DETERMINING THRUSTER-HULL INTERACTION FOR A DRILL-SHIP USING CFD

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ABSTRACT
In this paper CFD results are presented for the thruster-hull interaction effects for a drillship with 6 azimuthing thrusters. The results using different approaches to model or simulate the propeller are compared and their advantages and disadvantages are discussed. The approaches investigated are the so-called Frozen Rotor approach, where the propeller rotation is modeled, the Actuator Disk approach with prescribed body forces and the unsteady Sliding Interface approach where the motion of the propeller is simulated in time.

First, open-water calculations for a tilted thruster are carried out using the Frozen Rotor approach. The open-water calculations are repeated using the Actuator Disk prescribing the propeller thrust and torque distribution obtained from the Frozen Rotor calculations. The results with Actuator Disk are very similar for the unit thrust and nozzle thrust compared to the results using the Frozen Rotor approach. Furthermore, the results using the Frozen Rotor or the Actuator Disk are very close to the experimental results for the nozzle thrust.

The thruster-hull interaction of one active thruster under the drillship is investigated using the Actuator Disk approach, the Frozen Rotor Approach and the Sliding Interface approach. A comparison to experimental results is presented for the thruster-hull interaction coefficients. Using the Actuator Disk a good agreement with the experiments is obtained. The results using the Actuator Disk and Sliding Interface are very similar to each other, but the computational costs for the Sliding Interface method are at least a factor 20 higher. The results using the Frozen Rotor deviate due to an unphysical wake behind the thruster.

Based on the results presented in this paper we conclude that, using the steady-state approach with the Actuator Disk, CFD can be a cost-efficient and accurate method to determine the thruster-hull interaction effects at bollard pull conditions for a typical offshore vessel.

INTRODUCTION
To determine the Dynamic Positioning (DP) capability of offshore vessels, input for wind, current and wave loads are required as well as the thrust and thruster-interaction losses for the specific vessel and thruster layout at hand. The effective force generated by the thrusters during a DP operation can be significantly smaller than what would be expected based on the thrusters’ open water characteristics.

Within the Thrust Hydrodynamics Joint Industry Project (TRUST JIP) model tests, PIV measurements and CFD calculations were carried out to increase the insight in the physical phenomena and to quantify thruster interaction effects for different configurations, see for example [1]-[4].

Computational Fluid Dynamics (CFD) is proven to be a cost-efficient and accurate method to determine the wind and current loads, see for example [7]-[10]. Recently, CFD has been applied for the analysis of thruster-interaction effects, see for example [1], [11], and [12].

In [1] the performance and thruster-interaction for straight and tilted thrusters were compared using a so-called moving mesh technique, denoted by Sliding Interface method in this paper. Their initial attempts using a quasi-steady Moving-Reference-Frame, similar to the Frozen Rotor approach in this paper, gave a poor solution of the shape of the jet stream out of the thruster. In [12] a method similar to the Frozen Rotor approach was applied to obtain the thruster-interaction for a semi-submersible at model- and full-scale Reynolds number. Reasonable agreement with model test results and full-scale measurements was obtained. In [11] the CFD results are presented using an Actuator Disk for a thruster under a flat plate and under a barge. There, it was shown that the wake of the thruster was accurately predicted compared with results from PIV measurements. Furthermore, the thruster-interaction losses and the forces on the nozzle and barge agreed well with the measured results.
In this paper CFD results are presented for a drillship equipped with 6 azimuthing thrusters. The thruster-hull interaction effects are calculated for a range of azimuth angles and the results are compared to experimental results. Different approaches to model or simulate the propeller motion are investigated: Actuator Disk, Frozen Rotor and Sliding Interface. The advantages and disadvantages of each method are discussed.

DEFINITIONS AND NOMENCLATURE
The standard OCIMF sign convention is used as presented in Figure 1.

![OCIMF sign convention for the drillship (top view)](image)

Figure 1: OCIMF sign convention for the drillship (top view) where the directions indicate the current direction, i.e. 180 degrees current is head-on current and 0 degrees current is current coming from the stern. The corresponding azimuth angle of the thrusters for 180 degrees current is 0 degrees.

The non-dimensional coefficients used to express the general performance characteristics are the non-dimensional advance coefficient $J$, the thrust coefficient $K_T$ and the torque coefficient $K_Q$:

$$J = \frac{V_a}{nD}$$  \hspace{1cm} (1)

$$K_T = \frac{T}{\rho n^2 D^4}$$  \hspace{1cm} (2)

$$K_Q = \frac{Q}{\rho n^2 D^4}$$  \hspace{1cm} (3)

where $V_a$ is the advance velocity [m/s], $n$ the rotational speed with $n=\omega/2\pi$ with $\omega$ in [rad/s], $D$ the diameter [m] of the propeller, $T$ the propeller thrust [N], $\rho$ the density [kg/m$^3$] and $Q$ the propeller torque [Nm].

The thruster interaction $\eta$ is defined by:

$$\eta = \frac{F_{tot\,unit}}{F_{unit}} \times 100\%$$  \hspace{1cm} (4)

with $F_{tot\,unit}$ the total force on the vessel including the thrusters:

$$F_{tot\,unit} = F_{hub} + \sum_i T_{unit,i}$$  \hspace{1cm} (5)

where the unit thrust $T_{unit,i}$ of the thruster is the total force on the thruster defined by:

$$T_{unit,i} = T_{prop,i} + T_{nozzle,i} + F_{hub,i} + F_{strut,i}$$  \hspace{1cm} (6)

with $T_{prop}$ and $T_{nozzle}$ the propeller and nozzle thrust and $F_{hub}$ and $F_{strut}$ are the total force on the hub and strut of the thruster. During the calculations the forces on the different parts of the thrusters and vessel are monitored separately.

EXPERIMENTS FOR THRUSTER-INTERACTION
To investigate the thruster-hull interaction model tests at scale 1:40 were carried out for the drillship with 6 azimuthing thrusters with 7 degrees downward tilt, see also [3]. A general drill-ship design was taken with a generic moon pool configuration. The thrusters were placed in a configuration common for modern DP drill ships. The thrusters at the bow are placed under the vessel keel, while the thrusters at the stern are placed on a head-box. The aft thruster at the vessel center line was placed at a higher vertical position than the other 5 thrusters. Bilge keels were added to the model as well. A photograph of the model is shown in Figure 2.

During the thruster-hull interaction measurements one active thruster was rotated clock-wise and counter-clockwise at a low rotation rate. During this rotation the following quantities were measured: horizontal loads on the drill ship, thruster RPM’s, propeller thrust and torque, unit thrust and nozzle thrust of each thruster. From these measurements the thruster interaction loss can be derived as a function of azimuth angle.

![Drillship model as used for the thruster-interaction model tests. Scale is 1:40.](image)

NUMERICAL APPROACH
In this paper the results of CFD calculations are presented for the following different configurations:

- Tilted thruster in open-water conditions, which is used as reference for the thruster-hull interaction cases.
- Thruster-hull interaction for a drillship with 6 azimuthing thrusters. One thruster is active and the wake of this thruster is interacting with the hull of the vessel and the other (in-active) thrusters.

Assumptions
For the CFD calculations on the drillship the following assumptions are taken:

- The drillship and thrusters are kept fixed. A constant RPM of 1066 is considered with fixed azimuth angle;
- Stationary flow and forces are considered when using the Actuator Disk or Frozen Rotor method. Unsteady effects from the flow and from the thruster wake are not taken into account in these calculations.
• When using the Sliding Interface method the calculations are unsteady and thus unsteady effects are present in the wake.
• For bollard pull conditions \((J=0)\) a very small \((J\approx 0.001)\) uniform velocity inflow is considered at the inflow boundary to prescribe a preferred flow direction, see also \[11\].
• The effects of the free water surface are assumed to be negligible as the thruster wake is directed downward due to the tilt angle of the thruster. Also, hardly any disturbance of the water surface was observed in the measurements. Thus, the water surface is taken into account as a flat wall with free slip condition.

Approach

First, calculations at model-scale are carried out for a tilted thruster in open water conditions using the Frozen Rotor approach and an Actuator Disk approach.

The Frozen Rotor approach is a quasi-steady approach where the propeller and thrusters are geometrically included but the effect of the rotating blades are modeled. A computational mesh is constructed around the blades and other parts of the thruster. The thrust and torque distribution can be accurately determined using the Frozen Rotor approach. However, the wake behind the thruster using the Frozen Rotor is not physical, as shown in \[14\] and Figure 27(d). For more explanation on the Frozen Rotor approach see \[11\] and \[14\].

The Actuator Disk model substitutes the propeller blades with an ‘equivalent’ body-force distribution, approximately distributed over the volume cut out by the propeller blades \[4\]. The body-force distribution is an input to the model, requiring an estimation of this distribution before the calculation. For this the results from the Frozen Rotor approach can be used. Some flow features close to the Actuator Disk are not well captured, but the interaction with the nozzle and the downstream wake are predicted correctly as shown in \[11\]. Therefore, for thruster-hull interaction calculations this model is attractive due to the smaller computational costs.

For the thruster-hull interaction on the drillship, one thruster is active. The wake of this thruster is interacting with the hull of the vessel and the other thrusters. For the in-active thrusters the geometry of the propeller blades is included. As presented later in this paper, we also investigated the effect of omitting the propeller blades for the in-active thrusters to save computational cells. For the active thruster in the thruster-hull configuration three approaches are investigated: Actuator Disk, Frozen Rotor and Sliding Interface.

For the Actuator Disk the same thrust and torque distribution is applied as used in the open-water calculations. The Frozen Rotor calculations are carried out to investigate the applicability of this method for thruster-hull interaction.

The most accurate approach is to perform unsteady calculations with so-called Sliding Interfaces where the rotating propeller blades are taken into account. Enough rotations of the propeller, i.e. at least 40 propeller revolutions, need to be simulated to fully develop the wake downstream along the hull.

Geometry

For the thruster-hull calculations a drillship with 6 azimuthing thrusters have been considered as shown in Figure 3 and Figure 5. In Table 1 the main particulars of the drillship are presented. Thrusters 1 to 3 (T1-T3) are located under a headbox. Between thrusters 2 and 3 a skeg is positioned. The bilgekeels and the moonpool are included as well. The moonpool in the CFD calculations is simplified to be one rectangular volume. It is expected that this simplification has no influence on the calculated thruster-hull interaction. At the top of the moonpool a free-surface is present, which is modeled by a free-slip boundary.

The thrusters are so-called ‘tilted’ thrusters as they have a downward tilt angle of 7 degrees. The thrusters consist of a strut, hub, duct and blades as shown in Figure 4. The part of the hub rotating with the blades attached is taken as a separate surface and this part is denoted by Rotating-Hub.

For the thruster-hull interaction calculations the blades of the propellers have been taken into account except when using the Actuator Disk as then the blades of the active thruster are replaced by the Actuator Disk.

In the open-water calculations the strut is cut at the same height as the strut located under the drillship. With CFD we have investigated whether a long strut, as used in the open water measurements, or a short strut, as described above, has influence on the calculated thrust and torque of the thruster. We have found that for larger \(J\) values the efficiency of the thruster goes down when using the long strut due to the drag loads on the strut. For bollard pull conditions, i.e. \(J=0\), no difference was found. Note that these results are not included in this paper.
Figure 5: Geometry of the tilted azimuthing thruster under the drill-ship. On the left the thruster is shown without the blades as used for the Actuator Disk. To the right the thruster is shown with the blades as used in the Frozen Rotor and Sliding Interface approach.

Table 1: Main particulars of the drillship. Note that the values presented are full-scale values. The calculations and experiments have been carried out for model-scale 1:40.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Symbol</th>
<th>Value [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars</td>
<td>L_{PP}</td>
<td>210.1</td>
</tr>
<tr>
<td>Breadth</td>
<td>B</td>
<td>36</td>
</tr>
<tr>
<td>Draft</td>
<td>T</td>
<td>9.5</td>
</tr>
<tr>
<td>Propeller diameter</td>
<td>D</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Computational Domain

For the calculations a computational domain is used as illustrated in Figure 6 and Figure 7 with the side-walls placed at the tank wall locations. The width of the basin is 10m (100D) and the bottom is positioned at 5.5m (55D), thus making the basin practically unrestricted water conditions compared with the dimensions of the thruster. The inflow and outflow boundaries are placed at -4L_{PP} and 4L_{PP} from the center of the drill-ship. For the open-water calculations the tilted thruster is located at exactly the same position as where thruster 1 is located in the calculations with the drillship.

Figure 6: Computational domain for the open-water calculations with tilted thruster.

Figure 7: Computational domain for the drillship with 6 azimuthing thrusters.

Computational Grids

Computational grids are constructed with the grid generator software package Hexpress. Different grids are constructed for the tank domain with and without drill ship, for the drillship, for the thruster housing and for the blades depending on the propeller model being used. The thrusters are located in a cylindrical sub-domain inside the tank domain and under the drillship to be able to rotate freely for different thruster headings. The thruster mesh is copied and placed at the location of the six thrusters. The mesh around the drillship and the thrusters is refined towards the solid surfaces to resolve the boundary layers. The maximum y⁺ values are below 5 on the thrusters, propeller blades and vessel hull. The stretching ratio in normal direction to the solid walls of the grids in the boundary layer is set to 1.2.

For the open-water calculations the following meshes are used:
- Tank domain consisting of 0.4M cells, see Figure 8;
- Thruster housing consisting of 2.0M cells, see Figure 9;
- Thruster propeller without blades for Actuator Disk consisting of 0.2M cells, see Figure 10;
- Thruster propeller with blades for Frozen Rotor consisting of 3.4M cells, see Figure 10;

Thus, in total 5.8M cells (0.4M + 2.0M +3.4M) are used for the open-water calculations using a Frozen Rotor approach and 2.6M cells (0.4M + 2.0M + 0.2M) are used for the open-water calculations with Actuator Disk.

For the thruster-hull calculations the following meshes are used:
- Drillship consisting of 6.9M cells, see Figure 11 to Figure 13;
- Thruster propeller without blades consisting of 2.2M cells, see Figure 15;
- Thruster propeller with blades consisting of 5.4M cells, see Figure 16.

Thus, in total 20M cells (6.9M + 6*2.2M) are used for the complete drillship with 6 thrusters when the blades are not taken into account. When the blades are taken into account for the downstream thrusters the total amount of grid cells is 26.5M cells (6.9M + 2*5.4M + 4*2.2M) when using the Actuator Disk. When using the Frozen Rotor or Sliding Interface approach the grid consisted of 29.7M cells (6.9M + 3*5.4M + 3x2.2M).

In this study we have not carried out a grid sensitivity study as previously done in [11], but we kept the local grid resolution in the wake near the thruster similar to what was used in [11]. For a proper verification and validation study the numerical uncertainty (as well as the experimental uncertainty) should be determined.
Figure 8: Computational mesh for the open-water calculations.

Figure 9: Computational mesh on the surface of the thruster for the open-water calculations. The black lines denote the mesh on the surface of the thruster. Inside the duct and between the two interfaces another domain is taken into account with either blades present or an Actuator Disk model.

Figure 10: Computational mesh in the inside of the nozzle. The black lines denote the mesh on the surface of the duct, hub and blades. Also presented is the mesh on the upstream interface inside the nozzle. Left: the mesh when using the Actuator Disk both in the open-water calculations as in the thruster-hull calculations. Right: the mesh when using the Frozen Rotor or Sliding Interface approach.

Figure 11: Computational mesh around the aft part of the drillship. Presented in white are the interface surfaces around the sub-domain of the thrusters. The black lines denote the mesh on the surface of the drillship and the cylindrical interfaces around the thrusters. The blue lines denote the mesh on the water surface.

Figure 12: Computational mesh around the moonpool of the drillship. The black lines denote the mesh on the surface of the drillship. The blue lines denote the mesh on the water surface.

Figure 13: Computational mesh around the front part of the drillship. The black lines denote the mesh on the surface of the drillship and the cylindrical interfaces around the thrusters. The blue lines denote the mesh on the water surface.

Figure 14: Computational mesh for the sub-domain around the thruster. Presented in white is the interface around the thruster. The black lines denote the mesh on the surface of the thruster and the cylindrical interface around the thruster.
Figure 15: Computational mesh on the surface of the thruster for the thruster-hull calculations without blades. The black lines denote the mesh on the surface of the thruster. The white surface is the strut, the blue surface is the hub, the green surface is the rotating part of the hub and the yellow surface is the duct.

Figure 16: Computational mesh on the surface of the thruster with blades taken into account for the thruster-hull calculations. The black lines denote the mesh on the surface of the thruster. The white surfaces are the strut and blades, respectively. The blue surface is the hub, the green surface is the rotating part of the hub and the yellow surface is the duct.

CFD Code ReFRESCO

ReFRESCO (www.refresco.org) is a community based open-usage CFD code for maritime and offshore applications. It solves multiphase (unsteady) incompressible viscous flows using the Navier-Stokes equations, complemented with turbulence models, cavitation models and volume-fraction transport equations for different phases [13]. The equations are discretised using a finite-volume approach with cell-centered collocated variables, in strong-conservation form, and a pressure-correction equation based on the SIMPLE algorithm is used to ensure mass conservation [6]. Time integration, when used, is performed implicitly with a second-order backward scheme. At each implicit time step, the non-linear system for velocity and pressure is linearised with Picard’s method and a segregated approach is used. A segregated approach is adopted for the solution of all other transport equations.

The implementation is face-based, which permits grids with elements consisting of an arbitrary number of faces (hexahedrals, tetrahedrals, prisms, pyramids, etc.), and if needed h-refinement (hanging nodes). State-of-the-art CFD features such as moving, sliding and deforming grids, as well automatic grid adaptation (refinement and/or coarsening) are also available. Coupling with structural equations-of-motion is also possible and fully Fluid-Structure-Interaction (FSI) is being developed. For turbulence modeling, RANS/URANS, DDES, SAS, XLES, PANS and LES approaches can be used. The code is parallelized using MPI and sub-domain decomposition, and runs on Linux workstations and HPC clusters.

ReFRESCO (v2.3.0) is currently being developed, verified and validated for several maritime and offshore hydrodynamic applications at MARIN in collaboration with a number of universities around the world.

Numerical Settings

Steady-state (for Actuator Disk and Frozen Rotor) and unsteady (for Sliding Interface) calculations are carried out with ReFRESCO. The higher-order unstructured Quick scheme is employed for the space-discretization of the momentum equations and a first-order upwind scheme is used for the turbulence equations.

The SST k-ω turbulence model is used as fully turbulent flow in the wake of the thruster is assumed. No wall functions are employed as the maximum y+ values are below 5 on the thrusters, propeller blades and vessel hull. In the Sliding Interface calculations the time step was chosen to be 30 degrees per time step and the calculations were run for 40 propeller revolutions.

Boundary Conditions

For the bollard-pull calculations a very small inflow velocity is prescribed at the inflow boundary to ensure a direction preference of the flow. The inflow velocity is set to 0.01 m/s unless stated otherwise. The eddy-viscosity ratio $\mu_t/\mu$ and the turbulence intensity $I$ are chosen equal to 1 and 1%. For the pressure a zero normal gradient condition is imposed. At the outflow boundary a constant static pressure is prescribed equal to $p_{ref}$ and a zero normal gradient condition is imposed for all other quantities. At the water surface a free-slip wall condition is imposed, i.e. the normal velocity is set to zero. At the surfaces of the drillship and thrusters a no-slip boundary condition is imposed. A free-slip wall boundary condition is imposed on the tank bottom and side surfaces.

Initial Conditions

The initial conditions for the calculations are defined in each computational cell by setting the velocity equal to the prescribed velocity of the inflow boundary. Furthermore, the pressure is chosen equal to the reference pressure at the outflow boundary and the eddy-viscosity ratio equal to the inflow boundary settings. The Sliding Interface calculations are started from the Frozen Rotor solution.

Iterative Convergence

For most cases the residuals decrease by 5 orders or more. This is commonly considered to be sufficient iterative convergence. For some calculations the forces do not become constant, but they slowly vary by less than 1%. To obtain the forces in these cases the calculated results are averaged over the last 1000 iterations.
Actuator Disk Settings
In the Actuator Disk the forces of the blades on the fluid are modeled. The thrust and torque distributions can be prescribed using formulas, see [11] or taken from the results of a Frozen Rotor or Sliding Interface calculation. In this study they are taken from the calculated Frozen Rotor distribution in open water condition.

CFD RESULTS OPEN-WATER CALCULATIONS
To serve as reference, the open-water characteristics are calculated for the tilted thruster. First, the Frozen Rotor approach is used. Then, the open-water calculation at bollard pull is repeated with the Actuator Disk approach. The input for the Actuator Disk is taken from the Frozen Rotor calculations.

In Figure 17 the calculated results for \( K_{T,\text{prop}} \), \( K_{T,\text{noz}} \), \( K_{T,\text{tot}} \) and \( K_{Q} \) are compared with the open-water experiments. From Figure 17 it can be observed that for the propeller and nozzle thrust the CFD correspond within 2% with the experimental results especially at bollard pull conditions \((J=0)\). Thus, also the total thrust of the thruster is predicted well with CFD. For the propeller torque at bollard pull condition the CFD results over predict the measured values. The reason for this is not clear.

To investigate if the nozzle thrust and unit thrust are the same when using an Actuator Disk approach or a Frozen Rotor approach, the open-water calculation at bollard pull \((J=0)\) is repeated, but now using the Actuator Disk approach. The thrust and torque distribution for the Actuator Disk is taken from the Frozen Rotor calculations with \( T_{\text{prop}} = 7.98 \text{N} \) and \( Q_{\text{prop}} = -0.158 \text{Nm} \).

Table 2: Open-water results at bollard pull condition for tilted thruster for unit and nozzle thrust using Frozen Rotor approach and different thrust and torque distributions for Actuator Disk.

<table>
<thead>
<tr>
<th>Approach</th>
<th>FR</th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD average</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{\text{unit}} [N]</td>
<td>14.54</td>
<td>14.48</td>
<td>14.77</td>
<td>14.81</td>
<td>14.59</td>
<td>14.64</td>
</tr>
<tr>
<td>T_{\text{noz}} [N]</td>
<td>7.34</td>
<td>7.20</td>
<td>7.49</td>
<td>7.54</td>
<td>7.33</td>
<td>7.37</td>
</tr>
</tbody>
</table>

To investigate the sensitivity of the results to the input thrust and torque distribution, this thrust and torque distribution are taken from the four different blades, denoted below by AD1, AD2, AD3 and AD4, respectively. This means that for the AD1 calculation the thrust and torque distribution are taken from blade 1 of the Frozen Rotor calculation and the input for the AD4 calculation is taken from blade 4 as illustrated in Figure 18. The 'AD average’ denotes the thrust and torque distribution by averaging the distributions from blade 1 to 4.

In Table 2 the results for unit and nozzle thrust are presented using the different blade distributions. It can be observed that the calculated unit and nozzle thrust for the average distribution is within 0.6% compared with the Frozen Rotor results and that the results for different blade distributions are within 1% and 2.3% for the unit and nozzle thrust, respectively. In Figure 19 and Figure 20 the thrust and torque distribution for blade 1 to 4 and for the average are presented showing that the differences between the distributions on the blades are small.

From these results it can be concluded that for the tilted thruster in open-water the Actuator Disk approach gives very similar results for the unit thrust and nozzle thrust compared to the Frozen Rotor approach provided that the input for the thrust and torque distribution are taken from the Frozen Rotor approach.

Figure 18: Blade definition for open-water calculations.

Figure 19: Calculated thrust distribution for tilted thruster for different blades and for the average distribution for open-water calculation using Frozen Rotor approach.
Figure 20: Calculated torque distribution for tilted thruster for different blades and for the average distribution for open-water calculation using Frozen Rotor approach.

**CFD RESULTS THRUSTER-HULL INTERACTION**

In this section the results for thruster-hull interaction are presented. The definition of the thruster loss $\eta$ is defined in Equation (5). The results are obtained using three different approaches for the active thruster: the Actuator Disk, the Frozen Rotor and the Sliding Interface. The results are compared to experimental results. For the downstream thrusters the propeller blades are included, unless stated otherwise.

**Actuator Disk results**

The active thruster is modeled by the Actuator Disk with the settings used in the open-water calculations. In Figure 21 the results for the thruster-hull interaction are presented for active thruster 1 and 3, respectively. It can be observed that for the azimuth angles without thruster loss in the experiments the CFD results also do not predict an interaction loss. For the azimuth angles with thruster loss the difference is between 2-6% for both thrusters 1 and 3 when compared with the experimental results.

For thruster 1 at 180 degrees the thrust loss is slightly over-predicted by 8%. The reason for this is not clear at the moment. For this situation the wake hits the skeg of the vessel and attaches to the hull further downstream as illustrated in Figure 27. The overestimation of the thrust loss suggests that the wake might be deflected upwards more than in the experiments. For the bollard pull calculation an incoming velocity of 0.01m/s is prescribed, which might deflect the wake upwards. However, we also carried out a calculation with 0.001m/s and hardly any difference in thruster interaction was observed, i.e. 72.3% versus 71.7%.

Furthermore, as shown later in this paper, the unsteady result for this azimuth angle using the Sliding Interface method is very similar to the result with Actuator Disk. This indicates that unsteady effects in the wake between thruster and skeg are not the reason for this observed difference.

Note that from Figure 21 it can be observed that the CFD results are very close to either the clock-wise or the counter-clock-wise experimental results. In the experiments the thruster is slowly rotated causing the wake to stick to the hull for either the clock-wise or the counter-clock-wise measurement depending on the direction of rotation. Stationary experimental results are only available for a very limited number of azimuth angles. As CFD calculations are carried out with stationary thrusters this rotating effect is not present in the CFD results and therefore the CFD result is close to one of the clock-wise or counter-clock-wise measurements. To illustrate this the calculated wake behind the active thruster is presented for thruster 1 at 210 degrees in Figure 22.

From the results presented in this section we conclude that when using an Actuator Disk approach the trend in thruster-hull interaction is very well predicted compared with the experimental results. The calculated wake of the active thruster shows a physical shape and path. The main disadvantage of the
Actuator Disk approach is that the thrust and torque distribution has to be prescribed from either Frozen Rotor results or using formulas. These distributions may not be valid for the conditions considered. Care should be taken when the configuration is different from an open water situation, for instance with incoming current or when the inflow to the thruster is not uniform.

Figure 22: Velocity distribution in the wake of thruster 1 with azimuth angle of 210 degrees.

**Actuator Disk results without downstream propeller blades**

For two headings calculations are carried out without the downstream propeller blades to investigate the effect of the presence of these blades on the thruster loss. A significant amount of computational cells is required to capture the blades, thus calculation time is saved when these are left out.

However, from Table 3 it is clear that without the downstream propeller blades the thruster interaction loss is largely underestimated. This effect can be illustrated by the pressure distribution on the hull and downstream blades as shown in Figure 23 for the active thruster 1 at azimuth angle of 210 degrees and in Figure 24 for the active thruster 3 with azimuth angle of 90 degrees.

From the results presented in this section we conclude that the downstream thruster geometry including propeller blades should be considered to properly determine the thruster interaction effects.

**Table 3: Results for thruster-interaction with and without downstream propeller blades included.**

<table>
<thead>
<tr>
<th>Thruster &amp; angle</th>
<th>Interaction η</th>
</tr>
</thead>
<tbody>
<tr>
<td>With blades</td>
<td>Without blades</td>
</tr>
<tr>
<td>T1 - 210 deg</td>
<td>0.60</td>
</tr>
<tr>
<td>T3 - 90 deg</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Figure 23: Pressure distribution for thruster 1 active at 210 degrees with blades of downstream thrusters taken into account. The green iso-surface inside the nozzle of thruster 1 denotes the Actuator Disk.

Figure 24: Pressure distribution for thruster 3 active at 90 degrees with blades of downstream thrusters taken into account. The green iso-surface inside the nozzle of thruster 1 denotes the Actuator Disk.

**Frozen Rotor results**

The main disadvantage of the Actuator Disk approach is that the thrust and torque distribution has to be prescribed before the calculation. In the Frozen Rotor approach these distributions are calculated so no assumptions on the propeller have to be taken. The Frozen Rotor calculations are steady, but the propeller geometry has to be included requiring slightly more calculation time (~20%) than when using the Actuator Disk. The typical calculation time for each heading is 23 hours using 160 cores for the mesh with 29.7M cells.

In Figure 25 the Frozen Rotor results are compared with the experimental results and with the Actuator Disk results. For some headings the results with Actuator Disk and with Frozen Rotor are very similar to each other, for instance for 210
degrees. For most headings the Frozen Rotor results indicate a lower interaction than with Actuator Disk or in the experiments.

The nozzle and propeller thrust with both methods is very similar to each other, but the forces on the vessel and on the downstream thrusters are different between the two methods. This can be illustrated by comparing the wake behind the thruster and the pressure distribution on the vessel as shown in Figure 27. When using a Frozen Rotor approach the shadow of the blades is visible in the wake behind the active thruster. This is non-physical behavior. As a result the pressure distribution on the skeg, which is located directly behind the active thruster, is different. In this case the pressure is lower on part of the skeg, which can be seen by comparing Figure 27(c) and Figure 27(a), resulting in a lower loss when using the Frozen Rotor approach.

Based on the results presented in this section, we conclude that the Frozen Rotor approach is not a suitable method to determine the thruster-hull interaction as the wake behind the thruster is not physical.

![Figure 25](image)

**Figure 25**: Results for thruster-hull interaction comparing experimental results (solid lines) with CFD results using an Actuator Disk (green circles) or Frozen Rotor (red triangles) for thruster 1. For the experiments two curves are presented, one when the active thruster is rotating clock-wise (CW) and one when the active thruster is rotating counter-clock-wise (CCW).

**Sliding Interface results**

Theoretically, the most accurate approach is to perform unsteady calculations with so-called Sliding Interfaces where the rotating propeller blades are taken into account. However, the wake of the thruster has to be developed long enough in time to account for the correct interaction with the hull. As a result, the calculation time using the Sliding Interface approach is at least 20 times more than with the Actuator Disk, making it a costly method when multiple azimuth angles have to be considered.

In this paper three azimuth angles are considered for thruster 1 and the results are compared to the Actuator Disk results and experimental results in Figure 26. Using the Sliding Interface approach, very similar results are obtained compared with the Actuator Disk results. Note that only 3 azimuth angles have been considered, so to be able to state this as a general conclusion more azimuth angles should be calculated using the Sliding Interface approach.

In Figure 27(e) and (f) the pressure distribution on the hull of the vessel and the velocity distribution in the wake of the active thruster are presented using the Sliding Interface results. When comparing these results to the results using the Actuator Disk, see Figure 27(a) and (b), only small differences can be observed.

From the results presented in this section we conclude that the Sliding Interface results are very similar to the Actuator Disk approach in terms of interaction, pressure distribution on the hull and velocity distribution in the wake. Due to the long calculation times, we conclude that the Sliding Interface approach is not very efficient when the interaction has to be determined for multiple azimuth angles. Furthermore, we conclude that the Actuator Disk is a very efficient and accurate alternative to determine the thruster-hull interaction due to the very similar results compared to the Sliding Interface results and the short calculation times.

![Figure 26](image)

**Figure 26**: Results for thruster-hull interaction comparing experimental results (solid lines) with CFD results using an Actuator Disk (green circles) or Sliding Interface (orange diamonds) for thruster 1. For the experiments two curves are presented, one when the active thruster is rotating clock-wise (CW) and one when the active thruster is rotating counter-clock-wise (CCW).

**CONCLUSIONS AND RECOMMENDATIONS**

In this paper the use of CFD is investigated to calculate thruster-hull interaction under a drill-ship with 6 azimuthing thrusters. Furthermore, open-water calculations for a tilted thruster have been carried out using a Frozen Rotor approach and an Actuator Disk approach and the results have been compared to experimental results.

From the open-water calculations it can be concluded that using a Frozen Rotor approach the propeller and nozzle thrust from the CFD correspond well with the experiments especially at bollard pull conditions. Thus, also the total thrust of the
thruster is predicted well with CFD. For the propeller torque at bollard pull the CFD results overpredict the measured values. The reason for this is not clear. The Actuator Disk approach gives very similar results to the Frozen Rotor approach provided that the input for the thrust and torque distribution are taken from the Frozen Rotor approach. The results for the nozzle and unit thrust using the average blade distribution with Actuator Disk are within 0.6% compared with the Frozen Rotor results. Furthermore, compared with the averaged distribution the results for different blade distributions are within 1% and 2.3% for the unit and nozzle thrust, respectively.

For the thruster-hull interaction calculations three approaches to model or simulate the active propeller have been investigated, i.e. Actuator Disk, Frozen Rotor and Sliding Interface approach. Based on the results the following conclusions seem justified:

- With an Actuator Disk approach good results can be obtained for the thruster-hull interaction at bollard pull conditions compared with the measurements;
- To accurately predict interaction loss it is important to consider the complete geometry, i.e. including downstream propeller blades;
- With the Actuator Disk and with the propeller blades included for the downstream thrusters the interaction effects were predicted within 2-6% compared to the experimental results;
- One exception to the previous conclusion was found, i.e. for thruster 1 at 180 degrees an overestimation of 8% for the thrust loss was found. The reason for this is not clear at the moment as a lower inflow velocity or unsteady effects in the wake were found not to be the reason for this overestimation;
- The results using the Actuator Disk and the Sliding Interface approach are very similar to each other for the pressure distribution on the vessel, the velocity distribution in the wake and the thrust interaction loss;
- The results using the Frozen Rotor approach slightly underpredict the measured results and deviate from the Actuator Disk results due to a different calculated wake. Therefore, we recommend not to use the Frozen Rotor approach to determine the thruster-hull interaction;
- The Sliding Interface approach is the most accurate approach of the investigated methods. It does not require input assumptions on the propeller and unsteady wake effects are included in the calculation. However, the calculation times are at least a factor 20 more than for the Actuator Disk approach making the Sliding Interface method expensive to use for thruster-hull interaction where multiple azimuth angles and multiple configurations need to be considered.

The following recommendations for thruster-hull interaction calculations can be made:

- The thrust and torque distribution in the Actuator Disk model are taken from an open-water calculation using the Frozen Rotor approach. These distributions can also be taken from a Frozen Rotor calculation with the thruster placed under the drillship. It should be investigated if this approach results in better predictions for the thruster-hull interaction and what the computational costs are. However, we expect that the difference is small as the active thruster is below keel level in a nearly open-water flow environment.
- Unsteady behavior of the thruster wake when the thruster is slowly rotating, as done in the experiments, has not been investigated. Despite the high calculation times required these unsteady effects should be investigated to determine their influence. This could explain the difference between the clock-wise and counter-clockwise experimental results.

Based on the results presented in this paper we conclude that, using the steady-state approach with the Actuator Disk, CFD can be a cost-efficient and accurate method to determine the thruster-hull interaction effects under a typical offshore vessel.

We remark that the CFD calculations have been carried out at model-scale to be able to compare the results to experimental results. It is recommended to also carry out calculations at full-scale to determine the scale effects on thruster-hull interaction. We expect that for friction dominated forces, such as the force on the hull of the vessel, the interaction effects for full-scale can be different than for model-scale. For pressure dominated forces, such as the force on the skeg or a downstream thruster due to the wake hitting these objects, we expect that the thruster-loss is similar at full-scale as at model-scale. However, these expectations have to be investigated and quantified.

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Figure 27: Flow solutions for thruster 1 active at 180 degrees for pressure (left column) and velocity (right column) using Actuator Disk, which is denoted by the green iso-surface (top row), Frozen Rotor (middle row) and Sliding Interface (bottom row).