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V&V of RANS Solutions in the Prediction of Manoeuvring Capabilities

1. PURPOSE OF GUIDELINE

The purpose of this document is to give guidelines for the Verification and Validation (V&V) of numerical RANS based simulations of manoeuvring capabilities. Two different situations are taken into account:

I. *simulations of captive motion*

II. *simulations of free running manoeuvres*

In the first case, the goal is the prediction of the hydrodynamic forces and moments acting on the ship during prescribed motions, which currently is a widely used approach. In the second case, focus is on prediction of the trajectory when the self-propelled ship is free sailing; only controlled by its control surfaces or other steering devices. This procedure gives guidelines for classical IMO manoeuvres, e.g. zig-zag and turning circle, but the principle can also be applied to more general cases.

In the present guideline the verification covers estimation of the simulation uncertainty, while the validation covers the comparison between computations and measurements taking both the simulation and measurement uncertainties into account. Specific methods for estimation of experimental uncertainty for captive and free running model tests are described in QM7.5-02-06-04 "*Uncertainty Analysis: Forces and moment Example for Planar Motion Mechanism Test*" and QM7.5-02-06-05, "*Uncertainty Analysis: Free running manoeuvring model test* ", respectively and will not be treated in this guideline.

QM7.5-03-01-01 "*Uncertainty Analysis in CFD, Verification and Validation Methodology and Procedures*" provides the general methods to estimation of numerical errors and uncertainties, i.e. verification methods. Where possible, the present guideline utilizes this general theory in connection with the manoeuvring related application.

Verification is the process for assessing the numerical uncertainty U_{SN} and, if the conditions permit, the estimation (both in sign and value) of the simulation numerical error $\delta_{SN}(t_i)$ and the uncertainty in this estimation. Assuming that round-off errors are negligible, the numerical error is decomposed into contributions from iterative convergence $\delta_I(t_i)$, grid convergence $\delta_G(t_i)$, time step convergence $\delta_T(t_i)$ and other parameters $\delta_P(t_i)$:

$$\delta_{SN}(t_i) = \delta_I(t_i) + \delta_G(t_i) + \delta_T(t_i) + \delta_P(t_i) \qquad (1)$$

Correspondingly the numerical uncertainty is then given by:

$$U_{SN}(t_i) = U_I(t_i) + U_G(t_i) + U_T(t_i) + U_P(t_i) \qquad (2)$$

which assumes that the uncertainties are independent. This assumption will be used for all summations of numerical uncertainties in the procedure.

Validation is the process where benchmark experimental data D and simulation data S is compared in order to estimate validation uncertainty U_V and possible numerical modelling errors.

The comparison error E is defined as the difference between the experimental data D and the simulation value S (eventually the corrected value S_C):

$$E(t_i) = D(t_i) - S(t_i) = \delta_D(t_i) - (\delta_{SM}(t_i) + \delta_{SN}(t_i)) \quad (3)$$

The validation uncertainty U_V is defined as:

$$U_V^2(t_i) = U_{SN}^2(t_i) + U_D^2(t_i) + U_{input}{}^2(t_i) \quad (4)$$

The numerical simulation is validated at level of U_V when the simulation error is:

$$|E(t_i)| < U_V(t_i) \quad (5)$$

Here everything is written as a function of time, but, of course, this definition can be applied either for L_2 norm values, time instant values or harmonics, depending on how the analysis is carried out (QM7.5-03-01-01).

2. VERIFICATION OF SIMULATIONS OF CAPTIVE MOTIONS

The captive motions cover Planar Motion Mechanism (PMM) tests and Circular Motion type test (CMT).

The PMM test consists of two types of tests; the static straight-line test (static drift, static rudder etc.) and the dynamic harmonic motion tests (pure sway, pure yaw etc.). In CFD simulations the first type is typically treated as steady computations and the hydrodynamic forces and moments will in this case just be constant numbers.

The second type of test is treated as transient computations, since the flow is not steady due to the dynamic motion of the ship. In this case the solver is run to convergence on each time step. In this way the solution will show the development of the flow in time and the hydrodynamic forces and moments will be represented as time series.

Consequently, verification of the static simulations will be focused on constant force or moment values, while the dynamic simulations will cover verification of time series for forces and moments, either on time level or through Fourier Series.

In this guideline the numerical error δ_{SN} will cover contributions from the iterative solution procedure and the grid for steady simulations and contributions from the iterative solution procedure, the grid and the time step size for transient simulations.

2.1 Stationary straight-line motions

Focus in the static captive tests is computation of the hydrodynamic forces and moments, i.e. on the forces X and Y plus the yaw moment N for the 3DOF case and the forces X and Y plus yaw and heel moments N and K for the 4DOF case. For a given computed quantity S, for instance Y the related numerical uncertainty must be estimated.

For the iterative component or the statistical convergence, the uncertainty can be estimated by means of the convergence history of the considered quantity, which typically shows some oscillations throughout the solution. The running mean RM_Q of the force or moment quantity is used to estimate $U_{I,Q}$. Subscript Q represents X, Y, N or K. With $RM_{Q,\max}$ and $RM_{Q,\min}$ being the maximum and minimum of the running mean oscillations towards the end of the RM history, respectively, the iterative uncertainty can be estimated by

$$U_{I,Q} = \left| \tfrac{1}{2}(RM_{Q,\max} - RM_{Q,\min}) \right| \qquad (6)$$

It can be noted that $U_{I,Q}$ can be reduced by running the simulation longer.

With respect to the grid uncertainty $U_{G,Q}$, it U_G is estimated according to the approach given in Section 4 of QM7.5-03-01-01. The procedure is based on grid convergence studies obtained with a minimum of three systematically refined grids, G_1, G_2 and G_3. The relation between the cell sizes in the three grids is determined by $r_G = \Delta x_{G2} / \Delta x_{G1} = \Delta x_{G3} / \Delta x_{G2}$, which is the grid refinement factor. Using $r_G = 2$, means that the cell size is doubled between grids, but it often results in some of the grids becoming either too coarse or too fine. Instead it is recommended to use $r_G = \sqrt{2}$ instead. Usage of r_G values smaller than $r_G = \sqrt{2}$ is possible, but it may be difficult to obtain grid convergence due to very small changes in solutions between grids.

The changes in solutions between coarse and medium grids, $\varepsilon_{G_{32},Q} = S_{G3,Q} - S_{G2,Q}$, and between medium and fine grid, $\varepsilon_{G_{21},Q} = S_{G2,Q} - S_{G1,Q}$, are used to calculate the convergence ratio $R_{G,Q} = \varepsilon_{G_{21},Q} / \varepsilon_{G_{32},Q}$ for any simulated force or moment quantity Q. Based on this, three conditions can occur:

i) $0 < R_G < 1$ $0 < R_{G,Q} < 1$, grid convergence,

ii) $R_{G,Q} < 0$, oscillatory convergence and

iii) $1 < R_{G,Q}$, grid divergence.

In condition iii) no uncertainty can be estimated. This could indicate that even finer grids should be used. In condition ii) the uncertainty is estimated by

$$U_{G,Q} = \left| \tfrac{1}{2}(S_{G,Q,\max} - S_{G,Q,\min}) \right| \qquad (7)$$

where $S_{G,Q,\max}$ and $S_{G,Q,\min}$ are the maximum and minimum values of S obtained with the three grids. In some cases, a factor of safety can be used. In condition i) it is be possible to use generalized Richardson extrapolation in accordance with QM7.5-03-01-01.

With estimates for $U_{I,Q}$ and $U_{G,Q}$ the simulation uncertainty can be estimated for the relevant quantities based on

$$U_{SN,Q} = U_{I,Q} + U_{G,Q} \qquad (8)$$

Note that if grid error correction has been applied in the assessment of the grid uncertainty the following quantities must be applied for validation in section 4.1 below

$$Sc_Q = S_Q - \delta_{G,Q} \qquad (9)$$

$$U_{ScN,Q} = U_{I,Q} + U_{Gc,Q} \qquad (10)$$

2.2 Dynamic harmonic motions

In the CFD based simulations of the harmonic motions like the pure sway or pure yaw PMM conditions, the results are presented as time series of forces and moments.

In principle it is possible to do the verification at each instance of time, i.e. perform grid convergence studies at each time step. But usually it is difficult to obtain uncertainty estimates at all time steps with the methods in QM7.5-03-01-01. Figure 1 shows an example for the KCS container ship from SIMMAN2008, Simonsen and Stern (2008). As seen divergence and missing estimates is quite common over the considered PMM period T'.

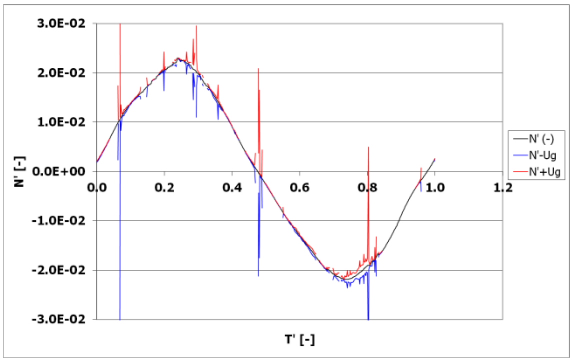

Figure1. Grid uncertainty for yaw moment.

Performing a time step study is not trivial, since only coinciding instances in time from the three studies can be covered. Further, same time intervals are required in the measurement for the validation. Finally, for the iterative component or the statistical convergence, it does not make sense to use the running mean to estimate the iterative uncertainty. The reason is that the motion dominated oscillations of the signal will give relatively large variation in the running mean even if subsequent periods of the signal are quite similar.

Instead of making the verification on the time series directly, it is recommended to approximate the time series of the forces and moments with Fourier Series, as it is done in Sakamoto (2009) and Sakamoto et al. (2012)

$$F(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t + \varphi_n) \tag{11}$$

where a_n is the n^{th} order Fourier harmonic and φ_n is the phase angle. The idea is to select an order of the approximation that gives a good representation of the time series and then perform the verification on the Fourier coefficients and phases. With this approach both iterative, grid and time step studies can be performed. Note that the same order must be used for the measured data in the validation process.

For the iterative component, the uncertainty is estimated by means of the convergence history of the Fourier coefficients. The approach is based on marching harmonic analysis as presented in Yoon (2009). Here, the convergence history of the Fourier harmonics is estimated by applying Fourier analysis on a window covering a single period of the time series, and then stepping the window throughout the time series.

The running mean $RM_{Q,n}$ of the n^{th} harmonic is used to estimate $U_{I,Q,n}$. Subscript Q represents, X, Y, N or K, while n represent the order of the harmonic. With $RM_{Q,n,\max}$ and $RM_{Q,n,\min}$ being the maximum and minimum of the running mean oscillations towards the end of the RM history, respectively, the iterative uncertainty can be estimated by

$$U_{I,Q,n} = \left| ½ (RM_{Q,n,\max} - RM_{Q,n,\min}) \right| \tag{12}$$

The grid uncertainty for the n^{th} harmonic $U_{G,Q,n}$ U_G is estimated according to the approach given in Section 4 of QM7.5-03-01-01. There are alternative procedures that consider the discretisation error/uncertainty due to time and space simultaneously (see e.g. Fathi et al, 2011). These will not be described here as the CFD committee's V&V approach is followed. Minimum three systematically refined grids, G_1, G_2 and G_3 must be applied using constant grid refinement factor r_G. Guidelines for selection of r_G are the same as for the stationary straight-line test described above.

The changes in simulated harmonics between coarse and medium grids,

$\varepsilon_{G_{32},Q,n} = S_{G3,Q,n} - S_{G2,Q,n}$, and between medium and fine grid, $\varepsilon_{G_{21},Q,n} = S_{G2,Q,n} - S_{G1,Q,n}$, are used to calculate the convergence ratio $R_{G,Q,n} = \varepsilon_{G_{21},Q,n} / \varepsilon_{G_{32},Q,n}$. Based on this, three conditions can occur:

i) $0 < \mathrm{R_G} < 1$ $0 < R_{G,Q,n} < 1$, grid convergence,

ii) $R_{G,Q,n} < 0$, oscillatory convergence

iii) $1 < R_{G,Q,n,}$, grid divergence.

In condition iii) no uncertainty can be estimated. In condition ii) the uncertainty is estimated by

$$U_{G,Q,n} = \left| ½ (S_{G,Q,n,\max} - S_{G,Q,n,\min}) \right| \tag{13}$$

where $S_{G,Q,n,\max}$ and $S_{G,Q,n,\min}$ are the maximum and minimum values of S obtained with the three grids. In condition i) it is be possible to use generalized Richardson extrapolation as proposed in QM7.5-03-01-01.

Finally, for the time component the uncertainty can be estimated by a systematic variation of the time step size. It is recommended to consider three time steps related by a time step refinement factor of 2. For each of the simulations with different time steps Fourier analysis is performed to compute the harmonics for the relevant forces and moments. Afterwards the changes in the n^{th} harmonic between large and medium time steps, $\varepsilon_{t_{32},Q,n} = S_{t3,Q,n} - S_{t2,Q,n,}$, and between medium and small time step, $\varepsilon_{t_{21},Q,n} = S_{t2,Q,n} - S_{t1,Q,n}$, are used to calculate the convergence ratio $R_{t,Q,n} = \varepsilon_{t_{21},Q,n} / \varepsilon_{t_{32},Q,n}$ As for the grid uncertainty three conditions can occur:

i) $0 < \mathrm{R_G} < 1$ $0 < R_{t,Q,n} < 1$, time step convergence,

ii) $R_{t,Q,n} < 0$, oscillatory convergence

iii) $1 < R_{t,Q,n}$, time step divergence.

In condition iii) no uncertainty can be estimated. In condition ii) the uncertainty is estimated by

$$U_{t,Q,n} = \left| ½ (S_{t,Q,n,\max} - S_{t,Q,n,\min}) \right| \tag{14}$$

where $S_{t,Q,n,\max}$ and $S_{t,Q,n,\min}$ are the maximum and minimum values of S obtained with the three time steps. In condition i) it is possible to use Richardson extrapolation as proposed in QM7.5-03-01-01.

With estimates for $U_{I,Q,n}$, $U_{G,Q,n}$ and $U_{t,Q,n}$ at hand the simulation uncertainty can be estimated for the relevant quantities based on

$$U_{SN,Q,n} = U_{I,Q,n} + U_{G,Q,n} + U_{t,Q,n} \tag{15}$$

Note that if grid and/or time step error corrections have been applied in the assessment of the grid or time step uncertainties the following quantities must be applied for validation in section 4.1 below

$$Sc_{Q,n} = S_{Q,n} - \delta_{G,Q,n} - \delta_{t,Q,n} \tag{16}$$

$$U_{ScN,Q,n} = U_{I,Q,n} + U_{Gc,Q,n} + U_{tc,Q,n} \tag{17}$$

2.3 Stationary circular motions

The CMT consist of circular motions, which based on a moving reference frame approach can be treated as steady computations. Therefore, verification can be done by following the same approach as used for the static PMM condition described in paragraph 2.1 above.

3. VERIFICATION OF DIRECT SIMULATION OF FREE RUNNING MANOEUVRES

The main objective of free running tests is prediction of the trajectory as a consequence of the prescribed motion of the control surfaces, e.g. the rudder. Tests or simulations are conducted to evaluate ship manoeuvring capabilities.

This section deals with the direct simulations of a manoeuvre, i.e. the trajectory, using a CFD solver.

Focus is on classical IMO manoeuvres like the ±35° turning circle and 10°/10° and 20°/20° zigzag tests.

Compared to CFD based PMM simulation, the free running simulation is complicated by the integration in time of rigid body motion (Newton second law) in the time loop of the RANS solver.

Ship motions are usually solved for in body-reference frame to simplify inertia matrix. RANS equations may be solved in earth reference frame or in body reference frame. The latter requires inclusion of the centrifugal force for the fluid due to frame acceleration. This is an additional difficulty in the discretized equations.

The time step is involved in many different parts of the solver (propeller running, wave run-up, courant number, Newton second law) and the verification and validation processes should be conducted carefully.

Moreover, simulations are driven by forces and no more prescribed by ship velocities. More specific motions are included by:

- using appendages controllers
- imposing the propulsion point
- performing simulations with 3 to 6 degrees of freedom

This influences both verification and validation since they will be carried out on position and heading and not on forces.

It is be possible to perform the verification process at each time step of the motion time series with the methods in QM7.5-03-01-01 using global convergence ratio and L2 norm of solution change over the period of time of interest.

This method can relatively easily be applied to grid studies, but, convergence studies towards the time step are difficult as described earlier in connection with the dynamic PMM simulation.

Concerning, the iterative component or the statistical convergence, the uncertainty is difficult to estimate over time directly based on RM since the time series now has an unsteady behaviour due to the motion of the ship.

A more practical approach is to consider global parameters as tactical diameter or advance in the verification, instead of the time series.

For the verification of turning circles it is recommended to consider the following global parameters:

- Tactical diameter
- Advance
- Transfer
- Yaw rate (once steady, see fig 3)
- Peak yaw rate

- Drift angle (once steady, see fig3)
- Speed loss
- Heel angle (if 4 DOF)

For zigzag test, relevant parameters are:

- First and second overshoot angles
- First and second overshoot time
- Peak yaw rate
- Period

3.1 Iterative convergence

For free running computations, the iterative convergence error is due to the inner iterations for implicit methods, or due to the number of sub iterations for pseudo compressible method.

To estimate iterative uncertainties, solutions are computed for different values of inner or sub iterations (S_{k1}, S_{k2}, ... S_{kn}). The largest variation between solutions is then taken as the uncertainty in the same way as done for static conditions:

$$U_I = \left| \tfrac{1}{2}(MAX(S_{ki,i=1\dots n}) - MIN(S_{ki,i=1\dots n})) \right| \qquad (18)$$

3.2 Grid and time step uncertainties

Grid and time uncertainties are estimated by generalized Richardson extrapolation. Solutions on minimum three grid levels and three different time steps with a systematic grid and time step refinement ratios r_G and r_t are required. For selection of refinement ratios see recommendation given in relation to the static analysis above. The remaining verification process for the global parameter of interest can be done in the same way as used for the stationary straight-line motion in 4.2 above. The only difference is that the verification is performed with global parameters instead of forces.

By focussing on the global manoeuvring parameters both flow and motion solvers are checked at the same time. From a practical point of view this is the most straight forward verification approach. In case a more detailed verification of the body motion integration scheme is required, the approach in 3.3 can be followed. This approach however requires access to the source code and is most suitable for code developers.

Figure 3 shows an example of time series of velocity drop, Yaw rate and drift angle for a steady turning circle simulation from Dubbioso et al. (2012).

3.3 Time integration model

Free running simulations require resolution of rigid-body equations for the ship. As the hydrodynamic forces are derived from the Navier Stokes (NS) solver, they are on the right-hand side of the body equations. Specifically, hydrodynamic forces include added mass force in line with ship acceleration. These forces may lead to an unstable resolution of the rigid body equation terms depending on ship acceleration, which are on both side of the equations, see 7.5-02-06-03 section 3.5.

A common solution to overcome this problem is to decrease the time step to reduce integration errors. Another solution is to use dummy added mass to re-enforce the left hand side of the rigid body equation which stabilizes the set of equations. So, one has to fix the time step and the dummy added mass accordingly.

Verification of the time integration model and the time step is difficult to achieve since it is embedded into the solver and linked to the hydrodynamic force and then to the time step of the accurate resolution of the NS equations.

Different ways are possible to verify both the time step for the rigid body equations resolution:

- Verify with a known problem which can be solved analytically and with a time constant similar to what is expected during the manoeuvre (response to step function or other). Function $\frac{d^2x}{dt^2}=((a^2-1)x-2a\cos(t).e^{-at})$ with a=-0.05 has the analytical solution $x=\sin(t).e^{-at}$. Numerical solutions of this equation using Predictor and Predictor-corrector schemes have been evaluated for different time steps and are presented below.

Depending of the time integration scheme, the required time step to reach convergence is different.

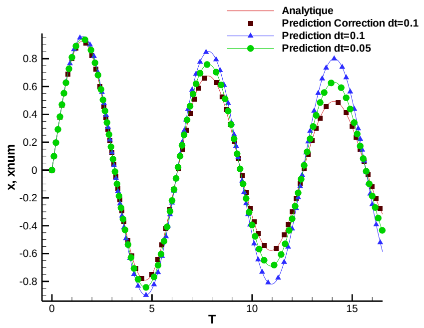

Figure 2: Verification of the time –integration scheme on a known solution.

- Simulate free roll motion using only hydrostatic force. This way time resolution of rigid body is disconnect from RANS equations resolution. Hydrostatics do not include any viscous damping or added mass effect, but just hydrostatic restoring moment. For small heel angles the hydrostatic restoring moment is assumed linear.

The roll equation is then similar to a pendulum equation without damping (19). The solution is periodic and the frequency is easy to check.

$$I_{oy}\ddot{\theta}+mgl\theta=0 \text{ and } T=2\pi.\sqrt{\frac{I_{oy}}{mgl}} \qquad (19)$$

with I_{oy} the roll inertia, θ the roll angle, m mass of the system and l the length of the pendulum.

Roll motion is a good candidate for time scheme verification since it is a high frequency motion which should require the smallest time step, see 7.5-02-06-03 section 3.5.

4. VALIDATION OF SIMULATIONS

Using the terminology from QM7.5-03-01-01, validation is defined as a process for assessing simulation modeling uncertainty by using benchmark experimental data and, when conditions permit, estimating the sign and magnitude of the modeling error δ_{SM} itself as described in QM7.5-03-01-01. To determine if validation has been achieved, the comparison error E is compared to the validation uncertainty U_V, which is the combined uncertainty of the measured data U_D and the simulation uncertainty, U_{SN}. If $|E|<U_V$, the combination of all the errors in D and S are smaller than U_V and validation is achieved at the U_V level. If $U_V \ll |E|$, the sign and magnitude of $E\approx\delta_{SM}$ can be used to make modeling improvements. It should be noted that high simulation and data uncertainties will make it easier to obtain validation, but at a high level. One should aim for low level validation as this indicates that the simulation is a good representation of reality. To obtain low level validation and more accurate results it is therefore important to have

simulations and measurements with low uncertainties.

4.1 Stationary straight-line and circular motions

Assuming that measured force or moment data is available together with the corresponding data uncertainty and that the verification procedure above has given the simulation uncertainty related to the computed force and moment results, the comparison error and validation uncertainty is determined on the basis of the equations:

$$E_Q = S_Q - D_Q \tag{20}$$

$$U_{V,Q}^2 = U_{D,Q}^2 + U_{SN,Q}^2 \tag{21}$$

or with correction

$$E_Q = S_Q - Dc_Q \tag{22}$$

$$U_{V,Q}^2 = U_{D,Q}^2 + U_{ScN,Q}^2 \tag{23}$$

Based on this, it can be determined if validation has been obtained or if modelling errors are present, indicating that the simulation model should be improved. If $|E_Q| < U_{V,Q}$, validation is achieved at the $U_{V,Q}$ level and if $U_{V,Q} << |E_Q|$, the sign and magnitude of E_Q approximately equals the modeling error, $E_Q \approx \delta_{SM,Q}$, which indicates the error introduced by the numerical model. Better validation can be obtained if the model is improved and the modeling error is reduced.

4.2 Dynamic harmonic motions

Following the same idea as used for the validation of the static straight line test, the comparison error and validation uncertainty for the n^{th} harmonic can be estimated from

$$E_{Q,n} = D_{Q,n} - S_{Q,n} \tag{24}$$

$$U_{V,Q,n}^2 = U_{D,Q,n}^2 + U_{SN,Q,n}^2 \tag{25}$$

or with correction

$$E_{Q,n} = D_{Q,n} - Sc_{Q,n} \tag{26}$$

$$U_{V,Q,n}^2 = U_{D,Q,n}^2 + U_{ScN,Q,n}^2 \tag{27}$$

If $|E_{Q,n}| < U_{V,Q,n}$, validation is achieved at the $U_{V,Q,n}$ level and if $U_{V,Q,n} << |E_{Q,n}|$, the sign and magnitude of $E_{Q,n}$ approximately equals the modeling error, $E_{Q,n} \approx \delta_{SM,Q,n}$, which indicates the error introduced by the numerical model. Again if the model is improved and the modeling error is reduced better validation can be obtained. So the modeling error can help guiding the need for model improvement.

4.3 Free running manoeuvres

For the validation, experimental data in terms of time histories of the ships trajectory must be available.

Validations have to be done at the same scale as the tests and results can be analysed in terms of:

- Time histories of position and heading
- Global manoeuvre parameters (tactical diameter, 1st overshoot, etc …)

Typically the uncertainties are not available for the time series themselves, but even so it is recommended to make a qualitative comparison between measured and calculated trajectory.

On the level of the global manoeuvre parameters, the validation can be performed according to the same approach as used for the static motions in Section 4.1.

If validations show large discrepancies, for free-running computations, the modelling errors may be due to:

- Propeller modelling: Computations including running propeller have been performed by Carrica (2008). Computational effort is very important (mesh-time step) but no model is introduced in the simulations. Common practise use models like actuator discs or BEM model. Work of (Broglia and al. 2011) show that the model should include a lateral force to get more accurate results on steady turning manoeuvre.

- Turbulence modelling: Computation of flow past a ship hull with drift and yaw may be sensitive to the turbulence model. Flow separation may occur on the aft part of the hull which strongly influences the hydrodynamic forces on the hull and the flow past the propeller (wake fraction) and the rudder. Also the modelling of rudder stalling may be influenced by the turbulence model.

- Free surface modelling: In CFD it is possible to perform the simulations with or without free surface. For ships operating at low Froude numbers, sometimes the free surface is neglected to simplify the computations. However, when simplifying the simulation it is important to keep in mind that it will influence the simulation results.

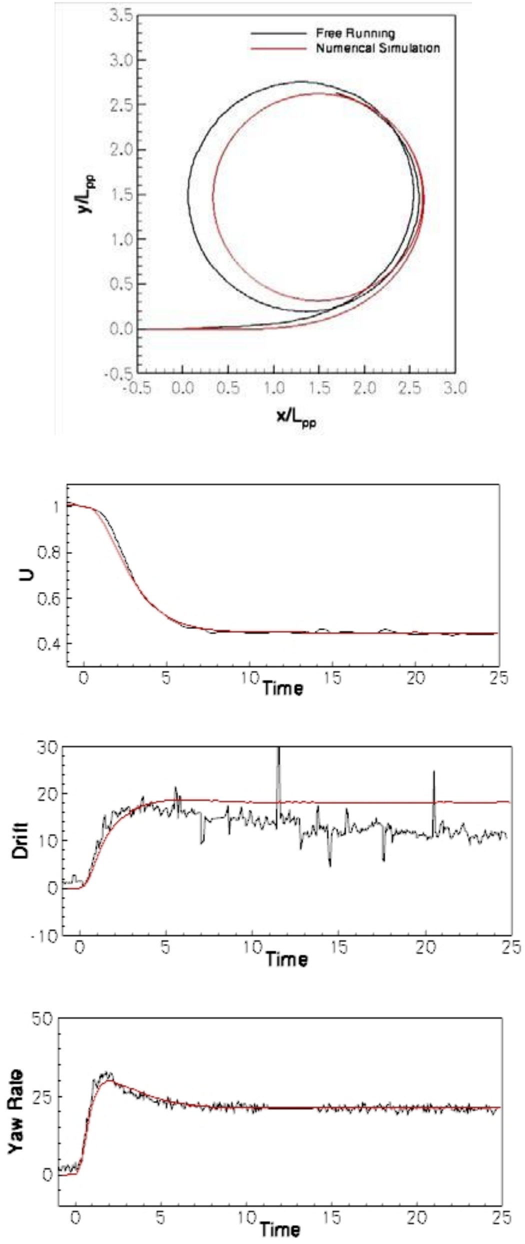

Figure 3: Numerical and experimental time series of velocity drop, drift angle and yaw rate in a turning circle simulations. Dubbioso et al. (2012)

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