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# Study of ship-to-ship interaction in shallow water with account for squat phenomenon

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ABSTRACT: Appropriate prediction of hydrodynamic interaction between moving ship hulls is important for adequate simulation of ship manoeuvring motion. In addition, in shallow waters the dynamic sinkage and trim of ships also known as squat may occur. This can influence the hydrodynamic characteristics of the ship hull as well as the interaction forces. Most of existing mathematical models for the ship-to-ship interaction consider only motion in the horizontal plane ignoring the mentioned influence and the possible error is hardly conservative. The present contribution investigates that influence using empiric methods for estimating the squat and interaction forces and moments which are combined. A series of numerical studies have been carried out comparing interaction forces obtained with and without account for squat. The results have shown that although the coupling effects are detectable in most cases they can be neglected in practical estimations.

## 1 INTRODUCTION

The computerized ship handling simulators are now recognized as an indispensable tool for training human operators thus serving for increasing safety of navigation. The implemented mathematical models often account for the hydrodynamic interaction between ships passing by each other, say in busy ports areas but the squat is typically treated as an uncoupled phenomenon. However, it is evident that as the actual underkeel clearance may depend on the dynamic squat, the ship hydrodynamic characteristics and the interaction forces in the horizontal plane will be altered, most likely aggravating the interaction effects.

In course of several last years a method for predicting interaction forces based on the online double-body potential computations has been under development as described in Sutulo & Guedes Soares (2008), Sutulo et al. (2012) and Zhou et al. (2015). Potentially, this method can account for the dynamic squat. However, in that case the algorithm would become much more complicated and some preliminary estimation of the coupling effects is desirable. Such estimation, whose results are presented in this paper, was carried out on the basis of published empirical methods for both the squat and the interaction forces.

The paper starts with an overview of the literature on ship squat and hydrodynamic interaction which is followed by the description of an empiric mathematical model where both phenomena are treated as coupled. Numerical results demonstrating the effect stemming from that coupling are presented.

The ship squat is caused by the change in the pressure distribution over the hull due to the ship motion. In response to that, the ship sinks and trims finding new equilibrium in the vertical plane. This happens in both deep and shallow water but is more pronounced in the latter case (Varyani 2006b).

Simple empirical squat models are abundant in the literature and a comparison between them can be found in PIANC (1997). These models neglect many significant factors like the hull geometry details and can be only used for approximate estimation.

Some popularity was gained by a simplified theory originally proposed by Dand & Ferguson (1973) and based on the strip method. Modifications of the original theory could be performed adding correction factors based on experiments (Lataire et al. 2012) or basing on deeper investigation of certain local effects like the propeller action and 3D corrections (Varyani 2006b). That simplified theory is limited to the subcritical flow showing unrealistic estimates at higher values of the Froude number based on the depth $F_h$.

More recent theories aim at overcoming this limitation solving the shallow water equation for the various flow regimes (Tuck & Taylor 1970; Gourlay 2008) but the validation studies are still in progress for those methods.

Gronarz (2006) studied experimentally the interaction between vessels in encounter and overtaking manoeuvre in inland waterways. Different vessel types with various main dimensions were investigated. The experiments are performed varying the lateral separation distances and the ship velocities ratios. Special attention was devoted to the acquisition of data on sinkage and trim during the interaction transients.

Varyani (2006a) presented semi-empirical formulas for the interaction lateral force and moment in shallow water for the encounter and overtaking manoeuvres in parallel motion. The method is additionally providing responses for the interaction force and moment depending on the lateral distance and on the velocity ratio.

It is evident that the close proximity manoeuvres can influence the squat magnitudes due to stronger blockage effects. Gourlay (2009) analysed close-proximity manoeuvres coupled with squat having produced regression formulas predicting the maximum squat values.

In the present study, the interaction formulation from Varyani (2006a) is modified to account for the squat effect calculated using the method also proposed by Varyani (2006b). Results obtained by Gourlay (2009) who demonstrated back dependence of the squat on the interaction phenomenon were also taken into account.

## 2 MODEL DESCRIPTION

### 2.1 *Coordinate systems*

The right-hand earth fixed coordinate system $O\xi\eta\zeta$ is used, located in the undisturbed free surface with $\zeta$ pointing downwards and $\xi$ pointing in the same direction of the assumed ships parallel courses. It is connected to the earth fixed frame a coordinate system attached to each ship with the $y$ axis pointing starboard, longitudinal axis $x$ pointing forward and thus $z$ axis pointing downward.

### 2.2 *Ship squat model*

The method consists of three main steps:

1. Divide the hull into sections, finding free surface and flow rate by the solution of the Bernoulli and continuity equation on each section.
2. The dynamic pressure distribution is determined and is added to the primary hydrostatic distribution providing the dynamic equilibrium.
3. Corrections related to three dimensional effects are applied.

The continuity and the Bernoulli equation provide the values for non-dimensional free surface elevation $\tilde{\zeta}$ and longitudinal fluid velocity disturbance factor $u$:

$$u = \frac{US}{S_0\left(1 - F_h^2\right)}, \quad \tilde{\zeta} = \frac{-F_h^2 S}{S_0(1 - F_h^2)}, \tag{1}$$

where $U$ is the ship velocity, $S_0$ is the channel sectional area and $S$ is the hull sectional area. The free surface elevation is obtained by multiplying its non-dimensional value by the water depth $H$.

With the free surface elevation known for each station, the hull pressure distribution can be calculated and then the hull mean sinkage $s$ and trim $\theta$ can be determined:

$$s = \frac{I_w A_1 - M_w A_2}{M_w^2 - A_w I_w}, \quad \tan\theta = \frac{A_w A_2 - M_w A_1}{M_w^2 - A_w I_w}, \tag{2}$$

where $A_w$ is the water plane area, $M_w$ is the longitudinal static moment of this area, $I_w$ is its longitudinal moment of inertia and:

$$A_1 = \int_{-L/2}^{L/2} B(x)\zeta(x)\,\mathrm{d}x, \quad A_2 = \int_{-L/2}^{L/2} xB(x)\zeta(x)\,\mathrm{d}x. \tag{3}$$

The local sinkage $\sigma(x)$ is:

$$\sigma(x) = \mathrm{s} + x\tan\theta \tag{4}$$

### 2.3 *Interaction between ships with account for the squat*

The values of lateral interaction force and moment on each ship can be calculated by:

$$Y_i = \frac{1}{2}\rho Y_i' V_1 V_2 B_i T_i, \quad N_i = \frac{1}{2}\rho N_i' V_1 V_2 B_i T_i L_i, \tag{5}$$

where $V_{1,2}$ are the ships velocity, $Y_i'$, $N_i'$, $L_i$, $B_i$ and $T_i$ are the non-dimensional sway and yaw interaction coefficients, length, breadth and draught of the $i$th ship respectively.

The above formulas are not valid for the moored-passing ship situation when either $V_1$ or $V_2$ is zero.

The formulas to calculate the pair $Y_i'$, $N_i'$ are modified to consider the squat effect. This modification consists in replacing the static draught $T$ with the effective dynamic draught $T_{\mathrm{eff}}$:

$$T_{\mathrm{eff}} = T + s_{\max}, \tag{6}$$

where $s_{\max}$ is the maximum local dynamic sinkage normally located either at the bow or at the stern.

#### 2.3.1 *Interaction in the encounter manoeuvre*

The interaction coefficients of the sway force and yaw moment for the encounter manoeuvre are calculated by (Varyani 2006a):

$$\begin{aligned}(Y_i', N_i') = {} & k_1 \cos\left(-0.86\pi\xi'\right) e^{-0.95\xi'^2}\left(1 - 0.18\xi'\right) k_2 \\ & \times \left(\frac{H/T_{\mathrm{eff}}}{1.5}\right)^{-2.25} \left(2\frac{S_p}{L}\right)^{-1.25} \left(\frac{L_1}{L_2}\right)^{-2.5} \\ & \times \left(\frac{1}{2}\frac{V_2}{V_1} + \frac{1}{2}\right),\end{aligned} \tag{7}$$

where the non-dimensional instantaneous stagger $\xi'$ is:

$$\xi' = \frac{2\left(\xi_1 - \xi_2\right)}{L_1 + L_2} \tag{8}$$

Table 1. Parameters for the encounter case.

| Parameter | $Y'$ | $N'$ |
|---|---|---|
| $k_1$ | –0.47 | 0.10 |
| $k_2$ | 1.00 | $(\xi' + \Delta)\, A(\xi')$ |

Table 2. Parameters for overtaking case.

| | Sway | | Yaw | |
|---|---|---|---|---|
| Parameter | Ship1 | Ship2 | Ship1 | Ship2 |
| $a_1$ | 0.11 | 0.23 | 0.10 | 0.34 |
| $a_2$ | 0.49 | 0.49 | 0.49 | 0.65 |
| $a_3$ | 0.37 | 0.00 | 0.07 | -0.05 |
| $a_4$ | 0.00 | $\pi/2$ | 0.00 | 0.00 |
| $a_5$ | 0.95 | 0.80 | 0.90 | 1.50 |
| $a_6$ | 0.98 | 0.18 | 0.30 | 0.18 |
| $a_7$ | 1.00 | 1.00 | 1.00 | $A(\xi')$ |
| $a_8$ | 2.20 | 2.20 | 1.80 | 2.20 |
| $a_9$ | 1.30 | 1.30 | 1.00 | 1.30 |
| $a_{10}$ | 0.35 | 0.35 | 1.50 | 0.35 |

and $k_1, k_2$ are presented in Table 1. In the expression in that table $\Delta$ is a parameter and $A(\xi')$ is defined by:

$$A(\xi') = 1 - a e^{-b(\xi' - \xi_0' + \Delta)^2}, \tag{9}$$

where $a$, $b$, $\xi_0'$, $\Delta$ are 0.30, 1.40, $-0.50$, $-0.10$ respectively.

These parameters are taken from Varyani (2006a) and are adjusted for $H/T$ since it is aimed to study the squat influence.

### 2.3.2 *Interaction in the overtaking manoeuvre*

The interaction coefficients are (Varyani 2006a):

$$(Y_i', N_i') = -a_1 \sin\left[-a_2 \pi(\xi' + a_3) + a_4\right] e^{-a_5 \xi'^2} \times (1 - a_6 \xi') a_7 \left(\frac{H/T_{\text{eff}}}{1.5}\right)^{-a_8} \left(2\frac{S_p}{L}\right)^{-a_9} \times \left(\frac{L_1}{L_2}\right)^{-a_{10}} \left(\frac{3}{4}\frac{V_1}{V_2} - \frac{1}{2}\right), \tag{10}$$

where $A(\xi')$ is given by equation 9 and $a$, $b$, $\xi_0'$, $\Delta$ are 0.65, 0.27, $-0.50$, $-0.01$ respectively, for the overtaken ship.

These parameters are taken from Varyani (2006a) and are adjusted for $H/T$ as for the encounter manoeuvre. The values of $a_j$ are presented in Table 2.

## 2.4 *Influence of close-proximity manoeuvres on squat model*

The mean sinkage can be calculated, accounting for close-proximity manoeuvres, as:

$$s_{m,\max} = (1 + \varepsilon_m) s_{m,steady}, \tag{11}$$

where $s_{m,steady}$ is the value of mean sinkage calculated before close-proximity manoeuvre takes place, (calculated from the squat model in previous section), and

$$\varepsilon_m = \frac{V_1^2 \sqrt{1 - F_{h_2}^{\,2}}}{V_2^2 \sqrt{1 - F_{h_1}^2}} f_m \left( \frac{S_p \sqrt{1 - F_{h_1}^2}}{L_m} \right), \tag{12}$$

where $F_{h_1}, F_{h_2}$ is the depth Froude number of the overtaking and the overtaken ships respectively and $f_m$ is a result of fitting against the last term is parenthesis in the previous expression. The fitting was performed both for a containership and a bulk carrier hull forms giving the regression expression:

$$f_m(\eta) = \frac{1}{2.2 + 9.4\eta^2}, \tag{13}$$

where $\eta = S_p \sqrt{1 - F_{h_1}^2} \Big/ L_m$.

The bow and stern sinkages can be estimated as:

$$s_{i,\max} = s_{i,steady} + \varepsilon_i s_{i,steady}, \tag{14}$$

where $\varepsilon_i$ is:

$$\varepsilon_i = \frac{V_1^2 \sqrt{1 - F_{h_1}^2}}{V_2^2 \sqrt{1 - F_{h_2}^2}} f_i \left( \frac{S_p \sqrt{1 - F_{h_1}^2}}{L_m} \right), \tag{15}$$

with $i = $ bow, stern and:

$$f_i(\eta) = \frac{1}{0.5 + d_i \eta^2} \tag{16}$$

where $d_i = 8.5$ *or* 8.6 for $f_{bow}$ or $f_{stern}$ respectively.

# 3 RESULTS

## 3.1 *Single ship squat in channels*

A bulk carrier vessel was used for performing calculations. The approximate $L \times B \times T$ dimensions are 200 × 28.20 × 10.24m with block coefficient $C_B$ equal to 0.80. Additionally, the bulk carrier sections characteristics is provided in figures 1 and 2.

Figure 3 shows the ship sinkage at forward and aft perpendiculars ($s_{FP}$ and $s_{AP}$respectively) of the bulk carrier. Additionally, the Static Underkeel Clearance (SUKC) is shown, measured as the difference between ship static draught and current water depth. The results are presented as function of the vessel velocity for a channel with dimensions $W/L = 1.5$ and $H/T = 1.2$.

It can be noticed that, qualitatively, the sinkage is positive according to sign convention, and it increases with increasing speed in an approximately quadratic form. The sinkage at the forward perpendicular is greater than at the stern since the bulk carrier with $C_B = 0.7$ was assumed to be even keel at the beginning.

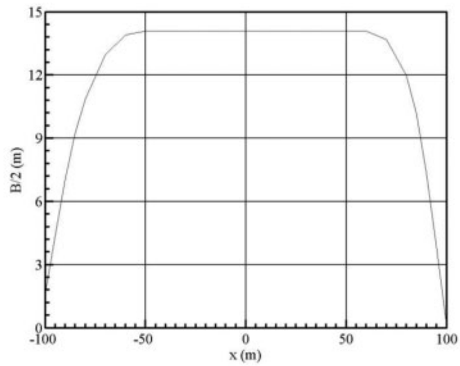


Figure 1. Half breadth at each station in meters.

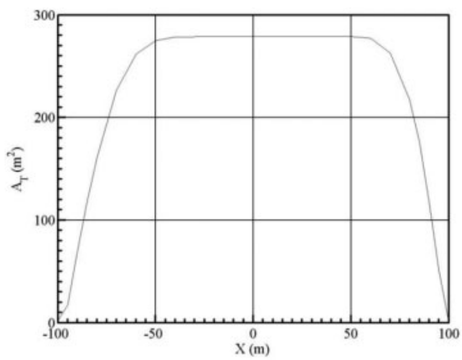


Figure 2. Sectional area curve.

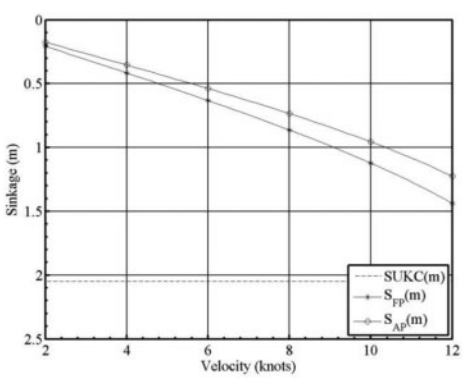


Figure 3. Ship sinkage at bow and stern versus velocity.

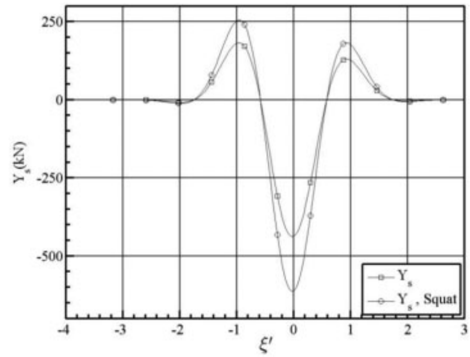


Figure 4. Interaction force acting on the ship in encounter manoeuvre, with and without accounting squat.

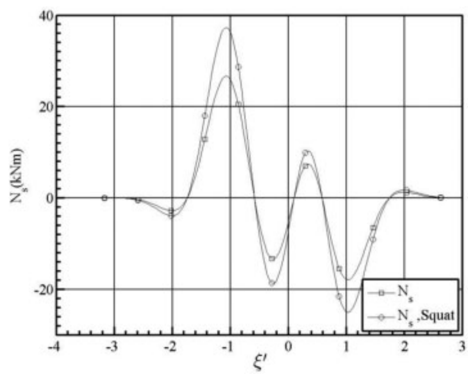


Figure 5. Interaction moment acting on the ship in encounter manoeuvre, with and without accounting Squat.

### 3.2 *Effects of squat in close-proximity manoeuvres*

#### 3.2.1 *Encounter*

A simulation was performed providing interaction curves at each ships relative position for the modified Varyani equations. Values of the maximum sinkage were taken according to Figure 3.

For both ships $u = 5$ m/s. The initial position for ship 1 is $\xi_g = -240$ m and $\eta_g = 120$ m and for ship 2 is $\xi_g = 240$ m and $\eta_g = 0$ m.

Figures 4 and 5 demonstrate the effect of accounting for the squat in interaction. It can be seen that accounting for the squat does not change qualitatively the force/moment responses but their magnitudes become higher around the peaks.

#### 3.2.2 *Overtaking*

Another study was performed for the situation of overtaking to check the modification on Varyani equations on that situation. Again sinkage is taken from Figure 3.

The simulation conditions of the faster ship 1 are $u = 5$ m/s, $\xi_g = -800$ m and $\eta_g = 120$ m. For the slower ship 2, they are $u = 2.5$ m/s, $\xi_g = 0$ m and $\eta_g = 0$ m.

In the overtaking case the squat influence is demonstrated in figures 6 and 7. Qualitatively, it can be traced the same conclusions as for the encounter case.

Inspection of the results for the overtaking manoeuvre shows that although the dynamic squat magnitude is larger for the faster overtaking vessel, the correction for the interacting loads are, on the contrary, larger for the slower ship.

This comes from the fact that the slower vessel has greater regressions coefficients than the faster vessel (observing sway and yaw moment in equation (10)

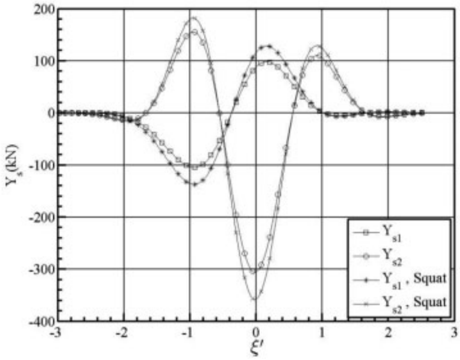


Figure 6. Sway interaction forces acting on ships 1 and 2 in overtaking manoeuvre, with and without accounting squat.

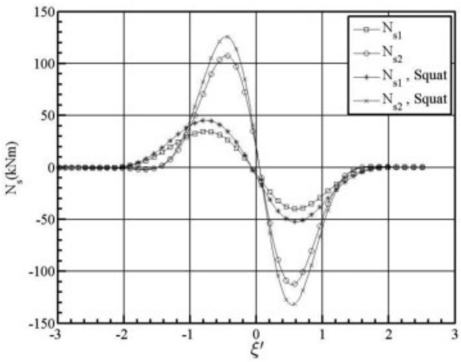


Figure 7. Yaw interaction moments acting on ships 1 and 2 in overtaking manoeuvre, with and without accounting squat.

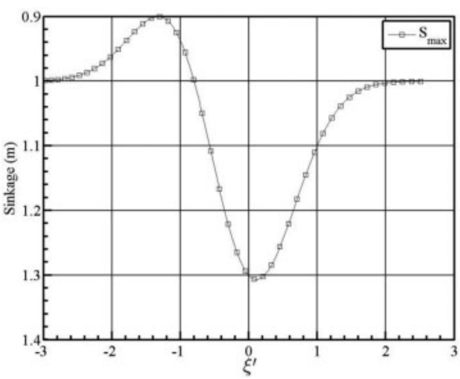


Figure 8. Sinkage at the bow due to close-proximity manoeuvres.

and related tables) compensating the additional squat of the faster vessel.

Therefore, conclusions on the ratio of correction amount of interaction force and moment between the slower and faster vessel cannot be directly translated from just squat considerations.

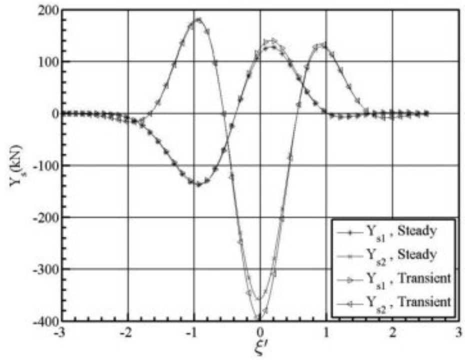


Figure 9. Sway interaction forces with and without accounting for back influence of close-proximity manoeuvres on squat.

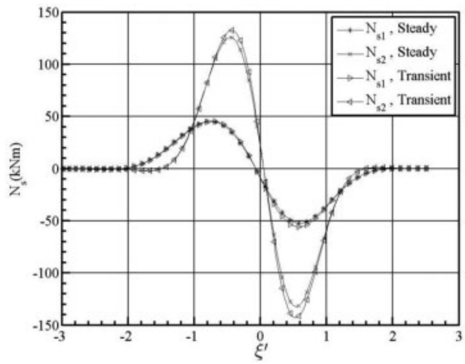


Figure 10. Yaw interaction moment with and without accounting for back influence of close-proximity manoeuvres on squat.

### 3.3 *Back influence of close-proximity manoeuvres on ship squat*

Figure 8 shows the evolution of the maximum sinkage at the bow considering the proper close proximity manoeuvre correction in overtaking (see eq. 14). The simulation condition studied was the same as the previous one. The plot shows that when the faster vessel bow is located nearly the stern of the overtaken ship the sinkage at the bow decreases. When the ships are amidships aligned, the bow sinkage achieves the maximum and after reducing until ships are far from each other.

Additionally, strong influence of close-proximity manoeuvres in squat is seen: the maximum sinkage became much larger when comparing to the situation that the interaction is neglected.

### 3.4 *Influence of the corrected squat on the interaction force and moment*

The influence of the squat is demonstrated in figures 9 and 10. It can be noticed that the squat correction to the interaction force and moment is larger when the both ships are abreast as could be expected.

## 4 CONCLUSIONS

A model coupling the interaction and squat phenomena is developed through modifications of semi-empirical formulas earlier suggested independently for each phenomenon. Additionally, interaction influences the ship squat and this was also taken into account.

The numerical investigation demonstrated that although the coupling effect is definitely detectable, its relative significance is moderate and in most cases is comparable to the inherent uncertainty of the methods for predicting the interaction forces and moments.

## ACKNOWLEDGEMENTS

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