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Improved DP-capability with tilted thruster units and smart controls algorithms

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Abstract

With the introduction of the 8° tilted thruster units, a large step forward has been made in the DP-capability of a vessel. The contribution of two main factors to the thrust loss, being hull-interaction and thruster-thruster interaction are now well understood. A third factor, which plays an important role is the algorithm for the thrust allocation of the various thrusters in operation. A virtual model has been made, in which the hull-interaction losses and the forbidden zones due to thruster-thruster interaction have been taken into account for a drill ship. Clear gains in performance can be obtained when a smart thrust allocation algorithm is used. In the paper the modern concepts (8° tilted units, smart controls) will be compared to conventional configurations to indicate the possible improvements.

Abbreviation / Definition

MC = Merit Coefficient
MM = moving mesh
MRF = multiple reference frame
OG = overlapping grid

1. Introduction

In the past the majority of the developments in improving the dynamic positioning capability of a vessel were focussing on the controls side. For simplicity the expected bollard pull thrust of the various azimuthing thrusters was related to the installed power. This simple approach of T/P=0.18 [kN/kW] has been used often and it could be found in the IMCA 140 document [1]. The thruster-hull interaction losses were implemented by a single reduction factor often.
Implementation of the so-called forbidden zones to avoid the thruster-thruster interaction has led to a more complex system. The naming of these interaction zones suggests that operation within these zones is dangerous, where in fact it is just not efficient. Avoiding certain steering angles will improve the overall thrust generation, but is not necessary from a safety or mechanical point of view.

With the improved knowledge of the performance of and the occurring flow phenomena around the azimuthing thrusters, it has been recognized that part of the optimization of the dynamic positioning capability can be found on the thruster side as well. This has been clearly recognized in the ABS DP calculation method [2], where various features are implemented on for example the impact of power density on thrust performance and on the benefits of tilted thruster units on thruster-hull interaction losses. The impact of power density can be directly translated in the choice of the propeller diameter of the thruster unit. This provides insight in performance gains when the choice between unit costs (Capex) and unit performance (Opex) has to be made.

The impact of the tilted thruster units is less straight forward, due to the various applied concepts of tilt and due to the differences in hull forms. Up to a tilt angle of about 5° it is possible to use a conventional 90° gearbox system for the azimuthing thruster. For larger nozzle tilt angles the propeller design and blade tip clearance will be compromised too much, leading to high thrust losses not weighing up to the gains. However, it has been found that the optimum tilt angle is about 8° [3]. For these kind of tilt-angles, it is required to use a gearset of 82°, to align the propeller shaft with the nozzle. An additional benefit of the alignment of the propeller and the nozzle is the option to use a smaller propeller blade tip clearance, which contributes to the optimum bollard pull performance.

Once the actual full scale unit bollard pull performance and the thruster-hull interaction losses have been determined, a DP-capability calculation of a vessel with multiple thrusters can be made. In such analysis the net available thrust per unit can be taken into account properly in order to determine the overall thrust

for each azimuth angle. For this calculation also the thruster-thruster interaction effects need to be taken into account. This can be achieved by implementation of the forbidden zones, as presented before [4].
In case of drill ships, where often three units are located close to each other, either in the bow or in the stern, it is possible that two forbidden zones overlap. In such case one large forbidden zone is formed. Since the actual sizing of the forbidden zones is based on optimum performance, it has been investigated what the impact is on DP-performance in case two forbidden zones overlap.

Next step which needs to be taken into account in the calculation of the DP-capability of a drill ship is the evaluation of the yawing moment. The forces need to be balanced in such way that the total yaw moment is eliminated. Balancing the thrust vectors of the different thruster units can be achieved in two ways, either 1) by reducing the magnitude of the thrust vector or 2) by changing the direction of the thrust vector. In case the steering angle of a thruster unit is changed, the lever arm to the ship centre point will change. As long as the steering angle adjustments are fairly small, more nett thrust remains, when compared to the modification of the thrust magnitude.

Next to the evaluation of the DP-capability of the azimuthing thrusters, also the performance in transit can be reviewed. One of the important questions is whether the improvements of the thruster-hull interaction phenomena are present in transit conditions. Besides the straight course sailing operation, steering of the thrusters in transit has been reviewed. Based on this evaluation, the most critical operating condition of a vessel has been determined, where high power, transit speed and large steering angles are combined. With proper knowledge of the worst case scenarios, operation of the vessel can be optimized to avoid these conditions and conditions with severe torque fluctuations which can have an impact on the lifetime of the thruster gears, can be avoided.

In this paper a comparison of the DP-capability will be made between a Wärtsilä WST-thruster with 8° tilted shaft (propeller and nozzle tilted) with 82° gearbox and a reference unit based on a configuration which is often applied in industry with a 5° tilted nozzle and a 90° gearbox. The used thruster geometries are shown in Figure 1. The alignment of the nozzle with the propeller for the 8° tilted unit can be recognized clearly. The 5° difference in alignment between the propeller and the tilted nozzle is indicated by the rectangular arrows inside of the nozzle. The propeller for the unit with the 5° tilted nozzle is adapted slightly in the tip region in order to avoid collision with the nozzle.

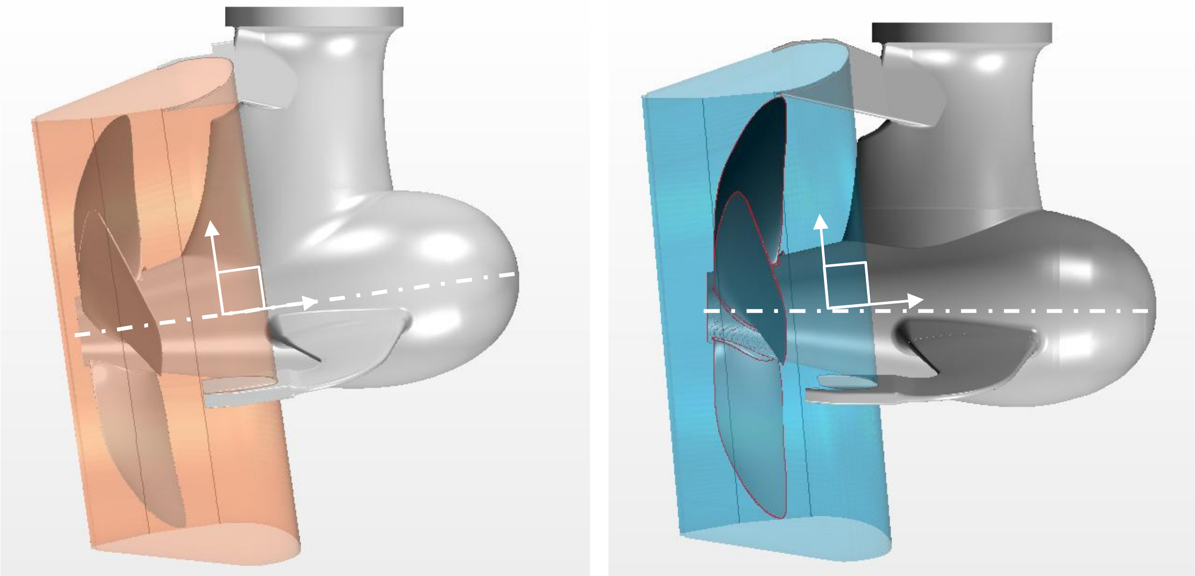

Figure 1: geometries of Wärtsilä WST-thruster with 8° tilted shaft and reference thruster unit with 5° tilted nozzle

2. Thruster performance evaluation methodology

The performance of the two thruster geometries has been determined, based on numerical flow simulations (CFD) on full scale using the commercial code StarCCM+. The actual full scale dimension are used in order to eliminate the impact of the Reynolds scaling effects. Research has shown that the scaling effects of steerable thrusters in bollard pull condition are significant [5].
Before the full scale CFD simulations can be used for analysis of the flow field, it is a necessity to carry out proper validation of the simulations. At the moment, a comparison of model scale experiments and CFD simulations of a steerable thruster is still the best way to validate the numerical approach. Results of the CFD validation process within Wärtsilä Propulsion have been presented before [4] and this validated methodology has been used as a basis for the currently presented results.

In the following sections a comparison will be made between the thruster configurations with 8° tilted shaft and with 5° tilted nozzle. For the open water performance calculations the quasi-steady multiple reference frame approach will be used. For the simulations where the interaction with the hull will be taken into account, a fully transient solution approach is required in order to solve the wake from the thruster properly. The specific issues regarding the implementation of the moving mesh will be discussed in more detail in section 2.2.

2.1 Open water unit performance

The CFD simulations for the open water performance determination of the two thruster configurations have been carried out in accordance with Wärtsilä internal guidelines. Figure 2 shows a cross-sectional view of the generated mesh for the 8° tilted thruster unit. For this unit two approaches have been compared, one where the background mesh was aligned with the inflow and one where the mesh was aligned with the propeller and nozzle. Results from both simulations were identical, which is a clear indication that the mesh impact on the results is negligible.

The CFD simulations have been carried out for the full-scale geometry in order to eliminate the Reynolds scaling effects. During the validation phase of the CFD simulations, comparisons have been made for model scale thrusters. It has been found that the Reynolds scaling effects are playing a role in the performance of the ducted propeller and for the drag of the thruster housing and strut. Therefore it has been decided to run all thruster simulations on the actual full scale, which might leave a small uncertainty due to lack of proper full scale validation material. This is still preferred above the very accurate results on model scale, which have certainly a larger off-set to the actual performance value.

An alternative performance evaluation procedure has been developed based on the axial pump efficiency of the ducted propeller system [5]. With this approach the actual pump efficiency both on model scale and full scale have been derived from the CFD simulations. The found pump efficiency are well in line with values which can be found in literature [6], ranging from 83% on model scale to 89% at full scale. Consistent application of this approach provides performance indicators, which enhance the confidence in the full scale values even more.

The use of the full-scale geometry in combination with time-dependent solutions puts emphasis on the limitation of the total cell count in the mesh to remain within acceptable timeframes for the calculations. To reach the optimum number of cells, it has been chosen to use so-called wall functions to solve the development of the boundary layer along the propeller, nozzle and thruster housing. The RANS equations are solved with the standard two equation k-ε turbulence model.

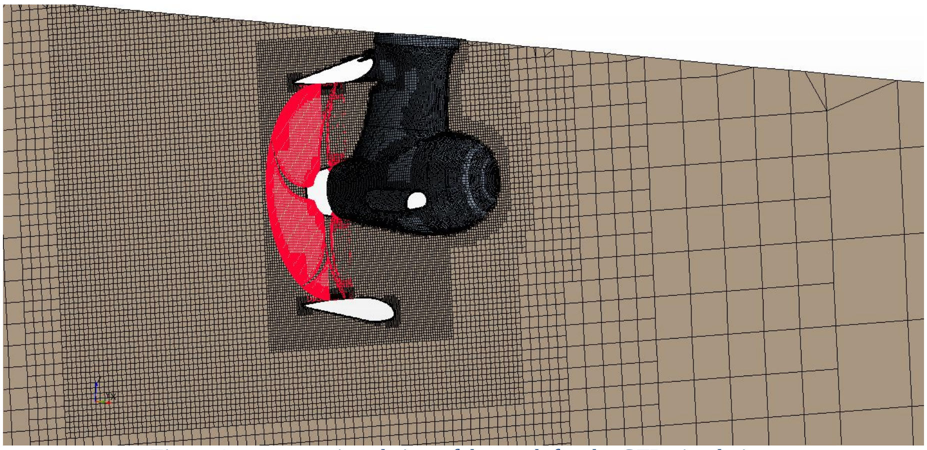

Figure 2: cross-sectional view of the mesh for the CFD simulations

The open water curves for both thruster configurations are shown in Figure 3. The total unit thrust of both thruster types is comparable over the whole range of advance coefficients. The contribution from the nozzle thrust shows a clear off-set however. The lower nozzle thrust for the 5° tilted nozzle is compensated by the higher propeller thrust. This higher propeller thrust is accompanied with a higher propeller torque however. Consequently the thrust/power ratio (T/P) at bollard pull/dynamic positioning mode is better for the 8° tilted shaft configuration, where the total thrust is slightly larger and the required torque at the same propeller RPM is clearly reduced. Up to an advance coefficient of J=0.6, which is representative for a ship speed of about 14 knots, the open water efficiency of the unit with shaft tilt is performing better.

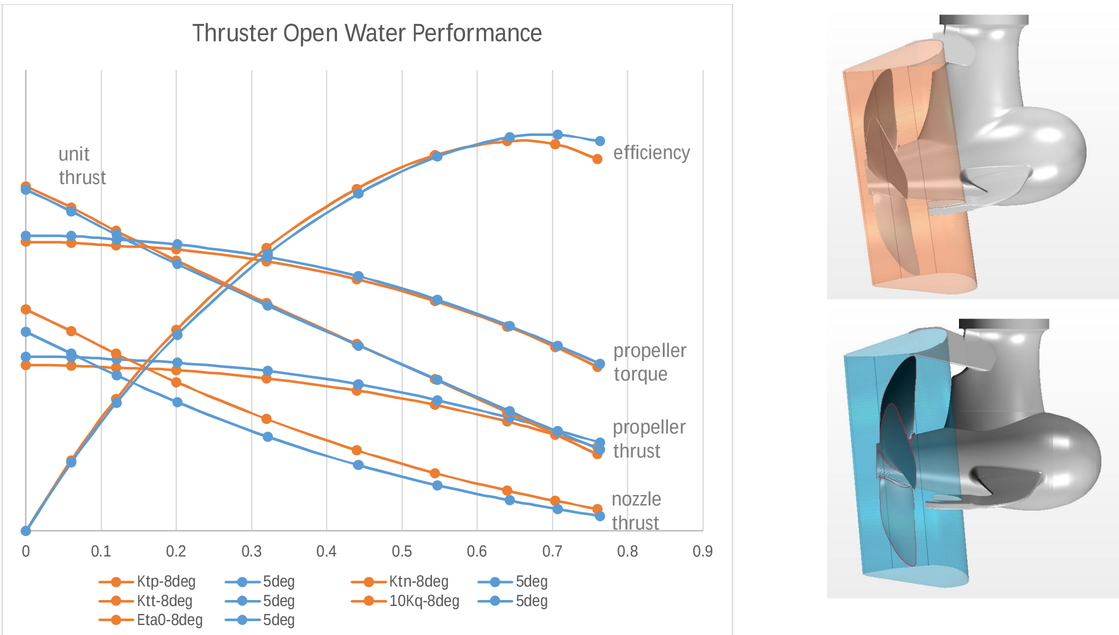

Figure 3: thruster open water performance for 8° tilted shaft unit and 5° tilted nozzle

The performance in DP mode, based on the ratio of total thrust/power (T/P) can be evaluated with the so-called Merit Coefficient (MC).

$$\frac{T}{P} = \frac{\rho \cdot MC^2}{\sqrt[3]{\left(P \Big/ \frac{\pi}{4} D^2 \right)}} \quad (1)$$

$$MC = \frac{(K_{tt}/\pi)^{3/2}}{K_q} \quad (2)$$

The Merit Coefficient is a measure for the hydrodynamic efficiency of the thruster design, which can be recognised in the streamlining of the housing, and the design of the nozzle and propeller. In order to get the highest Merit Coefficient it is important to minimize the propeller tip clearance in the nozzle. With a smaller clearance there is less flow through the gap from the blade pressure side to the suction side. The reduction of the Merit Coefficient due to the nozzle tilt leads to a reduction of thruster performance of about 2.2% thrust for equal power. This corresponds to 3.3% extra power requirement to reach a certain thrust level. For overall thruster performance the power density plays a role as well, as shown in Eqn (1). Increase of propeller diameter for the same power settings, therefore leads to improved performance of about 3.3% in thrust.

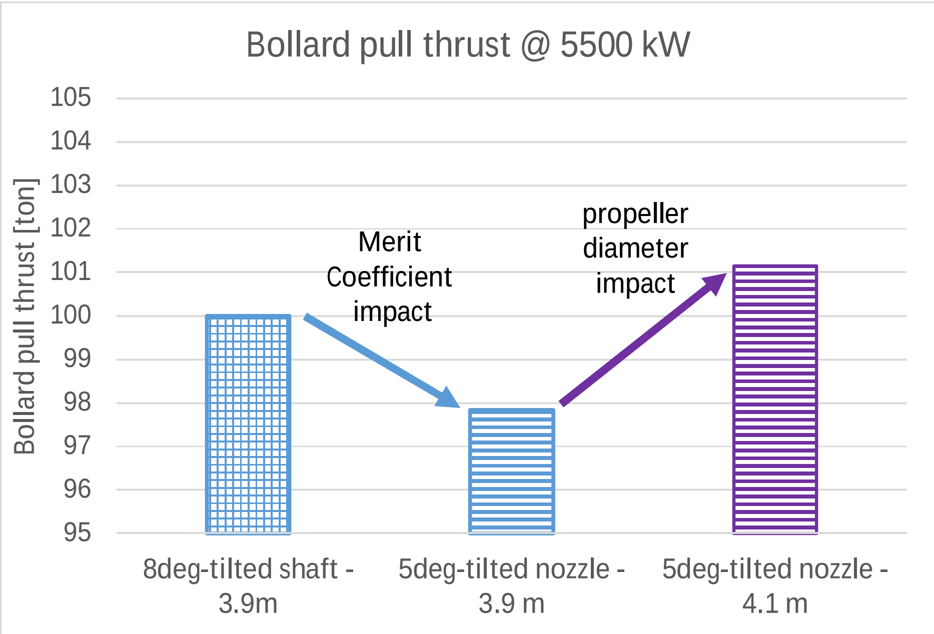

Figure 4: thruster bollard pull @ 5500 kW

The results from Figure 4 show that the reduction in hydrodynamic performance of the tilted nozzle can be compensated by a larger propeller diameter (-2.2% + 3.3%). Obviously, the overall unit performance of the 8° tilted shaft configuration would increase also with 3.3% in thrust in case the larger propeller diameter of 4.1 meter would be analysed.

In the next section, the impact of thruster-hull interaction will be reviewed in more detail. That analysis will show that the difference of about 1% in open water performance is small when compared to the difference in performance due to the hull interaction.

2.2 Performance under hull: thruster-hull interaction

The overall dynamic positioning capability of a vessel does not only depend on the thruster unit performance, but also to the thruster-hull interaction losses. With the introduction of the tilted units, either by nozzle or shaft tilt, the thruster-hull interaction losses have been reduced. This has been quantified by model scale experiments in various experiments [7-9]. Research on numerical simulations have proven that a fully transient calculation method is required to get the wake out of the thruster calculated correctly [10]. The fully transient moving mesh calculations require a moving mesh to model the actual dynamics of the rotating propeller properly. This moving mesh can be implemented in two ways, either by a sliding interface approach or by the more numerically expensive overlapping grids. In the sliding interface approach both parts of the mesh move along each other. The interface geometry for such approach needs to be axi-symmetrical, and preferably cylindrical. The other approach based on the overlapping grid (OG) methodology can be applied for any arbitrary mesh movement. In this way to different grids can move independently from each other and through a sophisticated interpolation scheme the two meshes (and solutions) are being coupled.

For thruster units where the shaft and nozzle are aligned, which can be either the conventional designs or the tilted shaft configurations, the moving mesh option can be applied without problems. For the thrusters with tilted nozzle, the moving mesh approach becomes more challenging.
To solve the issue of the misalignment between propeller and nozzle, the overlapping grid (OG) option needs to be used. The varying blade-tip-nozzle clearance is taken into account properly in this approach, and therefore the impact on the blade loading as well. With proper validation during the implementation of the overlapping grid method, it can provide the right flow field solution for both the aligned and the misaligned propeller-nozzle configurations. To be able to have the most correct comparison the OG method was used in both cases.

One of the important results from the flow simulations is the determination of the downward deflection of the wake, since that determines the thruster-hull interaction losses to a great extent. The calculated wake out of the thruster is shown in Figure 5 for the 8° tilted shaft configuration and the reference unit with 5° tilted nozzle. The deflection of the wake is indicated by the orange arrow. In both cases, the jet out of the thruster has a divergence angle of about 4°, which is reflected by the two dotted lines. Comparison of both configurations shows a clear difference in behaviour.

The calculated mean and minimum direction of the wake is listed in Table 1. In this table also the numbers for a conventional thruster without any tilt angle are listed, based on the outcome of previously performed CFD analyses [4]. Even though the values seem quite close for both configurations, it should be realised that there is a significant difference between the different variants. In case a positive minimum wake deflection is found, the wake will have an upward component and therefore it will interact with the hull. Once the wake interferes with the hull at some distance downstream of the thruster, hull interaction losses will occur and the additional losses due to the Coanda effect need to be taken into account as well.
However, in case the minimum value is negative the distance between the wake and the hull surface is continuously increasing, which will eliminate the hull-interaction. This trend is in agreement with the findings of Jürgens et al. [11], where the optimum tilt angle of 8° is shown and in agreement with the tilt-correction curve as implemented in the ABS Dynamic Positioning guide [12].
Evaluation of the minimum tilt angle shows that the effectiveness of the configuration with 5°-nozzle tilt is about half compared to the effectiveness of the 8° tilted shaft configuration when compared with a conventional straight thruster unit. This can also be observed in the ABS correction factor for thruster-hull interaction.

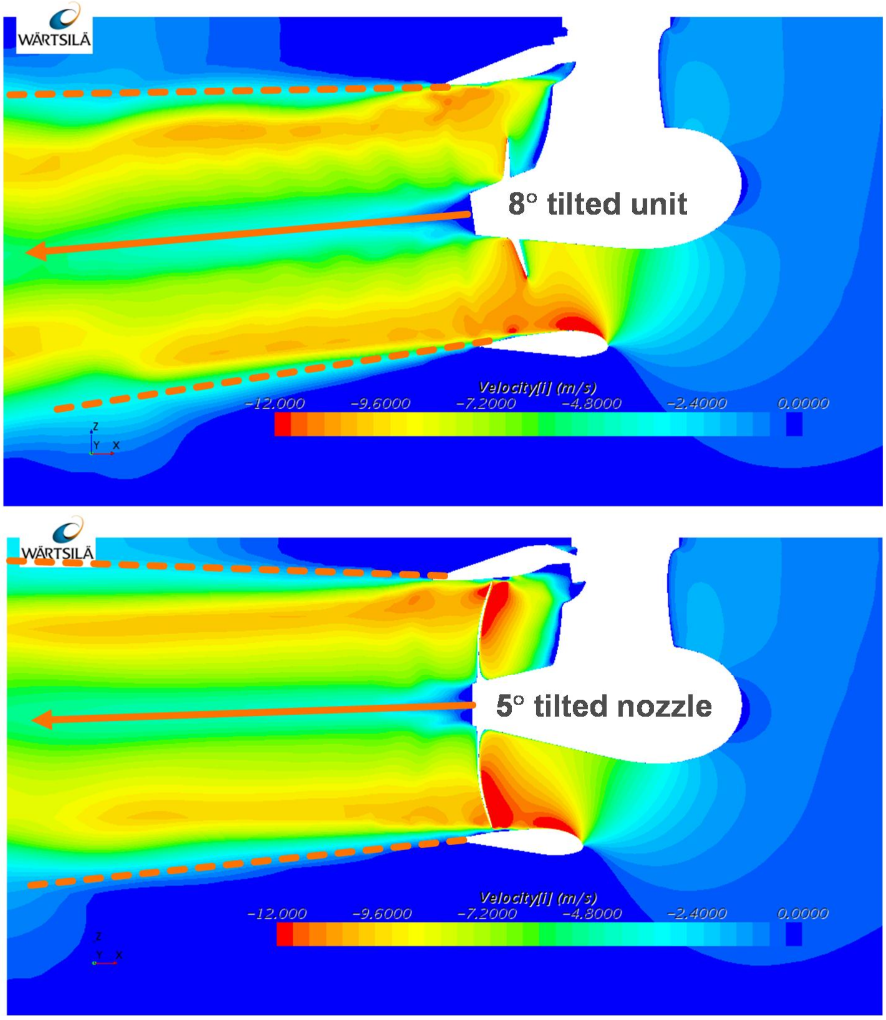

Figure 5: comparison of calculated wake of 8° tilted shaft and 5° tilted nozzle configuration

Type	Average wake deflection	Minimum wake deflection
8° tilted shaft	-5°	-1°
5° tilted nozzle	-2°	+2°
0° - conventional	0°	+4°

Table 1: calculated wake deflections for 8° tilted shaft, 5° tilted nozzle and straight conventional configuration

2.3 Thruster interaction impact on DP capability

The knowledge on the impact of the thruster configuration on the thruster-hull interaction losses can be used to determine the actual thruster performance over the complete 360°-azimuth range. After the calculation of the thruster-hull interaction losses for each thruster unit on board, the forbidden zones due to thruster-thruster interaction can be calculated. Based on the data of the thruster interaction losses an improved DP calculation can be made in which the actual performance is considered. Figure 6 shows the thruster performance of the two thruster configurations for a drill-ship with 6 thrusters. This performance data will be used in the DP-capability calculations in section 3.

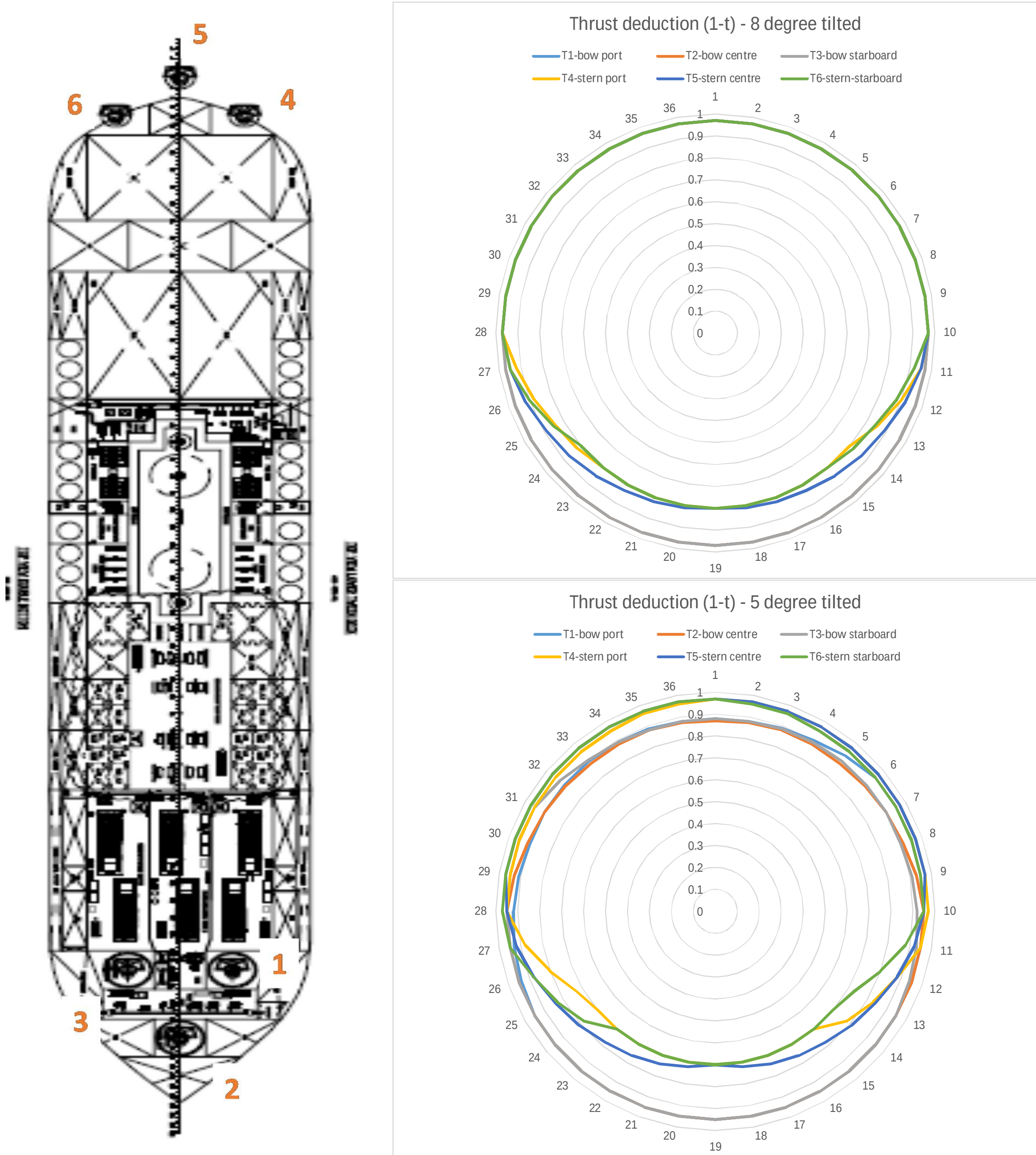

Figure 6: thruster performance including thruster-hull interaction losses

3. Drill ship thrust allocation strategy

In order to reach the maximum thrust in each azimuthing direction the contributions of the various units need to be balanced. Besides the losses due to thruster-hull interaction as discussed in the previous section, also the so-called forbidden zones need to be implemented in the overall thrust allocation strategy. It should be noted that the name 'forbidden zone' might be misleading, since it indicates a zone of significantly reduced performance due to thruster-thruster interaction effects. Thus, in case a thruster is being operated within a forbidden zone, it is not directly harmful for the thruster unit, but for the performance of the overall Dynamic Positioning system.
In the strategy described below, only the largest available thrust for a certain angle is compared for different thruster units to get a better inside in the differences in thruster units and allocation strategies. The environmental forces due to wind and current are not taken into account at this point.

3.1 Thruster-thruster interaction – forbidden zones

Thruster-thruster interaction can be based on the data as provided by ABS [12] or it can be derived from CFD simulations, in which the performance of two operating thruster units at different steering angles and distances need to be determined. The forbidden zone calculations for both a straight conventional unit and the 8° tilted shaft unit have been presented in 2013 already [4]. The impact of the tilted shaft on the forbidden zones has been derived from these CFD simulations. The differences between 5° tilted nozzles and 8° tilted shafts related to forbidden zones are moderate when distances of 10 propeller diameters or less are considered. Therefore, forbidden zones for thrusters with 5° tilted nozzles are calculated in the same way as for 8° tilted shaft designs, even if the latter is more favourable.

3.2 Effective unit thrust

The effective unit thrust is a combination of the actual thruster unit open water performance, as discussed in section 2.1, the thruster-hull interaction losses as presented in section 2.3 and the forbidden zones based on the thruster-thruster interaction. The thrust allocation strategy needs to be optimized in order to reach the largest total thrust in any direction. As mentioned before, the algorithm has to eliminate the yaw moment in the static operating condition. Two different approaches to get the different thrust vectors balanced will be discussed in the following sections. The different steps of the strategy are shown in the diagram of Figure 7, where the first option only uses load balancing and the second a combination of angle adjustment and load balancing.

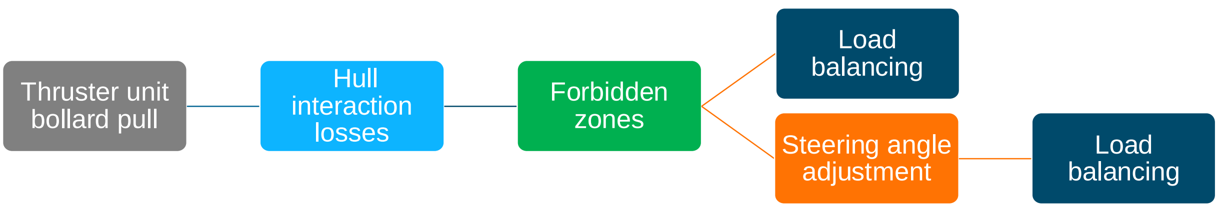

Figure 7: thrust allocation strategies

3.3 Forces and moments balancing by load balancing

The thrust allocation strategy based on the load balancing is the simpler model of the two. For each thruster the net-unit thrust based on the hull-interaction losses is calculated. In the next step it is checked whether the steering angle of the thruster is outside the forbidden zones. In case it is inside a forbidden zone, the algorithm calculates the minimum deflection angle to stay outside of the forbidden zone. In the third step the contributions of the various thruster units are summarized and the contribution to the yaw moment of each unit is calculated. In order to eliminate the resulting yaw moment, the loads of the thruster units with the largest contribution are adjusted. This process is repeated for each direction to determine the polar DP-plot for the vessel.

In case of thruster failure modes, the impact of the load balancing can become quite significant. The impact of differences in thruster-hull interaction losses can result in an unexpected difference in thrust forces generated in the bow and the stern, which in turn will result in larger load balancing impact.

3.4 Forces and moments balancing by steering angle adjustment

The second thrust allocation strategy as mentioned in Figure 7 is based on a combination of the adjustment of the steering angle and load balancing. The adjustment of the steering angles is applied to a number of units with the largest contribution to the yaw moment. Depending on the layout of the vessel and the direction of the environmental force, the contributions of the different units to the yaw moment can be modified by adjustments in the steering angle. The additional load balancing factor can therewith be reduced significantly, which results in a significantly increased total thrust.

A calculation has been made for the configuration with 8° tilted shaft and the reference unit with 5° nozzle tilt. As shown in Figure 4 the unit thrust performance of the larger unit (4100 mm) with 5° nozzle tilt is about 1.2% better compared to the smaller unit (3900mm) with tilted shaft. Nevertheless, the overall thrust performance of the 8° tilted shaft configuration is on average 3.5% better for the same amount of installed power, when both units are compared as shown in Figure 8. In case a comparison is made on the same overall DP-thrust performance, the 8° tilted shaft configuration will consume about 5.3% less power.
The largest difference in performance is found in astern direction, where the thruster-hull interaction is largest. It can also be observed that the performance of the 8° tilted shaft unit is exceeding the performance of the reference unit over the full 360° azimuth angle.

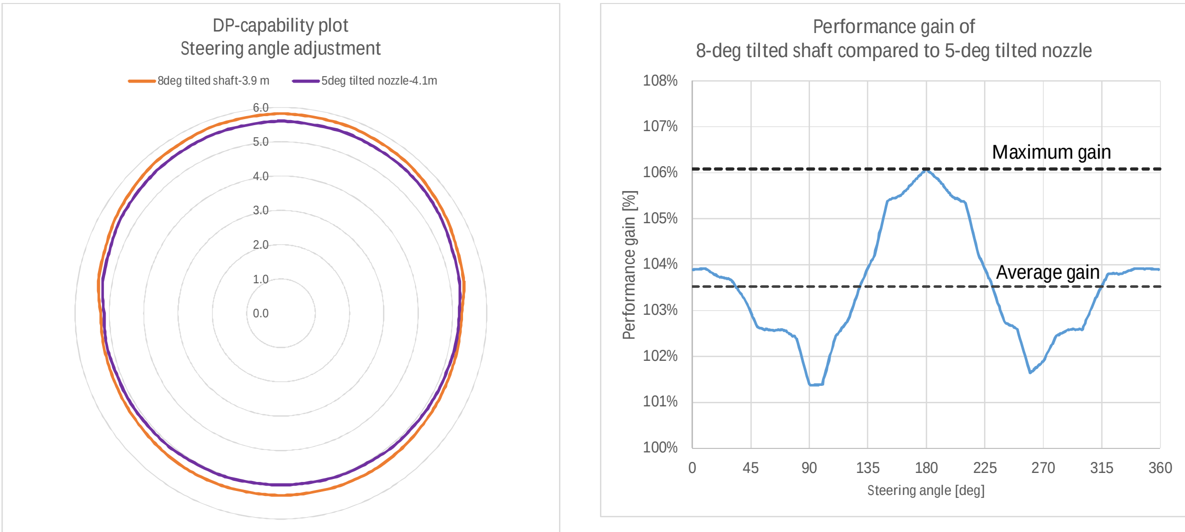

Figure 8: DP-capability comparison between 8° tilted shaft and 5° tilted nozzle configuration for 6 thrusters @ 5500 kW

4. Smart controls

As shown in Figure 7, different strategies can be followed to eliminate the yaw moment of the vessel due to the different contributions of the thrusters. The differences are only based on the controls strategy and the impact will be discussed in mode detail in the following section.
Another situation, where the controls strategy can make a difference, occurs when two forbidden zones overlap. In such situation one large forbidden zone might be implemented. An alternative solution, which provides better performance will be discussed in section 4.2.

4.1 *Gains from steering angle adjustment*

The impact of the thrust allocation algorithm to eliminate the yaw moment will be discussed in this section. This analysis is presented to create awareness of the impact of the controls strategy next to the overall hydrodynamic performance of the thruster units. Once the unit performance has been optimized and the thruster-interaction losses minimized, the next focus point is on the actual operation of the units to maximize the thrust over the whole 360° sector.

Figure 9 shows the comparison of the DP-capability plot for the situation in which the yaw moment is eliminated based on the load balancing approach and for the situation where the steering angles are adjusted. The averaged difference in DP-performance over the whole 360° sector is 15% in favour of the steering angle adjustment approach. The minimum thrust is almost 30% higher if steering angle adjustment is chosen instead of load balancing.

Figure 9: comparison of thrust allocation algorithms

The differences between the two approaches are significant. In the segments where the thrusters are aligned with the vessel direction (near 0° and 180°) a significant drop in performance is observed (expect for the exact 0° and 180° orientation). In these steering positions, the moment arms of the various units are small and the forces from port and starboard side are compensating each other. Relatively small disturbances of the overall force balance, lead then to large reductions in the load. In case the steering angle adjustments are implemented, the force balance can be improved significantly with small steering angle corrections. The impact on the overall thrust is then very limited and therefore a large improvement is found.
In the situation where the thrusters are oriented perpendicular to the vessel (around 90° and 270°), the force balance between the unit in the bow and the stern needs to be obtained. In these situations, also significant improvements can be obtained with the steering angle adjustments.

4.2 Corridor approach in case of overlapping forbidden zones

Drill ships with three thrusters located in the stern might have overlapping forbidden zones, depending on the type of units and the location of the thrusters. In case such situation occurs, as indicated in Figure 10, the controls system might treat the overlapping forbidden zone as one large sector. With a forbidden zone of such size, a significant impact on the DP performance will be observed. The performance of one single stern thruster unit is shown on the right side of Figure 10. In the region near 70° azimuth angle, the drop in performance is largest. In this direction the wake out of the thruster will go in between both downstream thrusters. In case a corridor is created, where the thruster is still allowed to operate, in this case at 70-71°, then the performance of the stern thruster unit increases significantly, as shown in Figure 11 on the right side. Since the concept of the forbidden zones is based on optimum overall performance, the corridor approach fits very well in that strategy.
The overall 360° averaged improvement in DP performance is fairly limited for the corridor approach, but in the segments where the corridor is used, the available thrust can be increased with 4-5%. In case the performance improvement is achieved in a critical sector for the DP-capability, a clear gain can be obtained with this application of smart controls.

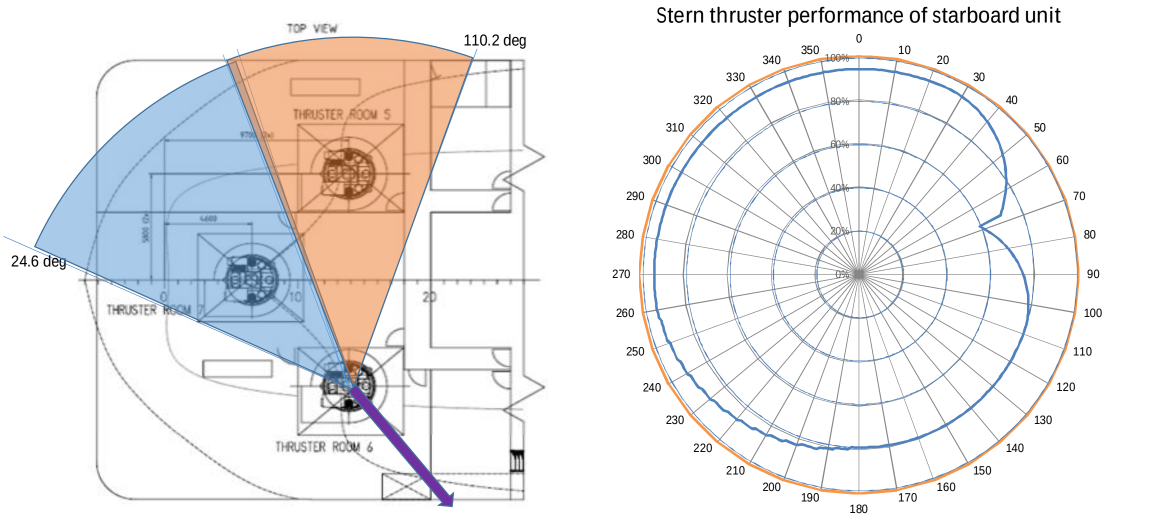

Figure 10: impact of two overlapping forbidden zones on thruster DP-capability

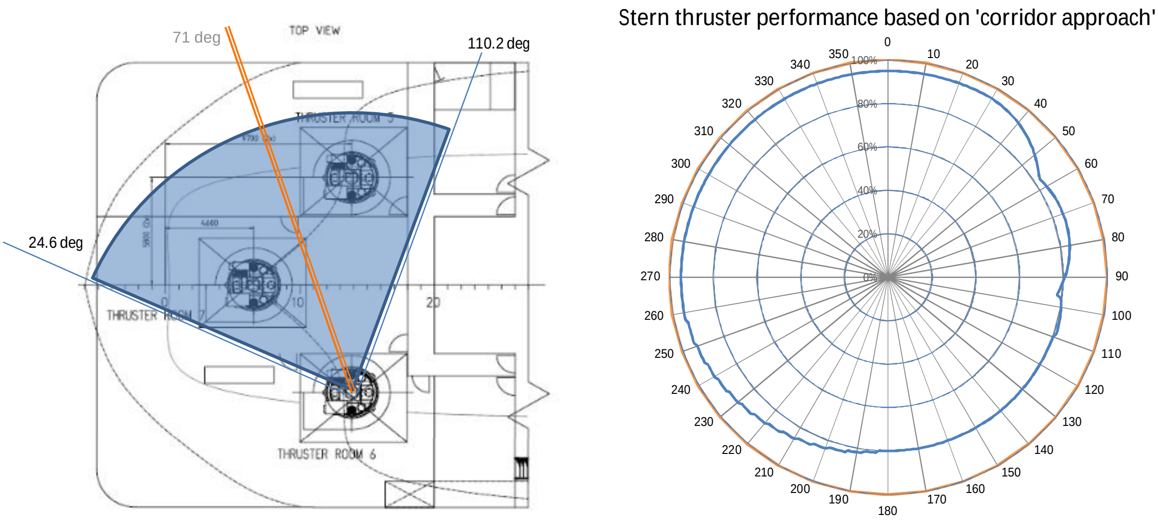

Figure 11: concept of Corridor approach and updated performance of thruster DP-capability

5. Conclusion

It can be concluded that the optimum DP-capability performance can only be achieved in case the hydrodynamic design of the thruster unit and the controls strategies are thoroughly analysed.

- Optimum thruster performance requires a streamlined design of the thruster unit, with a high standard propeller blade design, a nozzle which is dedicated for bollard pull/DP operation and a minimal propeller blade tip clearance. To secure the minimum blade tip clearance the propeller and nozzle need to be aligned.
- Thruster-hull interaction losses need to be minimized, which can be achieved with tilt angles of 8°. Given the previous statement, gearbox configurations with 82° transmission are to be used.
- For proper numerical flow simulations of the wake of tilted nozzle configurations a fully transient moving mesh option is required, which seems only feasible with the overlapping grid approach. All other numerical methods to analyse tilted nozzles will suffer from introduction of significant errors, which once more brings forward the requirement of validation of any numerical simulation to provide the required confidence in the accuracy of the results.
- Due to the significantly reduced thruster-hull interaction losses of 8° tilted shaft configurations, the overall DP-capability of a 3.9m thruster unit, clearly exceeds the performance of a reference unit, based on 4.1m propeller and 5° nozzle tilt, operating at the same power.
- The impact of the controls strategy on the overall DP-capability can be quite substantial. In case a poor algorithm for thrust-allocation is used, an overall loss in performance in the range of 15% could occur. For the 8° tilted shaft configuration the improvement in minimum available thrust can be upto 30% when a proper thrust-allocation algorithm is used.

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