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

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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.

1. 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

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Nomenclature

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
$a_1 \ldots a_9$	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
$E_{\ldots}(\ldots)$	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
$V_{\ldots}(\ldots)$	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

Fig. 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

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.

2. Description of the vessel

The case ship Landegode (Fig. 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.