Modelling of Close Proximity Manoeuvres in Shallow Water Channels

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ABSTRACT: An offline simulation code is developed to take into account ship to ship and ship to bank interaction forces in close proximity manoeuvres in access channels and harbour zones. The influence of squat effect on the interaction forces developed between ships is considered by taken into account semi-empirical regressions that considers water depth to draught ratios obtained from tank tests. At same time influence of interaction in squat is accounted considering additional blockage effects. The calculated forces comes as an input on the manoeuvring dynamic equations of free-surface vessels. Trajectories can be analysed and some rudder actions are studied to overcome the interaction forces and avoid collisions.

1 INTRODUCTION

A vessel spent most part of its lifetime navigating in deep waters and normally naval architecture analysis are mainly devoted to investigate ship behaviour on that operational profile. In recent years the increase both in vessels sizes and word fleet added to the intensification of use of marine resources (mainly with offshore platforms, wind farms, among others) imposed a scenario which management of traffic becomes very important duty and restricted waters are becoming shallower compared to the vessels size. This situation is even especially true in Europe where collisions and groundings represented 71% of accidents (EMSA, 2011).

With the increase in traffic and associated increased collisions and groundings, a major challenge for the ship course stability and manoeuvring capabilities becomes the interaction phenomenon. A huge variety of interactions configurations takes place on ship operational life meanwhile the main ones are:

- Ship assisted by tugs.
- Encounters between ships.
- Overtaking (including as a subclass vessel passing moored ship)
- With bottom and lateral channel boundaries.

In order to avoid collisions and groundings, the accurate prediction of interaction forces and moments gains importance. In the past, normally those phenomena are studied separately but nowadays many authors are accounting for the coupling of ship to ship and boundaries interactions (mainly bottom) increasing the refinement of the models.

For predicting interaction forces and moment, different techniques can be used:

- Empiric and semi-empiric methods.
- Potential flow methods disregarding free-surface effects i.e. accounting for only inertial hydrodynamic loads.
- Theoretical and numerical methods, accounting for free-surface and possibly viscous effects.

Bottom and bank interaction phenomenon solely will be detailed first and then it will be commented the ship to ship interaction.

1.1 Bottom and Bank Interaction

Bottom Interaction (Squat) is the decrease in under-keel clearance caused by vessels forward motion. The physical consequences of squat on a vessel is the presence of sinkage and trim.

The main experimental regression formulas available on the literature are given by Barrass (1979), and Millward (1990). More recent studies are developed by Gourlay (2014), who studied the problem using slender body theory, and Varyani (2006b) who revisited formulations using Bernoulli equation and division of the hull in strips given by Dand & Ferguson (1973). The main parameters can be listed as hull geometry, depth related Froude number, depth do draft ratio, presence of flow asymmetry like near bank and blockage factors (Ship cross section versus channel cross section).

Regarding bank interaction, one of the main parameters in the interaction is the speed (interaction forces and moments varying with the square of this
value). In certain point of the ship speed a long bow wave is generated between the bank and the ship generating a high pressure region there and thus in that case the attraction transform in repulsion. The speed point where this happen depends on water depth and proximity to the bank. Additionally, increase in bank proximity and decrease in depth increases the interaction. Banks in different size and geometry can also be considered as a variable.

Norrbin (1985) tested vertical and sloped long banks configurations varying the ship bank distance and forward speed. At the end proposed regressions formulas to deal with the forces and moments generated due to interaction. The regressions model developed by Norrbin (1985) will be detailed on section 4.1 and will be used inside offline simulation model. Vantorre, et al., (2003) analysed the situation of vertical, long bank experimentally varying ship models used, ship bank distance, water depth ratio, forward speed and the propeller action parameter. Finally, the author proposes regression formulas to deal with the interaction forces and moments involved.

1.2 Ship to Ship Interaction

Empiric and semi-empiric methods are one of the most fundamental methods since it is normally attempted to have greater flow similarity regarding a full-scale situation. Additionally, all the numerical methods depends on tank tests to be validated. Models studied could be equipped with propeller and rudder. The fact that the experiments normally requires a second carriage or some special tank arrangement imposes difficulties since there are few facilities in the world that possesses such capabilities.

The data recording of the tests enables the construction of models that could run inside of simulators and predict interaction forces and moments. Normally, the data acquisition has also limited capabilities and the consequences of that will be analysed further.

In fact, this is the most expensive and time consuming methods, due to the fact that inside just one interaction mode comes into play a large number of parameters that needs to be taken into account on experimental design. To overcome that, experiments focus their attention on just a limited number of interaction modes and parameters. The experiments are performed keeping certain fixed parameters while varying a specific one around an interest range of values and recording the time dependent interaction forces and moments values. From that it is developed a set of regression formulas regarding the parameters considered. The normal parameters taken into account are longitudinal relative positions, lateral separation, speed of the vessels, water depth to draft ratio and geometrical parameter of the vessels involved.

One well-known set of regressions was developed by Brix (1993). The author developed regression formulas for predicting forces in overtaking manoeuvres calibrated in terms of tank tests. The method accounts for all the horizontal forces and moment components but is applicable only on small ratio between ship sizes and in deep water. Vantorre et al. (2002) developed a set of regressions formulas for the surge, sway force and yaw moment peak values in encounter and overtaking (including when one of the vessels has zero velocity). The regressions takes into account the under keel clearance, separation and speed ratios between ships. Also uses different size and ship types in the evaluation.

Gronarz (2006) studied the interaction between vessels in encounter and overtaking at inland waterways. Different vessel types are used and with different main dimensions. Separation distances and velocities ratios are varied. Special attention is devoted to the data acquisition of sinkage and trim during the interaction transient which normally is not recorded on interaction tests but still important. Gronarz (2011) proposed new algorithms that could solve the problem of the maximum generated number of peaks that commonly appear when using regular regression equations with smaller vessel overtaking a larger one.

Within the same effort of interaction calculations Varyani et al. (2002) uses discrete vortex distribution numerical technique and slender body theory performing parametric variations of water depth, ship size, speed and separation distance to obtain new regression models for maximum peaks of sway forces and yaw moments for encounter and overtaking. It was also developed new generic models using the numerical results capable to estimate the transient behaviour of ship during the entire manoeuvre. Varyani et al. (2003) studied and validated the moored passing ship model against tank test results showing good agreement. The complete generic model was presented in Varyani (2006a) where encounter, overtaking (including ship passing moored ship) were presented. The generic equations model proposed by Varyani (2006a) will be implemented inside the offline simulation code in the present paper.

In order to overcome time and cost demanding experimental tests, some authors propose the use of the potential flow methods. These methods are dependent on a rather strong assumption that the potential zero-Froude-number interaction dominates over interaction caused by wave making or viscosity. There are strong reasons to believe that in many situations the main part of the interaction is captured by inertial hydrodynamic forces described by double-body potential flows (statement known as the Havelock Hypothesis). Earlier contributions were dealing with simple geometries like spheres or ellipsoids. For instance, a group of publications was based on using the slender body theory and matched asymptotic expansions.
2 DESCRIPTION OF THE MANOEUVRING MATHEMATICAL MODEL

2.1 Reference frame coordinate system

The reference frame coordinate systems comprise two reference coordinate systems: one attached to each vessel and other common to all the vessels (earth fixed reference system). Figure 1Figure 2 and Figure shows common situation of ship fixed reference coordinate system regarding each manoeuvre analysed. Earth fixed coordinate system will be positioned at the centreline of channel at its mouth. The equations of motion presented on next section will be solved for each vessel involved on the manoeuvre.

2.2 Equations of motion

The dynamic equations of motion (1) are organized in such a way that acceleration derivative force coefficients are presented on the left hand side as added masses (µ₁₁, µ₂₂, µ₂₆ and µ₆₆) and quasi-steady forces and moment (Xₕ, Yₕ, Nₕ), interactions forces and moment (Xₛ, Yₛ, Nₛ) and propeller thrust (Xₚ) on the right hand side. Additionally, m is the mass of the ship, xₙ and Izz are the longitudinal position of the centre of gravity and moment of inertia referred to the ship fixed coordinate system respectively. u, v, r are the state variables surge, sway velocities and yaw rate respectively, referred to the ship fixed reference coordinate system. The upper dot signs on top of that variables refers to their related accelerations.

Equations 2 presents the kinematics of the 3DOF model where ξₑ, ηₑ, ψₑ are the state variables advance, transfer and heading of the ship related to earth fixed coordinate system. The rudder angle δₑ will complete the definition of each ship state vector. Each pair of equation (1 and 2) must be solved for each vessel that is interacting.

\[
\begin{align*}
(m + \mu_{11})\ddot{u} - mvr - mx_g\dot{r}^2 &= X_q + X_p + X_s, \\
(m + \mu_{22})\dot{v} + (mx_g + \mu_{26})\dot{r} &= Y_q + Y_s, \\
(mx_g + \mu_{26})\dot{v} + (I_{zz} + \mu_{66})\dot{r} + mx_gur &= N_q + N_s, \\
\dot{\xi}_e &= u \cos\psi - v \sin\psi, \\
\dot{\eta}_e &= u \sin\psi + v \cos\psi \\
\psi_e &= r.
\end{align*}
\]

For the equation solutions, the model is adjusted to achieve the Cauchy form where only the variables derivatives terms are isolated in the left hand side and
each equation could be solved using discrete numerical integration methods for each time step. In the present code, Euler method was implemented in order to solve the equations due to its simplicity, provision of the required accuracy and more computational speed for the properly chosen time step.

Quasi-steady forces and moments, the propeller and rudder model will be commented on the next sections. The terms \( x, y, n \) related to the interaction forces and moments will be explained on the next separate chapter.

2.3 Quasi-steady forces and moments on the hull

The quasi-steady forces and moments are calculated as a function of its respective non-dimensional coefficients:

\[
X_q = X_q \frac{\rho v^2}{2} L T, \quad Y_q = Y_q \frac{\rho v^2}{2} L T, \quad N_q = N_q \frac{\rho v^2}{2} L^2 T;
\]

(3)

Where \( \rho \) is the water density, \( \sqrt{u^2 + v^2} \) , \( L \) is the length of the ship, \( T \) is its draught at the midship. The non-dimensional forces and moments coefficients \((X_q', Y_q', N_q')\) are calculated by a Taylor Multivariate Expansion approach regarding the non-dimensional kinematic parameters:

\[
u' = \frac{u}{v}, \quad v' = \frac{v}{v}, \quad r' = \frac{rL}{v}
\]

(4)

In the present model it will be used Taylor expansions until the cubic order. The manoeuvring coefficients considered and the computation of the related quasi-steady forces and moments are given by:

\[
X_q' = X_{quu} u'^2 + X_{quv} v' r' + X_{qu\delta} \delta_R^2,
\]

\[
Y_q' = Y_{qu} + Y_{qv} v' + Y_{qrr} r'^2 + Y_{qvv} v'^2 r' + Y_{q\delta} \delta_R + Y_{qv\delta} v'^2 \delta_R + Y_{q\delta R} v' \delta_R^2,
\]

(5)

\[
N_q' = N_{qu} + N_{qv} v' + N_{qrr} r'^2 + N_{qvv} v'^2 r' + N_{q\delta} \delta_R + N_{qv\delta} v'^2 \delta_R + N_{q\delta R} v' \delta_R^2 + N_{q\delta\delta} \delta_R^2
\]

where each hydrodynamic coefficient \((X_{quu}', \ldots, N_{q\delta\delta}')\) is calculated by multiplying the original coefficients, taken from mariner vessel, by trim correction, water depth dependency and adjustment coefficients. The added masses are calculated by:

\[
\mu_{11} = k_{11} m; \quad \mu_{22} = k_{22} m; \quad \mu_{66} = k_{66} m; \quad \mu_{26} = \mu_{22} x_G;
\]

(6)

\[
k_{11} = 0.5 \frac{T}{L}; \quad k_{22} = 2 \frac{T}{B} \left(1 - \frac{0.5B}{L}\right); \quad k_{66} = \frac{2T}{B} \left(1 - \frac{1.6B}{L}\right);
\]

2.4 Propeller and rudder model

For the propeller force computation, it is used the propeller 4th quadrant approach instead of the normal B series approach knowing some regression coefficients of the specific propeller curve.

Additionally to the hull dynamics and propeller, it was implemented the dynamic of the rudder. \( \delta_R \) is the state variable actual rudder angle and \( \delta^* \) the rudder order and it was formulated a time dependant expression for the rudder to achieve the desired angle from the actual one. Non-linearities included are dead-band zone \( \delta_0 \), rudder angle saturation \( |\delta_R| \leq \delta_m \) and rudder turn rate saturation \( |\dot{\delta}_R| \leq \epsilon_m \).

3 REGRESSION MODELS OF INTERACTION FORCES AND MOMENTS

The simulation code developed in this study uses data for three different types of manoeuvres in a channel or harbour area:

- Ship passing bank manoeuvre
- Encounter manoeuvre
- Overtaking manoeuvre

The models used were developed by Norbin(1985) and Varyani (2004). The sign convention adopted is presented in the next figures for the ship passing near bank, encounter and overtaking manoeuvres.

Figure 1. Ship passing bank right hand coordinate system and positioning of the bank regarding the vessel.
For each simulation case study, it was assumed a ship well known from the literature and that also possess all the manoeuvring coefficients needed to input in the model, the mariner vessel class. Dimensions of the Ship 1 are shown in next table. Ship 2 was chosen to have the same dimensions of Ship 1. It is also assumed that the channel or harbour area is very wide compared to ships greater breadth ($W_{channel} \geq 10B_{max}$) involved so that there was no need to account possible ship bank interactions on top of ship to ship interaction. It was not computed any related surge interaction forces due to the fact that it was not described surge related generic equations by Varyani (2004). Therefore it will be assumed that the vessel is able to overtake the additional resistance varying the propeller rotations.

Table 1. Mariner Class main dimensions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>120.0</td>
<td>m</td>
</tr>
<tr>
<td>$B$</td>
<td>26.0</td>
<td>m</td>
</tr>
<tr>
<td>$T$</td>
<td>8.7</td>
<td>m</td>
</tr>
<tr>
<td>$C_b$</td>
<td>0.7</td>
<td>[-]</td>
</tr>
</tbody>
</table>

3.1 Squat model

Barrass (1979) proposes a set of equations to deal with squat situations both in open and confined waters for a ship navigating in the last case on the Neutral Steering line.

$$z_{max} = \frac{C_b}{30} \left( \frac{S}{1 - S} \right)^{0.81} (0.514V)^{2.08}$$  \hspace{1cm} (7)

where:

- $z_{max}$ is the maximum sinkage with the maximum location dependent on the value of $C_b$:
  - If $C_b > 0.700$ trim by the bow.
  - If $C_b < 0.700$ trim by the stern.
  - If $C_b = 0.700$ no trim occur.

$V$ is the ship velocity in m/s, $C_b$ is the block coefficient and $S$ is the blockage factor calculated by the ratio between the sectional midship area of the ship ($BT$) and waterway sectional area ($WH$).

For low blockages around 0.100 and 0.265 even simpler formula can be used disregarding the blockage term and considering $C_b$ divided by 50 instead.

3.2 Ship passing near the bank model

For the ship passing bank manoeuvre it was not found on the literature a regression that simulates transients on the ship passing bank interaction (short bank regression) despite some physical effects are known. Thus, the long bank approach was used to simulate ship passing bank interaction derived by Norbin (1985) using the following relations to compute the forces considering a vertical bank (slope factor ($k$) equal to zero):

$$Y_{B_{k=0}} = 0.0926 + 0.372 \left( \frac{T}{H} \right)^2 FN_t^2 \eta_0$$

$$N_{B_{k=0}} = -0.0025 + 0.0755 \left( \frac{T}{H} \right)^2 FN_t^2 \eta_0$$  \hspace{1cm} (8)

where $\eta_0 = B/(W_{0s} - y_0)$ and $FN_t = V/(\sqrt{gL})$ defined by the common Froude number. $W_{0s}$ is the half width of the channel, $y_0$ is the offset from the ship centreline to the fairway centreline and $B$ is the breadth of the ship that can be shown on the next picture.

And then it was used the correction terms to account for a sloped bank:
\[ Y'_B = Y''_B = \left\{ 1 + 0.377\eta_0 k + 19.53u'' k + 0.0673k^3 - 0.0988(T/H)k^3 \right\} \]
\[ N'_B = N''_B = \left\{ 1 - 0.750\eta_0 k + 81.8u'' k + 0.0331k^3 + 0.0195(T/H)k^3 \right\} \]  
\( (9) \)

Where the bank slope is defined by \( 1: k \) and so \( k = 0 \) reduces to vertical bank case. It is also important that the separation parameter is now limited to the configuration of the sloped bank \( \eta_{0,\max} = 2(1 + 2k/(B/T)). \)

The final values of interaction force and moment will be somewhat different than usual due to the type of non-dimensional operation performed:

\[ Y_s = Y''_s \rho g \nabla \]
\[ N_s = N''_s \rho g \nabla L \]  
\( (10) \)

3.3 Encounter and overtaking models

The staggering (ST, from now on called \( \xi' \)) will be calculated as:

\[ \xi' = \frac{2(x_{G_b} + x_{G_d})}{L_1 + L_2}, \text{ (for encounter)} \]
\[ \xi' = \frac{2(x_{G_b} - x_{G_d})}{L_1 + L_2}, \text{ (for overtaking)} \]  
\( (11) \)

Thus the staggering (\( \xi' \)) is non-dimensionalized such that the values -1, 0, +1 correspond to bow-bow, midship-midship and stern-stern situations on encounter and bow-bow, midship-midship, stern-bow in overtaking. The non-dimensional sway force and yaw moment coefficients are expressed as:

\[ C_{yi} = \frac{Y_i}{\frac{1}{2} \rho V_1 V_2 B_i T_i} \]
\[ C_{ni} = \frac{N_i}{\frac{1}{2} \rho V_1 V_2 B_i T_i L_i} \]  
\( (12) \)

where \( i \) can be 1 or 2 related each coefficient to each ship.

3.3.1 Encounter model

For the encounter manoeuvre, the parametric variation performed was:

<table>
<thead>
<tr>
<th>( H/T )</th>
<th>1.2, 1.3, 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8, 2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.8, 0.9, 1.0, 1.2, 1.5</td>
</tr>
<tr>
<td>0.5, 1.0</td>
<td></td>
</tr>
<tr>
<td>1.5, 1.7, 1.9, 2.2</td>
<td></td>
</tr>
<tr>
<td>0.2, 0.25, 0.3, 0.4, 0.5</td>
<td></td>
</tr>
</tbody>
</table>

The maximum coefficients of sway force and yaw moment for encounter manoeuvre are calculated by:

\[ C_Y = -0.47 \cos(-0.86\pi \xi') e^{-0.95\xi'^2}(1) \]
\[ -0.18\xi') \left[ H \frac{T}{1.5} \right]^{-2.25} \left[ 2 \frac{S_p}{L} \right]^{-1.25} \left[ \frac{L_1}{L_2} \right]^{-2.25} \left[ \frac{1}{2} u_2 + 1 \right] \]  
\( (13a,b) \)

\[ C_N = 0.15 \cos(-0.86\pi \xi') e^{-0.95\xi'^2}(1 - 0.18\xi') \]
\[ + \Delta A(\xi') \left[ H \frac{T}{1.5} \right]^{-2.25} \left[ 2 \frac{S_p}{L} \right]^{-1.25} \left[ \frac{L_1}{L_2} \right]^{-2.25} \left[ \frac{1}{2} u_2 + 1 \right] \]

Table 3. Values of filter parameters to be used in equation 13b.
\[ \begin{array}{cccccc}
H/T_m & S_p/L & L_1/L_2 & U_2/U_1 & \xi'_a & \Delta \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.30 & 0.01 & -0.75 & -0.50 & 0.01 & 0.10 \\
0.01 & 0.10 & -0.10 & -0.00 & 0.01 & 0.10 \\
0.40 & 0.02 & -0.75 & -0.50 & 0.01 & 0.10 \\
\end{array} \]

3.3.2 Overtaking model

For the overtaking manoeuvre, the parametric variation performed was:

<table>
<thead>
<tr>
<th>( H/T )</th>
<th>1.2, 1.3, 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8, 2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.7, 0.8, 0.9, 1.0</td>
</tr>
<tr>
<td>0.12</td>
<td>2.0</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.5, 2.0, 2.5</td>
</tr>
<tr>
<td>0.2, 0.25, 0.3, 0.4, 0.5</td>
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</tr>
<tr>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>0.4, 0.5, 0.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Overtaking manoeuvre parametric variation.

3.3.2.1 Faster Ship 1 generic equations

The maximum coefficients of sway force and yaw moment are calculated by:

\[ \begin{array}{cccc}
H/T & L_1/L_2 & U_2/U_1 & Sp/L \\
1.2, 1.3, 1.5 & 1.0 & 2.0 & 0.5 \\
1.8, 2.0 & 0.7, 0.8, 0.9, 1.0 & 2.0 |
| 0.5 |
| 1.5 | 1.5, 2.0, 2.5 |
| 0.2, 0.25, 0.3, 0.4, 0.5 |
| 1.5 | 2.0 |
| 0.4, 0.5, 0.7 |
\]
\[ C_{V_1} = -0.11 \sin(-0.49\pi(\xi' + 0.37)) e^{-0.95\xi'^2} \]
\[ -0.98\pi^2 \left( \frac{H}{T} \right)^{-2.2} \left[ 2 \frac{S_p}{L} \right]^{-1.3} \left[ \frac{L_1}{L_2} \right]^{-0.35} \left[ \frac{3 U_1}{2 U_2} - \frac{1}{2} \right] \]
\[ C_{N_1} = -0.1 \sin(-0.49\pi(\xi' + 0.07)) e^{-0.95\xi'^2} \]
\[ -0.3\xi' A(\xi') \left( \frac{H}{T} \right)^{-1.8} \left[ 2 \frac{S_p}{L} \right]^{-1.0} \left[ \frac{L_1}{L_2} \right]^{-1.5} \left[ 3 U_1 - \frac{1}{2} \right] \]

Table 5. Values of filter parameters to be used in equation 14b.

<table>
<thead>
<tr>
<th>Const. for</th>
<th>a</th>
<th>b</th>
<th>( \xi'^0 )</th>
<th>( \Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H/T_m )</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>( S_p/L_m )</td>
<td>0.30</td>
<td>0.01</td>
<td>-0.75</td>
<td>-0.50</td>
</tr>
<tr>
<td>( L_1/L_2 )</td>
<td>0.01</td>
<td>0.10</td>
<td>-0.10</td>
<td>-0.01</td>
</tr>
<tr>
<td>( U_2/U_1 )</td>
<td>0.40</td>
<td>0.02</td>
<td>-0.75</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

3.3.2.2 Slower Ship 2 generic equations

The maximum coefficients of sway force and yaw moment are calculated by:

\[ C_{V_2} = -0.23 \cos(-0.49\pi\xi') e^{-0.95\xi'^2} \]
\[ -0.18\pi^2 \left( \frac{H}{T} \right)^{-2.2} \left[ 2 \frac{S_p}{L} \right]^{-1.3} \left[ \frac{L_1}{L_2} \right]^{-0.35} \left[ \frac{3 U_1}{2 U_2} - \frac{1}{2} \right] \]
\[ C_{N_2} = 0.34 \sin(-0.65\pi(\xi' - 0.05)) e^{-1.5\xi'^2} \]
\[ -0.18\pi^2 A(\xi') \left( \frac{H}{T} \right)^{-2.2} \left[ 2 \frac{S_p}{L} \right]^{-1.3} \left[ \frac{L_1}{L_2} \right]^{-0.35} \left[ \frac{3 U_1}{2 U_2} - \frac{1}{2} \right] \]

Table 6. Values of filter parameters to be used in equation 15b

<table>
<thead>
<tr>
<th>Const. for</th>
<th>a</th>
<th>b</th>
<th>( \xi'^0 )</th>
<th>( \Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H/T_m )</td>
<td>0.65</td>
<td>0.27</td>
<td>-0.50</td>
<td>-0.01</td>
</tr>
<tr>
<td>( S_p/L_m )</td>
<td>0.65</td>
<td>0.20</td>
<td>-0.50</td>
<td>-0.01</td>
</tr>
<tr>
<td>( L_1/L_2 )</td>
<td>0.67</td>
<td>0.22</td>
<td>-0.50</td>
<td>-0.01</td>
</tr>
<tr>
<td>( U_2/U_1 )</td>
<td>0.70</td>
<td>0.15</td>
<td>-0.50</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

4 SIMULATION RESULTS

On the following sections, it will be commented configurations regarding simulation general parameters, initial conditions of ship(s) and interaction parameters of each manoeuvre. After that, results concerning each manoeuvre will be presented and commented.

The concerning results are interaction forces and moments acting on the ship(s) versus non-dimensional stagger and the trajectory of the ship(s).

4.1 Ship passing near bank

4.1.1 Preliminary study

A simulation time of 16.66 minutes was performed with integration step of 0.05s.

Figure 5 shows the overall expected effect of a bank modelled using Norbin regression equations. A suction force and a bow out moment are noticeable. It can be seen from the trajectory plot (Figure 6) that a collision happens with other side bank if no countermeasures are taken. Also the bow out effect is even not noticeable due to the quasi-steady yaw moment that counter reacts it.

![Figure 5](image_url) Interaction forces and moments acting on the ship passing bank manoeuvre.

![Figure 6](image_url) Vessel trajectory without control.

Another possible cause of problems in manoeuvre is due to grounding associated with squat. As commented before, the formula used here for squat doesn’t account for the influence of the asymmetric flow due to bank and thus a conservative margin must be present. Next figure shows the overall evolution of the maximum sinkage. The first seconds must be disregarded since it was applied to the model suddenly...
the depth restriction and doesn’t represent the real dynamic reality. After the transient, it can be seen that maximum sinkage calculated was around 0.4 m. This results in a value around 1.5 m of underkeel clearance for the present study and thus giving margin for the added sinkage due to the flow asymmetry.

4.1.2 Ship passing near bank with control
A simple PD control in the yaw angle and rate of yaw is applied in the same simulation conditions defined on the previous action. It can be seen that now the vessel is following the straight path despite the action of interaction force and moment.

4.2 Encounter Manoeuvre
The simulation time will be configured as 8.3 minutes with integration time step of 0.5 seconds. The real interaction time is even short than the chosen simulation time. But it was used a larger simulation time in order to give the needed time to stabilize the ships in the straight path before interaction takes place don’t mixing the transients. The initial conditions on ship 1 and 2 are presented in Table 7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u) (m/s)</td>
<td>5.0</td>
</tr>
<tr>
<td>(n) (rps)</td>
<td>1.0</td>
</tr>
<tr>
<td>(v) (m/s)</td>
<td>0.0</td>
</tr>
<tr>
<td>(r) (rad/s)</td>
<td>0.0</td>
</tr>
<tr>
<td>(X_g) (m)</td>
<td>800</td>
</tr>
<tr>
<td>(Y_g) (m)</td>
<td>120</td>
</tr>
<tr>
<td>(\Psi) (rad)</td>
<td>(\pi)</td>
</tr>
<tr>
<td>(\delta) (rad)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The interaction parameters are presented in Table 8. They are stated in such a way that \(A(\xi')\) parameters used on its formula will be referred to \(H/T\) non-standard experimental value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H/T)</td>
<td>1.2</td>
</tr>
<tr>
<td>(L_1/L_2)</td>
<td>1.0</td>
</tr>
<tr>
<td>(U_2/U_1)</td>
<td>1.0</td>
</tr>
<tr>
<td>(Sp/L)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 9 shows the evolution of interaction forces as a function of the stagger. Despite there isn’t restriction on the sway motion imposed in the model, as can be seen in Figure 10, the qualitative behaviour of the evolutions seems similar to Varyani (2009) and also Vantorre (2002) for the sway interaction forces with two peaks of repulsion in the bow-bow stern-stern positions and one large suction on midship midship alignments.
Figure 10. Vessels trajectory in encounter manoeuvre without control.

Regarding yaw interaction moments, the qualitative behaviour appears similar to Vantorre (2002) and almost similar to Varyani (2006) results just not completely similar due to the smaller hollow and peak on larger relative distances not shown in Varyani graphs. Physically, the ship experience a large bow out moment followed by smaller bow in, again even smaller bow out passing midship-miship position and finally another bow in. Due to the disturbance forces the vessel is positioned in such a way that develops quasi-steady hydrodynamic forces and moments that acts in anti-phase with the interaction forces. When ceased the interaction forces and moments the quasi steady forces continue acting but with very low values and thus an action of the helmsman must take place in order to put the ship in right place again.

4.3 Overtaking manoeuvre

4.3.1 Preliminary Study

The simulation time will be configured as 8.3 minutes with integration time step of 0.5 seconds. The real interaction time is even shorter than the simulation time. But it was used a larger simulation for the same reasons as explained in previous section. The initial conditions on ship 1 and 2 are presented in Table 9.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Ship 1</th>
<th>Ship 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u)</td>
<td>m/s</td>
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<td>5.0</td>
</tr>
<tr>
<td>(n)</td>
<td>rps</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>(v)</td>
<td>m/s</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>(r)</td>
<td>rad/s</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>(X_g)</td>
<td>m</td>
<td>-800</td>
<td>0.0</td>
</tr>
<tr>
<td>(Y_g)</td>
<td>m</td>
<td>120</td>
<td>0.0</td>
</tr>
<tr>
<td>(\Psi)</td>
<td>rad</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>(\delta)</td>
<td>rad</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The interaction parameters are presented in Table 10. They are stated in such a way that \(A(\xi')\) parameters used on its formula will be referred to \(H/T\) non-standard experimental value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H/T)</td>
<td>1.2</td>
</tr>
<tr>
<td>(L_1/L_2)</td>
<td>1.0</td>
</tr>
<tr>
<td>(U_2/U_1)</td>
<td>2.0</td>
</tr>
<tr>
<td>(Sp/L)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 11 and Figure 12 shows the interaction forces and moments as function of stagger and the trajectory of the ships respectively.

For the sway forces, it can be observed that the overtaken ship passes with three peaks and the overtaking passes in two. Also the overtaken ship experiences a larger time feeling the interaction. First the overtaken vessel is repelled then attracted and finally repelled again. The overtaking ship is firstly repelled and then attracted by the overtaken one.

For the yaw moment both vessels experiments first a bow out moment and after that a bow in moment. The last phase of the manoeuvre is in fact the most pronounced for the occurrence of a collision as can be seen in the trajectory plot.

Beside the risk of collision, ships also suffer from grounding originated from squat phenomenon and
maximum sinkage increased due to the additional blockage effect.

After the initial transient, it can be seen that maximum sinkage calculated was around 1.1 m for the vessel overtaking on the next figure. This value alone can represent dangerous one since coupling with asymmetric conditions due to near bank is not accounted. When starting the overtaking the situation even come worst and achieves around 2.7m when the vessels are with midship sections aligned. This situation in grounding knowing that the original draught was around 8.7m and the considered depth is 10.4 m.

4.3.2 Comparison between deep water and shallow interaction prediction models
A comparison study was performed in order to compare deep and shallow water behaviour given by regression formulas from Brix(1998) and Varyani(2006a) (from now on just called Brix and Varyani). The comparison will not be complete since Brix only analyses the forces and moments acting on the overtaken vessel. Also Varyani do not show surge interaction forces regression formulas and that Brix shows. Despite of that the comparison aims to verify a possible combination of surge formula in Brix with Varyani if the magnitudes and qualitative behaviour seems coherent between both models, then one could deal with a complete set of interaction formulas for the horizontal plane manoeuvre in shallow restricted waters didn’t found on the literature.

It will be assumed for the comparative study the same simulation parameters and initial conditions stated for in the previous subsection. Figure 14 shows Brix and Varyani interactions regression formulas results for sway forces and yaw moments. It can be seen a similar qualitative behaviour but similarities ends on that point, since the interaction in shallow water is greater than in deep water. The same happens with the yaw moment being greater when analysing the peak magnitudes.

5 CONCLUSIONS
A review of the literature was performed and experimental results translated in regression formulas are used to model close proximity manoeuvres. Intervals of use of those formulas and comparisons between different authors were pointed out. Three most common situations of access channels and harbour area manoeuvres was simulated. Vessels involved behaviours, interaction forces and moments, trajectories and squat are analysed. Interaction forces and moments plots shows good qualitative agreement with the presented literature despite the fact that motions of the ships are not restricted. Qualitative differences when exists are explained. Quantitative results still shows some discrepancy of the literature and this could be attributed to the fact that the motions was not restricted in the present model.

REFERENCES


