The Influence of Shallow Water and Hull Form Variations on Inland Ship Resistance

E. Rotteveel and R.G. Hekkenberg

ABSTRACT

Effects of a hull form variation and shallow water on a 110-meter inland ship are presented as preliminary results of the Top Ships project, which is initiated in order to improve inland ship design tools and design guidelines.

KEY WORDS

Inland ships; ship design; shallow water; computational fluid dynamics; variations; resistance; propulsion;

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Ship breadth</td>
</tr>
<tr>
<td>C_B</td>
<td>Block coefficient: ( \frac{\nabla}{L \times B \times T} )</td>
</tr>
<tr>
<td>C_T</td>
<td>Total resistance coefficient</td>
</tr>
<tr>
<td>C_P</td>
<td>Pressure resistance coefficient</td>
</tr>
<tr>
<td>C_F</td>
<td>Frictional resistance coefficient</td>
</tr>
<tr>
<td>F_{sh}</td>
<td>Froude-depth number</td>
</tr>
<tr>
<td>h</td>
<td>Water depth</td>
</tr>
<tr>
<td>L</td>
<td>Ship length</td>
</tr>
<tr>
<td>L_{pp}</td>
<td>Ship length between perpendiculars</td>
</tr>
<tr>
<td>S</td>
<td>Ship wetted surface</td>
</tr>
<tr>
<td>T</td>
<td>Ship draught</td>
</tr>
<tr>
<td>V_S</td>
<td>Ship speed</td>
</tr>
<tr>
<td>w</td>
<td>Water width</td>
</tr>
<tr>
<td>y^*</td>
<td>Dimensionless wall distance (( u^* \cdot \frac{y}{v} ))</td>
</tr>
<tr>
<td>Y_{PROPELLER}</td>
<td>Propeller y-position</td>
</tr>
<tr>
<td>\nabla</td>
<td>Ship displacement</td>
</tr>
<tr>
<td>\omega_x</td>
<td>Vorticity about x-axis</td>
</tr>
</tbody>
</table>

INTRODUCTION

Inland ships are a main contributor to transport between several of the largest inland harbors in Europe (Vries, 2013). However, the hull form design for most of these ships is based on hands-on experience or copying earlier designs rather than studying hydrodynamic phenomena that occur in order to optimize the hull form. This approach to ship design does not necessarily introduce major problems, but does lead to sub-optimized designs. The designs of many of these inland ships incorporate sharp corners or a propeller tunnel that does not adequately align with the flow. Both of these can result in significant loss of energy and the idea, therefore, is that improvements can and should be made.

The main reason for the sub-optimal designs is that the design tools and guidelines available at the moment do not provide sufficient information to optimize the designs. For example, tools to evaluate a ship hull form design, such as the Holtrop & Mennen method (Holtrop, 1984), do not include the effects of specific inland ship design details such as the propeller tunnel, which has a serious effect on resistance as stated by Van der Meij (Van der Meij, 2014). Also, effects of shallow water are

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not included while they play an important role for inland ships. Such effects are assumed to be introduced from $h/T \leq 4.0$ (Muller, 1986), an $h/T$ ratio that is hardly ever exceeded when navigating on inland waterways. Furthermore, only few design guidelines are available for inland ships and those that are available (Heuser, 1994), do not provide detail beyond example drawings for certain ship sections, and hence do not provide sufficient information to assess why a certain ship design is good or bad.

Therefore, an inland ship designer will need to perform CFD computations or model tests in order to get an accurate idea whether a ship hull form design is good or bad and how it can be optimized. Unfortunately, such an approach is regularly omitted since the relatively low design budget does not allow for such studies to be conducted. Therefore, most inland ship designers need to design their ships using experience or copying earlier designs, leaving little space for significant improvements to efficiency.

In order to improve the design process for inland ships, the Top Ships project is initiated by a group of Dutch ship designers, together with MARIN and Delft University of Technology. Focusing on the stern hull shape of self-propelled inland cargo vessels, the aim of this project is to develop design guidelines, and an empirical stern hull evaluation tool, and to obtain a better understanding of the influences of shallow water on inland ships. Using these results, inland ship designers should be able to design further optimized ships as well as making a better trade-off between ship resistance, cargo capacity and fuel consumption.

To achieve the goals set for the Top Ships project, CFD calculations are conducted using the structured RANS-code Parnassos for systematically varied inland ships at varying water depths. The input for the varied inland ships is provided by a parametric hull form model built in Rhinoceros®. The CFD results will be stored in a database, from which the empirical stern evaluation method will be deducted. Also, design guidelines for inland ships and effects of water depth are deduced from this database.

This paper will present preliminary results that are part of the study. The paper focuses on the results of a selection of CFD calculations from the Top Ships project. Included is a case study on the effect of water depth for a specific inland ship as well as a case study regarding a specific hull form variation. The next section presents the approach which is employed to achieve the results. Section three presents the results accompanied by an explanation of the observations. Finally, conclusions and discussion are presented in the last section.

**APPROACH**

For the present paper, the double-propeller ship was selected. This section presents the ship and its main particulars along with an overview of the work done to generate hull form variations and setting up the computations.

**Investigated hull form and variations**

 Computations are conducted for a water depth variation study as well as a hull form variation study. For all computations presented, a ship with the same main particulars is used. The ship is a twin-propeller inland ship with a length of 110 meter, of which the main particulars are presented in table 1.

<table>
<thead>
<tr>
<th>Table 1: Main particulars of investigated ship</th>
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<tbody>
<tr>
<td>$L_{pp}$</td>
</tr>
<tr>
<td>$B$</td>
</tr>
<tr>
<td>$T$</td>
</tr>
<tr>
<td>$C_B$</td>
</tr>
<tr>
<td>$S$</td>
</tr>
</tbody>
</table>

This ship is subjected to a variation of water depth as well as a hull form variation. The following water depths are included in the water depth variation study:

- 10.5 m ($h/T = 3.00$)
- 8.75 m ($h/T = 2.50$)
- 7.00 m ($h/T = 2.00$)
- 5.80 m ($h/T = 1.66$)
- 4.20 m ($h/T = 1.20$)
For the hull form variation study, two of the above water depths (10.5 m and 7.00 m) are selected for investigation. The hull form variation applied affects the tunnel shape by shifting the intended propeller position sideways, from \( Y_{\text{PROPELLER}} = 2.0 \) m to \( Y_{\text{PROPELLER}} = 2.8 \) m in steps of 0.2 m. This variation is shown in figure 1. By shifting the propeller position, the tunnel girder curve is affected as well as the hull shape inside the tunnel.

The effect of propeller position has been investigated briefly in earlier research (Stein, 1986). It was observed in Stein’s study that it is preferable to situate the propeller closer to each other in case of shallow water. The reason for this is that in shallow water, most inflow into the propellers as well as into the ship wake is supplied from aside the ship. If a large space is present between the propellers, this space cannot be supplied with water from underneath the ship, and a strong wake occurs. According to Stein’s results, this occurs in extremely shallow water only. In most cases, it is better to situate the propellers further away from each other.

Set-up of a Parametric Inland Ship Model

In order to generate the hull forms according to the presented variation, a parametric model is set up. The model is built in Rhinoceros®, and focuses on the generation of a stern hull form. The model first generates a series of longitudinally oriented curves, which describe the main contours of the ship stern. Then, frames are drawn between these curves. Finally, surfaces are lofted over these frames. An example of the final surface is shown in figure 2. These surfaces together form a 3D representation of an inland ship stern. To create a full ship, a midship section and a standard bow shape are added. The next step is to generate a grid that can be used for CFD computations with Parnassos. This is done by first obtaining an approximation function that sufficiently accurate approximates the ship surface. A mesh is then generated using points obtained from this function. This mesh can be used to build a 3D grid for Parnassos. An example of the ship hull mesh is presented in figure 3. A requirement for the CFD/Parnassos approach employed for the present study is that the tunnel ends as well as the transom must be faired out. Also, the ship grid is extended by a flap surface at the bow and the stern (as shown in figure 3) to fit the ship grid into the 3D grid later on.

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Figure 1: Variation of the sideways propeller position. From left to right: \( Y_{\text{PROPELLER}} = 2.0, 2.4 \) and 2.8

Figure 2: Example of a 3D model of the stern of a double-propeller inland ship
In order to make the model represent existing, real ships sufficiently accurate, it has been adjusted by visually comparing model output and CAD drawings of existing ships. After adjustment, the model is able to provide an approximation for a wide variation of inland ships. The model is not required to generate ship hulls that exactly match existing ships, as the aim of the study is to investigate the trends in performance due to hull form variations rather than benchmarking existing ships.

**Computational Approach**

As was mentioned in the introduction, the Parnassos structured RANS-solver is employed for the calculations. This subsection gives an overview of the software, and presents the construction of the 3D grid used in the computations. Parnassos is a finite-difference RANS (Reynolds-Averaged Navier-Stokes) equation solver that takes advantage of the properties of a ship flow, which are strongly oriented in longitudinal direction. It therefore uses a multi-sweep marching process in the main flow direction to obtain a solution to the RANS equations. The software is able to obtain a solution within a very reasonable time frame: a typical computation can be completed within a day on a desktop computer. This is what makes the software suitable for the Top Ships project, for which a large number of computations is required. More information on Parnassos is provided in (MARIN, 2013) and (Hoekstra, 1998).

Since a large number of computations are to be conducted in the project, it is important that these computations converge towards a realistic solution without manual adjustments to each of the computations. Also, each of the computations should provide a result within an acceptable time frame since the choice of hull forms to be investigated will change depending on the outcome of the calculations. These requirements lead to the two following choices:

First, it is decided to employ a double body (symmetry at free surface, no waves) approach for the CFD calculations. This immediately excludes the estimation of wave resistance. But since inland ship navigate at relatively low Froude numbers, and wave resistance is mainly affected by the bow shape, it is assumed that the effects of stern hull form variations are not significantly affected by free surface effects. Therefore they can be studied without the inclusion of the free surface and wave resistance.

Second, the transom and the tunnel ends are faired out as shown in figure 3. In this way, flow separation is prevented on these two surfaces, which are perpendicular to the main flow direction. As a consequence, the effects of these surfaces are not accounted for in the estimation of ship resistance. However, most hull form variations that are applied for this study emerge further upstream and are thereby not significantly affected by separation at the transom or the tunnel ends.

Still, the effects of the free surface, transom and tunnel ends cannot be neglected completely. Therefore, computations including a transom, flat tunnel ends and a free surface are conducted for specific cases within the Top Ships project. In this way the effects can still be taken into account while the stability and performance of the bulk of the calculations can be ensured.

For the results presented in this paper, propeller modeling is not included. For the Top Ships project, propeller simulation is performed by applying a force field at the propeller disc. This force field imitates the force field produced by a ducted propeller. In this way, the effects of hull form variations on propeller inflow can be investigated more accurately. In order to investigate detailed flow features (and to investigate how such flow features are affected by hull form variations) near the
propeller duct, specific hull forms are selected during the Top Ships project for investigation through alternative, unstructured RANS flow solvers.

The grid used in the computations is constructed from five separate blocks. In a typical Parnassos computation for deep water, only one block is used. For shallow water, the domain has a very high width-to-height ratio (see figure 4) to prevent the wall from influencing the ship flow. This leads to a heavily distorted grid if it is constructed out of one block. An example of the five-block grid is given in figure 5. The block around the ship also consists of two blocks. The block split is positioned at the tunnel girder to prevent the grid from curling around the girder.

![Figure 4: Overview of grid blocks used. Water depth = 10.5 m](image)

The grid near the ship hull is contracted in such a way that the maximum \( y^+ \) value on the ship hull was lower than 0.4 during the computations. On the channel bottom, the maximum \( y^+ \) value exceeds the value of 1.0 in some cases, however this is assumed to have no significant effect on the flow near the hull.

![Figure 5: Detailed view of the grid structure. Water depth = 10.5 m](image)

**COMPUTATIONAL RESULTS**

This section presents the computational results obtained for this paper. The section is divided in two parts; the first part elaborates on the results from the water depth variation, and presents various shallow water effects in order to obtain a better understanding of shallow water effects. The second part presents the results of the hull form variation discussed in the previous section. The observations made and explanations provided are summarized in the next section.

**Effects of Shallow Water**

If a ship navigates in shallow water, the resistance increases. This has been observed by various researchers (Raven, 2012). Generally, the increase of ship resistance in shallow water is divided over two parts; one part is due to an increase of wave
resistance (since the wave speed becomes limited in shallow water); another part is due to a higher blockage ratio \((\approx (B \times T) / (w \times h))\) resulting in stronger return flow. The CFD approach employed for the present paper provides the investigation of the effect of blockage only, since the free surface is omitted in the computations. This subsection presents the results of a water depth variation study for an inland ship as presented in figures 2 and 3. The water depths included are 10.50, 8.75, 7.00, 5.80 and 4.20 meters. The results respectively show the effects of shallow water on:

- ship resistance,
- the resistance distribution,
- the flow around the ship stern, and
- the propeller inflow.

The effect of shallow water on ship resistance is shown in table 2. For the water depths investigated, this table presents the coefficients for pressure resistance, frictional resistance and total resistance.

### Table 2: Coefficients of pressure, frictional and total resistance (times 1000) for various water depths

<table>
<thead>
<tr>
<th>Water depth</th>
<th>h/T ratio</th>
<th>(F_{sh})</th>
<th>(C_P)</th>
<th>(C_F)</th>
<th>(C_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>3.00</td>
<td>0.355</td>
<td>0.348</td>
<td>1.832</td>
<td>2.179</td>
</tr>
<tr>
<td>8.75</td>
<td>2.50</td>
<td>0.389</td>
<td>0.342</td>
<td>1.828</td>
<td>2.170</td>
</tr>
<tr>
<td>7.00</td>
<td>2.00</td>
<td>0.435</td>
<td>0.350</td>
<td>1.882</td>
<td>2.231</td>
</tr>
<tr>
<td>5.80</td>
<td>1.66</td>
<td>0.477</td>
<td>0.439</td>
<td>1.932</td>
<td>2.371</td>
</tr>
<tr>
<td>4.20</td>
<td>1.20</td>
<td>0.561</td>
<td>0.809</td>
<td>2.042</td>
<td>2.851</td>
</tr>
</tbody>
</table>

The table shows that the effects of shallow water on the viscous pressure resistance and frictional resistance of the subject inland ship are limited for h/T values lower than 2.00. For h/T values lower than 2.00, the pressure resistance increases faster than the frictional resistance. This is explained by the fact that frictional resistance is mostly affected by the return flow speed (which increases in shallow water), while pressure resistance is mostly affected by changes of flow behavior. One of these changes is the formation of a strong wake at the ship stern, occurring because the space beneath the stern hull is not sufficiently supplied with water from underneath the ship. This wake formation can be observed in figure 6, which shows the distribution of the flow velocity in x-direction at the propeller position.

![Figure 6: Visualization of flow in x-direction in the stern area at x/Lpp = 0.477 for h = 5.80 (left) and h = 4.20 (right). Velocity is non-dimensionalized by \(u = U/Vs\). Note the wake formation for h = 4.20 near the center plane.](image)

Table 2 shows the effect of shallow water on overall ship resistance. Figure 7 presents the resistance distribution along the hull for a water depth of 7.0 m. This figure presents distribution of pressure resistance and frictional resistance separately. Such a figure can be used to determine which parts of the ship hull need to be improved. Figure 8 presents the distribution of total resistance for a variation of water depths. Using this figure, the effects of shallow water on ship resistance can be studied in more detail. For example, the figure shows that the differences from h/T = 3.0 to h/T = 2.0 are small, while significant changes can be observed from h/T = 2.0 to h/T = 1.2. Not only does the magnitude of the distribution increase, the minimum shown at the bow is slightly shifted backwards as well. Also, the resistance distribution at the stern for h/T = 1.2 is slightly smoother than the distributions for larger water depths. Furthermore the figure shows, in agreement with the statements made in table 2, that pressure resistance is much more affected by shallow water than frictional resistance. Still, the resistance
distribution provides similar information on shallow water effects as the total resistance; it mostly presents the increase of resistance at lower water depth.

**Figure 7:** Distribution of the resistance coefficients over the ship’s length, for $h/T = 2.0$ ($h = 7.0$ m). Addition of both lines results in the total resistance coefficient distribution.

**Figure 8:** Distribution of the total resistance over the ship’s length, for $h/T = 1.2$, 2.0 and 3.0. The distribution of separate resistance components ($C_p$, $C_f$) can be obtained using figure 7.
To get more information on the effects of shallow water on inland ship flow behavior, the flow must be studied in more detail. This can be done by figures similar to figure 6 or by visualizing the flow in 3D. Figure 6 already presents the detailed distribution of the longitudinal flow velocity at the x-position of the propeller, and shows that the flow pattern changes significantly in shallow water. Figure 9 presents a three-dimensional plot of the vorticity about the longitudinal axis (ω_x) at a series of x-planes. A green color indicates areas with small or no vortices, which means the flow is relatively uniform, and mostly moving in longitudinal direction. Red or blue areas indicate counterclockwise and clockwise rotating vortices respectively.

Figure 9: Vorticity about the longitudinal axis (red = counterclockwise, blue = clockwise, green = zero vorticity) plotted for a water depth of 7.0 meters (left) and 4.2 meters (right)

Figure 9 shows that for h/T = 2.0, a stronger vortex is left from the tunnel girder than for h/T = 1.2. This indicates that the tunnel girder of the subject ship is better suited for shallow water. More importantly, it shows that the design of the tunnel girder actually requires a ship designer to take into account the effects of shallow water. In order to provide a more detailed picture, figure 10 presents the vorticity left behind in the fluid. The figure shows that at h/T = 2.0, the vortex left behind from the tunnel (indicated by the dotted circle) is smaller.

Figure 10: Vorticity at X / Lpp = 0.6 about the longitudinal axis (positive = counterclockwise, negative = clockwise, zero = no vorticity) plotted for a water depth of 7.0 meters (left) and 4.2 meters (right)

Figure 11 presents the pressure distribution at the stern of the ship. The figures show, in accordance with the observations made from table 2 and figure 7, that the pressure at the stern is significantly lower in shallow water, leading to increased pressure resistance. Apart from a stronger low-pressure area however, it can also be observed that the low-pressure region is shifted outward, athwart ships, as well as shifted towards the bow (upstream). Comparing the left and right image, it appears that in shallow water, the bilge radius in the front end of the stern is more important than the radius in the aft end of the stern. This again implies that the choice for the bilge radius in the ship stern region also requires a designer to take the effects of shallow water into account, similar to the design of the tunnel girder.
Figure 11: Pressure distribution at the stern, plotted for water depths of 7.0 meters (left) and 4.2 meters (right).

Although propeller modeling has not been included for the presented study, it is included in further research on the Top Ships project. The flow at the propeller x-position is therefore presented in figure 12 for three different water depths. The images show that at decreasing water depth, the inflow pattern at the propeller disk changes. Also, the average inflow velocity decreases. This shows that the shallow water effect does not only affect resistance, it affects the propeller efficiency as well. Moreover, an active propeller affects ship resistance as well due to propeller suction.

Figure 12: Longitudinal velocity at the propeller x-position. From left to right: \( h = 10.5 \text{ m} \), \( h = 5.8 \text{ m} \), \( h = 4.2 \text{ m} \).

This subsection presented the results of a water depth variation study for a 110 m inland ship. From the observations made, the following conclusions are drawn:

- For the ship and speed investigated, the shallow water effect on resistance becomes significant for \( h/T \) values lower than two.
- Down to \( h/T = 2.0 \), both pressure and frictional resistance increase equally. In a more extreme case of shallow water (\( h/T = 1.66 \) and 1.2), the increase of pressure resistance is stronger than that of frictional resistance.
- The shallow water effect mostly influences the resistance contribution from the bow and the stern, as shown in figure 8.
- Figure 9 showed that the tunnel design should be adapted for a specific water depth, since the strength vortices shed from the tunnel girder depends on the water depth.
- Figure 11 showed that also the bilge radius in the stern region must be adapted for a specific water depth.
- Although the presented computations do not include propeller action, figure 12 shows that shallow water does not only affect resistance, it also significantly affects the propeller inflow.
Effects of propeller y-position

This subsection discusses the effect of moving the propeller position athwart ships. This variation has been presented in the previous subsection and is shown again in figure 13. First, the effect of the variation is investigated at the largest water depth included in the study. Then, it is presented how the water depth affects the influence of the hull form variation on resistance.

Figure 13: Variation of the sideways propeller position. From left to right: \(Y_{\text{PROPELLER}} = 2.0, 2.4\) and 2.8

The effect of the hull form variation itself, at a water depth of 10.5 meters, can be observed from total resistance already. Table 3 shows frictional and pressure resistance as well as total resistance for the four variations studied for this paper.

Table 3: Resistance coefficients (times 1000) for an inland ship with varied propeller lateral position

<table>
<thead>
<tr>
<th>Prop. position from centre</th>
<th>(C_F)</th>
<th>(C_P)</th>
<th>(C_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 m</td>
<td>0.4851</td>
<td>1.8705</td>
<td>2.3556</td>
</tr>
<tr>
<td>2.2 m</td>
<td>0.3792</td>
<td>1.8694</td>
<td>2.2486</td>
</tr>
<tr>
<td>2.4 m</td>
<td>0.3101</td>
<td>1.8673</td>
<td>2.1774</td>
</tr>
<tr>
<td>2.6 m</td>
<td>0.2663</td>
<td>1.8664</td>
<td>2.1327</td>
</tr>
<tr>
<td>2.8 m</td>
<td>0.2526</td>
<td>1.8660</td>
<td>2.1186</td>
</tr>
</tbody>
</table>

From the resistance coefficient values, it is clear that the effect of the lateral displacement of the propeller position mainly affects the pressure resistance. Also, the table shows that for bare-hull resistance, moving the propeller more outward results in a total resistance decrease of nearly six percent. Using the resistance distribution, it is possible to investigate at which location on the hull this variation has the largest effect. The total resistance distributions for cases where the propeller position is 2.2 and 2.8 meters are presented in figure 14.
Figure 14: Total resistance distribution for total resistance for \( Y_{\text{PROPPELLER}} = 2.2 \) and 2.8

The figure shows that the largest difference can be observed between \( x/L_{pp} = 0.44 \) and \( x/L_{pp} = 0.52 \). Outside of this region, the ship hull form is not affected by the variation, and neither is the resistance distribution. To identify how the resistance and the resistance distribution are influenced by the variation, the vorticity distributions at the propeller x-location for variants with propeller y-positions 2.2 and 2.8 are presented in figure 15.
Figure 15: Vorticity about the longitudinal axis for two hull form variants (left: $Y_{\text{PROPELLER}} = 2.2$, right $Y_{\text{PROPELLER}} = 2.8$) (positive = clockwise, negative = counterclockwise, zero = no vorticity) Water depth = 10.5 m. Note the difference between the vortexes shed from the tunnel girder.

The main difference than can be observed is that the vortex shed from the tunnel girder is smaller. This vortex therefore also contains less energy than the one shown in the left picture for a propeller $y$-position of 2.0 meters. In figure 16, the vorticity in the fluid is presented at a position 10 percent aft of the ship. This figure again shows that less vorticity is left behind in the fluid, leading to lower energy losses.

Figure 16: Vorticity about the longitudinal axis for two hull form variants (left: $Y_{\text{PROPELLER}} = 2.2$, right $Y_{\text{PROPELLER}} = 2.8$) (positive = clockwise, negative = counterclockwise, zero = no vorticity) Water depth = 10.5 m.

Similar to the water depth variation study, the propeller inflow is analyzed for the hull form variation study as well. Figure 17 shows a comparison between the longitudinal flow distributions for two hull form variants (with $Y_{\text{PROPELLER}} = 2.2$ and $Y_{\text{PROPELLER}} = 2.8$). From the figures, it can be observed that the main difference is that for $Y_{\text{PROPELLER}} = 2.8$, the average inflow velocity is higher. This difference is small, namely below 5 percent.
From the comparison shown in figures 15 and 16, it is observed that for a water depth of 10.5 meters and a $Y_{PROPELLER}$ value of 2.2 meters, the tunnel girder is not adequately aligned with the flow around the ship stern. It is important here to state that this applies at this specific water depth, because figure 9 in the previous subsection showed that it depends on water depth whether the flow aligns with the tunnel girder. Therefore, the hull form variation presented is investigated for a different water depth as well. Figure 9 showed that in shallow water, the vortex being shed from the tunnel girder becomes smaller for the ship investigated. This indicates that if one wants to optimize a stern design for shallow water, the tunnel girder curve should be deformed towards the ship center plane.

Table 4 presents the total resistance coefficients for the hull forms investigated, at two different water depths. From the values, it can be observed that the decrease of resistance for increasing $Y_{PROPELLER}$ in case of $h = 7.0$ meters is smaller than for $h = 10.5$ meters. That the relative change of resistance becomes smaller can be explained by the fact that the influence of shallow water on the total resistance is larger than the influence of the hull form variation. Also, the hull form variation only affects the resistance distribution locally, while the shallow water effects influence the resistance distribution over the whole ship. However, the decreased effect of the propeller position variation can also mean that the optimal propeller $y$-position has shifted or that the influence of the hull form variation becomes smaller in shallow water.

Table 4: Total resistance coefficient for propeller position variation at different water depths

<table>
<thead>
<tr>
<th>Prop. position from center</th>
<th>h = 10.5</th>
<th>h = 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 m</td>
<td>2.3556</td>
<td>2.4956</td>
</tr>
<tr>
<td>2.2 m</td>
<td>2.2486</td>
<td>2.4336</td>
</tr>
<tr>
<td>2.4 m</td>
<td>2.1774</td>
<td>2.3778</td>
</tr>
<tr>
<td>2.6 m</td>
<td>2.1327</td>
<td>2.3439</td>
</tr>
<tr>
<td>2.8 m</td>
<td>2.1186</td>
<td>2.3323</td>
</tr>
</tbody>
</table>

To determine if the optimal value for $Y_{PROPELLER}$ is shifted at lower water depth, figure 18 presents a graph comparison between the resistance coefficients at both $h = 10.5$ and $h = 7.0$. From the figure, it can be observed that the influence of the hull form variation becomes smaller in shallow water, rather than the optimal $Y_{PROPELLER}$ value has shifted. To investigate how the effect on resistance becomes smaller, a more detailed analysis is conducted. Figure 19 presents the resistance distribution for four cases: ship hull variants with propeller $y$-positions of 2.2 and 2.8 meters, each at two different water depths. The resistance distribution is plotted only for the region where the hull form variation’s effect is significant: the aft end of the ship.
Figure 18: Comparison of resistance graphs for variation of $Y_{\text{PROPELLER}}$ at $h = 10.5$ and $h = 7.0$.

Figure 19: Comparison of total resistance distribution at the stern for $Y_{\text{PROPELLER}} = 2.8$ and $Y_{\text{PROPELLER}} = 2.2$, each at water depths $h = 10.5$ and $h = 7.0$.

Figure 19 shows that the effect of a different water depth on the resistance distribution is approximately equal for most of the region, except between $x/Lpp = 0.49$ and $x/Lpp = 0.52$. In this region a small difference can be observed. For a $Y_{\text{PROPELLER}} = 2.8$, the resistance distribution in this area does not significantly change with water depth, but it does for a $Y_{\text{PROPELLER}} = 2.2$ meters. Also, it changes in accordance with the observation made from table 4: the contribution to resistance is lower in case
of a water depth of 7.0, and thus resulting in a smaller difference between the considered hull form variants at a water depth of 7.0 meters.

Figure 19 provides an explanation for the reduced effect of the hull form variation in shallow water. However, this explanation only applies to ships with a faired out transom and tunnel ends, because the difference between the resistance distributions observed in figure 19 occurs at the faired out part of the tunnel girder, which is not present at a real ship. In order to investigate whether the influence of the hull form variation actually decreases at decreasing water depth, additional computations need to be conducted that include the modeling of a flat tunnel end.

From the observations made in this subsection, the following conclusions can be drawn on the effects of the hull form variation investigated here:

- At a water depth of 10.5 meters (h/T = 3.0), the variation of the propeller y-position has a significant influence on the total resistance of the ship. A decrease of approximately six percent was observed when the propeller position was moved from y = 2.2 to y = 2.8. This hull form variation may therefore be taken in consideration if one wants to improve an inland ship hull.
- At a water depth of 10.5 meters (h/T = 3.0), the effect of the chosen hull form variation on the propeller inflow velocity (distribution as well as average) is small.
- At smaller water depth, the effect of the variation investigated becomes less, because the shallow water effects acting on the ship have a stronger influence on resistance than the variation itself. Other explanations that apply are that either the effect of the variation actually becomes smaller in shallow water, or the optimum of the propeller y-position changes in shallow water. Figure 18 shows no clear optimum shift, meaning that the effect of the hull form variation probably decreases at shallow water.
- Investigating the other explanations for the reduced effect of the variation, it is found that the resistance contribution of the faired out transom part is lower in case of shallow water, thereby explaining the decreased effect of the hull form variation. This faired out transom is absent for real ships, and therefore further investigation is required.
CONCLUSIONS AND DISCUSSION

The present paper showed some preliminary results of the Top Ships project. These results correspond to a water depth variation for a certain inland ship hull as well as a hull form variation tested at two water depths. This section describes the main conclusions drawn in the paper and also briefly presents future work in this project.

Conclusions

From the investigation of shallow water effects on an inland ship, it becomes clear that water depth should be considered when designing an inland ship hull. Due to a change of flow pattern from three-dimensional towards two-dimensional flow, the flow around the tunnel girder changes in such a way that the vortices shed from there change significantly at a different water depth. The same applies to the propeller inflow speed and distribution, which also change due to the change of flow pattern in shallow water. For both propeller inflow and the flow around the tunnel girder, designing a ship for a specific water depth leads to a sub-optimized ship at another water depth.

A hull form variation corresponding to the propeller y-position is investigated. This hull form variation specifically affects the curve of the tunnel girder. At a water depth of 10.5 m, the computational results showed that an approximate decrease of six percent for total resistance can be obtained. This makes the hull form variation interesting for further research.

When investigating this hull form variation at a different water depth, it is observed that the effect of this hull form variation decreases if the water depth is decreased to h = 7.0 m. The following explanations for this are mentioned:
- The shallow water effect on ship resistance is larger than the effect of the hull form variation. Therefore, the effect of the hull form variation becomes relatively smaller in shallow water.
- The optimal propeller y-position shifts towards the ship center. The optimum can therefore be closer to the propeller y-positions investigated, leading to a smaller effect relative to the starting value of the hull form variation.
- The effect of the hull form variation investigated becomes smaller in shallow water.

Analysis of the resistance distribution near the aft end of the ship showed that the resistance distribution at the faired out part of the ship in case of lesser water depth differs in such a way that it contributes to a smaller influence of the hull form variation in shallow water. As this faired out part is not present on real ships, it is concluded that for further investigation of the hull form variation investigated, additional computations are required, including the flat tunnel ends and transom (no fairing out of the ship stern) are required.

Future work

The results presented in this paper are preliminary results of the Top Ships project. This project aims at the development of an empirical tool aiding designers in the design of an inland ship hull form. Also, new design guidelines for inland ships are developed. In order to achieve these results, additional computations are required. Among these are:
- CFD computations without a faired-out transom and without faired-out tunnel ends.
- Estimation of wave resistance using CFD computation including wave formation at the free surface.
- CFD computations including propeller modeling through a ducted propeller-fitted force field / actuator disk.
- CFD computations using alternative (non-structured) RANS solvers in order to investigate specific inland ship features.

Furthermore, the Top Ships project includes the variation of other hull form aspects as well. This paper presents the variation of the propeller position, which is one of the variations included in the Top Ships project. Examples of variations which are investigated in the project are the length of the stern region, the width of the tunnel (at constant propeller y-position), specific variations of the tunnel girder curve and shape variations of the hull form inside the tunnel. Although the effect of the investigated hull form in this work is interesting, the effects of other hull form variations can be larger, making them even more important.

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