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.

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:

\[
\begin{align*}
(m + m_v)\dot{u}_G - (m + m_s)\dot{v}_G r_G &= X \\
(m + m_v)\dot{v}_G + (m + m_s)\dot{u}_G r_G &= Y \\
(I_Z + J_Z)\dot{r}_G &= N - x_G Y
\end{align*}
\]

(1)

where \(m\) – vessel displacement; \(m_v, m_s\) – added masses, \(I_v, I_s\) – moments of inertia, \(u_c, v_c, p_c, r_c\) – 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:

\[
\begin{align*}
X &= X_H + X_R + X_P \\
Y &= Y_H + Y_R + Y_P \\
N &= N_H + N_R + N_P
\end{align*}
\]

(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:

\[
X_H + m_s y_G r_G = \left( \frac{1}{2} \rho L d U ^2 \right) \times \left[ X_0 + X'_p \beta + (X'_{yr} - X'_{yG}) \beta' r + (X'_{yr} - X'_{yG}) \beta' r^2 + X'_{yG} \beta^4 \right]
\]

(3)

\[
Y_H - m_s x_G r_G = \left( \frac{1}{2} \rho L d U ^2 \right) \times \left[ Y'_{\beta} + (Y'_{yG} - Y'_{y}) \beta' r + Y'_{yG} \beta^2 r^2 + Y'_{yG} \beta^2 r^2 + Y'_{yG} \beta^2 r^2 + Y'_{yG} \beta^2 r^2 \right]
\]

(4)

\[
N_H = \left( \frac{1}{2} \rho L d U ^2 \right) \times \left[ N'_{\beta} + N'_{\beta} \beta + N'_{\beta} \beta^2 r + N'_{\beta} \beta^2 r + N'_{\beta} \beta^2 r + N'_{\beta} \beta^2 r \right]
\]

\[
X = X_H + X_R + X_P
\]

\[
Y = Y_H + Y_R + Y_P
\]

\[
N = N_H + N_R + N_P
\]

where \(\rho\) – water density, \(\beta\) - drift angle, positive to port side; \(X_0, X_{\beta}, X_{\beta\beta}, X_{y}, X_{\beta\beta}, Y_{\beta}, Y_{y}, Y_{\beta\beta}, Y_{\beta\beta}, Y_{\beta\beta\beta}, Y_{\beta\beta\beta}, N_{\beta}, N_{\beta\beta}, N_{\beta\beta\beta}, N_{\beta\beta\beta}, N_{\beta\beta\beta\beta}\) – resistance forces coefficients.

Figure 1. Coordinate system for ship movement modelling

\[
X_p = (1 - t_p) \cdot T;
\]

(4)

\[
T = \rho \cdot n_p^2 \cdot D_p^4 \cdot K_T (J_p);
\]

(5)

\[
J_p = \frac{u(1 - w_p)}{n_p D_p},
\]

where \(T\) – thrust force created by propeller can be calculated as:

\[
K_T (J_p) = k_0 + k_1 \cdot J_p + k_2 \cdot J_p^2;
\]

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

$$X_r = -(1-t_r) F_N \sin \delta$$
$$Y_r = -(1+a_r) F_N \cos \delta$$
$$N_r = -(x_R + a_H x_R) F_N \cos \delta$$

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

$$FN = \frac{1}{2} \rho A_R U_k^2 f_a a_R,$$

where $A_R$ – rudder area, $U_k$ – 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length, m</td>
<td>300</td>
</tr>
<tr>
<td>Length between perpendiculars, L, m</td>
<td>287</td>
</tr>
<tr>
<td>Breadth of vessel, B, m</td>
<td>48.2</td>
</tr>
<tr>
<td>Draught (mean / maximum) at load, d, m</td>
<td>12.5/15.0</td>
</tr>
<tr>
<td>Forward draught at trials, m</td>
<td>4.02</td>
</tr>
<tr>
<td>Aft draught at trials, m</td>
<td>10.16</td>
</tr>
<tr>
<td>Propeller diameter, Dp, m</td>
<td>9.7</td>
</tr>
<tr>
<td>Block coefficient (ballast), Cb</td>
<td>0.6044</td>
</tr>
<tr>
<td>Wet surface area, Q, m²</td>
<td>11656</td>
</tr>
<tr>
<td>Midship section plane coefficient, CM</td>
<td>0.9735</td>
</tr>
<tr>
<td>Rudder area, A_R, m²</td>
<td>78.95</td>
</tr>
</tbody>
</table>

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

$$\dot{u} = \frac{(1-t_r) \cdot \rho \cdot n_r^2 \cdot D_p^4 \cdot K_r \cdot (J_r) \cdot n_r \cdot \left| n_r \right|}{m + m_r}.$$

(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 $t_r$ and $n_r$ can be defined using approximate formulas:

$$t_r = 0.325 \cdot C_b - \frac{0.1885 \cdot D_p}{\sqrt{B \cdot d}};$$
$$w_r = 0.5C_b - 0.05.$$

Coefficients of the $J_r$ 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 $K_r$ and advance ratio $J_r$ coefficients formulas when negative revolutions are set, the thrust coefficient can gain incorrect value. This is because the $J_r$ 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:

$$\dot{T} = \rho \cdot D_p^4 \cdot K_T \cdot J_r \left( \frac{u}{n_r D_p} \right) \cdot \left| n_r \right|;$$

(9)

$$J_r = \left| \frac{u(1-w_r)}{n_r D_p} \right|.$$

(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:

$$Z = \frac{1}{N} \sum_{n=1}^{N} \left| U_{n2} - U_{n1} \right|,$$

(11)

where $U_1$ – 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 = \frac{\sum_{i=1}^{N} |U_{r_i} - U_{s_i}|}{N} + \frac{\sum_{i=1}^{N} |U_{s_{r_i}} - U_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |U_{r_{r_i}} - U_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |U_{s_{r_i}} - U_{s_{r_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
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\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}|}{N} + \frac{\sum_{i=1}^{N} |D_{r_{s_i}} - D_{s_{s_i}}|}{N} + \\
\frac{\sum_{i=1}^{N} |D_{r_{r_i}} - D_{s_{r_i}}}
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 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

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

Coefficients before and after adjustment / difference %

<table>
<thead>
<tr>
<th>$X_{\beta}$</th>
<th>$X_{\beta'}$</th>
<th>$X_{\gamma}$</th>
<th>$X_{\gamma'}$</th>
<th>$Y_{\beta}$</th>
<th>$Y_{\beta'}$</th>
<th>$Y_{\gamma}$</th>
<th>$Y_{\gamma'}$</th>
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<th>$Y_{\beta\beta'}$</th>
<th>$Y_{\gamma\gamma}$</th>
<th>$Y_{\gamma\gamma'}$</th>
<th>$Y_{\beta\gamma}$</th>
<th>$Y_{\beta\gamma'}$</th>
<th>$Y_{\gamma\beta}$</th>
<th>$Y_{\gamma\beta'}$</th>
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<tr>
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<td>0.3099</td>
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<td>0.6323</td>
<td>0.7173</td>
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<td>-0.1531</td>
<td>-0.00069</td>
<td>0.47811</td>
<td>0.1044</td>
<td>0.1795</td>
</tr>
<tr>
<td>0.318</td>
<td>0.27</td>
<td>0.031</td>
<td>0.067</td>
<td>0.00068</td>
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<td>0.1044</td>
<td>0.1795</td>
<td>0.0088</td>
<td>-0.2617</td>
<td>-0.1531</td>
<td>-0.00069</td>
<td>0.47811</td>
<td>0.1044</td>
<td>0.1795</td>
</tr>
</tbody>
</table>

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

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