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THRUSTERS SESSION

DP-capability of tilted thrusters

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Wärtsilä - ShipPower

Abstract

In this paper the results of full scale numerical simulations of the flow through a thruster unit and along a drill rig are presented. The development process of the numerical CFD (computational fluid dynamics) methods will be discussed briefly. The numerical simulations are used to determined the full scale thruster performance of a conventional straight thruster unit and a 8-degree tilted thruster unit. In the next steps the thruster-hull-interaction and thruster-thruster-interaction effects of both types of thruster units have been determined. From the various CFD calculations thrust-deduction factors have been derived, depending on the location on the vessel and the type of thruster unit.
The derived thruster-interaction factors for single units have been combined to determine the available thrust for a drill rig with 8 units. The results for the straight and tilted units are presented in polar plots to indicate the clear benefits of the tilted thruster units. For the presented example case the maximum increase of available thrust of the rig in side way operation is about 35%. In forward operation the gain in available thrust is 9%. The improved vessel performance is attributed to the significantly reduced interaction losses with the hull and with other thruster units. Due to the tilted units, the jet out of the thruster is deflected sufficiently downwards to avoid the interaction with the hull.

1. Introduction

The concept of steerable thrusters with a downward tilted propeller shaft has been known for quite some years now [1,2]. The idea of this configuration is to deflect the jet out of the thruster sufficiently downward, which should lead to reduced interaction losses with the hull. Tilt angles in the range 7-8 degrees should give the optimum balance between loss in unit thrust and gains in hull-interaction [2,3]. Despite the theoretical gains of the tilted units, the conventional thrusters with 90-degree gearbox transmission have not lost the interest of the market. In an attempt to get a part of the claimed benefits the nozzle has been tilted 3 to 5 degrees. In this way, it is expected that the jet will be deflected downwards as well.

The development of accurate numerical simulation methods (CFD) has opened the door to more detailed analysis of the full scale thruster performance. Until recently, only the performance analysis of a single thruster unit could be made [4, 5, 6], but nowadays an analysis of a vessel with multiple thrusters can be analysed within commercially acceptable time frames and costs [7].

The basic assumption that tilting the propeller shaft would lead to a performance loss has been analysed. From a theoretical point of view it is expected that the thrust is aligned with the propeller shaft and as a consequence the loss of thrust should then be related to the cosine of the tilt angle. Based on a series of model tests and CFD simulations it has been proven that this basic approach is not valid in general. In free sailing conditions, the conventional straight thruster unit is indeed slightly better compared to an 8-degree tilted thruster unit. However, in bollard pull conditions, the differences in performance are quite small. This is partly attributed to the alignment of the propeller and the nozzle, which enables a small constant blade tip clearance to the nozzle. This small clearance is beneficial for the bollard pull.

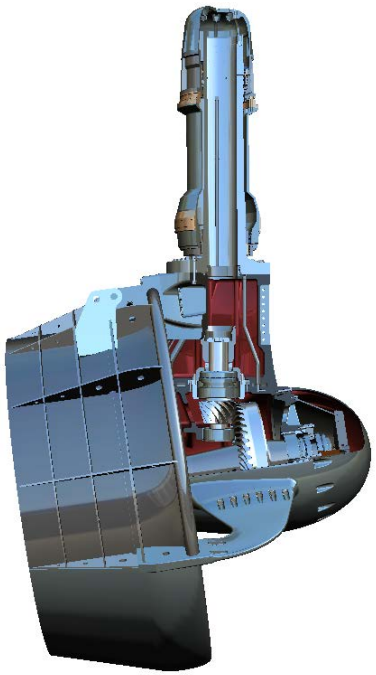


Figure 1: Tilted thruster unit with 82-degree gearbox.

In order to determine the effects of the interaction of the jet out of the thruster and the hull it is necessary to have an accurate solution of the jet downstream of the thruster. Based on the research carried out in the Marin Trust JIP, it has been concluded that only the very time consuming calculations based on the transient, moving mesh approach give valid answers. Nowadays these types of calculations can be run on a computer cluster within a number of days, which has brought these calculations within reach of maritime industry.

The transient calculations have been applied to determine the thruster-hull interaction effects and to determine the thruster-thruster interaction phenomena. Based on these results the thrust-deduction factors can be defined, which can be used to determine the forbidden zones of operation of a steerable thruster.

For a given drill rig with eight thruster-units the available thrust has been determined over the full 360-degree range. This analysis is based on the forbidden zone polar plots of each individual thruster. In case the demanded thrust direction is blocked by a forbidden zone of one of the thrusters, the steering angle is adapted to operate just outside the forbidden zone. This relative simple calculation method has been applied to the thruster-interaction effects of both a conventional thruster and a 8-degree tilted thruster unit. The differences in available thrust for given power are large in sideway operation. Even in forward operation there is a gain in thrust for a tilted unit.

2. CFD calculation method development

The performance of the thruster units is based on numerical flow simulations, also denoted as CFD (computational fluid dynamics) analyses. With the use of numerical flow simulations the full scale performance of the thrusters can be determined accurately. This eliminates the discussions on the Reynolds scaling effects, which have to be taken into account in case model tests are carried out. Nevertheless, a series of model test experiments has been carried out at Marintek in Norway to get a good data set for validation of the numerical simulations. The validation process of the method to calculate the thruster open water performance will be shown in section 2.1.

Besides the open water performance of a thruster unit it is important to know the thrust losses due to interaction of the wake out of the thruster with the hull and with other thrusters on the vessel. The calculation method for an accurate prediction of the shape of the wake is more complex compared to the thruster performance calculation. In sections 2.2 and 2.3 the analysis method for the calculation of the wake will be discussed. In section 2.2 the effect of the interaction with the hull will be addressed, whereas the interaction with another thruster is covered in section 2.3.

2.1. Open water thruster performance

The performance of a single thruster is determined first. In order to validate the numerical method a series of model tests measurements has been carried out to determine the performance of the thruster-unit. Figure 2 shows the test set-up of the unit.

The CFD calculations have been made with Star-CCM+ for the model scale unit (250 mm propeller diameter) and operating conditions as well as for the real full scale conditions (3900 mm). An example of the mesh is shown in figure 3. In this picture the concept of the trimmed mesh can be recognized. This mesh has a hexagonal background mesh with mesh refinement towards the thruster unit and an extrusion layer at the wall surfaces. Where both mesh types meet, the hexagonal cells are trimmed to fill the volume.
The CFD open water performance calculations are based on the Multiple Reference Frame option (also denoted as frozen rotor approach). In this way the quasi-steady solution method can be used. The standard two-equation k-ε turbulence model is used to capture the viscous effects in the flow.

The performance of the thruster unit (propeller thrust and torque, total thrust) is presented in dimensionless representation in the diagram of figure 4. The thrust and torque results are made dimensionless based on propeller diameter and RPM for different inflow speeds. Comparison of the calculated and measured model scale data shows that the agreement for thrust and torque is good over the whole operating range from bollard pull till best efficiency point.
Figure 5 shows an example of the pressure distribution on the surface of the thruster unit, which is a typical example of the output of a CFD analysis.

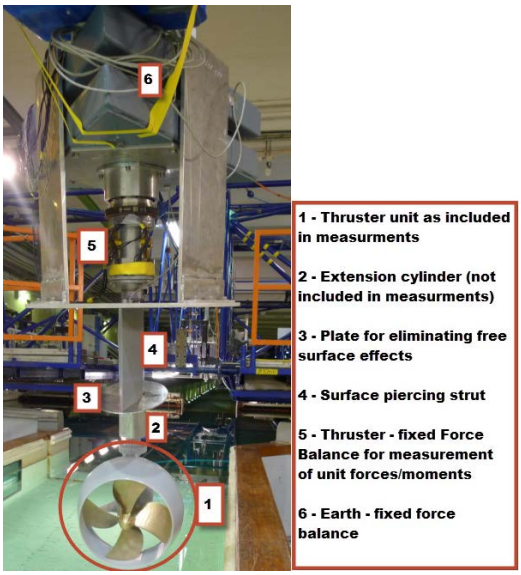


Figure 2: photo of model scale test set-up.

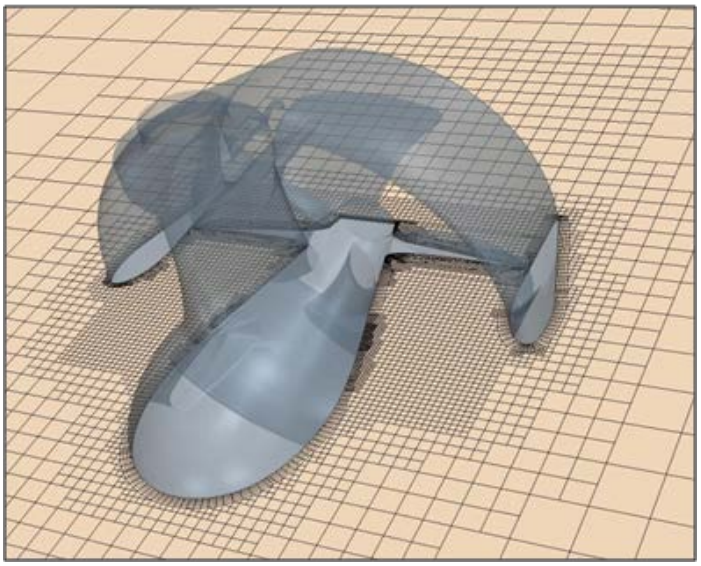


Figure 3: picture of the mesh of the thruster-unit as used in CFD analysis.

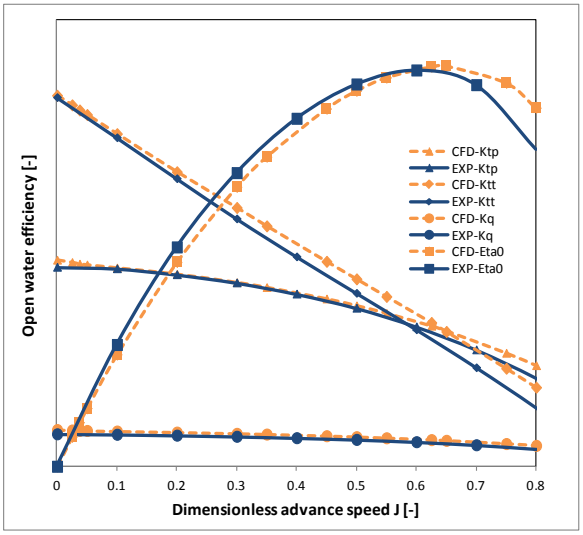


Figure 4: open water performance diagram of calculated and measured thruster performance.

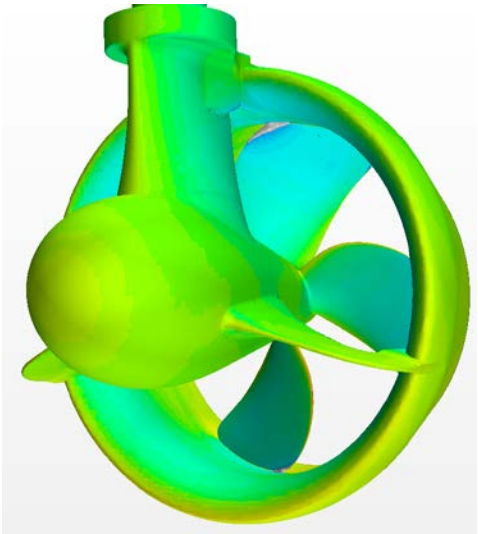
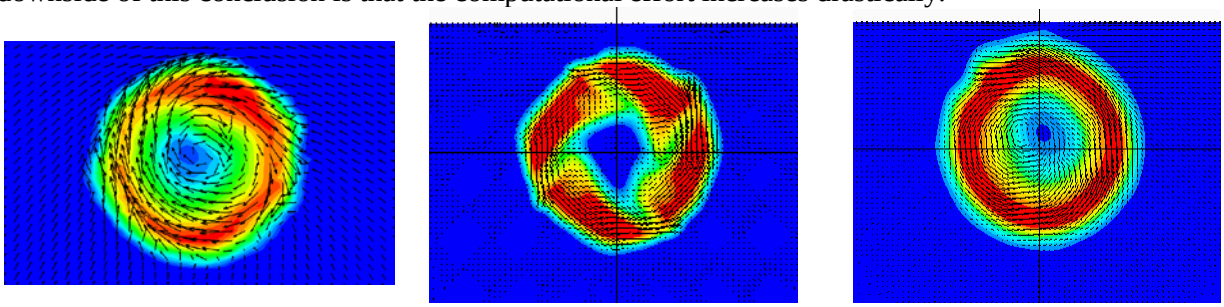


Figure 5: calculated pressure distribution of thruster unit.

2.2. Thruster-hull interaction determination

The results of the performance calculations of the thruster unit have been used to identify the location of the wake of the thruster and the shape of the streamtube. Because the performance calculations are based on the quasi-steady MRF method, a non-realistic velocity field is found downstream of the thruster. Although this has no impact on the performance prediction, it will not be accurate enough for a proper analysis of the effects of the wake downstream, when it interacts with the hull. In order to get an accurate wake prediction the calculation method is changed to the fully transient moving mesh method. In this way the propeller is rotated every time-step to get a realistic wake. In the Marin Trust JIP experimental data (PIV measurements of the wake) have been made available [8], which have been used to compare the results of calculations based on quasi-steady MRF and fully transient moving mesh. The results for one plane are shown in figure 6. The calculated result for the quasi-steady case clearly shows the effects of the four propeller blades. This phenomenon is not present in either the PIV measurements or the fully transient calculations. This comparison clearly supports the concept of fully transient moving mesh. The downside of this conclusion is that the computational effort increases drastically.



PIV measurements Quasi-steady MRF Fully transient moving mesh

Figure 6: Comparison of measured and calculated wake structures at a plane downstream of thruster unit.

2.3. Thruster-thruster interaction calculation

Besides the thrust losses due to interaction of the wake with the hull, there are also conditions possible in which the wake out of one thruster is interfering with another thruster unit. If the performance of the downstream thruster is influenced too much, then operation of the upstream thruster in that direction is forbidden. The angular section where operation is not allowed is denoted as forbidden zone.
In order to calculate the interaction between two thrusters, a numerical model has been made with two units which are located at a given distance from each other. The steering angle of the upstream thruster can be varied. In this numerical set-up a parametric study can be made for different steering angles and distances between the two thrusters. The calculations have to be carried out in the fully transient moving mesh mode to capture the wake accurately.
Experimental data from model tests have been used to review the outcome of the conventional straight thruster units [10]. The calculations for the tilted thruster unit have been carried out according to the same calculation procedure, to maintain numerical consistency.

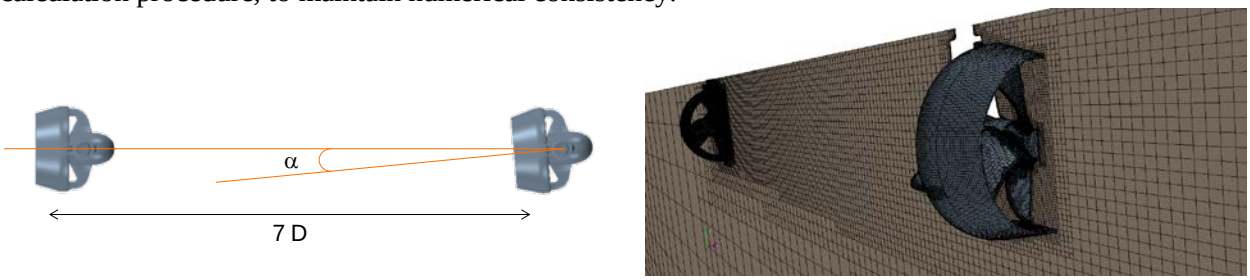


Figure 7: Set-up for thruster-thruster interaction calculations (left) and mesh for two aligned thruster units.

3. Results of numerical simulations

The developed numerical methods have been used to determine the performance of the isolated thruster units and the interaction with the hull and with other thruster units. In the following sections the results of the CFD analyses for a conventional straight unit and a tilted unit will be shown. The units are designed for equal input power, which enables a clear comparison of the performance of the two units. Figure 8 shows the 3D drawings of the two configurations. The difference in the gearbox can be recognized. For both units the same nozzle is used and due to the alignment of the nozzle with the propeller shaft, the tip clearance of the propeller remains identical for both units.

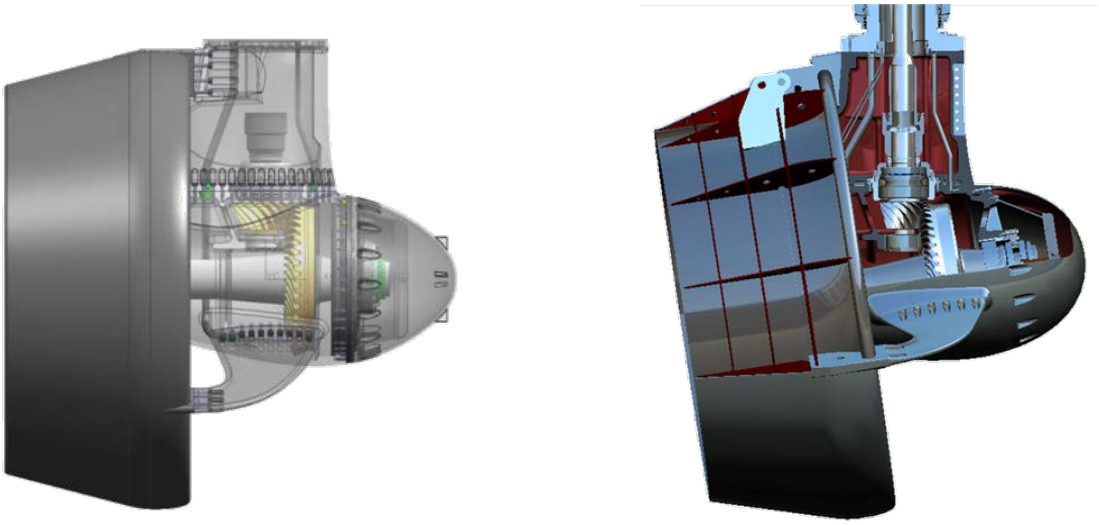


Figure 8: Geometry of straight conventional thruster unit with 90-degree gearbox (left) and 8-degree tilted thruster with 82-degree gearbox (right).

3.1. Open water performance of straight and tilted units

In figure 9 the open water curves of the straight and tilted unit are shown. In this diagram the dimensionless propeller thrust and torque, the nozzle thrust, the total unit thrust and the unit efficiency are shown. The advance speed is presented as dimensionless advance speed J.

The maximum difference in performance between the straight and tilted unit in free sailing condition is in order of 4-5%. However, this needs to be reviewed in more detail to get a proper indication of the differences. The best efficiency at free sailing condition is found at a J-value around 0.7. For this unit this represents a ship speed of about 14 knots, which will not be reached with a semi submersible drill rig. At a free sailing speed of 10 knots, equivalent to a J-value of 0.45-0.50, the difference in unit efficiency is reduced to about 2%.

In order to get a better indication of the performance difference at bollard pull condition (J=0), the so-called Merit coefficient can be used:

$$MC \equiv \frac{\left(K_{tt}/\pi\right)^{3/2}}{K_q}$$

In this coefficient the dimensionless unit thrust is represented with K_{tt} and the dimensionless shaft torque with K_q. The Merit coefficient can be regarded as the hydrodynamic quality factor of the thruster design. CFD calculations with different propeller designs in a given thruster unit showed that the Merit coefficient can be regarded constant over the power range of a certain thruster type. The value of the

Merit coefficient for the analysed pushing thrusters with nozzle is in the range 1.45-1.55, taking into account the drag generated by the thruster housing and strut. The bandwidth of the Merit coefficient can be estimated based on a theoretical description of the flow through a thruster unit, where a set of viscous loss coefficients and an axial-flow pump efficiency is required [6]. The concept to make a coupling between thruster-units and axial-pump theory is not new however [11].
From the CFD calculations of the full scale thruster units a Merit coefficient of 1.52 for the tilted unit and 1.54 for the straight unit has been derived. The small difference is attributed to the downward deflection of the wake, which results in a slightly lower thrust at constant torque.

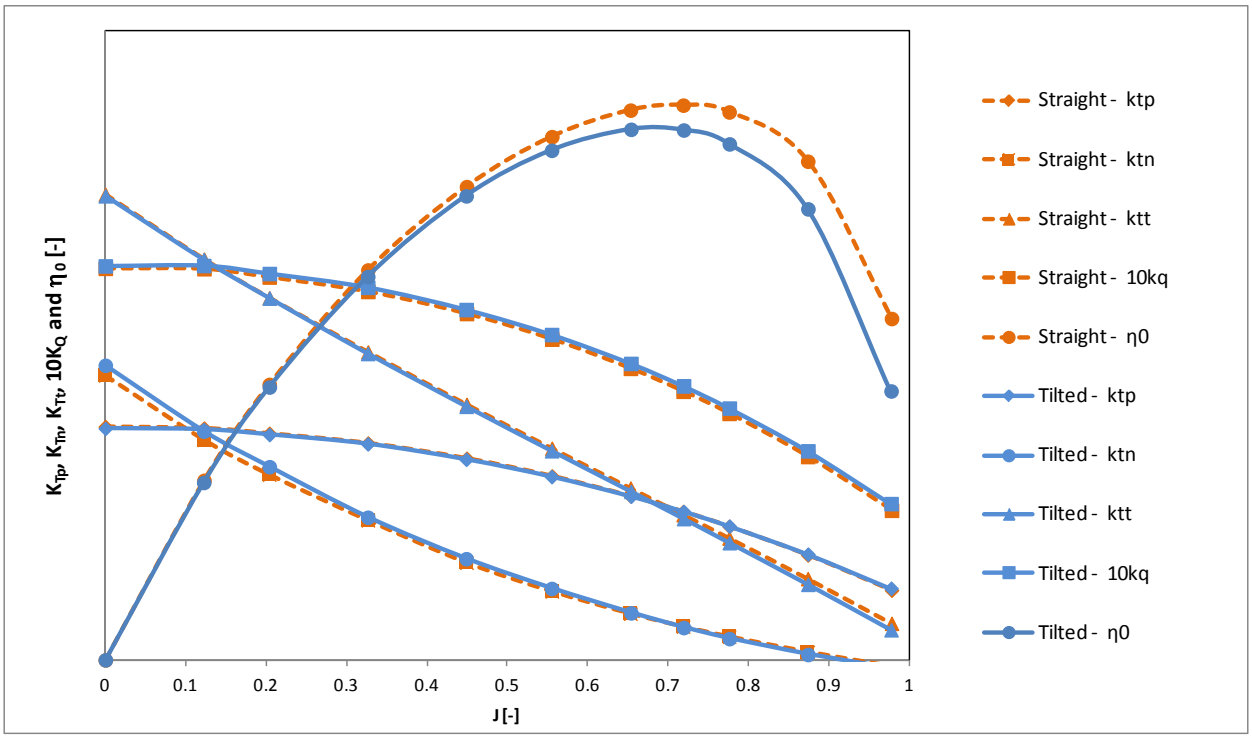


Figure 9: Comparison of open water efficiency of straight and tilted unit.

The benefit of the Merit coefficient becomes clear in the equation for the Thrust/Power-ratio of a steerable thruster:

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

In this equation the density of the water is represented by ρ, the input power by P and the propeller diameter by D. This equation shows that the T/P-ratio will be improved with a higher Merit coefficient or a lower power density. Reduction of the power density can be obtained by either an increased propeller diameter or reduced input power.

The guidelines of IMCA [12] indicate a constant T/P-ratio of 0.18 [kN/kW] for all steerable thrusters. If the Merit-coefficient is considered to be constant over the power range of a thruster, then it is obvious from the equation above that the actual T/P-ratio will still depend on the power density. Nevertheless, the IMCA guideline for T/P=0.18 [kN/kW] is a very good estimate as can be seen in the table 1. This table shows that the T/P-ratio exceeds the expected value at 4500 kW (0.185 vs. 0.18). On the other hand at the maximum unit power of 5500 kW a T/P-ratio of 0.173 is found. The exact match between the two formulas for the T/P-ratio is found at a power rating of 4850 kW.

Table 1: Thrust/power ratio for different power ratings for steerable thruster type

Diameter [m]	3.90	3.90	3.90
Power [kW]	4500	4850	5500
Power/Area [kW/m^2]	377	406	460
Merit Coefficient [-]	1.52	1.52	1.52
T/P [kN/kW]	0.185	0.180	0.173

3.2. Thruster-hull interaction analysis

The results of the CFD calculations for the thruster-hull interaction are shown in the figures 10 and 11 with streamline plots of the flow through the unit. In figure 10 the results for the thruster-hull interaction along the flat hull surface are shown. The streamlines out of the conventional straight unit interact at some distance downstream the unit with the flat hull surface. In the region marked with the dashed line, the streamlines deflect due to interaction with the hull. This will lead to higher velocities along the hull and consequently larger friction losses. The streamlines out of the tilted unit are deflected sufficiently downward to avoid any significant interaction with the flat hull surface. The thrust deduction for the straight unit is about 20% for given hull length and reduced to less than 5% for the tilted unit.

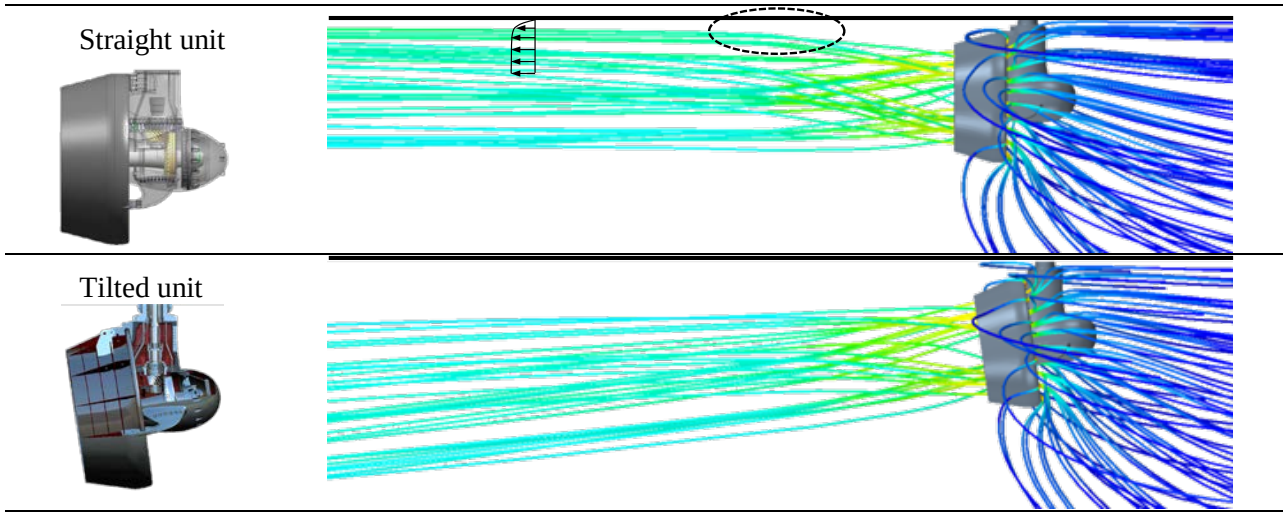


Figure 10: Comparison of thruster-hull interaction for thruster operating along the hull surface.

In figure 11 the streamlines are shown for the units operating in side way thrust direction on a semisubmersible rig. The wake of the conventional straight unit interacts with the second pontoon. This can be recognised by the deflection of the streamlines and by the increased pressure on the side of the hull surface (represented with the red colour). The wake of the tilted unit is deflected downward and consequently there is no significant interaction observed with the second pontoon. The thrust deduction factor for the straight unit is about 50%, whereas a thrust deduction less than 5% is found for the tilted unit.

The streamlines have been used to estimate the amount of deflection of the jet and the expansion angle of the streamtube. In line with expectations the core of the jet of the straight conventional unit is aligned with the horizontal shaft line. On the other hand, the 8-degree tilted unit has a downward deflection of 5 degrees, which is a significantly lower deflection compared to the shaft line.The expansion angle of the wake is in both cases about 4 degrees relative to the core deflection. The hydrodynamic downward deflection of 5 degrees of the tilted unit combined with the 4 degrees expansion angle leads to a minimum deflection of 1 degree downward. The limiting streamline of the flow out of the tilted unit will thus follow a 1 degree downward deflection and as a consequence there will be no significant interaction with the

second pontoon. Based on this approach it can be concluded that units with tilt-angles smaller than 8 degrees will show a certain amount of thruster-hull interaction. This is well in line with the findings presented in other publications [1, 2].

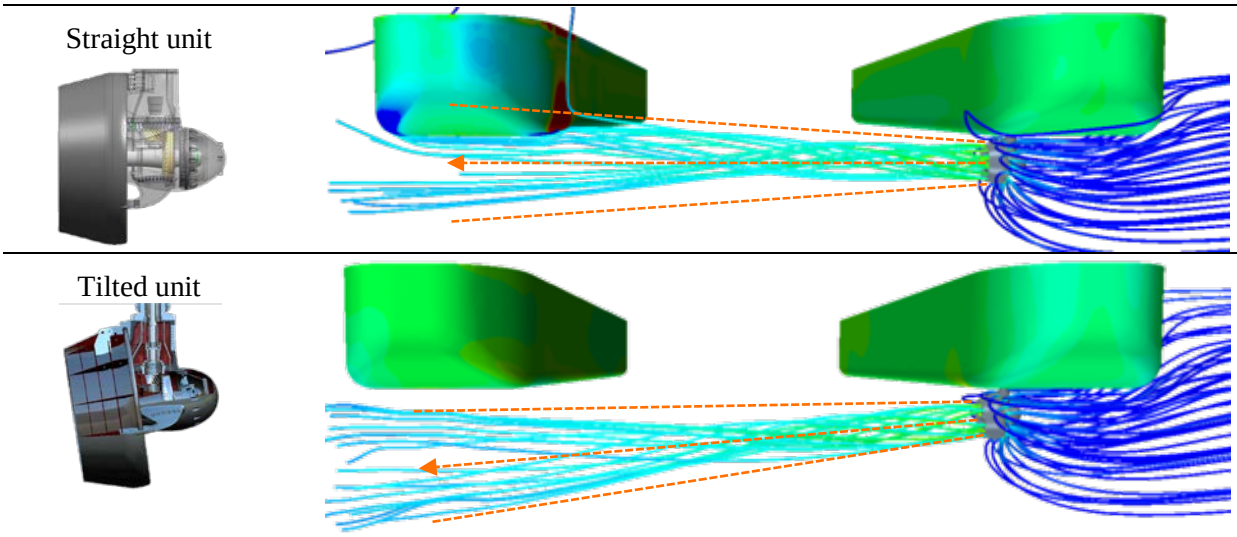


Figure 11: Comparison of thruster-hull interaction for thruster operating towards the second pontoon of a drill rig.

3.3. Thruster-thruster interaction analysis

The analysis of thruster-thruster interaction is more complex than the thruster-hull interaction. For the thruster-thruster interaction, the distance between the two units and the steering angle of the forward thruster are important parameters. The interaction of the two units can be visualised with aid of the streamtube out of the forward unit. This is presented in figure 12 for both units. The CFD results for the calculation at 5 degree steering angle are shown for both units. It is known from theory on forbidden zones that at a distance of 7 diameters, the forbidden zone is 16.8 degree [13]. At 5 degree steering angle quite some interaction between the two units is thus expected.

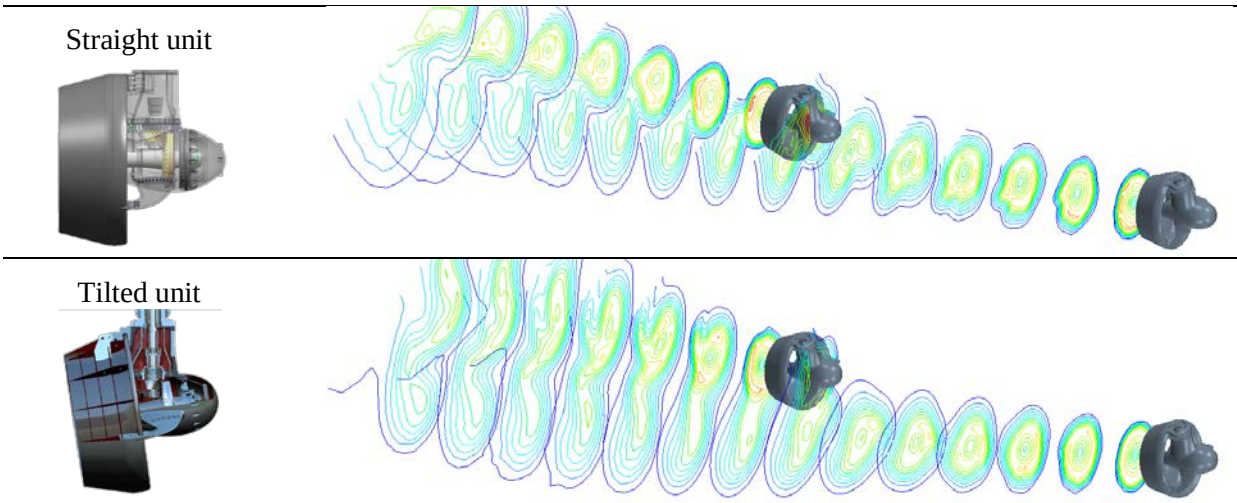


Figure 12: Comparison of thruster-thruster interaction for thrusters operating at 7 diameters distance and 5 degree steering angle for the forward thruster unit. The cross-sections represent the streamtube out of the thruster unit.

The interaction of the streamtube can be observed clearly from the results for the straight units in figure 12. The circular sections of the forward unit are ingested into the second units. In case of the tilted unit the interaction is much less, though still present at 5 degree steering angle. The streamtube shape becomes more oval due to the interaction with the second unit. The reduced interaction effect lead to a reduction of the forbidden zone of a tilted unit compared to the straight units.

4. Determination of forbidden zones

Based on the CFD calculations, as presented in the previous section, the main thruster interaction effects can be predicted:

- Thruster operation along the hull
- Thruster operation towards second pontoon
- Thruster-thruster interaction when two units are (closely) aligned

These three phenomena are shown in the sketch in figure 13, where an example case of a semi-submersible unit with 8 steerable thruster units is considered. The coloured arrows of the jet out of the thruster, representing different types of interaction, are used on the polar plot to show the effect in the thrust direction.

Operation in side way direction (denoted as interaction 90 degree) results in a significant thrust deduction of about 50% for the straight unit. The interaction loss due to the thruster-thruster interaction can be recognized by the small sections taken out of the polar plots. Depending on the thruster type and the distance between the units the forbidden zone angle is calculated.

For the tilted thruster unit the only significant loss in thrust is found in case of thruster-thruster interaction. In all other conditions a maximum of 5% thrust deduction is found.

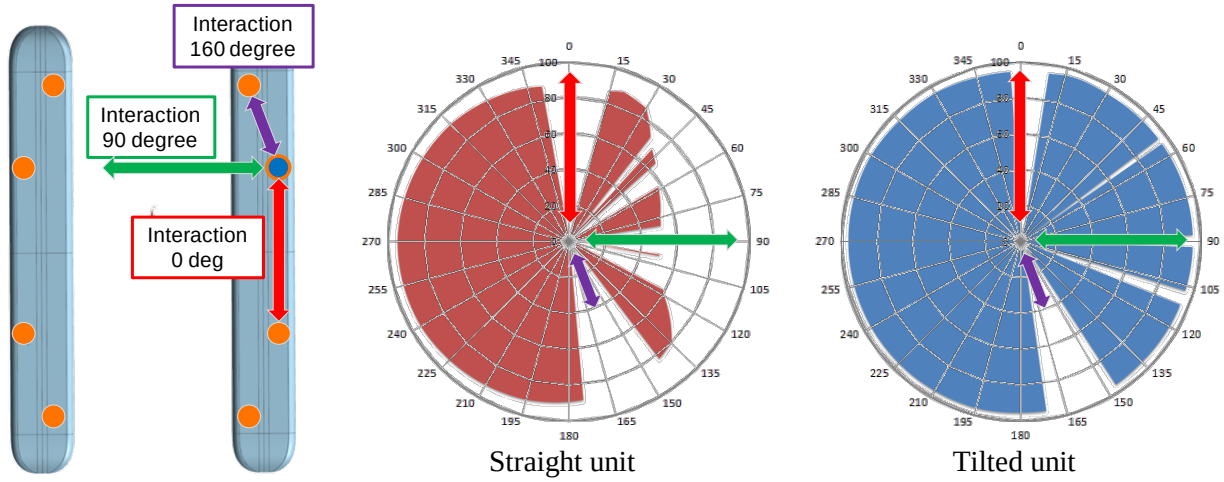


Figure 13: Comparison of the available thrust of 1 steerable thruster based on the location on the vessel as shown on the left . Results for straight unit are shown in the middle, results for the tilted unit on the right.

The effect of different thruster positions on the available thrust is shown for the straight thruster unit in figure 14. The interaction effect with the second pontoon and the thruster-thruster interaction occur at different steering angle of the units, which results in a different polar plot for the available thrust of a single unit. Given the symmetrical layout of the vessel, the performance of the other 6 units can be derived from the 2 base cases.

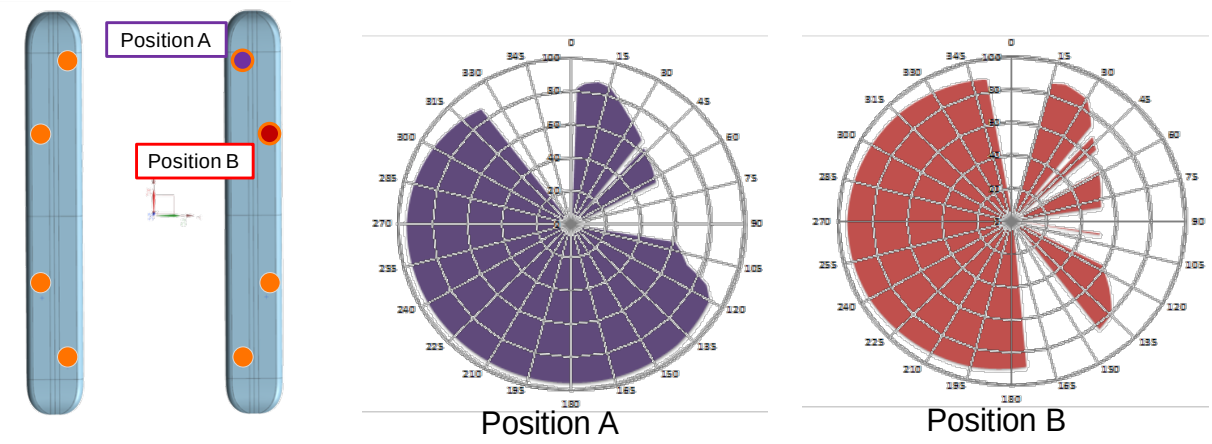


Figure 14: Comparison of the available thrust of 1 straight steerable thruster for 2 different locations on the vessel.

5. DP-capability analysis

The results for the isolated thrusters unit have been used to estimate the available thrust in a requested target direction. In order to get insight in the behaviour a simple numerical model has been made in which initially each thruster is positioned in the direction of the target thrust. Subsequently, the steering angle of each thruster is evaluated against all forbidden zones. In case a thruster unit is positioned in a forbidden zone, the steering angle is adjusted in order to stay out of the forbidden zone.
Based on this simple model the available thrust at full power is determined for a vessel with 8 units. The total thrust in the requested direction is normalised with the total available bollard pull thrust of the 8 units. The results of this analysis are shown in figure 15 for the straight and tilted units.

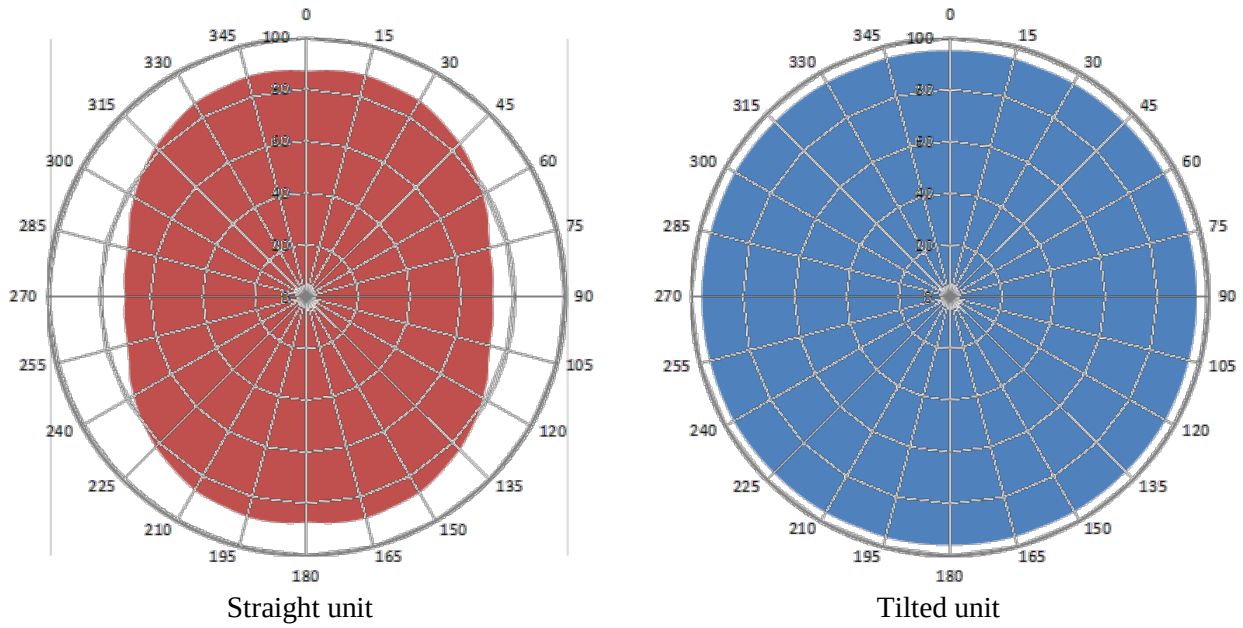


Figure 15: Polar plot of available thrust at constant power for straight (left) and tilted units (right) on a semisubmersible rig.

The differences between the straight and tilted unit can be evaluated in different ways. In figure 16 two methods are used to present the differences. On the left side both polar plots are plotted in one diagram. This figure shows that the straight unit (in red) covers only a part of the tilted version (in blue). The surplus of thrust of the tilted unit is thus where the blue colour of the tilted unit is shown.
In order to quantify this in more detail the relative difference between the thrust of the tilted unit and the straight unit is shown on the right side. The dashed green line in this diagram shows that the maximum thrust gain of the tilted unit is about 35% in side way operation (90 or 270 degree). The dashed red line shows the improvement in forward direction for the tilted units, which is about 9%. The average increase in available thrust over the complete 360 degree circle is about 19%.

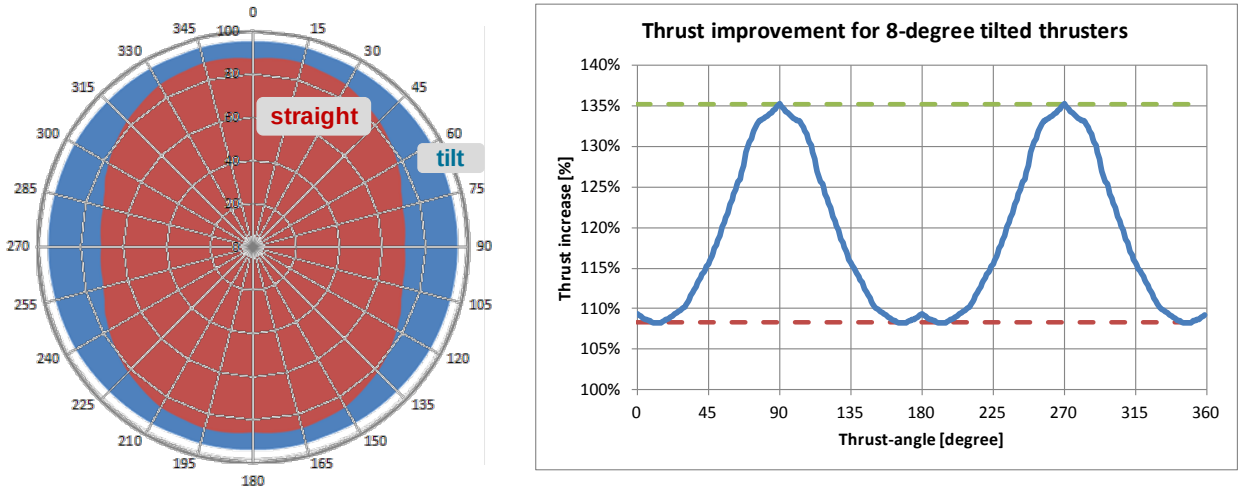


Figure 16: Polar plot comparison of straight and tilted unit (left) and relative comparison of available thrust over 360 degrees for all 8 thrusters on a semisubmersible rig.

6. Conclusions

The dynamic positioning capability of a drill rig with straight and 8-degree tilted thrusters units has been investigated with aid of numerical simulations. The benefits of the tilted thruster unit can be recognized from the polar plots with available thrust for given available power on the rig.
An example case has been analysed of a rig with 8 thruster units. The maximum increase of available thrust of the rig in side way operation is about 35%. In forward operation the gain in available thrust is 9%. The improved vessel performance is attributed to the significantly reduced interaction losses with the hull and with other thruster units. Due to the tilted units, the jet out of the thruster is deflected sufficiently downwards to avoid the interaction with the hull.
The presented research in this paper is based on full scale numerical analysis of the flow through the thruster unit and along the vessel. The numerical methods have been validated with available experimental data in order to confirm the required level of accuracy of the numerical simulations.

Acknowledgements

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