisely, series function approximations of these. The total system of equations is shown in Equation (1).

$$(M + M_A) \dot{\mathbf{v}} + C(\mathbf{v}) \mathbf{v} + D(\mathbf{v}) \mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) + \int_0^t h(t - \tau) \mathbf{v}(\tau) d\tau = \mathbf{q} \quad (1)$$

with $\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\theta}) \mathbf{v}$.

The excitation forces on the right-hand side of Equation (1) are given by:

$$\mathbf{q} = \mathbf{q}_{\text{wind}} + \mathbf{q}_{\text{wave}}^{(1)} + \mathbf{q}_{\text{wave}}^{(2)} + \mathbf{q}_{\text{prop}} + \mathbf{q}_{\text{man}} + \mathbf{q}_{\text{ext}}. \quad (2)$$

Unified Model- Yaw Example

In applying Equation (1), there are many aspects which are sensitive to implementation issues, especially in rigorously mixing low-frequency manoeuvring behaviour in a consistent manner with the wave-frequency seakeeping behaviour. Though this section is specific to both the seakeeping and manoeuvring implementations which are used in Vesim, the approach described is important to consider regardless of the methods used to implement a unified model. A primary problem found at SINTEF Ocean has been ensuring that the hydrodynamic added-mass forces, along with the corresponding coriolis-centripetal forces function correctly in: the manoeuvring framework; in the seakeeping framework; and especially in the unified framework.

The example here is of the yaw equation in three degrees of freedom. Taking the purely hydrodynamic parts of the yaw equation of the manoeuvring model, with only added mass and coriolis-centripetal moments ([3, Eq.3.34]), and neglecting all damping forces, the equation is:

$$N_{man} = N_{\dot{v}}^0 \dot{v} + N_{\dot{r}}^0 \dot{r} + (Y_{\dot{v}}^0 - X_{\dot{u}}^0) uv + \frac{1}{2} (Y_r^0 + N_v^0) ur, \quad (3)$$

where the notation for each derivative is in accordance with general form as given in the nomenclature, and where the superscript 0 denotes that the coefficients are present at low-frequency.

If these terms were to be substituted directly into a standard unified model, a mistake would typically be encountered, in that in many formulations, the added-mass and coriolis-centripetal terms might already be present. Therefore it is important to ensure that the asymptotic added-mass terms of the seakeeping formulation do not interfere with the manoeuvring added-mass terms.

In a slightly more complicated manner, it is also vitally important to ensure that the coriolis-centripetal terms of the manoeuvring model, such as the munk-moment in Equation (3), are also not modelled twice. For instance, these terms can appear in a seakeeping formulation in the form of speed-dependent added-mass terms (e.g. [4], which is the formulation used in ShipX/VERES). Again, the retardation functions in Equation (2), given by $\mathbf{h}(\mathbf{t} - \boldsymbol{\tau})$, already implement coriolis-centripetal forces which correspond to the added-mass terms, and so it is important to ensure that the manoeuvring model, as derived from experiment, does not include these terms again. Therefore, great care should be taken in evaluating any correction for these terms. Such correction can be made in the following manner:

$$A_{62}^0 = -N_v^0 \quad (4)$$

$$A_{66}^0 = -N_r^0 \quad (5)$$

$$\Delta A_{62}^\infty = A_{62}^\infty + N_v^0 \quad (6)$$

$$\Delta A_{66}^\infty = A_{66}^\infty + N_r^0. \quad (7)$$

The speed dependent damping corrections, or coriolis-centripetal moments, are calculated as:

$$B_{62}^U = (Y_{\dot{v}}^0 - X_{\dot{u}}^0) u \quad (8)$$

$$B_{66}^U = \frac{1}{2} (Y_r^0 + N_v^0) u \quad (9)$$

$$\Delta B_{62}^\infty = B_{62}^U u - B_{62}^U \bar{u} \quad (10)$$

$$\Delta B_{66}^\infty = B_{66}^U u - B_{66}^U \bar{u}, \quad (11)$$

where the superscript U indicate the speed dependent damping terms in the unified model.

This correction methodology is applied consistently in all the degrees of freedom, since the manoeuvring model and seakeeping model have the potential to clash with one another in many places.

Manoeuvring model

The manoeuvring terms in Equation (2), \mathbf{q}_{man} , can be discovered by a variety of methods. In VeSim's framework, there are two primary options. Firstly, to use the ShipX manoeuvring plugin, HullVisc, which is a strip-theory program, combined with heuristic tuning to an extensive database of ships [5]. Secondly, the option is to utilise experimental tests, and to form a set of hydrodynamic derivatives based on these, taking advantage of SINTEF Ocean's manoeuvring identification code, IDSIMAN [6]. This second form of manoeuvring analysis is the topic analysed here. In either case, the results are combined in the ShipX Vessel Simulator Plug-in for calculation of the retardation functions, and simulator setup. A comprehensive description of the methodologies involved in deriving and implementing effective simulation models can be found in the two papers [6, 7].

In the case of analysis arising from experiment, the manoeuvring model used in VeSim was developed through the study of vessels operating at either service speed in a seaway, or station-keeping/dynamic position. VeSim has been developed as a combined manoeuvring and seakeeping simulator. In VeSim, seakeeping is handled through the use of potential theory, which is solved in the time

domain using impulse response functions. The manoeuvring model utilises the approaches from [3]. The manoeuvring forces, $\mathbf{q}_{man} = [X_m, Y_m, N_m]^T$ equations in 3 degrees-of-freedom, which consider the zero frequency added mass effect, added mass coriolis-centripetal forces, linear lift and drag, cross flow drag, can be represented by:

$$\begin{aligned} X_m = & X_u^0 \dot{u} + Y_v^0 vr + \frac{1}{2} (N_v^0 + Y_r^0) r^2 \\ & + X_{uu}^L u^2 + X_{uuu}^L u^3 + X_{rvu}^L rvu \\ & + X_{vv}^L v^2 + X_{rv}^L rv + X_{uvv}^L uv^2 \\ & + X_{rr}^L r^2 + X_{urr}^L ur^2 + X_{u|v}^L u|v| \end{aligned} \quad (12)$$

$$\begin{aligned} Y_m = & Y_v^0 \dot{v} + Y_r^0 \dot{r} + X_u^0 ur + Y_{uv}^L uv + Y_{ur}^L ur \\ & + Y_{uur}^L u^2 r + Y_{uuv}^L u^2 v + Y_{vvv}^L v^3 \\ & + Y_{rrr}^L r^3 + Y_{rrv}^L r^2 v + Y_{vvr}^L v^2 r \\ & + Y_{|r|v}^L |r|v + Y_{|v|v}^L |v|v + Y_{|v|r}^L |v|r \\ & + Y_{|r|r}^L |r|r \end{aligned} \quad (13)$$

$$\begin{aligned} N_m = & N_v^0 \dot{v} + N_r^0 \dot{r} + (Y_v^0 - X_u^0) vu \\ & + \frac{1}{2} (N_v^0 + Y_r^0) ru + N_{uv}^L uv + N_{ur}^L ur \\ & + N_{uur}^L u^2 r + N_{uuv}^L u^2 v + N_{vvv}^L v^3 \\ & + N_{rrr}^L r^3 + N_{rrv}^L r^2 v + N_{vvr}^L v^2 r \\ & + N_{|v|v}^L |v|v + N_{|v|r}^L |v|r + N_{|r|v}^L |r|v \\ & + N_{|r|r}^L |r|r \end{aligned} \quad (14)$$

To enumerate the coefficients in Equations (12) to (14), utilising test data gathered through PMM, the coefficients are reshaped to the vector format:

$$\mathbf{F}(\boldsymbol{\theta}, \mathbf{v}_{man}, \dot{\mathbf{v}}_{man}) = \boldsymbol{\tau}_{man} \quad (15)$$

where $\mathbf{v}_{man} = [u \ v \ r]^T$, $\boldsymbol{\tau}_{man} = [X_h \ Y_h \ N_h]^T$, and finally $\boldsymbol{\theta}$ de-

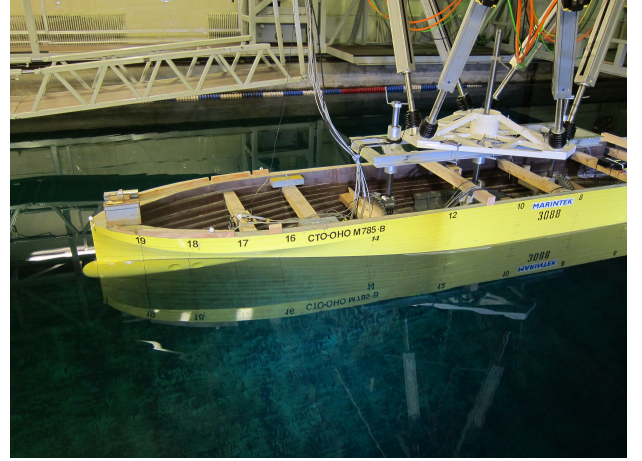


FIGURE 2. SCALE MODEL OF LANDEGODE MOUNTED IN SINTEF OCEAN'S SEAKEEPING CARRIAGE.

notes total parameter vector:

$$\begin{aligned} \boldsymbol{\theta} = & [X_u^0 \ Y_v^0 \ Y_r^0 \ N_v^0 \ N_r^0 \ X_{vv}^L \ X_{rr}^L \ X_{rv}^L \ X_{uvv}^L \\ & X_{rvu}^L \ X_{urr}^L \ Y_{uv}^L \ Y_{ur}^L \ Y_{uur}^L \ Y_{uuv}^L \ Y_{vvv}^L \ Y_{rrr}^L \\ & Y_{rrv}^L \ Y_{vvr}^L \ N_{uv}^L \ N_{ur}^L \ N_{uur}^L \ N_{uuv}^L \ N_{vvv}^L \ N_{rrr}^L \\ & N_{rrv}^L \ N_{vvr}^L \ X_{u|v}^L \ Y_{|r|v}^L \ Y_{|v|v}^L \ Y_{|r|r}^L \ Y_{|v|r}^L \ N_{|r|v}^L \\ & N_{|v|v}^L \ N_{|r|r}^L \ N_{|v|r}^L]. \end{aligned} \quad (16)$$

The optimisation problem given by:

$$\min_{\boldsymbol{\theta}} \frac{1}{2} \|\mathbf{F}(\boldsymbol{\theta}, \mathbf{v}_{man}, \dot{\mathbf{v}}_{man}) - \boldsymbol{\tau}_{man}\|^2. \quad (17)$$

is then the relevant task. The posed problem is solved using SINTEF Ocean's in-house tool, IDSIMAN, as described, for example in [6].

Verification and Validation

Verification of manoeuvring model

Two extensive sets of model tests were performed on the Landegode at SINTEF Ocean in the Towing Tank (see Figure 2). Both sets comprised of resistance and propulsion tests, augmented with planar motion mechanism (PMM) tests. These tests dynamically excite the captive model, and were combined with accurate force and moment measurements, so as to be used to fit to an advanced model utilising IDSIMAN. Details on the approach used are described in [6, 7].

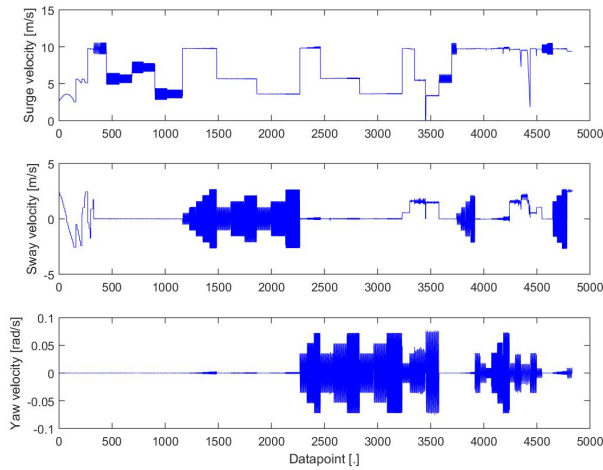


FIGURE 3. PMM DATASET: VELOCITIES.

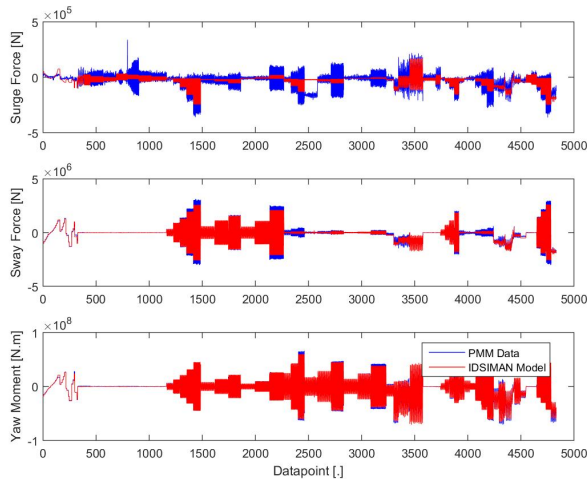


FIGURE 4. PMM DATASET: FORCE AND MOMENT COMPARISONS.

The procedure of regression is verified by checking that the test data is reasonably accurately recreated by the manoeuvring model. This approach can be seen in Figures 3 and 4. Figure 3 shows the complete concatenated database of about thirty PMM test runs, with various combinations of surge, sway, and yaw velocities. Figure 4 shows the corresponding measured forces and moments, alongside those “predicted” by the regressed IDSIMAN model. Both datasets: the one from experiment, and the other from VeSim’s calculated manoeuvring model, make similar predictions. This at least gives confirmation that the model can reasonably represent the measured test data.

Propulsion model validation

Several sets of model-scale validations have been performed to document the performance of the propulsion model used in the VeSim simulations. Rolls-Royce, the designer and manufacturer of Landegode, constructed an in-house simulation model of the propulsive units, which was designed to integrate with VeSim. Rolls-Royce graciously made this tool available to SINTEF Ocean, and it was utilised in the total simulation model of Landegode.

Part of the test program at SINTEF Ocean was in running static propulsion tests, in which the model was towed at steady speeds, with various steady rudder angles. These are therefore good candidates for validation of the rudder-propeller-interaction model, since the data was not used to derive the propulsion module itself. The test is partially described by Table 1.

In these tests, performed in the Towing Tank Laboratory, the boat is towed close to its model-scale self-propulsion-point. Several rudder angles are then applied. The tests were performed at zero sideslip ($\beta = 0^\circ$), and at a fullscale total velocity of 18kt or $U_0 = 9.75\text{m/s}$. All data is shown at their full-scale levels.

TABLE 1. RUDDER ANGLES APPLIED IN R2101.

Test Run	δ_r [°]					
R2101	25	30	35	-5	-10	-15

Figures 5 and 6 shows the results of one of the validation comparison tests. The rudder-propeller model performs well in sway and yaw, and reasonably in surge, though it is extremely accurate in surge at higher rudder angles. The differences in RPM in Figure 5 are present due to the differing self-propulsion points: the model scale tests are at the model-scale self-propulsion point (Froude scaled to full-scale values), while the simulations are performed at full-scale, and are therefore carried out at the full-scale self-propulsion point.

In these plots, it is quite clear that the global sway forces resulting from rudder angle variations match up quite well between simulation and model-scale experiment. Additionally, the global yaw moment shows excellent correspondence too. Larger differences are seen in the in surge forces, but these remain quite good.

Validation of manoeuvring model

Fullscale test data was gathered for the M/F Landegode in Week 33 of 2013. The tests were performed in relatively calm weather, just outside of Bodø. Many manoeuvres and

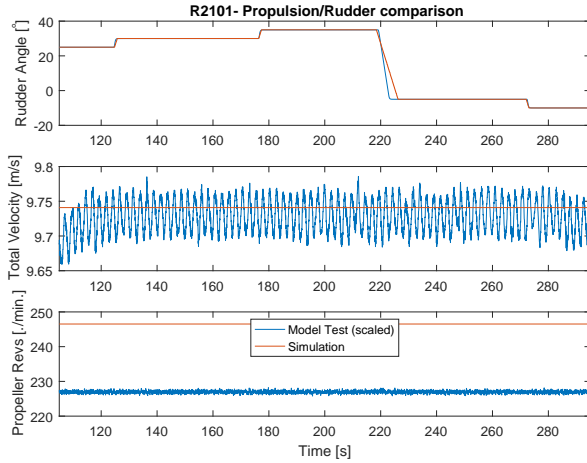


FIGURE 5. R2101: VELOCITIES AND RPM.

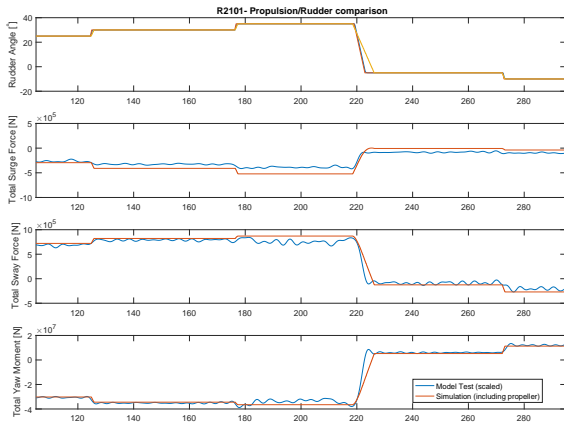


FIGURE 6. R2101: GLOBAL FORCES.

runs were carried out, and a comprehensive picture of Landegode’s calm-water manoeuvring performance was gathered. For brevity, a subsection of these tests are used in this paper. We present two zig-zag tests and a complete spiral test. The approach speed for all manoeuvres was about 19 knots, at 80% power. The loading condition used for these tests was $TF = 3.20m$, $TA = 4.20m$. These tests allow for close comparisons to be made between simulation and actual fullscale performance.

The quality of both zig-zag simulation tests are approximately the same. Agreement tends to be quite good overall. In both cases, there is a deviation in the first overshoot angle, while the behaviour both before and after this deviation shows very close agreement with those found in the fullscale tests. A large portion of the behaviour is well captured by

Run #	Manoeuvre	Key Parameters	Approach Speed
3007	Zig-zag	10/10	19kt
3009	Zig-zag	20/20	19kt

TABLE 2. FULLSCALE TESTS USED FOR VALIDATION.

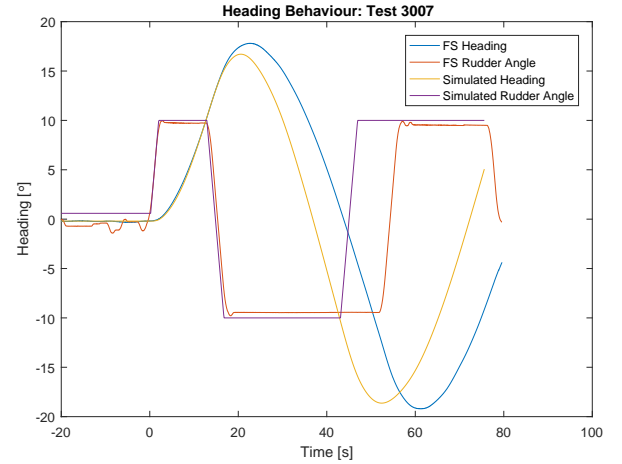


FIGURE 7. 10/10 ZIG-ZAG: HEADING.

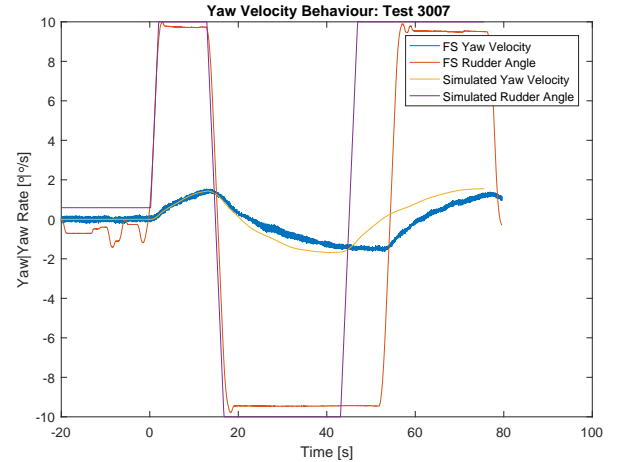


FIGURE 8. 10/10 ZIG-ZAG: YAW VELOCITY

the simulation model. Speed loss, shown in Figure 9 is well captured throughout. Sway velocity is likewise well captured. This loss in speed is somewhat better captured in the 20/20 zig-zag, in comparison to the 10/10.

There are however differences in both the yaw velocity behaviour and consequently the heading behaviour. The difference in heading behaviour is that the simulated boat

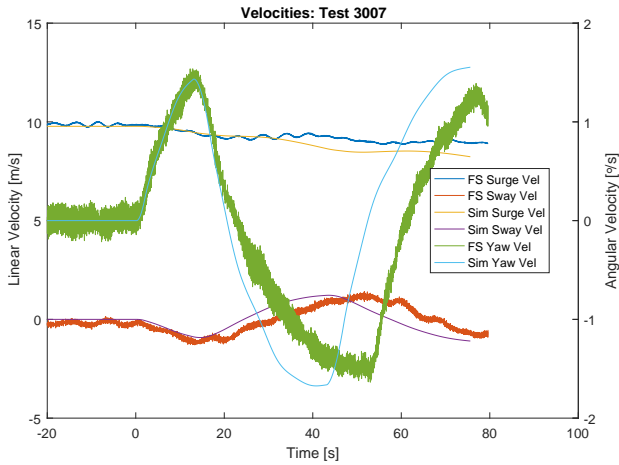


FIGURE 9. 10/10 ZIG-ZAG: BODY VELOCITIES

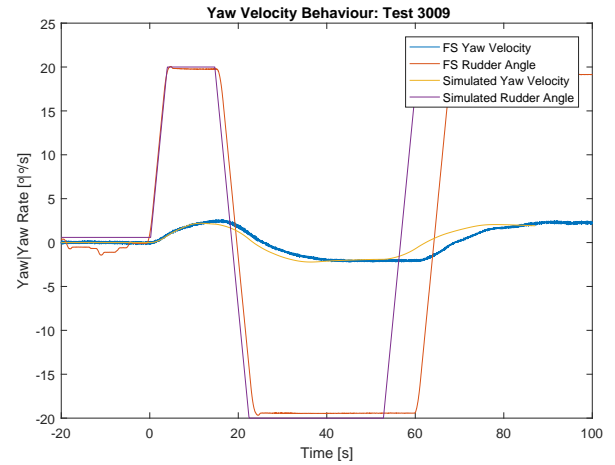


FIGURE 11. 20/20 ZIG-ZAG- YAW VELOCITY.

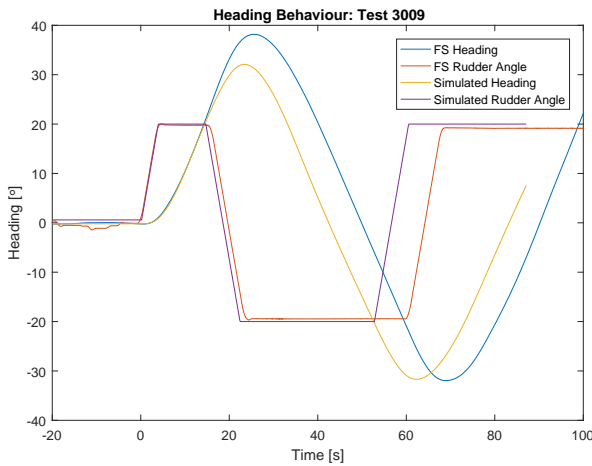


FIGURE 10. 20/20 ZIG-ZAG- HEADING.

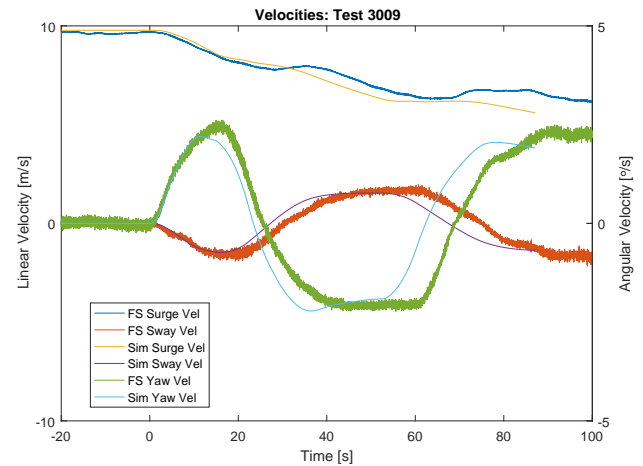


FIGURE 12. 20/20 ZIG-ZAG- BODY VELOCITIES.

slows its first overshoot more quickly than the fullscale boat. From examining Figure 7, the opening transit phase, from approximately 0s to 20s is captured very well. Additionally, the heading behaviour from about 30s onwards shows extremely close agreement with that seen in the fullscale test.

Complete Spiral Test Figure 13 compares a complete spiral test in both fullscale tests, and in simulation. Considerable agreement is found for negative rudder angles. For large positive rudder angles, the agreement is also good. For small positive rudder angles, the simulation shows a slightly more positive yaw rate, up to about 10° , at which agreement is good again.

Conclusion

The simulation framework used by SINTEF Ocean has generally shown itself to be of a very good predictive value. A toolchain has been demonstrated in which computational and experimental results can be used to make a ship-specific simulator model, which has been verified and validated. Simulation predictions with demonstrated predictive value, which can be formulated without tuning against fullscale tests have clear value to the marine industry generally, and the results shown within this paper demonstrate good progress towards that.

While good agreement is generally found between experiment and simulation, there remain areas of operation which could certainly be captured better. The sources of uncertainties in both the calculated model and in the model

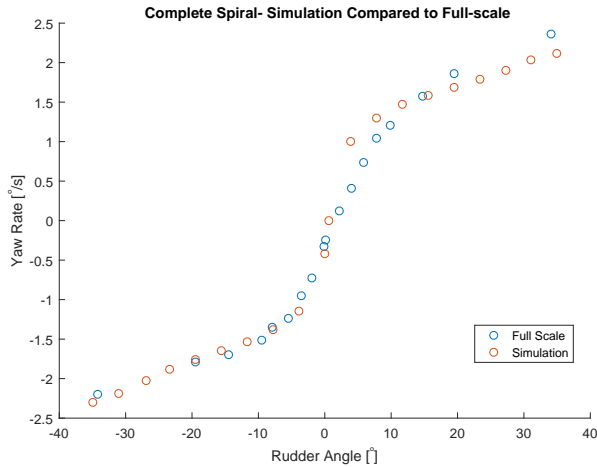


FIGURE 13. COMPLETE SPIRAL TEST.

tests themselves are quite numerous, and are not analysed in this paper. However, some improvements in SINTEF Ocean’s simulator model would likely play a large part in reducing these uncertainties.

VeSim does not as yet model the power take-off (PTO) systems used onboard the boat, meaning that the power delivered mid-manoeuve can vary between simulation and reality. More analysis is also required in coping with the inherent uncertainties of performing full-scale tests, and then comparing with simulation, for example applying the methods within [8]. Such approaches would lead to more insight into the actual accuracy of the simulations in this paper, and will form part of future work on this topic.

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