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## ITTC Quality System Manual Recommended Procedures and Guidelines

### Procedure

## Verification & Validation of Manoeuvring Simulation Models


7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-06	Manoeuvrability
7.5-02-06-03	Verification & Validation of Manoeuvring Simulation Models

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Prepared by	Approved
Manoeuvring Committee of the 30 <sup>th</sup> ITTC	30 <sup>th</sup> ITTC 2024
Date 07/2023	Date 09/2024

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## Verification & Validation of Manoeuvring Simulation Models.

### 1. PURPOSE OF PROCEDURE

This procedure proposes the necessary steps and documentation for the verification & validation (V&V) of a simulation model. The procedure is valid for a simulation model based on

- empirics,
- captive tests (PMM or CMT) or
- virtual captive tests (CFD).

The procedure can be applied to

- specific manoeuvring models (valid for one ship) or for
- generic manoeuvring prediction methods.

This procedure is intended to help assess the V&V, and quality of a manoeuvring simulation model, related to the IMO standard manoeuvres. Any validity check is a difficult task due to the lack of reliable full-scale results to compare simulations with. There is however a considerable amount of model scale validation material available. The need for accurate simulations justifies significant attention in this area.

### 2. INTRODUCTION

The development of a manoeuvring simulation model can have many purposes. A distinction can be made between:

- (a1) models for prediction of ship manoeuvrability.
- (a2) models for use in simulators.


Prediction of standard ship manoeuvres (a1) is needed at the design stage to ensure that a ship

has acceptable manoeuvring behaviour, as defined by the ship owner, IMO or local authorities.

The ship manoeuvring behaviour predicted by simulation model may be different depending on the used model, even though the simulation model was validated by the benchmark data. If the ship manoeuvring behaviour has deviations according to the used model, or the verification of the model is insufficient, then it is better to use the conservative simulation results to predict and to ensure the ship manoeuvrability. A conservative model is the one that makes the manoeuvre more difficult in the simulator than the real one.

Simulator, or time-domain, models (a2) are used in real-time, man-in-the-loop simulators, or fast-time simulators for training of deck officers or investigation of specific ships operating in specific harbours or channels. For these purposes, the simulation often has to model a specific ship in deep and shallow water (finite water depth), as well as interactions with the environment in the form of wind, current, waves and tugs. Lateral restrictions are also possible, which are referred to as restricted water, that includes banks, ship-ship interaction, etc. Other purposes might exist, but these cover those most commonly encountered.

The requirements for the V&V are the same for both types of models. However, the amount of required data and, hence, the validation effort is much larger for simulator models (a2) since they typically address more parameters and operating conditions than the models used for prediction of ship manoeuvrability (a1). For these reasons, those guidelines apply to models (a1) and can be used as a basis for the development of models (a2).

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The generation of a manoeuvring model covers a series of steps, which must be validated and documented individually:

1. Ship particulars
2. Mathematical Model Structure
3. Prediction of the Hydrodynamic forces
4. Modelling of forces in the mathematical model (derivatives, coefficients, tables, direct simulation of forces)
5. Integration method
6. Simulation software
7. Simulated manoeuvres

Each of the above steps is addressed in the following sections.

### 3. DOCUMENTATION OF A MANOEUVRING SIMULATION MODEL

This section is valid for prediction of IMO type standard manoeuvres alone (a1) and for models in a (full mission or fast time) simulator which have to perform in addition to standard manoeuvres many other manoeuvres (a2). The simulator models (a2) are in general more extensively described than the (a1) models.

A simulation model should be documented in a way such that the methods and assumptions used are stated and the parameters, for which the model is valid, are clearly given. Furthermore, the documentation should include simulated standard manoeuvres and possibly address the expected accuracy of these simulations.

The purpose of the manoeuvring simulation model must be stated and a definition of the nomenclature and coordinate systems used must be given.

The various simulation models with different complexities are applied to predict ship manoeuvrability. The required complexity of the

model may be different depending of the purpose of the simulation model. The purpose of the model can be distinguished as follows:


1. Prediction of ship manoeuvrability in deep water;
2. Prediction of ship manoeuvrability in shallow water;
3. Prediction of ship manoeuvrability in restricted water;
4. Prediction of ship manoeuvrability using 4-DOF or 6-DOF model;
5. Use of simulator for training of crews.

The simulation model (1) is normally used to verify if a vessel complies the IMO regulations for the standard manoeuvres (such as turning circle, zigzag, crash-stop). The hydrodynamic forces measured in model tests in a deep-water towing tank are used to construct the mathematical model.

The simulation models (2) and (3) are used to predict the ship response in shallow and confined water. The purpose of the simulations is the assessment of new ports; the maximum ship size allowed in the port or to verify the operational limits of the port, among others. The simulations can also be used for training purposes, risk assessments and definitions of emergency procedures in case of failures.

The utilization of 4-DOF or 6-DOF models are required when the vertical motions of the ship play an important role in the manoeuvring prediction, such as for high-speed vessels, low GM vessels and manoeuvring in waves and wind.

The hydrodynamic forces and moments acting on the ship advancing in the shallow and restricted water should be considered and modelled in the model for ship-bank interaction and

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ship-bottom interaction effects. For 4- or 6-DOF model the roll angle should be included in the model for the viscous roll damping and the restoring force. The mathematical model structure of 4- or 6- DOF model and model in shallow/restricted water are in general more complex than the model in deep water.

### 3.1 Ship Particulars

For a model to be used in the prediction of ship manoeuvrability ( $a_1$ ), at least the following ship particulars should be given:

**Type of ship** (container, LNG, etc.)

#### Hull data

- Design displacement
- Design draft
- $L_{PP}$
- $L_{OA}$
- Breadth moulded

#### Actual loading condition

- Draft fore/aft or mean draught/trim
- Displacement
- Wetted surface
- Longitudinal centre of buoyancy
- Moment of inertia in yaw
- $\overline{KG}$ ,  $\overline{BM}$ ,  $\overline{KB}$ , moment of inertia in roll (4-DOF model)
- Approach speed and/or service speed

#### Engine characteristics

- Engine type
- Shaft power
- Engine RPM

#### Data on propulsors

- Type
- Number of propulsors
- Position
- Diameter

- Thrust and torque open water characteristics
- Type dependent data (e.g. for propellers: direction of rotation, no. of blades, pitch ratio at  $0.7R$ , area ratio  $A_E/A_O$ ; for pods: lateral area, pod diameter, length)


#### Data on steering devices

- Type
- Number of steering devices
- Position
- Type dependent data (e.g. for rudders: type of rudder (spade, horn, flap), movable rudder area, total rudder area, height, length, aspect ratio, thickness, maximum rudder rate, maximum rudder angle)

Other useful information for documentation includes

- a set of hydrostatic data (at least for the given loading condition);
- drawings of the rudder and propulsor areas, including contour and profiles;
- a body plan and stern and stem contours of the ship;
- description and drawings of appendages on the hull, including bilge keels, additional fins, etc.;
- if possible, photographs of the ship;
- for models to be used in real-time simulators, profiles exposed to wind should be included, as well as their corresponding frontal and lateral windage areas;
- a table giving the ship speed at various control settings in deep and shallow water;
- data on thrusters and other auxiliary manoeuvring devices, including number, position, design thrust, etc.

A recommended example of how to document ship particulars of a simulation model is given in Hwang, 2004.

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### 3.2 Prediction of the Hydrodynamic Forces

A simulation model is usually based on Newton's Second Law, applied to a rigid body for six degrees of freedom:

- Translation modes:

$$\begin{aligned} & \text{mass} * \text{acceleration} \\ & = \sum \text{external forces} \end{aligned}$$

- Rotation modes:

$$\begin{aligned} & \text{mass moment of inertia} * \text{angular acceleration} \\ & = \sum \text{external moments} \end{aligned}$$

The mass properties of the vessel in the various degrees of freedom are generally well-known. The external forces and moments are primarily of hydrodynamic origin for marine vessels, and include effects of the hull itself, along with those of steering devices and propulsors. Additionally, forces and moments exerted by tugs, moorings, environmental forces, etc., are included as applicable in the external forces. Naturally, the accuracy of the various force and moment models greatly affects the accuracy of the simulations.

A variety of possible sources are available for the estimation of hydrodynamic forces and moments; they can be distinguished as follows:

- (b1) Data base (type ship concept);
- (b2) Regression equations from data base;
- (b3) Captive model tests (see Procedure 7.5-02-06-02 rev.6, 2021);
- (b4) Free model tests with system identification;
- (b5) Full scale trials with system identification;


(b6) Calculation of forces resulting from prescribed kinematics by CFD techniques (see Procedure 7.5-03-04-02);

(b7) Direct Manoeuvring Simulation using CFD.

Several of these methods (b2), (b3), (b4), (b6) and (b7) were studied and their performance was compared in the SIMMAN 2008, SIMMAN 2014 and SIMMAN 2020 workshops on validation of manoeuvring mathematical models.

It should be noted that some of these methods, such as (b4) and (b5), often do not include explicit definition of the hydrodynamic forces. One conclusion from the SIMMAN 2008 workshop was that these methods are not applicable outside the combination of motion parameters where the mathematical model is created. Some encouraging results have been obtained by grey box identification of the 3DOF manoeuvring model (Mei, et al., 2020; Efremov and Milanov, 2019).

A distinction between force predictions from generic databases (b1, b2) and ship specific data (b3, b4, b5, b6, b7) has to be made. If either database method is used, it should be clearly documented to what extent the current design is represented in the database that is being used as source. As an example, a database that consists only of full form tankers, cannot be used for prediction of forces on a container ship. The adequacy of a database for a given vessel can be assessed by comparing appropriated parameters such as  $T/L_{PP}$ ,  $B/T$ ,  $C_B$ , approach speed, etc. This was clearly demonstrated in the SIMMAN 2008 workshop. Therefore, it is recommended that the adequacy of the (b1) and (b2) methods is demonstrated by comparison to several vessels within the range of applicability of the method. If applicable, the free model tests results produced by the SIMMAN 2020 workshop should be part of this validation.

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Simulation models based on captive tests (b3) should be developed based along well established methodologies. Methodologies therefore need to be well established within the institute. The applicability of the methods needs to be validated by comparison with free model tests or full-scale measurements. In particular, it is important to model ships with low GM and higher speeds, using 4 DOF mathematical models. That implies that the roll angle should be a parameter in the test matrix. Both the SIMMAN 2008 and SIMMAN 2014 workshops have clearly demonstrated the large difference in the performance between 4-DOF models and 3-DOF models for such ships.

For the cases (b4, b5), free model tests and full-scale trials with system identification, it is essential to demonstrate that force representation is also adequate to describe manoeuvres which are not included in the trials or tests. This extrapolation may be difficult, although models that contain only the necessary effects will usually be the most successful. Oltmann (1996) gives an example wherein free model zig-zag tests were used to create an adequate mathematical model. A subsequent, independent comparison with a full-scale turning circle was successful, showing that the model created from zigzag data was applicable to steady state turning. In fact, this same study also illustrates an effective scaling of forces.

In the case of free model tests (b4) and full-scale trials (b5), one should demonstrate that the system identification method gives good results either using the own data (showing that the simulations predict the tested manoeuvres used for the system identification) or applying the same procedure for other independent benchmark data. Similarly, the use of CFD to calculate forces (b6) should be validated against benchmark captive force measurements. Finally, simulation making use of CFD (b7) can be validated against benchmark manoeuvres from either free sailing model tests or full-scale trials. The use of

system identification results to validate CFD calculations, and vice versa, is not recommended.


As a final note, the use of full-scale trials for the purpose of identifying forces (b5) often have the difficulty of uncontrolled or poorly documented environmental conditions, such as second-order wave forces, wind, currents, and non-uniform sea bottom. These effects, which degrade the quality of data significantly, can be minimized through careful selection of the trial site and conditions of weather, wave height, and tidal flow. The environmental conditions should be measured and documented as accurately as possible.

The environmental conditions (hydro/meteo data on the state of the sea and weather conditions) should be measured and documented reliably and accurately as possible. The hydro/meteo data (wind, waves, water levels, currents, water density, miscellaneous) collection/prediction guidelines which were provided by the local authorities may be used to secure the environmental conditions. The PIANC Report n° 117 – 2012 presents the good-practice on how to obtain reliable environmental data to be used in port manoeuvring analysis.

Furthermore, the vessel should be instrumented as well as possible in order to record ship motions. Thereby it may be possible to model the environmental effects in the mathematical model or at least to develop upper bounds of their impact on the overall response (see Procedure 7.5-04-02-01).

#### 4. VERIFICATION

Verification of a model is the process of verifying that it is correctly developed concerning the conceptual model. To verify the ship manoeuvring simulation model it is necessary to

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confirm that it matches specifications and assumptions for the model concept.

#### 4.1 Mathematical Model Structure

For the complexity of the mathematical model, the following distinctions are made:

- • Whole-ship models (Abkowitz (1964) or modified)
- • Modular models of components
- • Direct simulation (CFD)

Whole-ship (global forces) models are typically used for the prediction of ship manoeuvrability, whereas modular models may be used additionally for real-time simulator models. In the latter case, the human operator has access to a large number of sensors and interacts with a variety of vessel subsystems. While whole-ship models and modular models are typically quasi-steady, CFD models enable the simulation of transient manoeuvres by increasing the resolution at the fluid level. For example, the verified structure of the hydrodynamic part of the 4DOF simulation model – SIMMAN2020 (Quadvlieg et al., 2024) - can be accepted.

#### 4.2 Modelling of Forces in the Mathematical Model.

The hydrodynamic forces acting on the ship can be represented mathematically in many forms, from the fairly simple Abkowitz derivatives for prediction of first quadrant manoeuvres, to a full four-quadrant deep and shallow water simulator model.

Forces are described with the following means:

1. Hydrodynamic derivatives (obtained from measured or calculated forces)
2. Look-up tables of the forces
3. Look-up tables of the forces

8. Algebraic equations (empirical or theoretical)
9. Direct simulation (CFD)

For any approach, the proposed mathematical model must be able to reproduce the original force data with sufficient accuracy. Following the procedure applied in the SIMMAN2020 workshop, data fitting of mathematical model terms should be accomplished with an estimation of the goodness of the fits, in most cases through the factors R-squared and standard deviation  $\sigma_{\text{fit}}$  or other statistical estimations. Such procedures are usually included in the approved software products oriented to the experimental data fitting. An example of the analysis of the mathematical model hydrodynamic derivatives evaluation is given in the following section.

##### 4.2.1 Hydrodynamic forces in X-equation

- Propulsion terms, as a difference between ship thrust and resistance force in the 1<sup>st</sup> quadrant are represented by a 2<sup>nd</sup>-order polynomial  $a_0 + a_1x + a_2x^2$ , where  $x = u'$  or by propulsion ratio  $\eta = \frac{J_0}{J} = \frac{U_0 n}{n_0 U}$ . If manoeuvre is performed in other quadrants, to avoid singularities and follow the similarity rules it can be used expression  $\frac{u}{\sqrt{u^2 + n^2 D^2}}$
- Surge force dependency on sway  $v$  and yaw  $r$  velocities, obtained from steady straight-line towing with drift angle is expressed by parabolic curve function functions  $X'(v'^2)$  and  $X'(r'^2)$ . The parabolic character of the function is caused by the presence of speed-squared cross flow.
- Cross-coupling effects of the above velocities catch well with the derivative  $X_{vr}$ .

An example from Quadvlieg et al. (2024) of the total X-force fitting applied to the PMM experimental data is given in Figure 1, by which



the shaded area is the fit +/- the standard deviation from the fit.

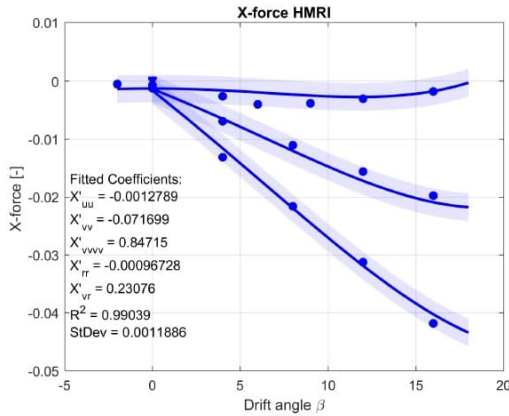


Figure 1: Derived experimental values from the captive tests, including the fit of the experiments. The shaded area is the fit +/- the standard deviation from the fit, Quadvlieg et al. (2024).

#### 4.2.2 Hydrodynamic force and moment in Y, N-equations

- Straight-line towing with drift angle can be considered as given for sway force  $Y'$  and the corresponding yaw moment  $N'$  the following approximation formulas, which can be obtained based on the crossflow drag concept using 2<sup>nd</sup> order approximation of odd function:

$$Y'(v') = Y'_0 + Y'_v v' + Y'_{vv} |v'| v'$$

$$N'(v') = N'_0 + N'_v v' + N'_{vv} |v'| v'$$

or a 3<sup>rd</sup>-order polynomial is used, accounting for odd function characters.

- The “pure yaw” dynamic test data are used for the calculation of yaw velocity derivatives, utilizing a similar form of functional dependencies.
- In system-based simulation models, an important role is played by nonlinear cross-coupling terms, in particular when the rudder is put hard over. For example, the evalu-

ation of these terms is done by using combined captive test “yaw-static drift” tests where the drift variations are usually within a narrow range. The form of corresponding terms usually used is:  $Y'_{vrr} v' r'^2$ ;  $Y'_{vvr} v'^2 r'$ ;  $N'_{vrr} v' r'^2$ ;  $N'_{vvr} v'^2 r'$ . Therefore, caution is needed when analyzing the statistical error of approximation.

- The dependency of linear sway and yaw derivatives on advance speed is expressed by terms  $Y'_{vu} v' u'$ ;  $Y'_{ru} r' u'$ ;  $N'_{vu} v' u'$  or equivalently by  $Y'_{v\eta} v' \eta'$ ;  $Y'_{r\eta} r' \eta'$ ;  $N'_{vu} v' \eta'$ ;  $N'_{ru} r' \eta'$ . Examples of total Y-force and total N-moment fitting are illustrated in Figures 2 and 3, where the terms in approximation expressions and error are given.

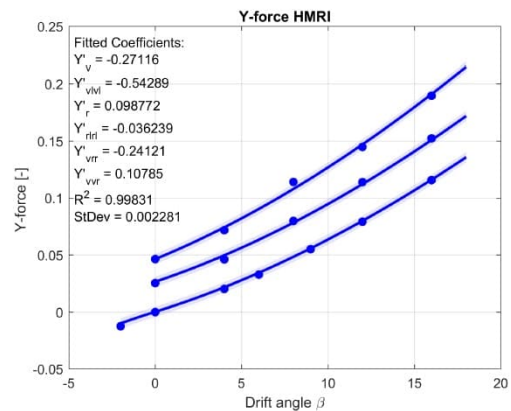


Figure 2: Sway force, Quadvlieg et al. (2024).

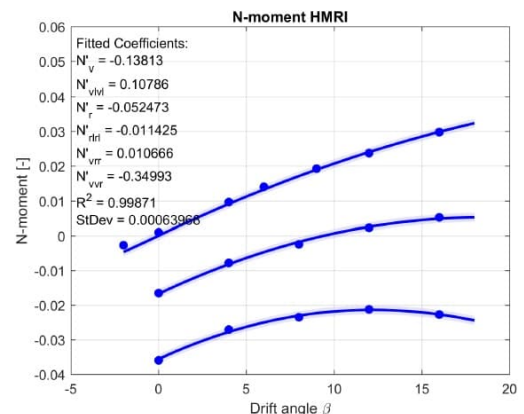


Figure 3: Yaw moment, Quadvlieg et al. (2024).

Results from a PMM test for a ROPAX vessel are shown in Figure 4, as an example; the measured yaw moment is given as function of drift angle and speed. The PMM tests covered three speeds to account for the speed loss during a turning circle. The proposed mathematical model for the yaw moment,  $N'(\beta, u')$ , is:

$$N'(\beta, u') = N'_{\beta}\beta + N'_{\beta|\beta}|\beta|\beta| + N'_{\beta\beta\beta}\beta^3 + N'_{\beta u}\beta u'$$

Here non-dimensional surge and sway velocities are given as:

$$u' = \frac{u - U_0}{\sqrt{u^2 + v^2}}, \quad \tan\beta = -\frac{v}{u}$$

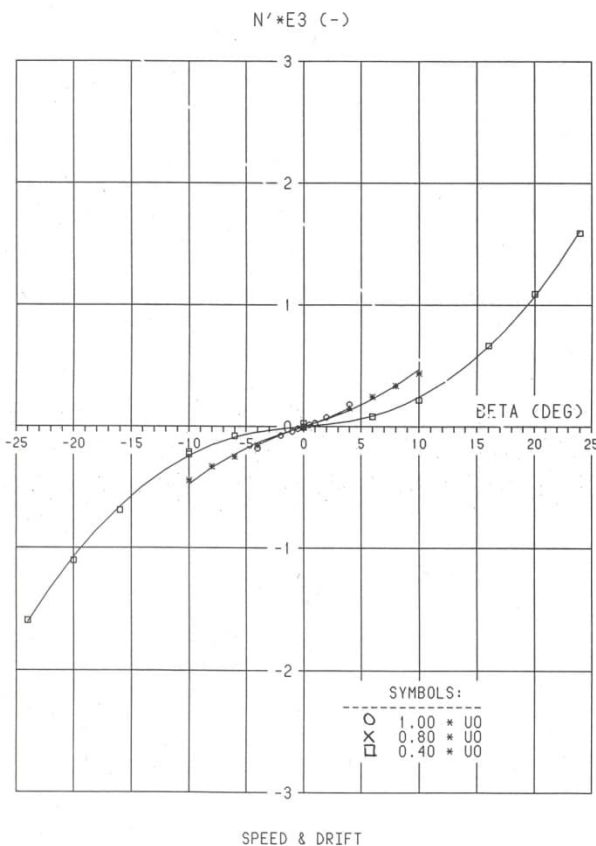


Figure 4: Comparison of measured and predicted yaw moment. Lines indicate simulation model.

As the figure shows, the proposed mathematical model captures the measured yaw moment reasonably well, with regard to variations in both  $u'$  and  $\beta$ .

When databases or regression equations (b1, b2) are used, the obtained force formulation corresponds to the structure of the mathematical model. Validation of the mathematical model is therefore impossible in these cases.

Documentation of the mathematical model should include:


- Form of the model
- Nomenclature
- Non-dimensionalisation used
- All state variables
- The range of state variables for which the mathematical model is valid
- Interaction terms in modular models

All effects that are included in the mathematical model should be defined. As an example, if the model includes propeller rotational speed, the strategy for relating engine power and rpm during simulation should be explained.

### 4.3 Integration Method

Once the governing differential equations are known, a large variety of integration methods exist to make a time-domain simulation. The implementation must be validated against a known problem with a time constant similar to what is expected for the ship manoeuvres and which can be solved in an analytical way. For example, the step response of a first- or second-order system can be used.

The solution must also be checked for convergence, i.e. the time step and integration procedure used should be sufficient to model the frequencies included in the simulations. At the lower end, a 3-DOF model for prediction of

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IMO manoeuvres can be considered low frequency, for example the zigzag manoeuvre. The inclusion of roll motion immediately adds a higher frequency into the calculation, so that a smaller time step or a higher-fidelity integration scheme is required. Also, the viscous roll damping coefficient adjustment method must be documented. Full scale data or numerical methods (based on Procedure 7.5-02-07-04.5: Numerical Estimation of Roll Damping) may be used. Full 6-DOF models bring in higher resonance frequencies in heave, roll and pitch. Simulator models may introduce even more resonant components, due to interaction with moorings, fenders, and tugs, as well as waves.

To verify the numerical time-integration of the ship motion equations by Schoop-Zipfel a sample equation analytical solution has been compared with two numerical – Euler and Runge-Kutta methods. It reveals for Euler integration zero deviation for the velocity and deviation with a gradient for the position and zero deviation for the Runge-Kutta 4th-order integration scheme – Figure 5. Based on this it can be recommended in fast-time maneuvering simulation studies for comparative analysis to apply both methods.

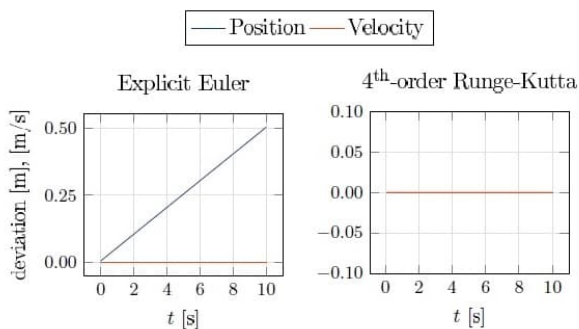


Figure 5 Linear acceleration: difference of the numerical and analytical solution

A proper time integration method should be encompassed which works with a small enough time step so that all phenomena are captured.

#### 4.4 Simulation Software

The mathematical model and the integration method that is implemented must be validated through relevant test and debug cases.

#### 4.5 Simulated Manoeuvres

The following documentation should be included for each manoeuvre performed in simulation:

- Definition of manoeuvre
- Track plot with heading indication
- Table containing time series of state variables (see below)
- For zigzag manoeuvres, time series plot of rudder and heading
- For 4-DOF models, include time series plot of roll angle


Derived manoeuvring indices (overshoot angles, turning circle parameters etc.)

The list of state variables to be tabulated should at least include:

- Rudder/steering device angle(s)
- Horizontal position in a fixed frame of reference ( $x$ ,  $y$ )
- Longitudinal speed
- Transverse speed or drift angle
- Heading
- Yaw rate
- Propeller rpm and pitch, if applicable

A 4-DOF model should also include roll angle.

A simulator model sometimes requires the documentation of more parameters depending

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of the purpose of the model. Examples of additional parameters are:

- Thrusters forces and RPM
- Tug forces
- Mooring line forces
- Shallow waters parameter (depth to draft ratio)
- Restricted waters parameters (such as bank characteristics)

As noted previously, it is important that the proposed mathematical model covers the various parameter ranges encountered in the simulated manoeuvres. It should be verified that the data used by the model during the simulation are covered by the validity range of the model.

The time resolution of the output tables and the representation of the various parameters should be consistent with the application.

A recommended example of how to document the manoeuvres of a simulation model is given in Hwang, 2004.

## 5. VALIDATION

The validation process checks the accuracy of the model's representation of the real system. A model should be built for a specific purpose and its validity determined for that purpose.

### 5.1 Introduction

Generally, the method of prediction applied must be validated against benchmark data, and the documentation of such validation should be available in the form of a report or published paper.

For predictions based on captive model testing (b3), the recommended procedure for uncertainty analysis is given in Procedure 7.5-02-06-

02: Uncertainty Analysis, Example for Planar Motion Mechanism Test.

System identification is a separate task from making the force measurements, however, and is not included in the mentioned procedure. The case where both free model tests (b4) and captive model tests (b3) exist for the same vessel in the same condition is an excellent basis for validation of the system identification process. Except for scaling effects, captive model tests, with augmentation by free model tests for highly non-linear manoeuvres, present the best prospects for control of overall modelling uncertainty. The errors will be generally limited to sensor and actuation errors, which are not difficult to quantify, and unavoidable errors induced by a finite-dimensional model.

For mathematical models based on full-scale trials and system identification (b5), the main difficulty lies in the quality of the data which complicates control of experimental and system identification errors. The hydrodynamic forces themselves are simply not available.


For (a2) simulations it is important to collect the qualitative impressions of experienced pilots that know the vessel(s) and the tested area. A questionnaire regarding the level of realism of the simulation model can be applied.

All the benchmark data that can be used for validation purposes are described in the Guideline Benchmark Data for Validation of Manoeuvring Predictions (7.5.-02-06-06).

### 5.2 Validation Procedure

The MC recommends the step-by-step validation of manoeuvring simulation models using benchmark data, model test data, full scale data and pilot expertise as follows:

Step 1 - Fast-Time simulations and comparison with benchmark, model and/or full-scale data:

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- Validation of deep-water standard manoeuvres;
- Validation of shallow water standard manoeuvres in a constant  $h/T$  relation (flat bottom);
- Validation of restricted water manoeuvres, based on simple bank geometry;
- Validation of free running trajectories, based on turning circle and overshoot angles;

Step 2 – Real-Time simulations commanded by local pilots and qualitative evaluation based on his/her expertise:

- Validation of manoeuvres performed with known vessels, ports and typical environmental conditions;

If any step indicated that the model must be changed, the model parameters can be adjusted inside the range that is compatible with their uncertainty. The variation of the parameters related to the nominal values must be documented in the simulation report. In step 1, the assessment of the free running trajectories using benchmark data such as SIMMAN 2008, SIMMAN 2014 and SIMMAN 2020 could be effective in the validation of manoeuvring simulation models.

As guidelines the SIMMAN2020: “Analysis of trajectory submission” methodology can be used. The procedure consists of a comparative analysis of the experimental data and the results obtained from the simulations for IMO manoeuvres, referring to the following kinematic parameters:

- 35deg Turning manoeuvre: advance  $ADV$ , tactical diameter  $TD$ , steady turning radius  $R_C$ , speed drop  $V_C/V_0$ , drift angle  $\beta_C$ , yaw rate  $r'_C$ .

- 20/20 Zig-zag Maneuver: first OVA1 and second OVA2 overshoot angles, initial turning ability  $ITA$ , half period  $T_{1/2}$  between 3<sup>rd</sup> and 2<sup>nd</sup> execute, maximum values of non-dimensional yaw rate  $r_{max1}$  and  $r_{max2}$ .

The standard deviations of the error values for individual kinematic parameters are calculated as well as the resulting summary error. For example, the summary result of simulation data benchmarking, performed by Quadvlieg et al (2024) is given in Figure 6, where the following methods are used: EMP-empirical, WHS-whole-ship, MOD-MMG and CFD simulation models.

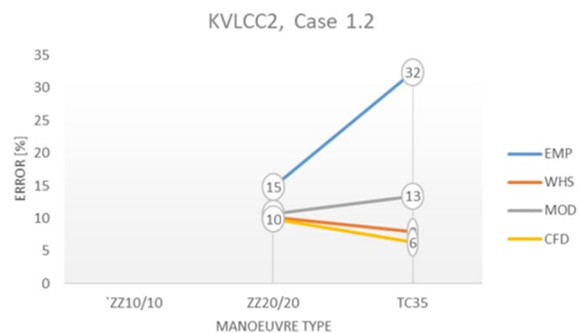



Figure 6: KVLCC2 tanker case – summary of prediction error, Quadvlieg et al. (2024)

A questionnaire was distributed among different institutes to identify how they proceed the validation of their simulation models. Further details on the questionnaire results can be found in the report of the 29<sup>th</sup> Manoeuvring Committee (2020). The results are shown below, emphasizing that each participant could choose more than one option (so the percentage may sum more than 100%):

- Based on previous experience with other ships or benchmark data (Step 1 and/or Step 2): 76%
- By using our expert judgement (Step not defined): 63%

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- By comparing the trajectories with free running tests (Step 1): 61%
- By comparing the trajectories with CFD (Step 1): 36%
- By comparing the simulations with pilot cards or wheel house posters (Step 2): 33%
- With the use of an experienced pilot in a real time simulation (Step 2): 29%

The questionnaire also identified which part of the model the respondents adjust in order to calibrate the model. 49% of them adjusted the coefficients (the distribution of the coefficients mostly tuned are seen in the Figure 7) and 22% the ship characteristics (rudder area for example).

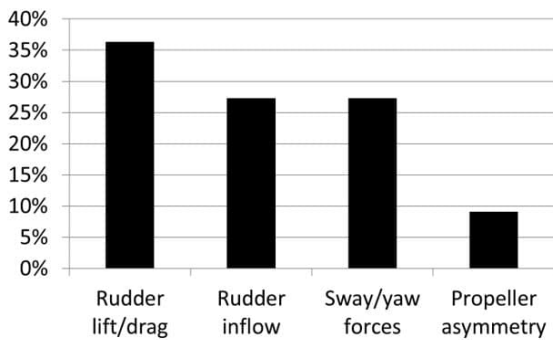


Figure 7: Coefficients mostly tuned to validate mathematical models

### 5.3 Potential Causes of Prediction Uncertainties

There are a number of uncertainty causes affecting accuracy, related to each of the validation steps mentioned above.

- Prediction of forces is presumably the main contributor to the uncertainty of the final simulation result. Sources can include sensor noise and nonlinearities in physical tests, approximations and extrapolations inherent in the database models, and the difficulties of CFD analysis. For each of the methods

(b1-b7) mentioned in this procedure, a validation procedure should be implemented. However, at the present time of writing, only the procedure “Captive Model Testing” exists. Reference is therefore given to this procedure.

- Modelling of forces in a mathematical model: uncertainty here lies primarily in the applied method for representing the forces as functions of the state variables.
- The mathematical model structure may be inappropriate to capture the desired effects, or may not cover the range of state vectors and environments encountered in manoeuvring.
- Integration method uncertainties are usually small compared with the other sources, provided the time step is small enough to handle frequencies in the physical problem.
- Simulation software errors are unavoidable and occur occasionally.
- Simulated manoeuvres should be made with high resolution both temporally and spatially.
- For shallow water validation, the blockage effects due to the towing tank lateral walls may affect the experimental results, since the presence of the walls increase the hydrodynamic forces on the ship compared to the unrestricted water condition (Toxopeus et al., 2013)

### 5.4 Sensitivity Analysis

As noted above, to perform a formal sensitivity analysis on calculated manoeuvres from a mathematical model is a cumbersome task, due the presence of nonlinear effects in most models. However, it is still necessary to address the uncertainty of calculated manoeuvres in some quantitative way.

For direct manoeuvring predictions based on databases and regression equations (b1, b2) sensitivity analysis may be difficult because of the

lack of any data specific to the vessel in question. Little advice can be given except to check the ship parameters against the population of ships represented in the database.

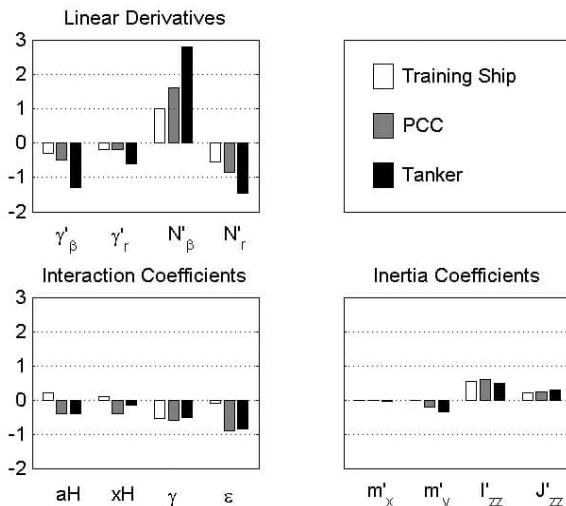


Figure 8: Relative sensitivity (ratio of change in estimated results when each parameter is individually increased 10%) of various parameters on the first overshoot angle in a 10-10 zigzag test in a simulation model. (adapted from Ishiguro et al, 1996)

For situations in which a mathematical model has been created, however, the evaluation of manoeuvring sensitivity is a matter of repeated simulations, while varying the parameters in turn. The study may sweep through the parameters systematically, or randomly; the latter case is attractive if a large number of parameters exists and the effects of multiple variations need to be considered.

An example case of sensitivity analysis results is illustrated in Figure 8, from Ishiguro et al. (1996).


Sensitivity analysis has been discussed in the Manoeuvring Committee Report of the 22nd ITTC and in the procedure 7.5-02-06-04 on uncertainty analysis for manoeuvring predictions based on captive model tests.

## 6. LIST OF SYMBOLS

$A_e/A_0$	Propeller area ratio
$B$	Breadth
$\overline{BM}$	Transverse metacentre height above centre of buoyancy
$C_B$	Block coefficient
$DOF$	Degree of freedom
$\overline{GM}$	Transverse metacentric height
$h$	Water depth
$\overline{KB}$	Vertical centre of buoyancy
$\overline{KG}$	Vertical centre of gravity
$L_{OA}$	Length between perpendiculars
$L_{PP}$	Length between perpendiculars
$X'$	Non-dimensional surge force
$Y'$	Non-dimensional sway force
$N'$	Non-dimensional yaw moment
$R$	Propeller radius
$T$	Draught
$u$	Surge velocity
$U_0$	Nominal speed
$v$	Sway velocity
$x$	Longitudinal position
$y$	Transverse position
$\beta$	Drift angle

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