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Features of an Ultra-large Container Ship Mathematical Model Adjustment Based on the Results of Sea Trials

O. Pipchenko, M. Tsymbal & V. Shevchenko
National University "Odessa Maritime Academy", Odessa, Ukraine

ABSTRACT: The research addresses the problem of an ultra-large container ship mathematical model adjustment based on sea trials. In order to verify the model's adequacy, simulated data had to be compared to the trial report data, which was obtained in ballast condition with significant trim. In such circumstances, model coefficients cannot be calculated by known methods and have to be corrected as per trial data. It is proposed to determine translational motion coefficients first. To get optimal results, it was also proposed to divide the objective function into kinematic and dynamic components, with each component being assigned a weighting factor. A separate objective function component was assigned to the zig-zag maneuver, which includes the first and second overshoot angles.

1 INTRODUCTION

Despite the fact that the total number of navigational accidents (collisions, allisions, groundings) has decreased in the last decade, emergency cases involving large-tonnage vessels are quite frequent. As for today, modern container fleet keeps growing in size and capacity. For example, the container ship OOCL Hong Kong with a length of 400 meters, a width of 59 meters and a draft of 16 meters, with a capacity of 21,413 TEU was launched in 2017. At the same time, according to insurers' assessments (*Allianz 2018*) the loss of a container ship with a cargo capacity of 20,000 TEU could cost as much as 1 billion US dollars. Obviously, with the increase in the size of ships, the problem of ensuring their navigation safety in narrow waters becomes even more critical. Mathematical modelling and simulation are necessary processes involved into design and operation of ships and port facilities. At the same time, physical modelling using scaled models is time consuming and expensive, which, if necessary, is performed at the final design stage. Proper mathematical modelling helps to find out limitations and possible problems or look for optimal solutions at early design stage as well as in the subsequent design process.

This research is directed to the ULCS class container ship mathematical model adjustment on the basis of existing sea trial data.

2 PREVIOUS RESEARCH ANALYSIS

Extensive research dedicated to the vessel maneuvering modeling was carried out in the past and published by numerous authors. Generally speaking, we can divide existing models in two groups: linear models, which include course control with constant speed, which are widely used for autopilot design (*Pipchenko, Shevchenko 2018*) and non-linear models, which include vessel dynamic calculation in wide motion parameters range.

The most common are 3 DoF (degrees of freedom) maneuvering models of two main types. In the first case it's a system of equations for longitudinal and transverse speed and rate of turn in relation to a vertical axis as shown by Fossen (2002), Kijima et al. (1993), Perez & Blanke (2003), Yasukawa et al. (2015), Yoshimura et al. (2012); in the second case it's a system of equations for forward movement speed, drift angle and rate of turn in relation to a vertical axis as shown by Gofman (1988) and Pershitz (1983).

From a mathematical modeling perspective, when forces of different nature such as wind and wave forces, currents, tugs, thrusters are considered, especially in case of maneuvering calculation at near zero speeds, it is more convenient to build a model with the motions separated by dedicated axis.

Forces and moments acting on a ship can be calculated using equations from various sources such as Kijima et al. (1993), Perez & Blanke (2003), Yasukawa et al. (2015), Yoshimura et al. (2012), ITTC (2005), ABS (2006) and others.

Model coefficients may be found by formulas, generalized for a number of ship types, which in return usually leads to calculation errors, still too big for navigational safety evaluation.

The other approach is to apply both parametric and functional approximation using neural networks as suggested by Pipchenko and Zhukov (2007), but later requires a substantial amount of experimental data, which is not always cost-effective.

Therefore, if we choose the approach way, after preliminary model coefficients calculation, it should be adjusted according to available experimental data.

3 EQUATIONS OF MOTION

The system of equations which describes vessel motion on the horizontal plane can be presented as:

$$\left.\begin{aligned}(m+m_x)\dot{u}_G-(m+m_y)v_G r_G&=X\\(m+m_y)\dot{v}_G+(m+m_x)u_G r_G&=Y\\(I_{zz}+J_{zz})\dot{r}_G&=N-x_G Y\end{aligned}\right\}\qquad(1)$$

where m – vessel displacement; m_x, m_y – added masses, I_{kk}, I_{zz} – moments of inertia, J_{kk}, J_{zz} – added moments of inertia, u_G, v_G, p_G, r_G– longitudinal and transverse speed and rate of turn with respect to horizontal and vertical axes related to the vessel center of gravity; X, Y, K, N – hydrodynamic forces and moments acting on ship.

Hydrodynamic forces and moments can be presented as:

$$\left.\begin{aligned}X&=X_H+X_R+X_P\\Y&=Y_H+Y_R+Y_P\\N&=N_H+N_R+N_P\end{aligned}\right\}\qquad(2)$$

where H - hull; R – rudder; P – propeller; W – wind; BT – bow thruster.

Forces and moments acting on a ship hull can be derived on the basis of the model offered by Yoshimura (2012). Water resistance forces and moment (X_H, Y_H, N_H) together with forces and moment of inertia can be given as follows:

$$\left.\begin{aligned}&X_H+m_y v_g r_g=\left(\frac{\rho}{2}LdU^2\right)\times\\&\left\{X'_0+X'_{\beta\beta}\beta^2+\left(X'_{\beta r}-m'_y\right)\beta r'+\left(X'_{rr}-x'_G m'_y\right)r'^2+X'_{\beta\beta\beta\beta}\beta^4\right\}\\&Y_H-m_x u_g r_g=\left(\frac{\rho}{2}LdU^2\right)\times\\&\left\{Y'_\beta\beta+\left(Y'_r-m'_x\right)r'+Y'_{\beta\beta\beta}\beta^3+Y'_{\beta\beta r}\beta^2 r'+Y'_{\beta rr}\beta r'^2+Y'_{rrr}r'^3\right\}\\&N_H=\left(\frac{\rho}{2}L^2dU^2\right)\times\\&\left\{N'_\beta\beta+N'_r r'+N'_{\beta\beta\beta}\beta^3+N'_{\beta\beta r}\beta^2 r'+N'_{\beta rr}\beta r'^2+N'_{rrr}r'^3\right\}\end{aligned}\right\}\qquad(4)$$

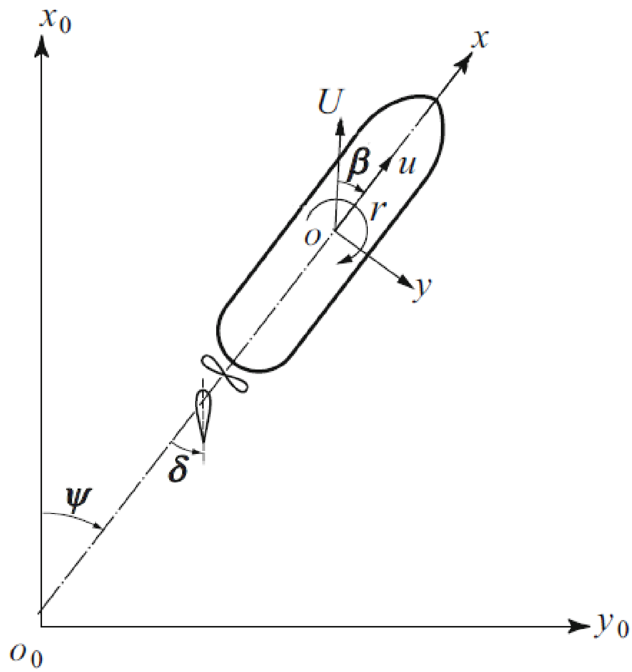

Figure 1. Coordinate system for ship movement modelling

where ρ – water density, β - drift angle, positive to port side; X_0, $X_{\beta\beta}$, $X_{\beta\beta\beta\beta}$, X_{rr}, $X_{\beta r}$, Y_β, $Y_{\beta\beta\beta}$, Y_r, Y_{rrr}, $Y_{\beta\beta r}$, $Y_{\beta rr}$, N_β, $N_{\beta\beta\beta}$, N_r, N_{rrr}, $N_{\beta\beta r}$, $N_{\beta rr}$ – resistance forces coefficients.

Thrust force created by propeller can be calculated as:

$$X_P=(1-t_P)\cdot T;\qquad(4)$$

$$T=\rho\cdot n_P^2\cdot D_P^4\cdot K_T\left(J_P\right);$$

$$K_T(J_P)=k_0+k_1\cdot J_P+k_2\cdot J_P^2;\qquad(5)$$

$$J_P=\frac{u\left(1-w_P\right)}{n_P D_P},$$

where T – propeller thrust, t_P – thrust deduction coefficient, n_P – propeller revolutions, D_P – propeller diameter, K_T – thrust coefficient, J_P – propeller slip, w_P – hull influence coefficient.

Forces and moment created by rudder can be defined by formulas:

$$\left.\begin{aligned} X_R &= -(1-t_R)F_N \sin\delta \\ Y_R &= -(1+a_H)F_N \cos\delta \\ N_R &= -(x_R + a_H x_H)F_N \cos\delta \end{aligned}\right\} \tag{6}$$

where F_N – normal force created on the rudder: t_R, a_H, x_H – coefficients, which reflect hydrodynamic interaction between hull, propeller and rudder; x_R – distance from midship section to rudder stock.

$$FN = \tfrac{1}{2}\rho A_R U_R^2 f_a \sin a_R,$$

where A_R – rudder area, U_R – water flow speed on the rudder, f_a – lifting factor, a_R – effective inflow angle on the rudder.

Coefficients of equations (3), (4) and (6) can be defined according to methods given in Kijima et al. (1993), Perez & Blanke (2003), Yasukawa et al. (2015), ITTC (2005), ABS (2006) and others or can be taken from databases for ship with proportional dimensions (*Yoshimura et al. 2012*).

4 LOGITUDINAL MOTION MODEL ADJUSTMENT

It is reasonable to start the mathematical model coefficients adjustment from ship forward motion equation as it can be separately allocated from common system of equations (*Pipchenko et al. 2017*). During further adjustment ship forward motion equation coefficients will not be changed.

Corresponding scripts for ship motion calculation and further adjustment were written in MATLAB R2016b.

Typical trial maneuvers, which involve longitudinal motion, are acceleration, crash stop and inertial stopping. In this case data was taken from sea trials report of 10000 TEU, 2015 year-built container ship Maersk Sirac. Main parameters of this vessel are given in Table 1.

Table 1. Maersk Sirac – vessel information

Parameter	Value
Overall length, m	300
Length between perpendiculars, L, m	287
Breadth of vessel, B, m	48.2
Draught (mean / maximum) at load, d, m	12.5/15.0
Forward draught at trials, m	4.02
Aft draught at trials, m	10.16
Propeller diameter, D_P, m	9.7
Block coefficient (ballast), C_b	0.6044
Wet surface area, Ω, m²	11656
Midship section plane coefficient, C_M	0.9735
Rudder area, A_R, m²	78.95

To perform calculations, ship motion equation along X axis can be expressed in following form:

$$\dot{u} = \frac{(1-t_P)\cdot\rho\cdot n_P^2\cdot D_P^4\cdot K_T(J_P) + \tfrac{1}{2}X_0\cdot\rho\cdot L\cdot d\cdot U^2}{m+m_x}. \tag{8}$$

Coefficient X_0 = - 0.014 for this case, was estimated from sea trials. It is important to note that absence of X_0 credible value increases uncertainty of other coefficients values during adjustment. When X_0 experimental value is absent it is useful to apply resistance calculation methods on still water (*i.e. Holtrop, 1982*).

Coefficients t_P and w_P can be defined using approximate formulas:

$$t_P = 0.325\cdot C_b - \frac{0.1885\cdot D_P}{\sqrt{B\cdot d}};$$

$$w_P = 0.5C_b - 0.05.$$

Coefficients of the J_P can be approximated by known propeller trials data. In our case this data is absent and in first approximation relation between ship speed and propeller revolutions was received (figure 2).

If we have a close look on a thrust K_T and advance ratio J_P coefficients formulas when negative revolutions are set, the thrust coefficient can gain incorrect value. This is because the J_P will be negative when the speed is positive and, as follows, parts of the equation (5) will be deducted from coefficient k_0.

To obtain realistic values for astern maneuver equations (4) and (5) shall be presented as:

$$T = \rho\cdot D_P^4\cdot K_T(J_P)\cdot n_P\cdot|n_P|; \tag{9}$$

$$J_P = \left|\frac{u(1-w_P)}{n_P D_P}\right|. \tag{10}$$

After equation (4) coefficients adjustment using Nelder–Mead method the calculations result is almost matches with the experiment, with average deviation of 0.26 knots. The objective function used in optimization has following form:

$$Z = \frac{\sum_{n=1}^{N}|U_{Tn} - U_{Sn}|}{N}, \tag{11}$$

where U_T – sea trials measured speed, U_S – speed as result of simulation.

But further calculation of crash and inertial stopping maneuvers doesn't give a satisfactory result. This is because the optimization program adjusts only coefficient k_0 while other coefficients decrease almost to zero. This, in turn, excludes propeller advance effect from the model. Therefore, to achieve adequate optimization results it is necessary to include all three maneuvers: acceleration, inertial and crash stopping into objective function calculation.

Considering the above, the objective function (11) will look like:

$$Z = w_1 \frac{\sum_{n=1}^{N} \left| U_{Tn} - U_{Sn} \right|}{N} + w_2 \frac{\sum_{n=1}^{N} \left| U_{CSTn} - U_{CSSn} \right|}{N} + w_3 \frac{\sum_{n=1}^{N} \left| U_{ISTn} - U_{ISSn} \right|}{N} + w_4 \frac{\sum_{n=1}^{N} \left| D_{CSTn} - D_{CSSn} \right|}{N} + w_5 \frac{\sum_{n=1}^{N} \left| D_{ISTn} - D_{ISSn} \right|}{N}, \quad (12)$$

where D – track reach, w – weighting factor, index CS – crash stop, IS – inertial stopping.

As errors in distance and speed have different order it is necessary to normalize them using the weighting factors. In our case w = [1 1 1 0.001 0.001].

As a result of re-optimization, the coefficients k_1, k_2 and k_3 will be adjusted which gives the result with satisfactory accuracy, shown on figures 2-4 and in table 2.

Table 2. Speed trial adjustment results

Parameter			Value
Average speed deviation during acceleration, Δ_U			0.26 knots
Average speed deviation during crash stopping, Δ_{UCS}			0.59 knots
Average speed deviation during inertial stopping, Δ_{UIS}			0.50 knots
Crash stop track reach calculation relative error, Δ_{DCS}			0.04 % / 1.0 m
Inertial stopping track reach calculation relative error, Δ_{DIS}			1.5 % / 77.1 m
Coefficients before adjustment		Coefficients after adjustment	
k_0	k_1	k_0	k_1
0.16	-0.068	0.06104	0.8632
k_2	k_3	k_2	k_3
0.074	0.022	-1.0901	0.067

5 MANEUVERABILITY MODEL ADJUSTMENT

Typical maneuvers for ships' turning capacity trials are turning circles and zig-zag 10/10°.

According to the trial report data the propeller revolutions during turning circle will change from 83 rpm to 54 rpm.

As shown in table 1, sea trials were conducted with ship in ballast condition with the trim of 6.14 m and the average draught of 7.09 m. Ship's average operational draught is usually twice bigger and trim is close to zero. In this regard, model coefficients calculation using empirical formulas will lead to big errors.

At this stage of model adjustment, it is important to define which parameters reflect the accuracy of the obtained results and a corresponding form of objective function.

In this case, it is useful to divide an objective function Z into dynamic Z_D and kinematic Z_K parts. From sea trials data on a turning circle maneuver we can get the following parameters: ship's speed, heading, coordinates, advance and tactical diameter. Consequently:

$$Z_D = w_1 \frac{\sum_{n=1}^{N} \left| U_{Tn} - U_{Sn} \right|}{N} + w_2 \frac{\sum_{n=1}^{N} \left| r_{Tn} - r_{Sn} \right|}{N}; \quad (7)$$

$$Z_K = w_3 \left(\frac{\max(X_T) - \max(X_S)}{\max(X_T)} + \frac{\max(Y_T) - \max(Y_S)}{\max(Y_T)} \right) + w_4 \frac{\sum_{n=1}^{N} \Delta D}{N \cdot \max(X_T)} \quad (8)$$

$$\Delta D = \sqrt{(X_T - X_S)^2 + (Y_T - Y_S)^2},$$

where ΔD – position error; w_i – weighting factor; index T – trial data; index S – calculated data; max (X_T) – position, indicating turning circle tactical diameter; max(Y_T) – position, indicating advance.

Let's pick first and second overshoot angles errors as zig-zag maneuver objective function component:

$$Z_Z = w_5 \left(\left| \frac{\Delta\psi_1^T - \Delta\psi_1^S}{\Delta\psi_1^T} \right| + \left| \frac{\Delta\psi_2^T - \Delta\psi_2^S}{\Delta\psi_2^T} \right| \right) \quad (9)$$

As errors in distance and speed have different order lets normalize them using the weighting factors. In our case w = [1; 180·60/π; 2; 1; 0.2].

Consequently, objective function will be defined as:

$$Z = Z_D + Z_K + Z_Z \quad (10)$$

Further it is useful to define coefficients which have to be adjusted. In our case the algorithm will vary 19 coefficients included in hull resistance and rudder forces equation:

$$X'_{\beta\beta}, X'_{\beta r}, X'_{rr}, X'_{\beta\beta\beta\beta},$$
$$Y'_{\beta}, Y'_{r}, Y'_{\beta\beta\beta}, Y'_{\beta\beta r}, Y'_{\beta rr}, Y'_{rrr},$$
$$N'_{\beta}, N'_{r}, N'_{\beta\beta\beta}, N'_{\beta\beta r}, N'_{\beta rr}, N'_{rrr}, \varepsilon, \gamma_R, a_h$$

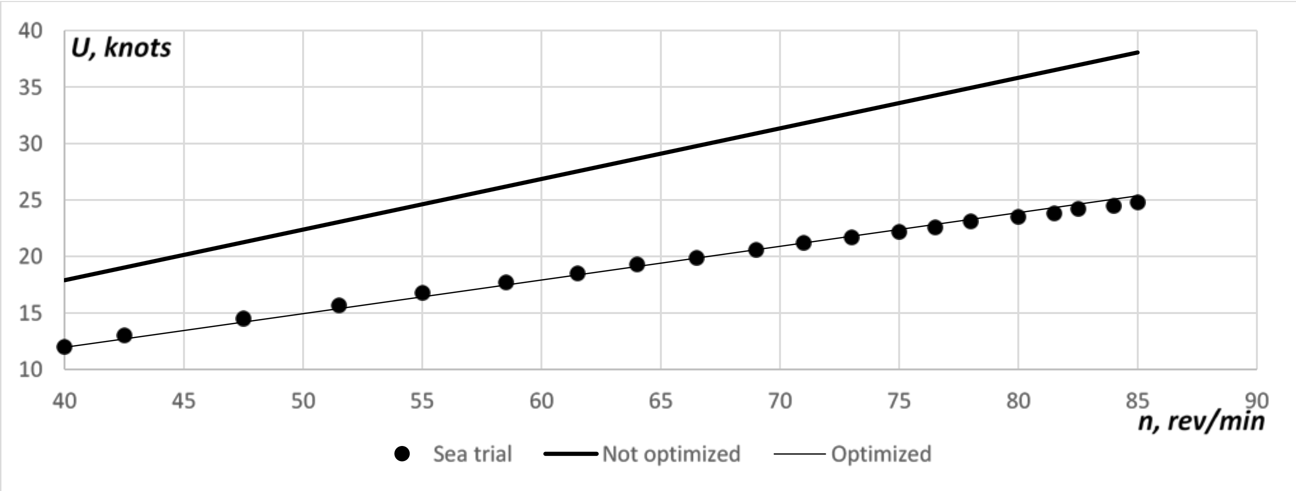

Figure 2. Relationship between the ship's speed and propeller revolutions

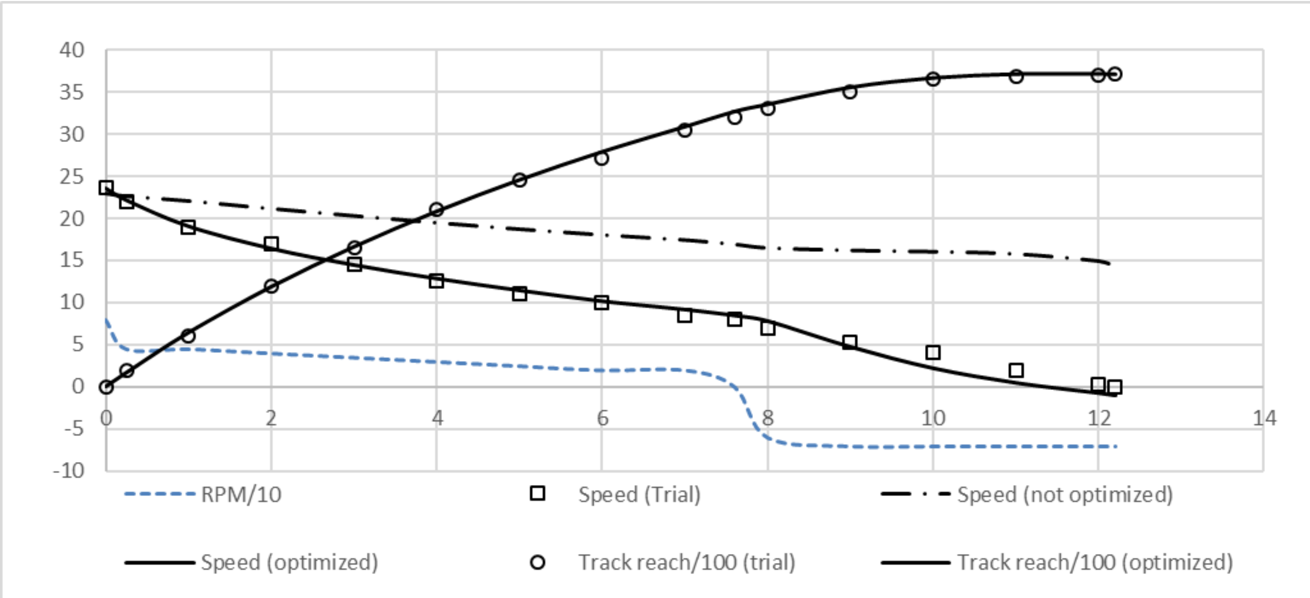

Figure 3. Crash stopping curves

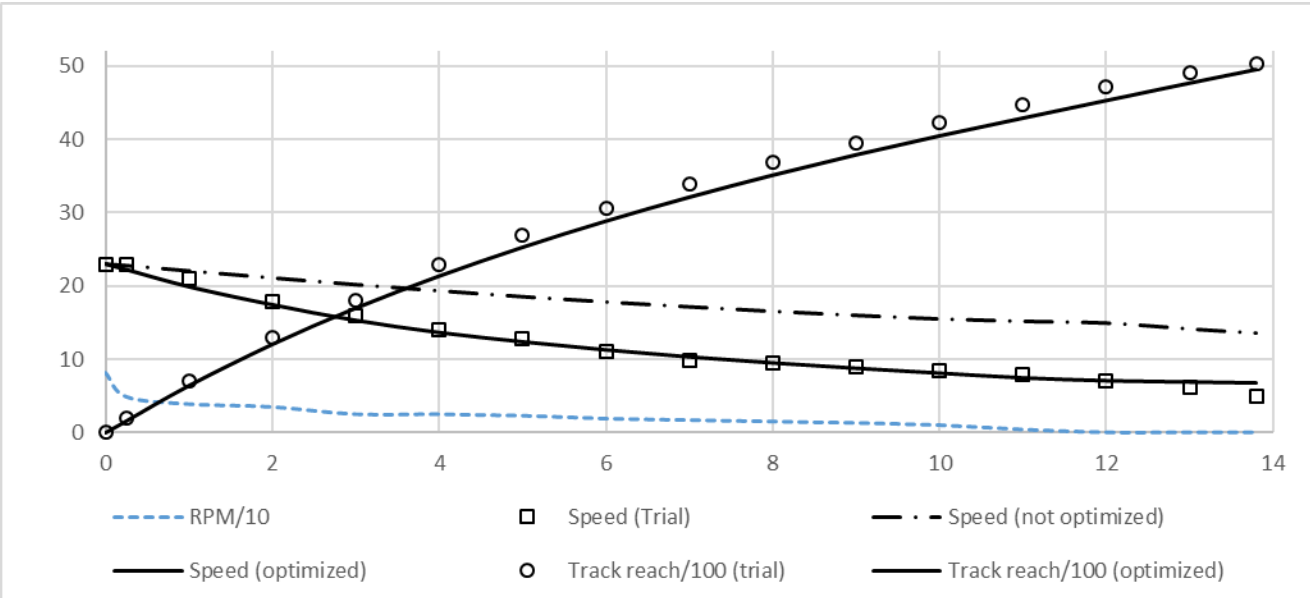

Figure 4. Inertial stopping curves

Ship movement model coefficients adjustment algorithm block-diagram is shown on figure 5. As described above, the first stage is ship longitudinal motion model adjustment. Model initial coefficients are chosen from appropriate database. Then the model calculation and trials data comparison is conducted. If the model accuracy doesn't satisfy chosen criteria, adjustment by the Nelder–Mead method is conducted. As a result, refined coefficients will be recorded to database.

The modelling results at the first step and after coefficients adjustment are given on figures 6-8 and in table 3. As seen, adjustment procedure allows to decrease modelling errors sufficiently.

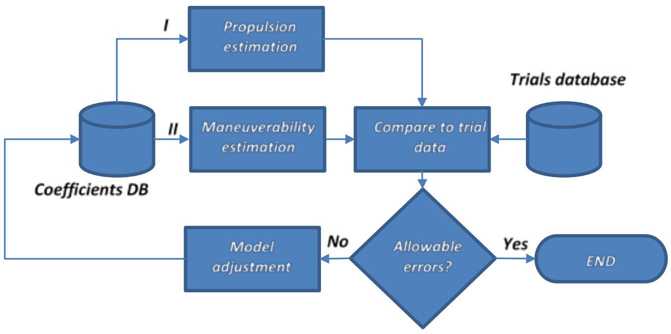

Figure 5. Ship motion mathematical model adjustment algorithm block-diagram

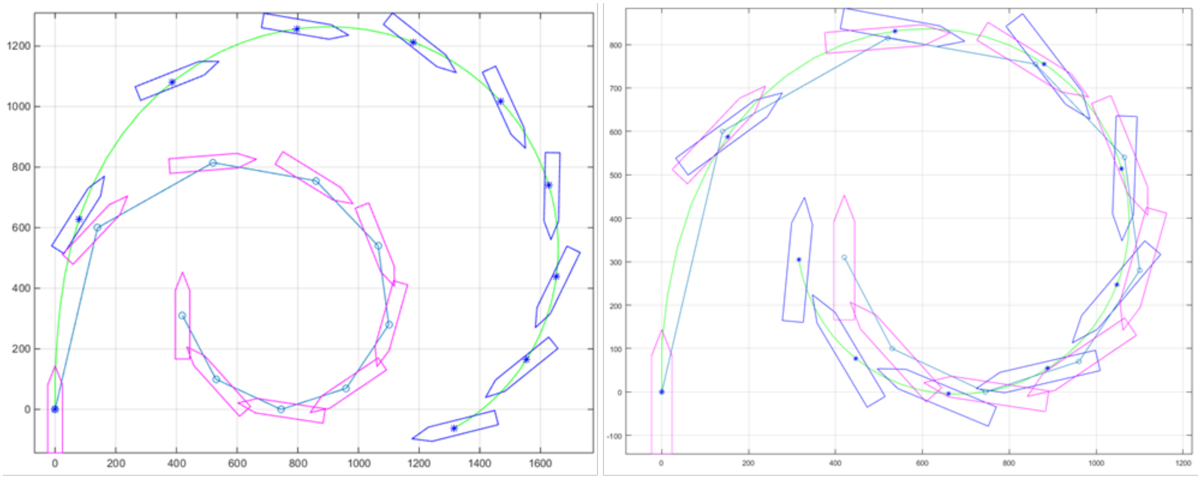

Figure 6. Starboard side turning circle trajectory
*Left – before adjustment; right – after adjustment; o – trials data, * - calculation data.*

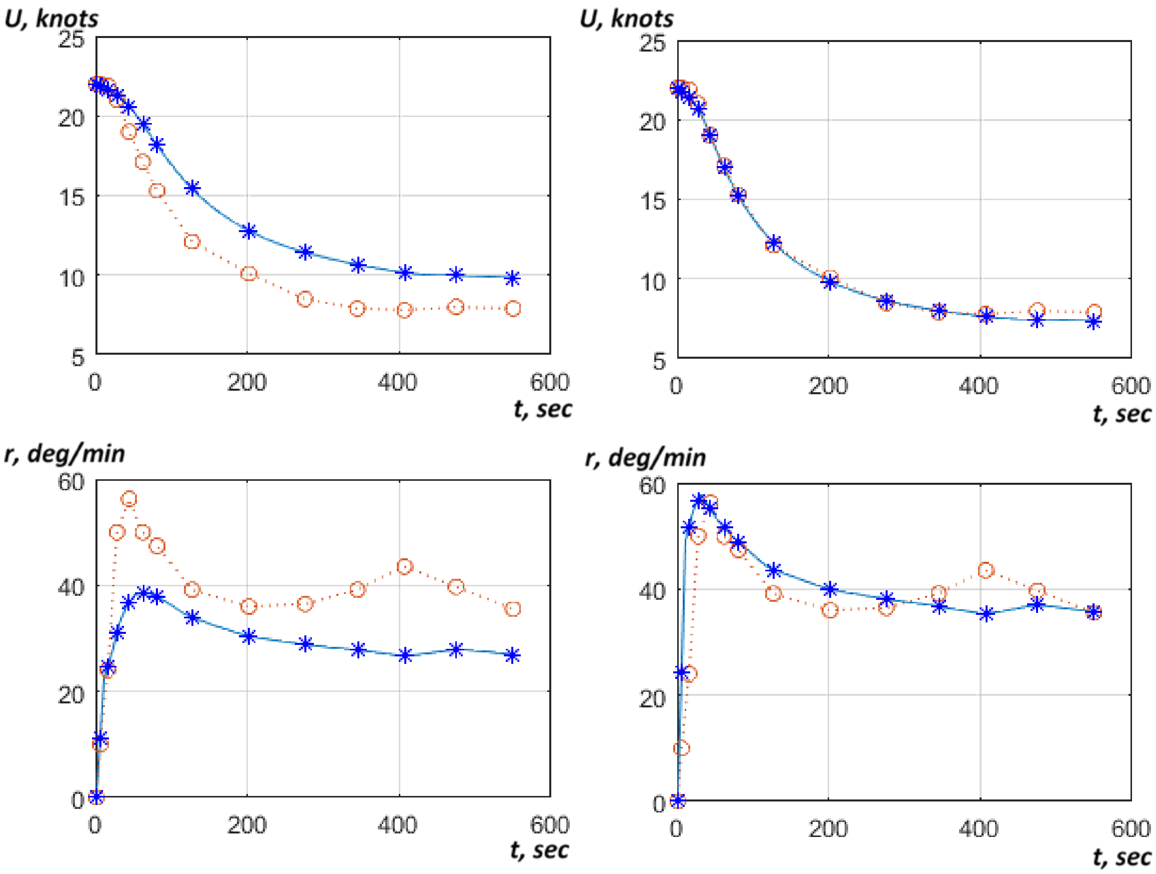

Figure 7. Starboard turning circle ship motion parameters.
*Left – before adjustment; right – after adjustment; o – trials data, * - calculation data.*

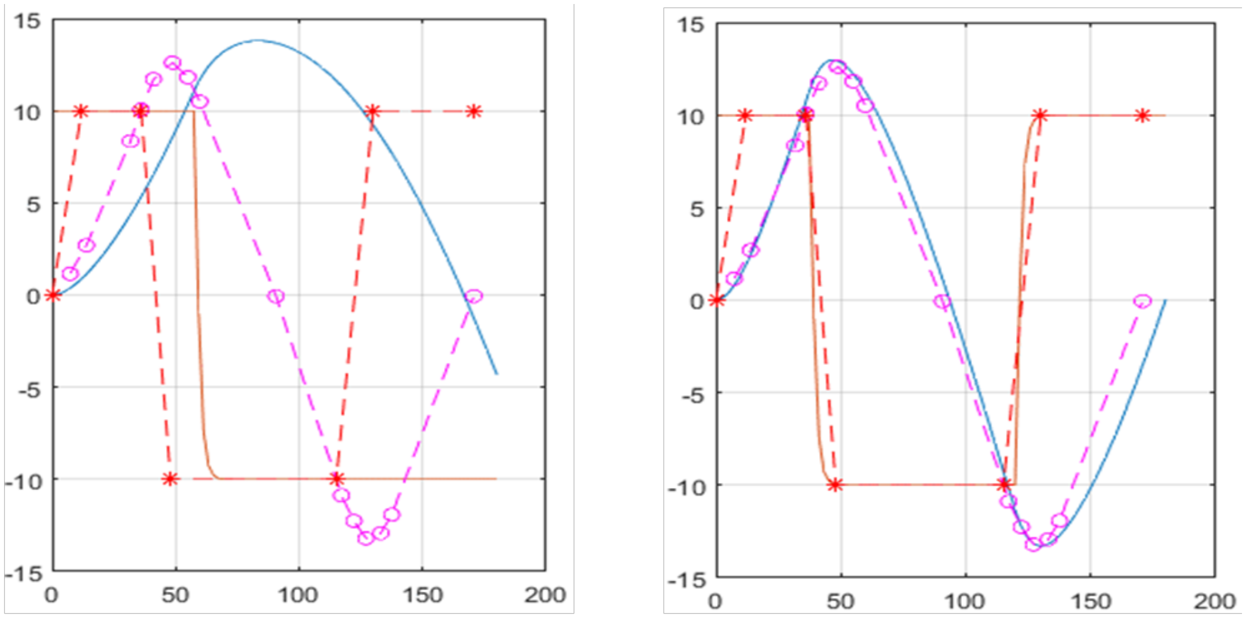

Figure 8. Course-keeping abilities parameters: zig-zag 10/10.
Left – before adjustment; right – after adjustment; dashed line – trials data; solid line – calculation data

Table 3. Mathematical model adjustment results

Parameter	Trials	Before adjustment	After adjustment
Advance, m	830.9	1255	836
Turning circle tactical diameter, m	1164.3	1630	1148.3
1-st overshoot angle, °	2.5	3.8	3.0
2-nd overshoot angle, °	3.2	-	3.3
RMSD position	-	589.2	49.9
RMSD course	-	28.5	10

Coefficients before and after adjustment / difference %

$X'_{\beta\beta}$	$X'_{\beta r}$	X'_{rr}	$X'_{\beta\beta\beta\beta}$	Y'_{β}	Y'_{r}	$Y'_{\beta\beta\beta}$	$Y'_{\beta\beta r}$	$Y'_{\beta rr}$	Y'_{rrr}
-0.0626	-0.1149	-0.00068	0.4182	0.3099	0.1207	1.5816	0.6323	0.7173	0.0088
-0.2617	-0.1531	-0.00069	0.47811	0.1044	0.1795	2.7160	0.9423	1.3620	0.001
318	**33**	**2**	**14**	**66**	**49**	**72**	**49**	**90**	**89**

N'_{β}	N'_{r}	$N'_{\beta\beta\beta}$	$N'_{\beta\beta r}$	$N'_{\beta rr}$	N'_{rrr}	ε	γ_R	a_h
0.0179	-0.03025	0.2407	-0.6018	0.077	-0.03	0.902	0.350	0.3674
0.0087	-0.03	0.2259	-0.6445	0.109	-0.055	1.344	0.312	0.3422
52	**4**	**6**	**7**	**41**	**79**	**49**	**11**	**7**

6 CONCLUSIONS

In order to verify the model's adequacy, simulated data had to be compared to the trial report data, which was obtained in ballast condition with significant trim. In such circumstances, model coefficients cannot be calculated by known methods and have to be corrected as per trial data.

It is proposed to determine translational motion coefficients first. To get optimal results, it was also proposed to divide the objective function into kinematic and dynamic components, with each component being assigned a weighting factor. A separate objective function component was assigned to the zig-zag maneuver, which takes into account the first and second overshoot angles.

The mathematical model adjustment was performed using the Nelder-Mead downhill simplex method, which allowed to obtain high accuracy results in order to fit both vessel transitional dynamics process and output kinematic parameters such as track reach, advance and tactical diameter.

It is important to note that obtained coefficients fit only the specific vessel, on the other hand, the algorithm and obtained objective functions may be applied to a wider scope of vessels with different shapes and dimensions.

REFERENCES

ABS Guide for Vessel Maneuverability, 2006
Allianz Global Corporate & Specialty. Safety and Shipping Review 2018. http://www.agcs.allianz.com/
Fossen T. I. 2002 Marine Control Systems. Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles. *Marine Cybernetics, Trondheim, Norway*
Gofman A. D. 1988. Движительно-рулевой комплекс и маневрирование судна. *Справочник. Л.: Судостроение.*
Holtrop J., Mennen G. 1982. An Approximate Power Prediction Method. *International Shipbuilding Progress, 29, 335*

Ho-Young Lee, Sang-Sung Shin. 1998 The Prediction of ship's manoeuvring performance In initial design stage. *Practical Design of Ships and Mobile Units. Elsevier Science.*

IMO MSC 76/23, 2002. "Resolution MSC.137 (76), Standards for Ship Manoeuvrability," Report of the Maritime Safety Committee on Its Seventy-Sixth Session-Annex 6

Kijima,K., Tanaka,S. Furukawa, Y. and Hori, T. 1993. On a Prediction Method of Ship Manoeuvring Characteristics/ // Proc. of MARSIM-93, Vol.1.

MAERSK SIRAC 2015. Sea Trial results. Hyundai Heavy Industries.

Pershitz R. Ya. 1983. Управляемость и управление судном. – *Л.: Судостроение*

Pipchenko A. D., Zhukov D. S. 2007. Development of the Ship Dynamics Model on the Basis of an Artificial Neural Network. *IAMU №5, Vol. 1. Tokyo. Japan, 2007*

Pipchenko O., Kopanskiy S., Shevchenko V. 2017. Refinement of an ultra large container vessel mathematical model based on the speed trials results. *Shipping & Navigation. NU OMA Research journal (2017) 27*

Pipchenko O., V. Shevchenko, 2018. Robust automatic ship heading controller for various conditions. *Marine Intellectual Technologies - Scientific journal № 4 (42) V.4*

Pipchenko O., Tsymbal M., Shevchenko V. 2018 Recommendations for Training of Crews Working on Diesel-Electric Vessels Equipped with Azimuth Thrusters. *TransNav – the International Journal on Marine Navigation and Safety of Sea Transportation. Vol. 12, Issue 3.*

T. Perez, M. Blanke, 2003. Mathematical Ship Modeling for Control Applications. *(Technical Report) DTU Technical University of Denmark.*

The Manouvering Committee. Final Report and Recommendations to the 24th ITTC, 2005.

Yasukawa H., Yoshimura Y. 2015. Introduction of MMG standard method for ship maneuvering predictions. *Journal of Marine Science & Technology* (2015) 20.

Yoshimura Y., Masumoto Y. 2012. Hydrodynamic database and manoeuvring prediction method with medium high-speed merchant ships and fishing vessels. *International MARSIM Conference. 2012.*