Global sensitivity analysis and repeated identification of a modular maneuvering model of a passenger ferry

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Abstract

In the paper a modular manoeuvring model of the passenger ferry "Landegode" is built, validated and studied. Global sensitivity analysis based on the variance decomposition is performed to assess the sensitivity of the individual model coefficients on the simulation outcomes. It is found that uncertainty in both hull hydrodynamic coefficients and the steering and interaction coefficients can result in significant uncertainty in the simulation results. The most influential coefficients are defined for the standard IMO manoeuvres. The possibility of identification of "true" values of the coefficients from full scale trials is studied. Such analysis would allow improving empirical predictions of the coefficients. It is found that different combinations of the model coefficients result in similar time-series. This indicates the presence of correlation between the coefficients. Thus, although the identified coefficients can be used for simulations of the ship manoeuvring, it is impossible to identify the single "true" value for each coefficient from these sea trials.

Keywords

MMG model, maneuvering, global sensitivity analysis, identification

List of symbols

α_R	Effective inflow angle to rudder
β	Hull drift angle at midship
β_P	Geometrical inflow angle to propeller
β_R	Effective inflow angle to rudder
γ_R	Flow straightening coefficient
δ	Rudder angle
ε	Ratio of wake fraction at rudder and propeller position
η	Ratio of rudder area within propeller slipstream to total rudder area
κ	Coefficient to determine increase of longitudinal inflow velocity to rudder due to propeller
ρ	Water density
ψ	Yaw angle of ship

$\Delta_{95\%}$	Width of 95% confidence interval in percent
Λ	Rudder aspect ratio
∇	Ship displacement
$a_1 \dots a_9$	Regression coefficients for propeller thrust characteristic
a_H	Rudder force increase factor
f_α	Rudder lift gradient coefficient
l_R	Effective longitudinal rudder position
m	Ship mass
m_x, m_y, J_z	Surge added mass, sway added mass, yaw added moment of inertia
n_P	Propeller revolutions per second
o-x-y	Coordinate system fixed to the ship with the origin at midship
std	Standard deviation
t	Thrust deduction factor
$t\ [s]$	Time (on figures)
t_R	Steering resistance deduction factor
u, v, r	Surge velocity, sway velocity and yaw rate
u_R, v_R	Longitudinal and lateral inflow velocity to rudder respectively
w_P	Wake coefficient in propeller position
w_{P0}	Wake coefficient in propeller position in straight motion
x_G	Longitudinal position of center of gravity relative to midship
x_H	Longitudinal position of application of additional force due to rudder action
x_P	Longitudinal position of propeller relative to midship
x_R	Longitudinal position of rudder relative to midship
A_R	Rudder area
B	Ship breadth
C-X-Y	Earth fixed coordinate system
C_b	Block coefficient
CI	Confidence interval
D_P	Propeller diameter
$E_{\dots}(\dots)$	Mathematical expectation
F_N	Rudder normal force

G1	Group of first 21 model coefficients in Table 6 related to hull
G2	Group of last 10 model coefficients in Table 6 related to steering and interaction effects between hull, propulsion and steering
I_{zG}	Yaw moment of inertia of the ship in the center of gravity
J_P	Propeller advance ratio
K_T	Propeller thrust characteristic
L_{pp}	Length between perpendiculars
OA1, OA2	First and second overshoot angles of zigzag test
P_P	Propeller pitch to diameter ratio
S_{Ti}	Total effect of factor *i*
U	Total velocity of midship
U_R	Total inflow velocity to rudder
$V_{...}(\dots)$	Variance
X_H, Y_H, N_H	Surge force, sway force, yaw moment due to hull hydrodynamic effects
X_R, Y_R, N_R	Surge force, sway force, yaw moment due to steering
X_P	Surge force due to propulsion system
$X'_{uu}, X'_{vv}, X'_{vr}, X'_{rr}, X'_{vvvv}, Y'_v, Y'_r, Y'_{vvv}, Y'_{vvr}, Y'_{vrr}, Y'_{rrr}, N'_v, N'_r, N'_{vvv}, N'_{vvr}, N'_{vrr}, N'_{rrr}$	Non-dimensional hydrodynamic derivatives of the hull

Introduction

Ship manoeuvring models are used for prediction of manoeuvring performance of ships on the design stage, training of pilots in simulation centers and other engineering studies. One of the most popular types of model used for simulation of ship manoeuvres is the Maneuvering Modeling Group (MMG) model [1]. In this model, forces for hull, propulsion and steering subsystems are defined separately and then interaction between the subsystems is taken into account in form of interaction coefficients. The hull coefficients can be defined from model tests, CFD simulations, potential codes or empirical formulas, such as [2]. However, the determination of the interaction coefficients is more complicated and costly, since it demands the propulsion and steering devices to be included in the simulation or experiment. Therefore, in practice more attention is paid to the hull hydrodynamic coefficients, while the interaction coefficients are rarely defined using experimental methods or CFD simulations. Instead, some reasonable values are assumed or empirical formulas are used. This can potentially lead to large errors in the manoeuvring predictions. It is therefore important to understand how sensitive are the results of the simulations of typical manoeuvres to the uncertainties of the model coefficients. In addition, it is desirable to develop methods to predict the interaction coefficients which give sufficient accuracy. One of the possible ways is to use captive model test [1]. However, the precision of this approach is expected to be limited due to scale effects. Alternatively, system identification methods can be used. System identification of manoeuvring coefficients is widely applied in many studies, for instance [3–5]. Often, inertial, propulsion and steering coefficients are considered as known constants (typically from empirical formulas) and only hull hydrodynamic coefficients are identified. Moreover, Hwang [6] pointed to the effect of simultaneous drift of the coefficients during identification, which result in hydrodynamic derivatives drifting to wrong values together during identification. However, if the identification of the coefficients of MMG model is possible, given reasonable initial approximations, more reliable empirical formulas for prediction of interaction coefficients can be developed.

The goal of this paper is to undestand sensitivity of the model predictions to various model coefficients, including hull hydrodynamic coefficients, steering and interaction coefficients, and to investigate the possibility of identification of the MMG model coefficients having good initial guess for the hull hydrodynamic coefficients. In the first part of the paper, we present the MMG model of a passenger ferry “Landegode” which is used as a case vessel in a research project “Sea Trials and Model Tests for Validation of Shiphandling Simulation Models” [7]. The model is based on PMM test results, strip theory code and empirical data. The model is validated against the results of standard IMO full scale manoeuvres, including 35° turning circle, 10°/10° zigzag and 20°/20° zigzag executed to port and starboard sides. In the second part of the paper, we perform global sensitivity analysis based on variance decomposition to estimate the effects of individual coefficients to the outcomes of trials. In the third part of the paper, we estimate the coefficients of the model using random initial approximations of the coefficients. The estimation process is repeated multiple times. Thus, repeated convergence to local minimum can be avoided. To minimize possible simultaneous drift effect of the hull hydrodynamic coefficients, the penalty for large deviations from initial values is included in the cost function being optimized.

Description of the vessel

The case ship Landegode (Figure 1) is a passenger ferry owned by Torghatten Nord and operating near Bodø in Norway. The ferry was built in 2012. Table 1 contains main dimensions of the ferry. The ferry is equipped with single-screw single-rudder propulsion system with controllable pitch propeller. Landegode is chosen for this study as this is a modern ship and the results of PMM tests and full scale trials are available.

Figure 1. Ferry “Landegode”.

Table 1. Main dimensions of ferry "Landegode".

Length overall [m]	96.0
Breadth midship [m]	16.8
Draught (max) [m]	4.2

Mathematical model

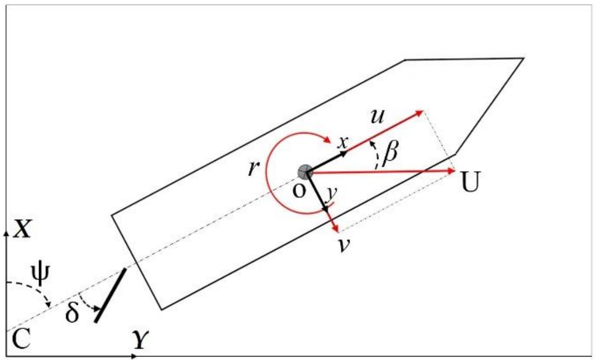

Figure 2. Coordinate system. C-X-Y is Earth fixed coordinate system which is considered inertial. o-x-y is body fixed coordinate system with the center at midhip.

Simulation model used in the paper for analysis of full speed trials is similar to the MMG model [1]. Note that although the following expressions are taken from [1], they are based on decades of previous research and widely used in many papers. For the sake of brevity, the links to original publications are not provided. For more details see [1] and corresponding references. The equations for surge, sway and yaw motions are:

$$(m + m_x)\dot{u} - (m + m_y)vr - x_G m r^2 = X_H + X_R + X_P \tag{1}$$

$$(m + m_y)\dot{v} + (m + m_x)ur + x_G m\dot{r} = Y_H + Y_R \tag{2}$$

$$(I_{zG} + x_G^2 m + J_z)\dot{r} + x_G m(\dot{v} + ur) = N_H + N_R \tag{3}$$

Velocity dependent hydrodynamic forces have the following form:

$$X_H = \frac{1}{2}\rho L_{pp}^2 U^2\,(X'_{uu}u'^2 + X'_{vv}v'^2 + X'_{vr}vr + X'_{rr}r'^2 + X'_{vvvv}v'^4) \tag{4}$$

$$Y_H = \frac{1}{2}\rho L_{pp}^2 U^2\,(Y'_v v' + Y'_r r' + Y'_{vvv}v'^3 + Y'_{vvr}v'^2 r' + Y'_{vrr}v' r'^2 + Y'_{rrr}r'^3) \tag{5}$$

$$N_H = \frac{1}{2}\rho L_{pp}^3 U^2\,(N'_v v' + N'_r r' + N'_{vvv}v'^3 + N'_{vvr}v'^2 r' + N'_{vrr}v' r'^2 + N'_{rrr}r'^3) \tag{6}$$

Where X'_{uu}, X'_{vv}, X'_{vr}, X'_{rr}, X'_{vvvv}, Y'_v, Y'_r, Y'_{vvv}, Y'_{vvr}, Y'_{vrr}, Y'_{rrr}, N'_v, N'_r, N'_{vvv}, N'_{vvr}, N'_{vrr}, N'_{rrr} - non-dimensional polynomial hydrodynamic coefficients, $U = (u^2 + v^2)^{1/2}$ - total speed of the ship. Note that only L_{pp} is used to make the forces and moment in these expressions non-dimensional, contrary to L_{pp} and draught in [1].

Surge hydrodynamic force due to propeller:

$$X_P = (1 - t)\rho n_P^2 D_P^4 K_T(J_P, P_P) \tag{7}$$

Thrust coefficient K_T is modelled as a polynomial depending on propeller advance ratio J_P and pitch to diameter ratio P_P, the latter is needed since the propeller has controllable pitch:

$$K_T(J_P, P_P) = a_1 + a_2 P_P + a_3 P_P^2 + a_4 J_P + a_5 J_P P_P + a_6 J_P P_P^2 + a_7 J_P^2 + a_8 J_P^2 P_P + a_9 J_P^2 P_P^2 \tag{8}$$

Advance ratio J_P is calculated as

$$J_P = u(1 - w_P)/n_P D_P \tag{9}$$

Propeller inflow angle

$$\beta_P = \beta - x'_P r' \tag{10}$$

affects the propeller wake fraction w_P according to

$$w_P = w_{P0} \exp(-4\beta_P^2) \tag{11}$$

There are also alternative expressions discussed in [1], but as far as no model tests or other ways to estimate the coefficients in the more complicated formulas for w_P are available, the simplest expression is used.

Steering forces due to rudder are estimated using expressions

$$X_R = -(1 - t_R) F_N \sin\delta \tag{12}$$

$$Y_R = -(1 + a_H) F_N \cos\delta \tag{13}$$

$$N_R = -(x_R + a_H x_H) F_N \cos\delta \tag{14}$$

F_N is rudder normal force and calculated as

$$F_N = \frac{1}{2} \rho A_R U_R^2 f_\alpha \sin\alpha_R \tag{15}$$

The steering model has a number of simplifications, for instance, the tangential force is neglected. The coefficient t_R reflects combined rudder-hull effect of surge resistance reduction during manoeuvring. a_H and x_H reflect increase of the steering force and moment due to presence of hull.

Total rudder inflow velocity U_R and rudder effective angle of attack α_R are expressed as

$$U_R = (u_R^2 + v_R^2)^{1/2} \tag{16}$$

$$\alpha_R = \delta - \tan^{-1}(v_R/u_R) \tag{17}$$

Longitudinal inflow velocity to rudder is calculated as

$$u_R = \varepsilon(1 - w_P) \sqrt{\eta \left\{1 + \kappa\left(\sqrt{1 + \frac{8K_T}{\pi J_P^2}} - 1\right)\right\}^2 + (1 - \eta)} \tag{18}$$

The expression takes into account the increase of the inflow to the rudder due to the propeller thrust.

The transverse inflow velocity component is affected by flow straightening effects and is calculated as

$$v_R = U \gamma_R \beta_R \tag{19}$$

where

$$\beta_R = \beta - l' r' \tag{20}$$

l' is effective longitudinal rudder position which can differ from geometrical rudder longitudinal coordinate.

Model coefficients

Although Yasukawa [1] demonstrates how to determine all the interaction coefficients experimentally, it is rarely done in practice. Traditionally much more attention is paid to the hull hydrodynamic coefficients. Thus, we define hull hydrodynamic coefficients for sway force and yaw moment from PMM tests. A total number of 19 test series is used for identification. Figure 3 compares original time-series of sway force and yaw moment measured in PMM and reproduced with the model. Two oscillating cycles for each test are presented. One can see that the model fits experiments very well. Surge hydrodynamic coefficients are estimated using the strip theory code "HullVisc" developed by SINTEF OCEAN as a part of the ShipX package [8]. Coefficient X'_{uu} is estimated from straight-line motion of the real ship to ensure correct loading of the propeller. Open water diagram for the controllable pitch propeller is provided by the propulsion system designer based on CFD simulations.

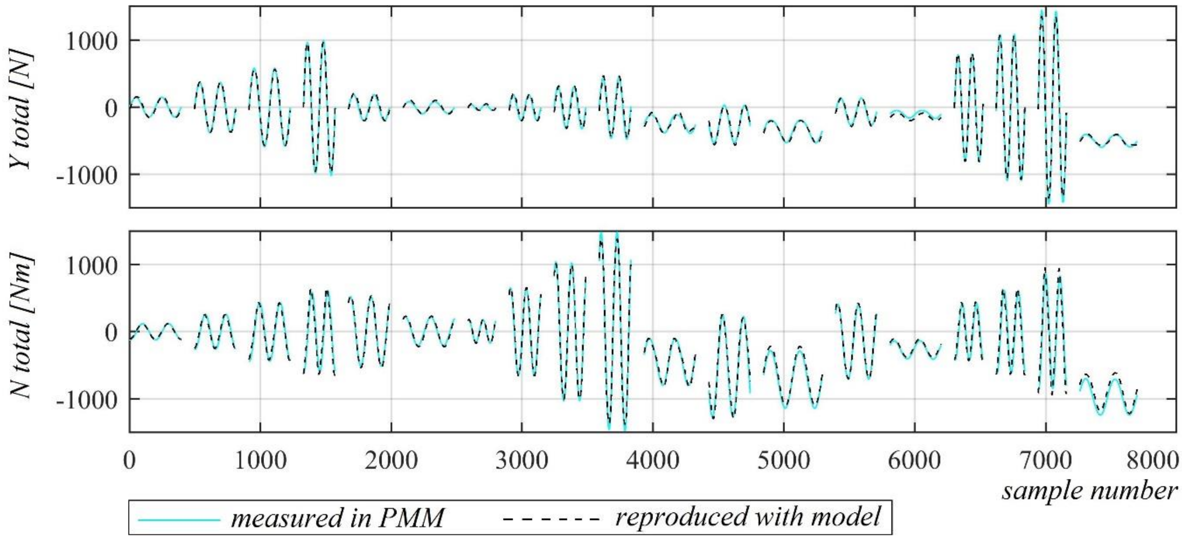

Figure 3. Identification of sway and yaw coefficients of the model from PMM tests.

Some interaction coefficients are estimated using formulas found in [9]:

$$a_H = 40\nabla/L_{pp}^3 \tag{21}$$

$$x'_H = -(0.4 + 0.1C_b) \tag{22}$$

$$\gamma_1 = 1.77C_b + 0.18 \tag{23}$$

$$\gamma_2 = 1.37C_b + 0.41 \tag{24}$$

$$\varepsilon = 2.71C_b\frac{B}{L_{pp}} + 0.92 \tag{25}$$

The following expressions for t_R, w_{P0}, ε, γ and f_α are found in [2]:

$$1 - t_R = 0.28C_B + 0.55 \tag{26}$$

$$w_{P0} = 0.5C_B - 0.05 \tag{27}$$

$$f_\alpha = \frac{6.13\Lambda}{\Lambda+2.25} \tag{28}$$

Thrust deduction is estimated using an expression from [10]:

$$t = 0.6 w_{P0} \tag{29}$$

For the effective longitudinal rudder position l' the geometrical rudder position is used. The coefficients are collected in Table 2 - Table 5.

We would like to stress that the empirical regressions are often based on the ships built decades ago, while Landegode is a modern ship. Moreover, different empirical formulas can be found in literature, sometimes resulting in completely different values for the coefficients. Often, application ranges where the formulas are applicable are not presented. Finally, simple formulas cannot take into account all important effects affecting the values of the coefficients. For instance, the study reported in [11] shows that rudder profile significantly affects manoeuvring results, while in the expression for rudder lift coefficients only aspect ratio is used.

Table 2. Main ship parameters.

$m\ [kg]$	2.56e+6	$L_{pp}\ [m]$	95.6	$\nabla\ [\mathrm{m}^3]$	2497.6
$I_{zG}\ [kgm^2]$	1.46e+9	B/L_{pp}	0.175		
$x_G\ [m]$	-9.3	C_B	0.433		

Table 3. Hydrodynamic coefficients and added masses, e-4.

m'_x	2.30	X'_{vvvv}	241.90	N'_v	-30.52
m'_y	57.52	Y'_v	-106.92	N'_r	-15.66
J'_z	3.93	Y'_r	11.15	N'_{vvv}	-314.76
X'_{uu}	-7.72	Y'_{vvv}	-980.67	N'_{vvr}	-561.30
X'_{vv}	-33.80	Y'_{vvr}	-456.81	N'_{vrr}	-122.47
X'_{vr}	23.20	Y'_{vrr}	-140.65	N'_{rrr}	-15.49
X'_{rr}	-2.80	Y'_{rrr}	-16.49		

Table 4. Parameters of propulsion model.

$D_p\ [m]$	3.2	a_2	0.761	a_7	-0.574
x'_P	-0.496	a_3	-0.087	a_8	0.431
w_{P0}	0.17	a_4	-0.091	a_9	-0.053
t	0.10	a_5	-0.113		
a_1	-0.156	a_6	-0.072		

Table 5. Parameters of rudder model.

x'_R	-0.5	t_R	0.33	$\gamma_R(\beta_R > 0)$	0.31
A_R	7.68	a_H	0.11	$\gamma_R(\beta_R < 0)$	0.51
Λ	1.33	x'_H	-0.44	l'	-0.5
f_α	2.28	ε	1.13		
η	0.97	κ	0.5		

Comparison with full scale trials results

To assess the quality of the model, we compare results of its simulation with measurements made during full-scale trials of the “Landegode” ferry. Note that the same control input (time-series of rudder, rps and propeller pitch) is used in simulations and experiments. Comparison of tracks for 35° starboard and port turning circles is shown in Figure 4. Corresponding velocities are shown in Figure 5 for starboard and Figure 6 for port trials. Comparison of time-series of heading and velocities for 10°/10° zigzag to starboard, 20°/20° zigzag to starboard and 20°/20° zigzag to port sides are shown in Figure 7 - Figure 9 respectively.

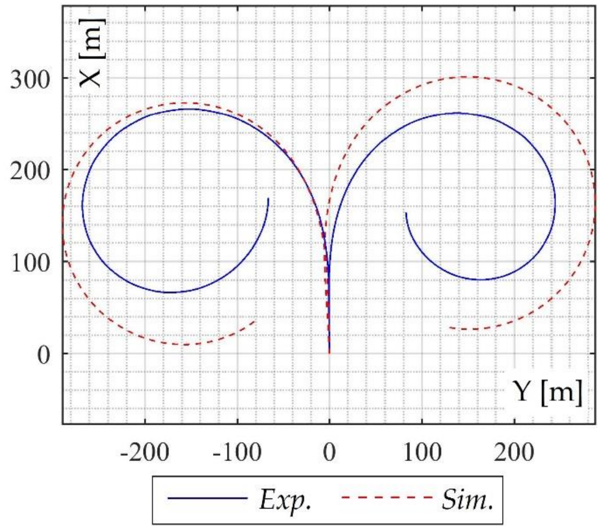

Figure 4. Comparison of tracks of 35° turning circle for simulations and full scale ship.

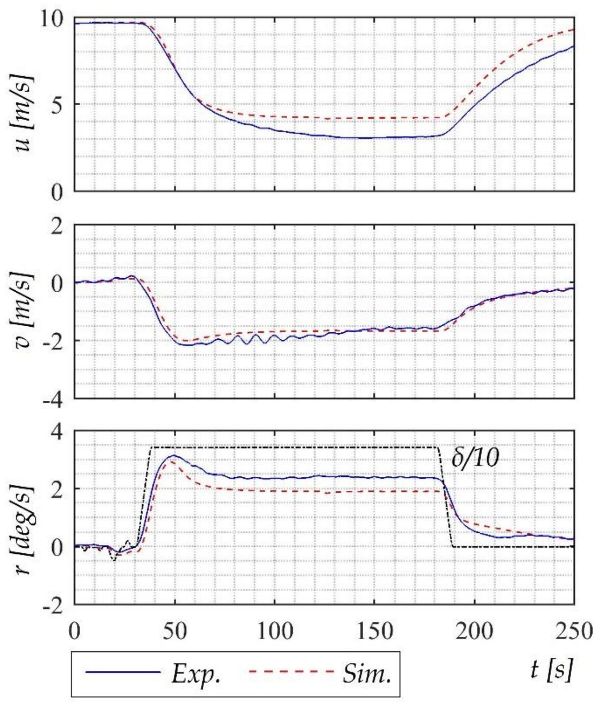

Figure 5. Comparison of velocities of 35° turning circle to starboard for simulations and full scale ship.

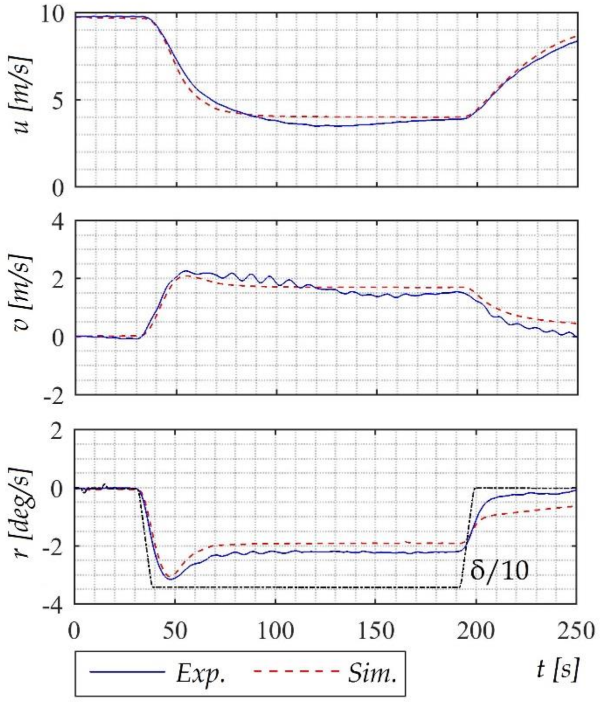

Figure 6. Comparison of velocities of 35° turning circle to port for simulations and full scale ship.

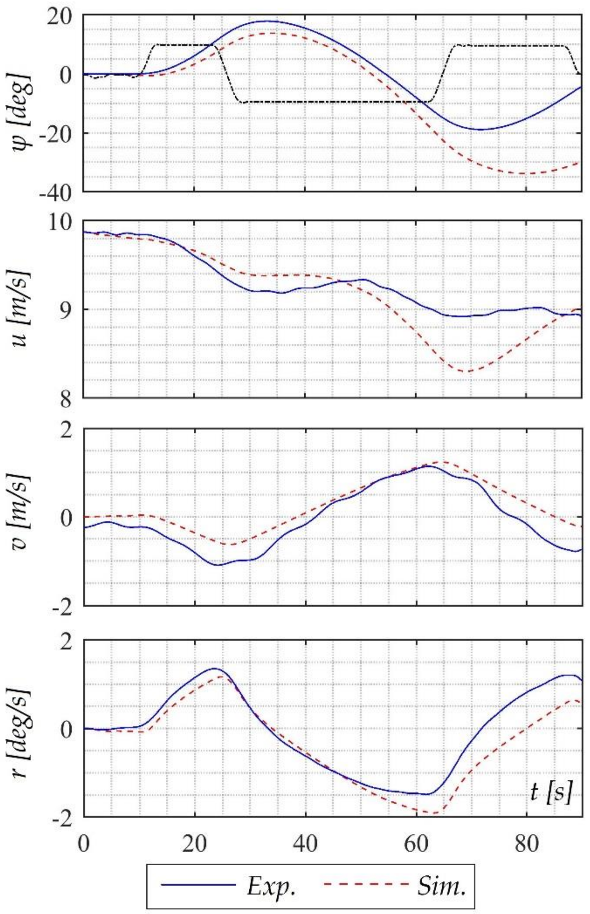

Figure 7. Comparison of heading and velocities of 10°/10° zigzag to starboard for simulations and full scale ship.

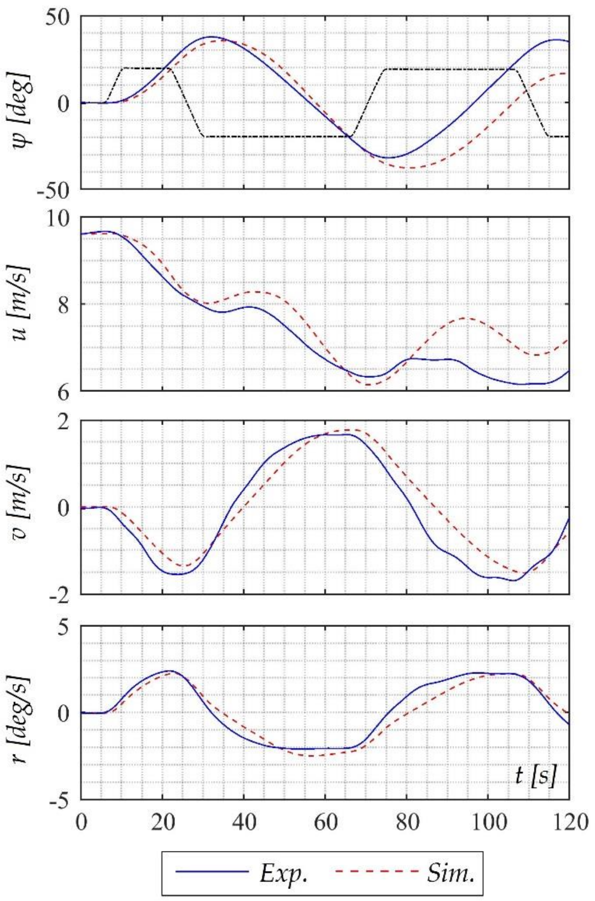

Figure 8. Comparison of heading and velocities of 20°/20° zigzag to starboard for simulations and full scale ship.

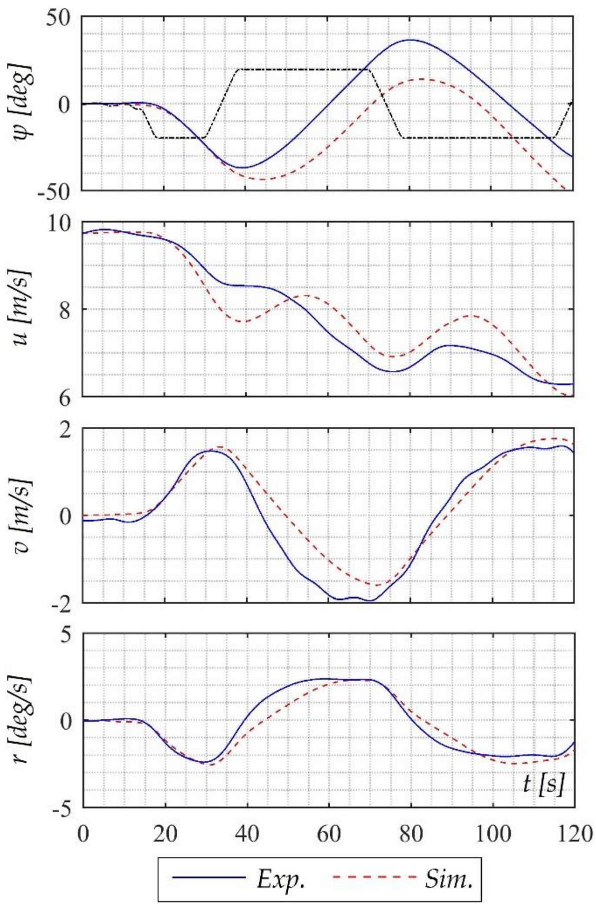

Figure 9. Comparison of heading and velocities of 20°/20° zigzag to port for simulations and full scale ship.

One can see that the time-series of the velocities and yaw rate for 35° turning circle (Figure 5 and Figure 6) look very much alike for simulations and experiments, except for some difference in yaw rate during the steady rotation part. This leads to the visual difference between the tracks (Figure 4). 20°/20° degrees zigzag to starboard side is reproduced rather well (Figure 8), especially the first part including the first overshoot. Fit of the 10°/10° to starboard (Figure 7) and 20°/20° zigzags to port side (Figure 9) is noticeably worse. Thus, the combination of PMM tests, empirical formulas, CFD and potential code provided a model that predicts ship manoeuvring in a realistic way, even though there surely are some deviations from the full scale trial results. The deviations of the simulated results from the experimental results can be due to model errors, including simplification of the model structure and imprecise model coefficients, but also partly due to unknown environmental effects affecting the results of full scale trials.

Sensitivity analysis

To understand how the model parameters affect the results of the simulations, we perform sensitivity analysis. Due to the highly nonlinear system, a global sensitivity analysis is preferable. We use the variance decomposition to calculate total effects for each parameter [12]. The total effect S_{Ti} of some model parameter *i* is a number between 0 and 1, indicating the influence of this parameter on the results of the simulation. $S_{Ti} = 0$ means that the parameter *i* has no influence on the results of the simulation. The index is defined as

$$S_{Ti} = E_{\boldsymbol{X}_{\sim i}}\left(V_{X_i}(Y|\boldsymbol{X}_{\sim i} = \boldsymbol{x}^*_{\sim i})\right)/V(Y) \quad (30)$$

Where $\boldsymbol{X}$ – the vector of model parameters, $\boldsymbol{X}_{\sim i}$ – the vector of model parameters except i-th, $V_{X_i}(Y|\boldsymbol{X}_{\sim i} = \boldsymbol{x}^*_{\sim i})$ - the variance of the result of the model simulation $Y(\boldsymbol{X})$, where all input parameters except for i-th are fixed in some values $\boldsymbol{x}^*_{\sim i}$ from their possible range of variation and i-th parameter can change it's value, $E_{\boldsymbol{X}_{\sim i}}(\dots)$ – expectation of the argument taken over all possible values of $\boldsymbol{X}_{\sim i}$, $V(Y)$ – unconditioned model variance. Thus, $S_{Ti}V(Y)$ shows expected residual variance, if all parameters except one are fixed. More details and a practical way of calculation of S_{Ti} is found in [12]. An example of application of the global sensitivity analysis based on the variance decomposition to manoeuvring problems is found in [13].

To calculate the total effects, one has to define possible ranges of variation for the model parameters. These ranges significantly affect the values of the total effects. For instance, if some parameter is deterministic and has zero range of variation, the corresponding total effect is equal to zero. The possible range of variation of the model parameters can hardly ever be defined objectively. However, such a problem is typical for all kinds of sensitivity analysis. For instance, in the classic example of indirect sensitivity analysis by Hwang [6], all the coefficients are changed by 20% to calculate sensitivities. The approach used in this paper is more flexible and allows using any types and size of distribution for the model parameters. Although the total effects calculated in this paper should be treated carefully and considered in combination with the corresponding input distributions, the analysis still gives useful insights in the model internal structure and importance of the individual and groups of the coefficients for the simulations. Thus, care must be taken to pick the variations of input parameters properly.

We assume uniform distribution of all the parameters. Table 6 contains all non-fixed parameters with corresponding distributions.

Table 6. Variation ranges of the model parameters.

I_z	+/- 10%	Y'_{vvv}	+/- 10%	w_{P0}	0.1 … 0.3
m'_x	+/- 10%	Y'_{vvr}	+/- 10%	t	0.0 … 0.2
m'_y	+/- 10%	Y'_{vrr}	+/- 10%	a_H	0.1 … 0.4
J'_z	+/- 10%	Y'_{rrr}	+/- 10%	t_R	0.1 … 0.4
X'_{uu}	+/- 10%	N'_v	+/- 10%	x'_H	-0.5 … -0.4
X'_{vv}	+/- 10%	N'_r	+/- 10%	$\gamma_R(\beta_R > 0)$	0.3 … 0.7
X'_{vr}	+/- 10%	N'_{vvv}	+/- 10%	$\gamma_R(\beta_R < 0)$	0.3 … 0.7
X'_{rr}	+/- 10%	N'_{vvr}	+/- 10%	l'	-0.8 … -0.4
X'_{vvvv}	+/- 10%	N'_{vrr}	+/- 10%	ε	1.0 … 1.2
Y'_v	+/- 10%	N'_{rrr}	+/- 10%	f_α	2.0 … 2.5
Y'_r	+/- 10%				

The variation range +/- 10% is chosen for the hull hydrodynamic parameters, added masses and moment of inertia and rigid body moment of inertia. This variation is in agreement with the one used in [6], and we believe that it is a good estimate for possible precision of those coefficients. The remaining hull related model parameters are considered constant. The open water propeller characteristic is also considered constant for simplicity. For the remaining ten coefficients in Table 6 some typical ranges are assumed based on common sense, different model examples and reference sources such as [14,15].

As the only distinction in the model between starboard and port side trials is the slight difference in flow straightening effect coming from the propeller rotation direction, we present the results only for the starboard trials, noting that for the port trials total effects for $\gamma_R(\beta_R > 0)$ and $\gamma_R(\beta_R < 0)$ are opposite. Additionally, the variance decomposition analysis allows estimating joint sensitivity of a group of parameters. Thus, for each trial the total effects of two groups of coefficients are presented. The first group (designated as G1) contains the first 21 coefficient from the Table 6 – the hull hydrodynamic coefficients, the added masses and the moment of inertia, while the second group (designated as G2) contains the remaining 10 coefficients, describing the steering part and hull-propeller-rudder interactions.

Before we present the results of the sensitivity analysis, it is useful to define what the resulting scatter of the simulation outcomes corresponding to the uncertainty of the model parameters in Table 6 is. Figure 10 shows simulated time-series of the heading and the rudder angle for 10°/10° zigzag manoeuvre, and Figure 11 shows the plot for the 35° turning circle trial. Although one can use several different indices characterizing the results of the trials, we will limit the analysis to only four characteristics for each type. For zigzag trial these indices are the first and second overshoot angle, and the times from the first rudder execute when the overshoot point is reached (the latter two characterize the length of the manoeuvre). For the turning circle the indices are the advance, the transfer, the tactical diameter and the yaw rate during steady turning. The relative width of the 95% confidence interval is calculated as

$$\Delta_{95\%} = 4\frac{std(index)}{mean(index)}100\% \tag{31}$$

The results are presented in Table 7. One can see that the resulting scatter of all the indices characterizing the results of the simulations is significant, sometimes approaching the value of the index itself. Thus, it is highly important to understand which of the parameters contribute the most to this scatter.

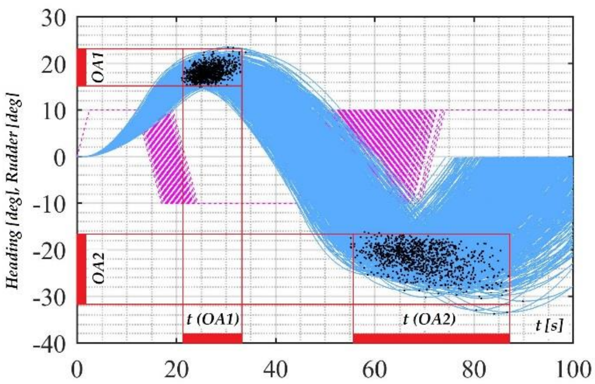

Figure 10. Results of the Monte Carlo simulations of the 10°/10° zigzag to starboard.

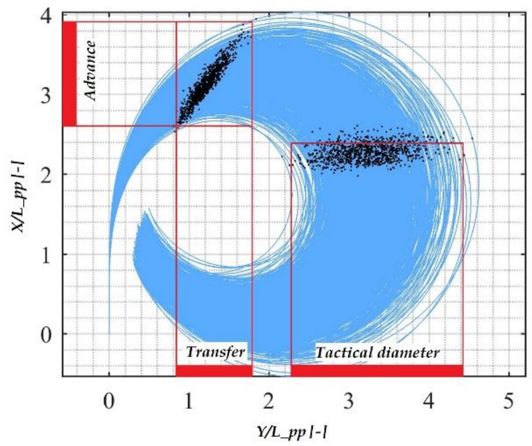

Figure 11. Results of the Monte Carlo simulation of 35° turning circle to starboard.

Table 7. Relative width of the 95% confidence intervals for the simulation outcomes in percent according to (31). OA – overshoot angle, t (OA) – time after the first rudder execute when the overshoot is reached. See Figure 10 and Figure 11.

	OA1 [%]	**OA2 [%]**	**t (OA1) [%]**	**t (OA2) [%]**
10°/10° zigzag	70.9	95.8	36.1	36.8
20°/20° zigzag	55.1	53.1	30.7	29.5
	Advance [%]	**Transfer [%]**	**Tact. Diam. [%]**	**Yaw rate [%]**
35° turning circle	29.4	56.3	48.0	28.3

Total effects of the individual model coefficients, as well as combined effects for the groups G1 and G2 are presented in Figure 12 for 10°/10° zigzag, Figure 13 for 20°/20° zigzag and Figure 14 for 35° turning circle. It is useful to understand what particular values of the total effect coefficient means. From Eq. (30) it follows that the total effect is the relative expected residual variance due to one particular coefficient, when the other coefficients are fixed. Thus, the scatter due to single coefficient according to Eq. (31) is equal to total scatter multiplied by the square root of the total effect. For instance, the total scatter of the tactical diameter resulting from uncertainty of the model parameters in Table 6 is 48%, according to Table 7. Parameter ε has $S_{T\varepsilon} = 0.14$ (Figure 14). Thus, the expected scatter due to the single parameter ε is around 18%.

From the figures one can see that for most of the manoeuvring indices the rudder and interaction coefficients (G2) significantly contribute to the resulting scatter. This contribution is especially strong for timewise characteristics of the zigzags. From the hull hydrodynamic coefficients, only a few significantly affect the manoeuvring indices. The linear derivatives N_v' and N_r' are important for overshoot angles of 10°/10° zigzag. For 20°/20° zigzag, both linear coefficients N_v' and N_r' and nonlinear coefficients N_{vvr}' and N_{vrr}' are important. For the 35° turning circle, the strongest effect is observed for the coefficient N_{vrr}', while other linear and nonlinear coefficients in yaw are less important. From the second group of coefficients, the overshoot angles of zigzags are mainly affected by the flow straightening coefficients with smaller effect of l'. Timewise characteristics of the zigzags are mainly affected by a_H, ε and f_α. The remaining coefficients are much less important. For the turning circle, the relative effect of the interaction coefficients is weaker than for zigzag tests. The strongest effect is observed for ε, a_H, γ_R and f_α are also affecting the geometrical indices.

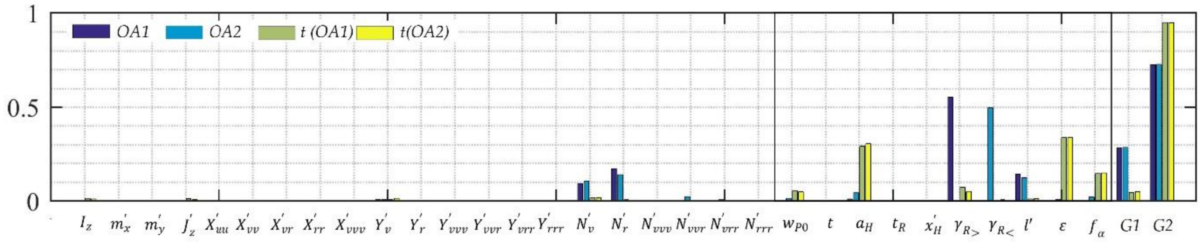

Figure 12. Total effects of the model coefficients on the outcomes of the simulations of the 10°/10° zigzag to starboard.

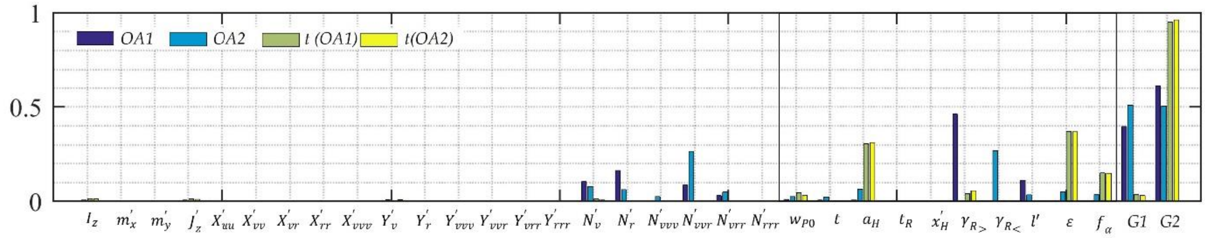

Figure 13. Total effects of the model coefficients on the outcomes of the simulations of the 20°/20° zigzag to starboard.

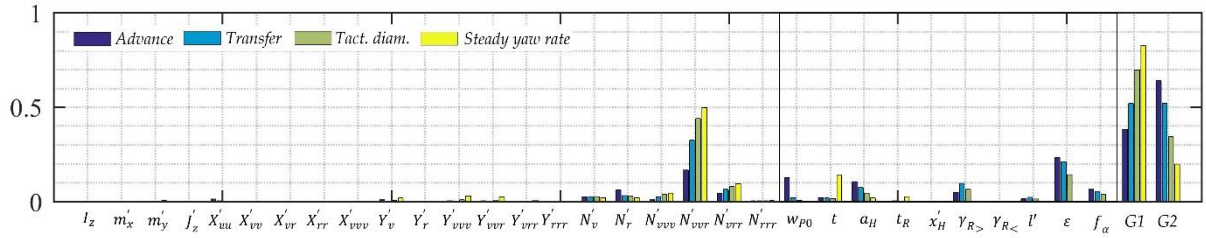

Figure 14. Total effects of the model coefficients on the outcomes of the simulations of the 35° turning circle to starboard.

Model tuning

The sensitivity analysis shows that the hull-propeller-interaction coefficients significantly affect the predictions of the ship manoeuvres. However, in practice it is much more complicated and expensive to define interaction coefficients than the hull manoeuvring coefficients, both experimentally and by means of CFD, as both propeller and rudder should be considered. Moreover, it is not yet well understood how the coefficients are affected by scale effects. Thus, it is desirable to develop satisfactory empirical formulae to predict the interaction coefficients with sufficient accuracy. One of the possible ways is to use system identification to define the coefficients from full scale tests data. In this section, we perform multiple model optimization with random initial coefficients according to the distributions in the Table 7. The random initial values are important to understand if the values of the coefficients converge to the global minimum or local minima. The cost function used for optimization is mean squared difference between experimental and simulated time-series of normalized surge, sway and yaw velocities for eight trials: 35° turning circles to port and starboard, two 10°/10° zigzags to starboard, three 20°/20° zigzags to starboard and one 20°/20° zigzag to port. Similar trials are included to minimize possible effects of random factors such as environment. In addition, penalty is added to avoid large deviations of the hull hydrodynamic coefficients from original values. The quasi Newton algorithm implemented in Matlab solver 'fminunc' [16] is used for optimization. To conveniently assess the similarity of two time-series, the following expression is used (y represents experimental data, $\hat{y}$ – simulated data):

$$fit = \left(1 - \frac{\|y - \hat{y}\|}{\|y - mean(y)\|}\right) \cdot 100\% \quad (32)$$

First, we compare optimized models where all 31 coefficient from Table 6 are adjusted and models where only the last 10 coefficients are tuned. 20 models for each of the optimization settings is identified. Then, the fit is averaged for all the trials for each model. Table 8 presents mean fit and 95 % confidence interval calculated as four multiplied by standard deviation.

Table 8. Average fit of the optimized models and the data.

	u	v	r
All coefficients are tuned			
mean fit	75.83	82.32	93.14
95% CI	2.38	0.57	0.13
Last ten coefficients are tuned			
mean fit	69.95	78.70	88.05
95% CI	0.37	0.24	0.13

One can see that the models where only interaction coefficients are tuned fit the experimental data worse than the models where all the coefficients are tuned. This can indicate insufficient accuracy of the hull hydrodynamic coefficients identified by means of PMM tests, for instance due to scale effects. For all the models the fit is best for yaw velocity, and worse for sway and surge velocity. This can be partly explained by possible uncertainties of experimental data due to environmental effects such as wind, current and waves. Finally, spread between the models is very small, which means that the simulation of the models resulted in very similar time-series. Examples of yaw rate time series for 20°/20° zigzag and 35° turning circles are presented on Figure 15 and Figure 16. The blue lines correspond to the models where only interaction coefficients are tuned and the red lines correspond to the models where all the coefficients are tuned. Each of the lines represent twenty simulated time-series plotted with the same colour. The repeatability is so good that it is almost impossible to distinguish the individual time-series.

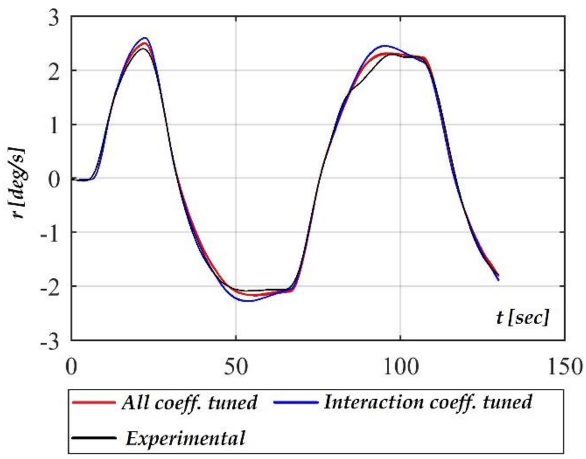

Figure 15. Comparison of tuned models with experimental time-series of yaw rate for 20°/20° zigzag trial to starboard (each thick line representing simulations consists of twenty independent lines representing individual simulations of models with different coefficients).

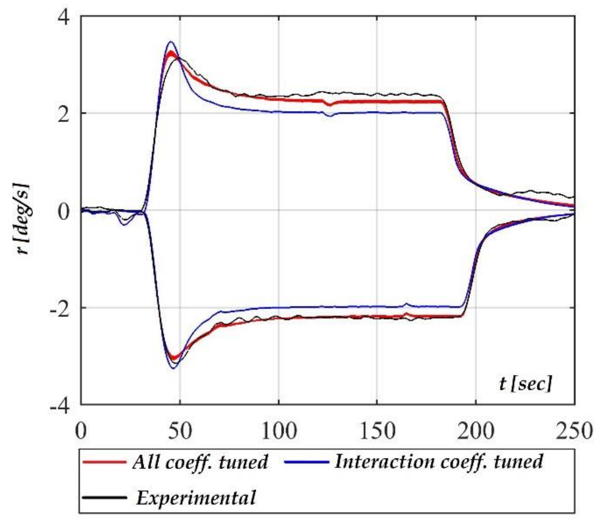

Figure 16. Comparison of tuned models with experimental time-series of yaw rate for 35° turning circles to starboard and port.

However, the tuned coefficients do not converge to similar values. Figure 17 shows resulting ranges of the hull hydrodynamic coefficients for optimized models relative to the original coefficients. One can see that several coefficients changed significantly, including highly sensitive yaw moment linear and nonlinear coefficients. Figure 18 shows the values of interaction and rudder coefficients for the case when all the coefficients are tuned. Thus, we conclude that the coefficients converge to their local optimal values rather than to the global optimal values which can be treated as “true” values. Moreover, any of the local optima cannot be prioritized because they result in similar fit of the experimental data. Therefore, the “true” values of the model coefficients cannot be identified in principle, which shows that creating reliable empirical formulas for the interaction coefficients based on the identification data is impossible in practice. If the hull hydrodynamic coefficients are considered fixed, the scatter of the remaining coefficients is smaller for most of the coefficients (Figure 19). However, in addition to the worse fit of experimental time-series, some values (for instance, t_R and l') are outside of the range these parameters can belong to. Moreover, some of the coefficients having significant influence on the results of simulations have large scatter (a_H, ε and f_α).

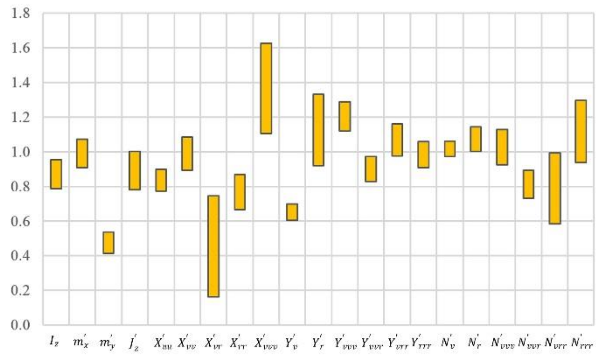

Figure 17. Relative values of the hull hydrodynamic coefficients after the model tuning (all coefficients are tuned).

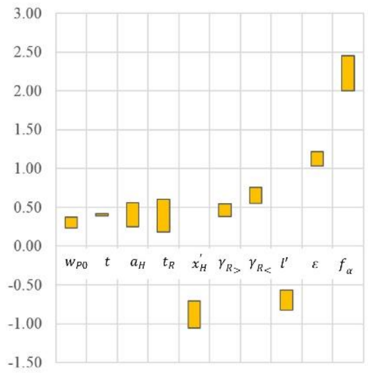

Figure 18. Absolute values of the steering and interaction coefficients after the model tuning (all coefficients are tuned).

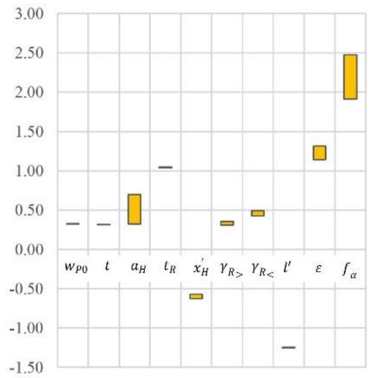

Figure 19. Absolute values of the steering and interaction coefficients after the model tuning (only these coefficients are tuned).

Finally, it is useful to see how the tuned models perform for the trials not used for the identification. There are no available tests from full scale trials which are distinct enough to perform the proper validation. However, it is possible to simulate such trials using the identified simulation models and assess how good the repeatability of the simulation results is. As the control input for the validation manoeuvre, we use stepwise function presented on Figure 20. The input is generated in such a way that it covers rudder angles in range 10 – 25 degrees. The length of each step when the rudder is kept constant is enough for the models to reach steady rotation. We perform simulation for the propulsion settings corresponding to the identification trials (17.5 knots approach speed) and also for a lower speed (11.5 knots) to see how the models are extrapolating. The resultant time-series of velocities are presented on Figure 21. One can see that the models with different coefficients result in almost identical time-series of velocities. Thus, the coefficients has the same correlation even for extended range of applications. Therefore, additional trials will not improve the identifiability of the coefficients.

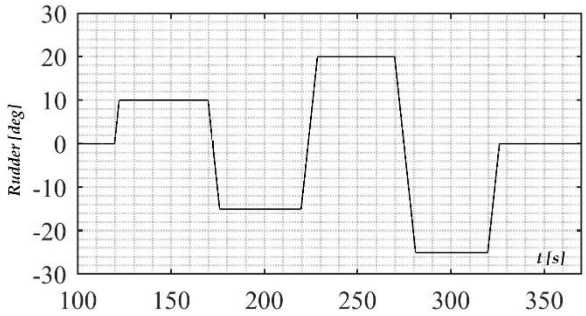

Figure 20. Rudder input for comparison of tuned model.

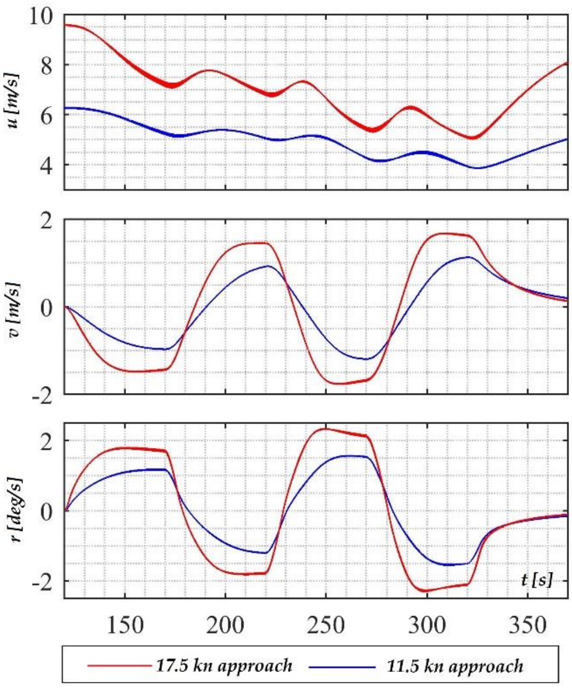

Figure 21. Results of the simulations of the case trial performed for 20 tuned models and two speed ranges.

Discussion and conclusions

In this paper we presented and studied the MMG modular simulation model of the "Landegode" ferry. The hydrodynamic coefficients of the models were identified from oscillating PMM tests (for sway and yaw) and strip theory code (for surge), while for steering system and interaction coefficients empirical formulas were used. The comparison with the results of full scale trials revealed some differences, although the behaviour of the model is similar to the real ship for all the tests. It is not possible to conclude what is the source of this difference.

The global sensitivity analysis based on variance decomposition was applied to understand which of the coefficients affect the outcomes of the simulations the most. The analysis showed that both hydrodynamic coefficients and steering and interaction similarly significantly affect the results of the simulations. It was found that among the hull hydrodynamic coefficients, yaw moment derivatives have the strongest effect. N'_{vvr} and N'_{vrr} are the most influential for large rudder angle trials. These coefficients can be identified only from combined sway and yaw motions which can be taken into account during the design stage of the PMM experiments. However, the precision of the model can be significantly limited by steering and interaction coefficients, as in practice they are rarely measured with the same accuracy as the hull hydrodynamic coefficients. Thus, further studies are recommended to understand what is the sufficient accuracy of the interaction coefficients and if more effort should be made to estimate them with higher precision.

To investigate the possibility of identification of interaction coefficients from full scale trials, the model tuning with random initial approximations for the coefficients was done. Two series of the identification were performed: in the first one only steering and interaction coefficients were adjusted, and in the second one in addition hull hydrodynamic coefficients and the moment of inertia of the ship were tuned. Twenty models were identified for each setting. In both cases the identified models converged to the same time-series, being closer to the full-scale time-series in the case when all the coefficients were tuned. However, the coefficients did not converge to the same "true" values and had significant scatter. In the case where only steering and interaction coefficients were tuned, some unfeasible values of the identified coefficients were observed, indicating possible errors in model structure or hull hydrodynamic coefficients. Moreover, additional trials of a new type not used for the identification for two different approach speeds and propeller settings were simulated to see if the correlation between the coefficients is the same for different application ranges. The resulting time-series of velocities were also almost identical. Thus, the "true" values of the model parameters cannot be identified for the MMG model from full scale tests. And although grey box system identification of MMG model can be useful as it provides a set of model coefficients which can result in time-series close to those observed for a real ship, extrapolation using such a model should be carefully studied.

Acknowledgements

This research, a part of the SimVal project, was sponsored by the Norwegian Research Council (225141/O70); the authors acknowledge this support. The authors thank Torghatten Nord, Rolls-Royce Marine, and SINTEF Ocean for their assistance in obtaining the full-scale data used in the study. These organizations were involved in the data collection but not in the data analysis and writing of this article. In addition, these organizations were involved in the decision to submit the article for publication.

Conflicts of Interest

None

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