Steering Torque Determination of Pulling Open Thrusters

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STEERING TORQUE DETERMINATION OF PULLING OPEN THRUSTERS

MASTER THESIS

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STEERING TORQUE DETERMINATION OF PULLING OPEN THRUSTERS

by

Amit V. Parab

in partial fulfillment of the requirements for the degree of Master of Science Mechanical Engineering: Sustainable Process and Energy Technology

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ABSTRACT

The use of azimuth thrusters as main propulsion device and for manoeuvring of ships is increasing over the past decades. However, the understanding of hydrodynamic loads acting on such devices in oblique inflow conditions is still an interesting area of research as it is generally believed that such loads can be partially responsible for the failure of parts of power transmission system to the thruster. A deeper understanding of such loads can provide critical mechanical design considerations for the parts involved in transmitting power such as bevel gears, bearing and seals as well the parts of thruster housing. Thus, the aim of this research is to provide an insight into the behavior of hydrodynamic loads of a pulling open type steerable thruster particularly the steering moment, including extreme oblique inflow conditions at various ship speeds and power absorption.

A numerical investigation of steering thrusters is performed for various conditions. For this a turbulence model is used and for simulating manoeuvring tests transient conditions are used where as open water tests are simulated using quasi steady conditions. These simulations are based on RANS method for solving the flow with standard k-epsilon model with a high y+ wall treatment around an azimuth thruster system. A commercial code of Star CCM+ is used for performing the simulations. Post processing results give an insight into the critical flow regions and contribution of loads and moments of the system. Validation is done with available model scale data, tested at MARIN institute at Netherlands. The results showed an acceptable agreement to do further analysis of the steering moment behaviour at various steering angles and advance ship speeds.

Behaviour of various hydrodynamic loads is discussed in the results section. In general, the various hydrodynamic forces were found to be increasing with increase in steering angles and symmetrical for mirrored conditions. As numerical simulations provide the feasibility of studying loads on individual components, the contribution of individual parts of the thruster for different forces and moments was also analyzed. The side force moment created by the propeller side is balanced mainly by anti moments created by the skeg and the remainder is taken up by the steering motor torque to keep the thruster at a particular steering position under such external hydrodynamic loads. Detailed asymmetrical flow fields are discussed which arise due to oblique angle and spinning of fluid due to propeller rotation.

Finally, the pulling thruster under study was compared with a ducted pushing thruster for hydrodynamic loads and the results are discussed in detail. The steering moments in both cases rise very steeply with steering angles and are significant at higher steering angles. Also, in case of a pulling thruster there is a fluctuating steering moment present even in straight inflow conditions unlike the pushing unit, which can be of interest when comparing these two type of configurations.
ACKNOWLEDGEMENTS

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## NOMENCLATURE

### Symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>m</td>
<td>Propeller Diameter</td>
</tr>
<tr>
<td>n</td>
<td>rps</td>
<td>Rotation per unit time</td>
</tr>
<tr>
<td>P</td>
<td>m</td>
<td>Pitch of propeller</td>
</tr>
<tr>
<td>P/D</td>
<td>-</td>
<td>Pitch-diameter ratio</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>Radius of Propeller</td>
</tr>
<tr>
<td>λ</td>
<td>-</td>
<td>Full Scale to Model Scale Ratio</td>
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### Forces and Moments

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Description</th>
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<tbody>
<tr>
<td>$F_x$</td>
<td>N</td>
<td>Thrust</td>
</tr>
<tr>
<td>$F_{x\text{sail}}$</td>
<td>N</td>
<td>Thrust in sailing direction</td>
</tr>
<tr>
<td>$F_y$</td>
<td>N</td>
<td>Side force</td>
</tr>
<tr>
<td>$F_d$</td>
<td>N</td>
<td>Drag Force</td>
</tr>
<tr>
<td>$M_z$</td>
<td>N-m</td>
<td>Steering Moment</td>
</tr>
<tr>
<td>$Q$</td>
<td>N-m</td>
<td>Torque</td>
</tr>
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</table>

### Non- dimensional coefficients

<table>
<thead>
<tr>
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<th>Description</th>
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<tr>
<td>$J$</td>
<td>Advance Coefficient</td>
</tr>
<tr>
<td>$K_{F_x}$</td>
<td>-</td>
</tr>
<tr>
<td>$K_{F_{x\text{sail}}}$</td>
<td>-</td>
</tr>
<tr>
<td>$K_{F_y}$</td>
<td>-</td>
</tr>
<tr>
<td>$K_Q$</td>
<td>-</td>
</tr>
<tr>
<td>$K_{M_z}$</td>
<td>-</td>
</tr>
<tr>
<td>$K_{yF_x}$</td>
<td>-</td>
</tr>
</tbody>
</table>
K-xFy - Side force Moment Coefficient
η_o - Open water Efficiency
Cd - Drag Coefficient

**Blade angles and speeds**

α Deg Angle of attack or angle of incidence of airfoil
β Deg Hydrodynamic pitch angle or advance angle
Θ Deg Pitch angle
δ Deg Steering angle
Va m/s Advance Velocity of propeller
Vr m/s Relative velocity
U m/s Blade velocity or tangential velocity
Chapter 1

Introduction

With the technological development of ship propellers over the past century, steerable thrusters have also gained importance and it makes use of propeller technology for manoeuvring a ship. Manoeuvring of ships comprises of all operations other than going ahead or astern in a straight course. It consists of change of course, sideways motion and dynamic positioning. A thrust vector is enabled to direct in the desired direction to achieve the required turning moment on the whole ship body.

Steerable Thrusters are similar to propellers in working. They provide axial thrust and in addition they can be rotated 360 degrees about their vertical axis by a steering gear box. They can be fitted on offshore vessels instead of a propeller and a rudder combination and perform the steering function.

Conventionally, an airfoil shaped rudder is placed downstream of the propeller which uses part of the main thrust to create a lateral force and hence the required turning moment. However, rudders are limited to 30 to 35 Degrees due to the flow separation phenomenon on the suction side of the rudder. But, in steerable thrusters all the thrust developed can be used more effectively.

Furthermore, steering the thrusters at oblique angles will result in lateral Hydrodynamic loads and consequential moments. These loads such as the thrust eccentricity moment and the side force moment are considerable for the transmission system to the thruster. It is important to understand these loads to decide on the strength of the affected mechanical components.

To perform this critical hydrodynamic load calculation and to understand the flow physics in detail for different components, a numerical approach is essential. Over the experiments, a numerical approach is more feasible to perform simulations with various operating conditions and to analyze the effects of variation in Hydrodynamic loads. Hence a CFD model is created for this hydrodynamic analysis and results are validated with model scale measurements.

1.1 Problem statement

This research at Wärtsilä, focuses on the CFD analysis of an open pulling thruster operating in oblique inflow conditions, for different ship speeds and pitch settings. The analysis gives insights into the occurring physical phenomena. Literature study of available model tests and conceptual study of the forces and moments acting on the unit are part of the task. The study also includes comparison with a LMT3510-thruster, which is a ducted pushing thruster. For validation purposes at model scale a report is used of model tests of a pulling thruster, tested at MARIN.

1.2 Thruster Application in Sea-going vessels

One of the basic applications of thrusters is ship manoeuvring as explained earlier. Another is Dynamic Positioning, which is to keep a vessel stationary w.r.t. sea bottom against the external forces, without anchoring. The external forces are due to current and strong winds. Dynamic Positioning is used on oil drilling rigs, supply vessels where it is must to keep stations close to the rig, diving support vessels, fire fighting vessels, and single buoy mooring
(mooring of tankers to oil supply buoys). Thrusters are also used for towing and pushing and in main ship propulsion.

1.3 Thrusters Nomenclature

The basic parts of a steerable thruster unit are propeller, gearing system for controlled transmission of power, gearing system for steering of thruster body and a Shank, Hub, Pod to house these systems. The different parts of the thruster considered in this hydrodynamics analysis are shown in figure 1.2. A skeg, essentially is used as an additional hydrodynamic device to contribute to the steering moments. A diesel or electric drive motor system is generally used to power a thruster. A quick, basic propeller nomenclature is first mentioned here in Figure 1.1 below. It is important to note that any section of a blade cut by any cylindrical plane whose axis is coinciding with the axis of the propeller rotation, is an aerofoil profile and results in the similar hydrodynamic forces as that of an aerofoil.

![Figure 1.1 Propeller Nomenclatures][1]

Generally, depending on the orientation of the propeller and housing, steering thrusters system are classified in two types. When the thruster housing is located upstream of the propeller it is considered to be of pushing type thruster, while it is pulling or tractor type when the thruster housing is located downstream of the propeller. The type of steerable thruster under study is a pulling type thruster and it is without a duct or nozzle. It has a controllable pitch type propeller and so the pitch of the propeller can be varied to control the power transmitted. The specifications for the thruster under study are shown in table 1.1 below.

<table>
<thead>
<tr>
<th>Number of Steerable Thruster units</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Brake Power</td>
<td>5000 kW/per thruster</td>
</tr>
<tr>
<td>Diameter</td>
<td>4m</td>
</tr>
<tr>
<td>Pitch at 0.7 Radius</td>
<td>4.568m</td>
</tr>
<tr>
<td>P/D at 0.7 R</td>
<td>1.142</td>
</tr>
<tr>
<td>Number of Propeller Blades</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1.1 Thruster Specification
The inflow of fluid results in forces on the thruster parts at the outside and hence the different parts considered in the CFD analysis are the propeller blades, shank, skeg, hub and hub cap, pod. These parts are treated in the simulations as separate entities, such that after the CFD simulation runs, it is also possible to analyze each part of the thruster separately for their behaviour.

1.4 Propeller Hydrodynamics

1.4.1 General Propeller hydrodynamics

Considering general dynamics, for studying the fluid motions around the thrusters’ body, a velocity triangle is considered in Figure 1.3, while, for the study of fluid forces acting on the thrusters’ body a free body diagram is used along with the pressure contours and streamlines, to get a better insight of the hydrodynamic forces acting on the thruster under study in Figure 1.4. Contours and streamlines are drawn on a cylindrical plane of 0.7 Radius of the propeller. This is a significant radius, and it is often used as a representative for the propeller. It is significant because half the area of the propeller disk is within a circle of radius 0.7R and consequently, the other half is outside this region; hence the pressure at this circular line is the average pressure over the full propeller disk. As discussed earlier, the resulting cut section of this surface with the blade is an airfoil profile. In Figures 1.3 and 1.4, from the results of simulations performed, a 0.7 R cylindrical plane is used to illustrate the airfoil principle in the thruster. The pressure side is on the shank side and the suction side is on the Hub cap side indicating that the lift force of the airfoils is in the forward direction.

In Figure 1.3, a velocity triangle is drawn for the fluid velocities at the blade, the observer is considered to be moving along with the solid blade. It is important to introduce the various angles and velocities involved with the thruster dynamics at this stage, as they will be used frequently throughout this report.
As shown in figure 1.3 below:

\( \alpha \) is the angle of incidence or angle of attack of airfoil
\( \beta \) is the Hydrodynamic pitch angle or advance angle
\( \Theta \) is the Pitch or Blade angle
\( V_a \) is the Advance Velocity of propeller
\( V_r \) is the Relative velocity
\( U \) is the Blade velocity or tangential velocity
\( P \) is the Pitch of propeller
\( n \) is the Rotation per unit time

As the propeller is rotating in water, it cannot advance by Pitch of propeller, \( P \) times rotation rate, \( n \) and a certain difference will occur. The difference between \( P \) times \( n \) and advance velocity, \( V_a \) is called the slip of the propeller. An increase in angle \( \alpha \) of the thruster, results in increase in lift, until stall occurs similar to an airfoil. The variation in angle \( \Theta \), results in change of power transmitted to the fluid around the thruster. The thruster in this study is analyzed for two values of pitch deflection angle, 0 deg and 3.7 deg, which in turn gives different values of power transmitted at different ship speed and steering angles.

The free body diagram illustrating the force mechanics coming on a single section of a blade is shown below in Figure 1.4. An input rotating force i.e. torque is provided to the blades. The work is done by the blades on the fluid; in turn the airfoil sections of blade create a lift force due to pressure difference on either sides of the blade. Another force, drag gets produced and it is a component involved due to skin friction of blade (shear forces), pressure forces (form drag) and lift induced drag. The overall mechanism, results in an output component of force vector in forward direction called thrust. The pressure contours on the cylindrical plane shows the pressure experienced by the fluid. A high pressure zone behind the propeller blade and low pressure zone ahead of the blade also explains the production of thrust force.
1.4.2 Hydrodynamic steering forces:

Consider the case when we steer the ship by creating a thrust vector, $T$ at an oblique angle, $\delta$ to the inflow. Hence, we create a moment on the whole ship (Thrust times eccentric distance of force from centre of turning of the ship), good enough to turn the ship as desired. The free body diagram illustrating the steering forces and moments on thrusters is shown above in Figure 1.5. However, it is important to realize here, that the Hydrodynamic steering moment, $M_z$ required to turn the thruster is different than the ship turning moment described above. Hydrodynamic steering moment is the system of moments acting on the steering shaft of the thruster unit due to external fluid forces. The steering moment or
torque provided by the steering motor is a moment to keep the thruster at its particular angular position against the external Hydrodynamic forces and some internal forces. The steering moment comprises of two moments, the thrust force moment and the side force moment. Due to the variation in thrust force magnitude produced by the individual blades, the mean thrust force produced has an eccentricity from the rotation axis resulting in a thrust eccentricity moment along the steering shaft axis. While, the side force moment arises due to difference in drag forces of water flow on the left and right of the thruster unit. The steering moment considering only the hydrodynamic forces is thus given by a cross product of thrust and side forces as follows:

\[
M_z = M_{\text{thrust}} + M_{\text{side force}} = F_x r_y - F_y r_x
\]  

Where:

\(F_x\) is the Thrust force.
\(F_y\) is the Side force.
\(r_y\) is the Thrust eccentricity.
\(r_x\) is the Side force eccentricity.

Determining this Hydrodynamic Steering moment \(M_z\) and its behaviour for different inflow angles ‘\(\delta\)’, ship speeds and pitch deflection angles and understanding the physical behaviour of the flow over the components separately and also as a whole unit is the main aim of the project.
Chapter 2

Numerical Modeling – CFD

The Navier-Stokes equations are the basic governing equations which describe how the velocity, pressure, density and viscosity of a moving fluid are related. They are a set of coupled partial differential equations and once the velocity and pressure field is solved for, other quantities of interest, such as drag or lift forces may be found. Analytical solutions are possible for simple geometries with some assumptions, but for complex geometries like thrusters an analytical approach is too difficult. Hence flow over the thrusters can be solved by approximations to the equations and hence a numerical approach is used here. A commercial code Star CCM+ is used for this task of analysing thruster hydrodynamic forces as described earlier.

Assumptions:
- The flow is considered to be three dimensional, incompressible and viscous.
- The flow is assumed to be isothermal as there are negligible temperature variations.
- Gravity effects are neglected.

2.1 Governing Equations

Considering the diameter of the propeller as a characteristic diameter and for operating inflow speeds of 12 knots to 18 knots, the Reynolds number based on propeller diameter and inflow velocity for the flow has a range of 2.5E7 to 3.7E7. The flow around the thrusters is in the turbulent regime, as characterized by the Reynolds number, signifying that the inertial forces are dominating over viscous forces. Reynolds averaging of NS equation is used to statistically describe the flow and simplify the solution of the governing equations of turbulence. To obtain the Reynolds-Averaged Navier-Stokes (RANS) equations, the Navier-Stokes equations for the instantaneous velocity and pressure fields are decomposed into a mean value and a fluctuating component. The averaging process may be thought of as time averaging for steady-state situations and ensemble averaging for repeatable transient situations. Assuming incompressible flow, a Reynolds averaging approach results in the following NS-Equations in index formulation:

\[
\text{Continuity Equation: } \frac{\partial \bar{u}_i}{\partial x_i} = 0
\]  
(2.1)

\[
\text{Momentum equation: } \frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial \bar{u}_i \overline{u}_j}{\partial x_j}
\]  
(2.2)

Here, there are four equations, but ten unknowns: pressure, three velocity components and six Reynolds stress components. The averaging process thus introduces additional terms which act as stresses in the fluid, called Reynolds stress. We need a closure model for these Reynolds stresses and this leads to turbulence modelling through numerical approach, as an analytical approach is not feasible.

2.2.1 Turbulence Modeling

Boussinesq in 1887, proposed a way relating the turbulence stresses to the mean flow to close the system of equations as follows:

\[
-\rho \left( \bar{u}_i' \bar{u}_j' \right) = \nu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho \nu \delta_{ij}
\]
Where:

- $\mu_t$ is the turbulent viscosity or eddy viscosity.
- $k$ is the turbulent kinetic energy and defined as follows:
  \begin{equation}
  k = \frac{1}{2} \overline{u_i' u_i'}
  \end{equation}

- $\delta_{ij}$ is the Kronecker delta, which is unity when $i=j$ and zero if $i \neq j$.

To determine these two turbulent quantities $k$ and $\mu_t$, various eddy viscosity turbulence models are used. Eddy viscosity models use the concept of a turbulent viscosity $\mu_t$ to model the Reynolds stress tensor as a function of mean flow quantities. The $k-\epsilon$ and $k-\omega$ models are the two equation models widely used in commercial CFD codes. These two-equations are complete in a sense that no flow-dependent specifications such as mixing length are required. K-Epsilon models provide a good compromise between robustness, computational cost and accuracy and hence are a good choice for the given problem of simulating a thruster. The first transported variable determines the energy in the turbulence and is called turbulent kinetic energy. The second transported variable is called the turbulent dissipation which determines the rate of dissipation of the turbulent kinetic energy.

Jones and Launder presented a model equation for the $k-\epsilon$ model in 1972 as follows:

Turbulent eddy viscosity: $\mu_t = C_\mu \frac{k^2}{\epsilon}$  \hspace{1cm} (2.4)

where, $C_\mu$ is a constant.

In standard K-Epsilon model,

The transport equation for TKE is as follows:

\begin{equation}
\frac{\partial k}{\partial t} + \overline{u_j} \frac{\partial k}{\partial x_j} = P + \frac{\partial}{\partial x_i} \left( \frac{\nu_t}{\sigma_k} + \nu \right) \frac{\partial k}{\partial x_i} - \epsilon \end{equation}

with $P = 2\nu_t \overline{S_{ij}S_{ij}}$  \hspace{1cm} (2.5)

The budget of the above terms, physically, is as follows:

Rate of change of $k$ + Transport of $k$ by convection = Rate of production of $k$ + Transport of $k$ by diffusion - Rate of destruction of $k$

Similarly the transport equation for $\epsilon$ is as follows:

\begin{equation}
\frac{\partial \epsilon}{\partial t} + \overline{u_j} \frac{\partial \epsilon}{\partial x_j} = \frac{\epsilon}{k} \left( C_{\epsilon 1} P - C_{\epsilon 2} \epsilon \right) + \frac{\partial}{\partial x_i} \left( \frac{\nu_t}{\sigma_\epsilon} + \nu \right) \frac{\partial \epsilon}{\partial x_i}
\end{equation}

(2.6)

The budget of the above terms, physically, is as follows: Rate of change of $\epsilon$ + Transport of $\epsilon$ by convection = Rate of production of $\epsilon$ - Rate of destruction of $\epsilon$ + Transport of $\epsilon$ by diffusion

The coefficients $C_\mu$, $C_{\epsilon 1}$, $C_{\epsilon 2}$, $\sigma_\epsilon$, $\sigma_k$ are constants in the model.
To improve the performance of K-Epsilon model a special treatment is needed in the viscous wall region. A high $y^+$ wall treatment is used. The high wall treatment assumes that the centroid of near-wall cell lies within the logarithmic region of the boundary layer.

2.2 CFD

2.2.1 Computational Domain:

During operation, the ship thruster is surrounded by sea water. The model testing of the propeller was done in a towing tank with considerations for simulating under similar conditions and is further discussed in report, “Calm water Model tests for a Thruster Propelled Yacht Carrier” [1] by MARIN. Similarly, the size of the computational domain needs to be defined around the imported CAD thruster model considering physical aspects. Figure 2.1 and 2.2 below shows domain for model and full scale simulations.

The dimensions of the block (static domain) are considered such that the jet from the propeller will not be disturbed by boundary conditions. Hence, a good length of domain is provided along the propeller rotation axis to eliminate chances of such effects.
The fluid is rotating near the propeller and can be defined in this numerical model in two ways. Basically, the rotating of propeller blades is a transient problem, so we can simulate the rotation of the propeller either with physical rotation applying finite steps in degrees or considering a quasi steady approach.

In the quasi steady approach, the frame of reference of the propeller will be set to be rotating. The propeller is considered as a wall boundary and the rotating frame of reference is associated with the cylinder consisting the mesh. The transient term is not considered. Hence there are no moving parts and only the fluid experiences the rotation behaviour. It is called the MRF, Moving Reference Frame method or Frozen rotor approach. In this kind of mathematical framework, Centrifugal and Corolis forces are considered on the rotating fluid in the NS equation as it reduces the complexity of computational process. This mathematical formulation is taken care by the commercial code used. However, in this case only average values of the transport quantities of the rotation will be produced as a result. While doing the open water characteristics study, this Quasi Steady approach is preferred to compare averaged experimental results (forces and moments) for the complete rotation, as it saves a lot on computational time compared to the Moving mesh method discussed below.

A moving mesh method is employed for capturing transient effects of the fluid in a propeller rotation. Unlike the quasi steady approach, the transient term is now considered in the formulation of the NS equation. The rotor is set to be physically moving at an equivalent time step of two degrees propeller rotation. Hence, the associated cylindrical mesh region around the propeller blades rotates every single time step i.e. two degree of rotation and redefines the sliding interface. This unsteady approach costs a lot of computing time, but provides results of transport quantities at all two degree steps of angular rotation unlike the quasi steady approach which provides only an average value of the whole rotation. This method is used for simulations of steering case, so we can study the fluctuations in hydrodynamic loads during a propeller rotation.

2.2.2 Boundary conditions

Figure 2.1 and 2.2 shows boundary conditions applied to the domain. A uniform flow is prescribed at the inlet of the domain and implies that the flow is unaffected by hull of the ship. The values of turbulence intensity and turbulence length scale are prescribed based on experience of previous results of CFD simulations at the Hydrodynamics department, as initial conditions. As the fluxes into the top boundary are zero, the top boundary is prescribed as a symmetry boundary. At the wall of the thruster a wall boundary condition is prescribed to have a no-slip condition, such that the tangential velocity of fluid is equal to the wall velocity and normal velocity of fluid goes zero. The remaining outlets are prescribed as a pressure boundary condition with atmospheric pressure.

2.2.3 Meshing:

As the gradients of transport quantities, velocity and pressure near the propeller blades are very high a very fine mesh is provided in the cylindrical domain unlike the static domain where a coarser mesh is preferred as the gradients of transport quantities are not that steep. This coarse meshing where gradients are less steep, reduces a lot of computation time. After geometry is imported and a computational domain is setup a high quality mesh is to be created. A cad model is imported as a surface mesh; tessellation is done in triangles to get an initial gauge of the surface. Further manually the surface is prepared by repairing free
edges, intersecting surfaces, etc. to ensure a closed surface or if more repairs are present surface wrapping can be used. A ‘Surface Remesher’ is used to retriangulate an existing surface to improve the overall quality of the surface mesh and to optimize it for the next step of volume meshing. Initially a subsurface is created between the boundary of core mesh and prism layer mesh. The core meshing is done by a trimmer tool, it utilizes a mesh constructed from hexahedral cells from which it cuts and trims the core mesh. Near the wall of the propeller a Prism Layer Mesher is used. Orthogonal prismatic cells are grown next to wall boundaries in the volume mesh. These cells are used to accurately simulate the boundary layer flow close to walls.

![Meshed Domain](image)

**FIGURE 2.3 MESHED DOMAIN SHOWN IN VERTICAL SECTION PLANE ‘ZX’**

<table>
<thead>
<tr>
<th>Volume Mesh: Number of cells</th>
<th>Rotating Region</th>
<th>Static Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Scale</td>
<td>1.6M</td>
<td>0.68M</td>
</tr>
<tr>
<td>Model Scale</td>
<td>1.3M</td>
<td>0.7M</td>
</tr>
</tbody>
</table>

**2.2.4 Physics:**

As discussed in section 2.2, the flow is characterized as turbulent based on the Reynolds number value. A standard K-epsilon model with high y+ wall is preferred for this turbulence modelling to capture flow effects in the viscous wall regime. A preference is given to reduce numerical error for better accuracy of the results, and so the convection term is discretized by opting upwind scheme in second order accuracy over a first order accuracy. The diffusion term is discretized by the commercial code by a default central differencing scheme and the transient term is discretized by default Euler implicit with a second order accuracy for better accuracy of results. The commercial code used employs a numerical algorithm SIMPLE for pressure-velocity coupling to solve the NS equations. The fluid properties used are, density of water is set to be constant as it is an incompressible fluid. For the model scale simulations it is set to be constant at 1000kg/m³, as it is fresh water and a constant density value of 1025kg/m³ is set for the full scale simulations, as it is sea water. The dynamic viscosity for both model scale and full scale is taken as 0.001 Pa/s.
2.2.5 Convergence Criteria:

In the numerical model the iterations are subjected to certain stopping criteria. Torque and thrust values are the monitored criteria and an asymptotic convergence is set, such that for the last 500 iterations results in torque value and thrust value should be within 1% respectively, to help confirm that there is a steady state now and that the numerical errors are least.
CHAPTER 3

VALIDATION

Before analyzing the thrusters’ results from numerical simulations, the numerical model is first validated with available experimental data. Measurements for this thruster unit were carried out by Maritime Research Institute Netherlands MARIN. During the experiments, the ship and its thrusters are scaled down to model scale to carry out various tests like the towing tests, self propulsion tests, open water tests, manoeuvring tests, and these are described in Appendix A.1. The models that are scaled down require geometric, kinematic and dynamic similarity to be followed with the full scale. Dimensionless numbers are used to correlate measurements that are made on the model with a full-size ship, for equivalent values of length, velocity, time and further derived quantities. Thus experiments can be carried out on a relatively smaller and less expensive model. A feasible linear scale ratio of 20 was established based on the availability of a stock propeller of 0.2m at MARIN, to represent the full scale propeller diameter of 4m. The geometrical details can be found in the MARIN report, “Calm water Model tests for a Thruster Propelled Yacht Carrier” [1]

Based on similarity correlations Froude and Reynolds proposed some scaling laws. It is however not possible to fulfill both Froude and Reynolds scaling laws. Reynolds scaling will result in model forces as big as on the ship scale and so Reynolds scaling is impractical and Froude scaling is used. Hence the Froude number is kept constant for model scale and full scale and then the full scale results are corrected for Reynolds scale effects. A detailed explanation on scaling including similarity correlations, Reynolds and Froude scaling method can be found in Offshore Hydromechanics by J.M.J. Journée and W.W. Massie [9]

Measurements were carried out on a model of the ship equipped with two open pulling type thrusters as shown in Figure 3.1. Forces in both longitudinal (thrust) and lateral (side-force) direction were measured. The steering moment on the units was derived from the measured forces. The procedure for conducting the model tests and the extrapolation procedure for resistance and propulsion test results are presented in Appendices of the MARIN report, “Calm water Model tests for a Thruster Propelled Yacht Carrier” [1]
3.1 Non-Dimensional Coefficients
Generally in marine propulsion the performance characteristics of a thruster in straight inflow conditions are represented by open water parameters. It relates the forces and moments acting on the thruster components with advance speed of the ship. These forces and moments in marine literature are commonly expressed in non-dimensional characteristics, for comparing performances characteristics of various sizes and geometries of propellers at various ship speeds and pitch settings. However, in this study, when thrusters are in oblique inflow conditions, a steering moment due to external hydrodynamic forces has to be also considered. Such moments will be also non-dimensionalized to compare steering moment behaviour of various thruster units.

3.1.1 Straight inflow Parameters
The performance characteristics of a propeller in Marine domain are represented on an open water curve as shown in figure 3.1 with some arbitrary values. In the open water tests the RPM is kept constant and the longitudinal speed of the model is varied in the towing tank. Measurements are done of the thrust and torque for different ship speeds in a straight inflow condition. A relation of thrust, torque and efficiency v/s model speed is shown below in figure 3.1 in a non dimensional form.

The various non-dimensional characteristics are explained as follows. Let us first consider the various terms with which the forces and moments are non-dimensionalized.

- \( D \) is the propeller diameter [m]
- \( V_a \) is the advance speed [m/s]
- \( n \) is the rotational speed [rps]
- \( T \) is the propeller thrust [N]
- \( Q \) is the Propeller Torque [Nm]
- \( \rho \) is the mass density of the fluid [kg/m\(^3\)]
Figure 3.2 shows velocity triangle as was shown in section 1.4.1. Here the hydrodynamic pitch angle $\beta$, generally given at the significant radius of 0.7R is given as:

$$\beta_{0.7R} = \frac{V_a}{0.7\pi n D}$$  \hspace{1cm} (3.1)

The non-constant part from above equation, is considered as advance coefficient from the formulation of Hydrodynamics pitch angle as follows:

**Advance Coefficient**, $J = \frac{V_a}{n D}$  \hspace{1cm} (3.2)

The physical interpretation of advance coefficient is as follows. As the value of $J$ increases, angle $\beta$ increases from equation 3.1. Thus, in general, for the same pitch angle $\Theta$, angle of attack $\alpha$ decreases and this results in decrease of the lift coefficient. This means with increase in $J$ there is a decrease in lift and hence the thrust as can be seen in figure 3.1

Let us now consider non-dimensionalizing thrust and torque. The idea for non dimensionalizing this quantities follows from the concept of lift or drag coefficient. The thrust coefficient is a dimensionless coefficient that relates the thrust generated by a propeller to the density of the fluid around the body, a characteristic velocity and a characteristic area. The characteristic velocity here is the tangential velocity caused by input rotation and the characteristic area is propeller disk area. Thus the thrust coefficient,

$$K_t = \frac{T}{\frac{1}{2} \rho V^2 Area} = \frac{T}{\frac{1}{2} \rho (0.7\pi n D)^2 (\pi D^2)}$$  \hspace{1cm} (3.3)

Considering the constant part of the above equation in $K_t$, the thrust coefficient is given as:

$$K_t = \frac{T}{\rho n^2 D^4}$$  \hspace{1cm} (3.4)

On similar lines torque coefficient is given as follows:
STEERING TORQUE DETERMINATION OF PULLING OPEN THRUSTERS

Torque Coefficient, \( K_q = \frac{Q}{\rho n^2 D^5} \) \hspace{1cm} (3.5)

The moment \( K_q \) is relatively small and is always scaled up by a factor of 10, only for graphical purposes. Let us now consider the efficiency of the propeller. It is given as the ratio of power transformed by propeller in thrust and advance velocity by the power available to the propeller in form of torque and rotation.

Open water efficiency, \( \eta_0 = \frac{T \nu_a}{Q 2 \pi n} \) \hspace{1cm} (3.4)

Thus, from equations 3.2, 3.4 and 3.5,

\[ \eta_0 = \frac{1}{2 \pi n K_q} \] \hspace{1cm} (3.6)

### 3.1.2 Oblique inflow Parameters

Manoeuvring Tests are done for the thrusters to find the steering torque and thrust to define power of the required steering motor. To compare steering behaviour of thruster at various steering conditions of ship speeds and power absorbed, as well to compare with various thrusters with different geometries a non dimensionalization is done for the steering forces and moments.

The Hydrodynamic steering moment as described in section 1.4.2 is given by:

\[ M_z = M_{\text{thrust}} + M_{\text{Side force}} = F_x^* r_y - F_y^* r_x \] \hspace{1cm} (3.7)

The non dimensionalization of parameters for steering case is comparable to the coefficients of open water characteristics as discussed in section 3.1.1 and is as follows:

Side Force Coefficient, \( K F_y = \frac{F_y}{\rho n^2 D^4} \) \hspace{1cm} (3.8)

Steering Moment Coefficient, \( K M_z = \frac{M_z}{\rho n^2 D^5} \) \hspace{1cm} (3.9)

Side force Moment Coefficient, \( K x F_y = \frac{x F_y}{\rho n^2 D^5} \) \hspace{1cm} (3.10)

Thrust Moment Coefficient, \( K y F_x = \frac{y F_x}{\rho n^2 D^5} \) \hspace{1cm} (3.11)

### 3.1.3 Non-Dimensionalization of Propeller Pitch

The propeller pitch, \( P \), is the increase in axial direction of the propeller unit due to one rotation of propeller screw. The pitch of the propeller is controlled by variation of pitch angle \( \Theta \) as shown in figure 3.2 and considering no slip it is given by:

\[ \text{Pitch angle, } \Theta = \tan^{-1} \left( \frac{P}{2D} \right) \] \hspace{1cm} (3.12)

Thus, a non-dimensional constant of \( P/D \) is used to express the pitch angle variation. An increase in this ratio means an increase in pitch angle. The power absorbed increases with increase in pitch angle. Hence the study in this research is also made at different values of
3.2 Open Water Characteristics Results

A numerical model as described in section 2.2 is initially created and results are first validated for open water characteristics in a straight course. In this case the angle between the ship displacement and flow around the ship is zero degrees. The advance speed is varied from zero to until the value of the thrust produced is zero; in this case such a velocity is 15.56m/s i.e. a J of 1.16. As discussed in section 3.1, the RPM is kept constant and thrust and torque are measured. The CFD results of thrust and torque are validated with MARIN results for model and full scale. As shown below, the model and full scale corrected MARIN data matches with Full Scale CFD data.

3.2.1 Experimental Results

It is important here to first discuss the experimental results before considering the CFD results in the following sections. The experimental results from MARIN report [1] for open water characteristics are discussed here in graphical form for dimensionless groups of thrust, torque, efficiency, velocity in order to keep the thruster unit comparable to different thruster units. The figure 3.2 below shows the experimental results. The model scale propeller results are shown in dotted lines. The full scale results are calculated from model scale results by using Froude scaling with some corrections for Reynolds scaling and are shown by solid lines. The calculated full scale results are shown separately for the propeller and for the whole thruster unit. The whole thruster unit includes the propeller and also the housing. From the figure 3.2 it can be seen in general that, Kt and Kq decrease with increasing advance coefficient J. The experiments are stopped when no further thrust is produced. The efficiency curve shows an optimum value of J, after which there is a drop in the efficiency.

![Graph showing experimental results](image)

**FIGURE 3.2 OPEN WATER CHARACTERISTICS - EXPERIMENTAL**
(Model Prop v/s Full scale Unit v/s Full Scale Prop)
While scaling the model scale results to full scale some corrections are added. The difference between model scale unit and full scale unit in figure 3.2 is due to this corrections. Correction of scale effects includes the following considerations when scaling to full scale:

1. The scale effect of the inflow velocity (wake)
2. Scale effects on the propeller blade friction
3. Scale effect on the drag of the housing is considered with Reynolds Scaling effect. The drag of the housing is the difference of total unit thrust and thrust force of the blades.

Only the first two corrections are considered when scaling for only propeller to full size whereas all three corrections are considered when scaling for the whole unit. This is the reason for the shift in dimensionless parameters in Figure 3.2 at full scale between the whole thrusters’ unit curves and only propeller curves from the model scale results. This scaling affects are important be considered when comparing the CFD results.

### 3.2.2 CFD Results

Before discussing the CFD results, it is important to note that there is some difference in the geometry of the model propeller and the propeller which is used on the ship. A matching stock propeller in performance characteristics, but with a different geometry was selected at MARIN for model testing. It has been therefore mentioned in section 4.6, MARIN report [1] that the power-speed relation of the thruster unit for the model tests will be different from the one on full scale. Only at the correct power for which the pitch setting was calculated, the two curves can be compared. This comparison has to be in range nearby the free sailing point on the efficiency curve, as the efficiency is maximum around this range. Figure 3.3 shows CFD results v/s experimental results at full scale for the thrusters unit. As discussed above, the two curves can be compared near the free sailing point, which is here around J values of 0.6 to 0.9. Indeed, there is close match in the efficiency and this is good enough for validation of the simulation.

The possible difference in thrust and torque values in figure 3.3 arises from the difference in the use of a model stock propeller and the blades being used for an actual ship. For similar blade profiles the Kq curve should have been more or less parallel to each other; however it intersects here at a J value of 0.4, and this is certainly due to variation in blade profile. The efficiency curve increases with increase in advance coefficient J, which is a function of advance velocity, until a maximum is reached around 0.9 J. After this point for an increase in value of J there is a dramatic decrease in efficiency and this area is not of interest anymore for design of propeller. There is a reasonable agreement for different operating conditions from bollard pull (zero J) to free sailing condition (0.9 J). According to the results, it seems the numerical model is able to capture trends for this straight inflow condition.
3.3 PITCH DEFLECTION IMPACT

As mentioned earlier, while experimental testing, a stock propeller with difference in blade geometry was used by MARIN, which they suggested would be a close match in performance to the designed propeller P/D ratio of 1.142. Before performing the various steering cases, a further CFD study is performed here to confirm the use of the stock propeller with a different geometry. By using the open water characteristics, a comparison is done between the model stock propeller results and the designed propeller CFD results. In this study, the P/D ratio of designed propeller will be varied in CFD simulations and compared with the results of the stock propeller. Steering thruster experiments were performed at MARIN at speeds from 12 Knots to 18 knots and hence a value range of 0.56 J to 0.84 J is considered for matching the Efficiency, Thrust, Torque in Figure 3.4, 3.5, 3.6 respectively. The stock propeller results are shown by dashed lines and the CFD results of designed propeller at various P/D ratios are shown in solid lines. As seen in the figures, the stock propeller used by MARIN for experiments is a close match with the designed propeller at the P/D ratio of 1.142 for the J values of 0.56 to 0.84. Hence, we can now consider analyzing the various steering cases and are mentioned in following section.
FIGURE 3.4 OPEN WATER CHARACTERISTICS, ETA EXP V/S CFD

FIGURE 3.5 OPEN WATER CHARACTERISTICS, KT EXP V/S CFD
3.4 Steering Case Results

As mentioned earlier, manœuvring tests were done for the thrusters to find the steering torque and thrust to define the power of the required steering motor and results were reported by MARIN [1]. The ship model is driven by a measuring carriage at constant speeds represented by ship speeds of 12, 14, 16 and 18 knots in the model basin. The Propeller rotation is kept constant at 735 RPM which is the self propulsion point of the ship. The thrust and side forces are measured for different ship speeds and the steering moment is evaluated from them.

3.4.1 CFD Results

While performing the numerical simulations to analyze the steering behaviour of the thruster, a number of positive and negative steering angles are considered, so as to realize the behaviour of hydrodynamic steering forces over a larger angular range. This steering of the thruster, results in an oblique inflow condition. The performance curves showing steering moment, thrust and side force are plotted in a non-dimensional form against these steering angles. This non dimensionalization scheme is discussed in section 3.1.2.
The Figure 3.7 shows the full scale thruster unit comparison of CFD simulations with experimental test data. This experimental data is obtained from model tests and then scaled to full scale with corrections as mentioned in section 3.2. A few more steering cases with different power absorption and speeds were simulated for studying thrusters' behaviour further and are shown in Appendix E. The CFD results show a good enough agreement with the experimental results over the whole range of steering angles, especially the thrust force in sailing direction and the side force. However, there is a deviation in the steering moments, but there is good match in the trend. The steering moment increases with increasing steering angle as expected. As discussed in section 3.2.2, the variation in blade geometry could be a possible reason for differences in the steering moment magnitudes. Also, the full scale results for the whole unit are calculated from model scale by Froude scaling with some corrections from Reynolds scaling as shown in MARIN report [1]. There could be a possible scaling error from model test data to full scale.

However, there is a good qualitative match over the whole range of data for open water characteristics as shown in figure 3.3 and steering case as shown in figure 3.7. Therefore, the numerical model is good enough to get a better insight in the purpose of studying behaviour of loads and performances and will be discussed in coming chapters.
Chapter 4
Simulation Matrix and Steering Case Behaviour

4.1 Simulation Matrix

To define the power required for steering motors manoeuvring tests were performed at MARIN [1]. A number of thrusters’ force and steering moment measurements under several conditions were carried out. There are two azimuthal steering thrusters fitted under the ship and are referred by Port and Starboard side. In Figure 4.1 the sign conventions for the steering forces and moments which were measured at MARIN are shown.

During the experiments, in the ship coordinate system the thrust, Fx is considered positive in the sailing direction and the lateral force Fy has a positive sign in the port side direction as shown above. When the propeller is steered the side force Fy still has its vector perpendicular to the propeller rotation axis, while Fx is measured only in the sailing direction. However, during numerical simulations two coordinate systems are considered. In the Ship Coordinate system, thrust $F_{x,\text{ship}}$ is the same as Fx above and is considered as positive in the sailing direction of the ship. Another coordinate system is local and is called as the Propeller Coordinate system. During straight course and steering, the positive thrust direction ($F_{x,\text{local}}$) is always aligned with the shaft axis of the propeller rotation and the side force ($F_y$) is in the lateral direction with respect to $F_{x,\text{local}}$ component. The Steering Moment
Mz in both experimental and numerical simulations is the hydrodynamics moment in the XY plane due to the thrust and side force and acts on the steering shaft.

During the manoeuvring tests done at model scale an equivalent Ship propeller rotation rate, Ns is kept constant at 165 RPM, being the self propulsion point of ship for medium yacht draft as determined in the propulsion tests at MARIN [1]. As discussed earlier, here the model scale ratio $\lambda = 20$.

By Froude scaling,

$$N_m = \frac{N_s}{\sqrt{\lambda}} \quad (4.1)$$

Hence, $N_m$, the RPM of the model propeller is kept as 735 RPM. The open water test simulations were performed at both full and model scales. However, the numerical steering cases are performed at full scale only, due to availability of corrected test data at full scale and hence a constant RPM of 165 is used during steering simulations. Keeping the RPM constant, the parameters for which various simulations were done are presented below:

**Speed range:** The whole thruster unit and also different components of the thruster have a different magnitude of forces and moments at various speeds. The ship model was propelled at speeds represented by ship speeds of 12, 14, 16 and 18 knots at MARIN[1] to understand the effects of varying the speed on the steering behaviour of thruster. Hence, the simulations are performed for this speed range.

**Pitch Deflection or Pitch/Diameter range:** At different P/D ratios, there is a different power absorption. Thus by varying the P/D ratio one can study corresponding effects of change in power absorption on the Steering loads and moments. At no deflection of the blade a low pitch/diameter value of 0.965 is obtained. To have a higher power absorption case, a high Pitch/Diameter of 1.142 is considered. For a pitch/diameter ratio of 1.142 the blades are rotated by 3.7 degree. These two cases are considered during simulations.

**Steering angle:** As the purpose of performing manoeuvring tests is to check the steering behaviour a number of steering angles are considered. Positive as well as negative steering angles are considered for the reason that the flow field is not symmetrical. The difference in this flow asymmetry lies in the inflow pattern to shank and skeg resulting due to spinning of the blades. A detailed interpretation is mentioned in Section 5.1.

Thus, considering all the parameters above, a matrix of 80 simulations cases is formed, with four speed ranges, two pitch/diameter ratios and ten steering angles. A graphical representation is shown in Figure 4.2 below. As represented the forces and moments to be plotted in later sections are functions of the steering angle, ship speed and P/D ratio.
4.2 Steering Case Behaviour

The steering moment and forces of the ship due to hydrodynamic forces are represented for all the cases below. A quite similar trend for force and moment analysis is found for high and low pitch. In the following sections only the graphs for low P/D of 0.965 are shown, whereas the graphs for high P/D of 1.142 can be found in Appendix A2.

Note: It can be interesting to the reader, new to thruster hydrodynamics, at this point to refer chapter 5, simultaneously. It would help the reader to associate the physics of the forces and moments in graphs for whole thruster unit shown below, with the flow visualizations used to study behaviour of individual parts for forces and moments in chapter 5.

4.2.1 Thrust:

The effect of changing the steering angle and J values on the thrust produced is shown in figures 4.1 and 4.2 above. As previously mentioned for non-dimensionalizing purposes the thrust Coefficient is given by,  \( K_t = \frac{F_x}{\rho \pi^2 D^4} \)
It is seen that the total thrust coefficient increases with increasing steering angles. This happens because of a reduction in the inflow axial velocity due to the change of steering angle of the thruster unit. Eventually the angle of attack increases resulting in an increase of thrust until stall occurs. It can be also seen as discussed in detail in section 5.2.1 that the higher the J, the higher is the angle of attack, alpha and so is the thrust produced. A similar trend is also seen in the open water characteristics curve in figure 3.2, where the thrust was increasing with decreasing advance coefficients for straight inflow conditions. As seen from the above graphs the thrust for both postive and negative steering angles is quite similar, so only a few negative steering angle simulations are performed. However, it is quite noticeable that the flow pattern past the thruster is different for positive and negative steering angles due to inflow pattern to shank and skeg resulting due to the spinning of the blades and this is explained in detail later in section 5.1.

There is an inflexion point in the figure 4.1 where all thrust values for different J intersect at around 55-60 degrees. This happens just before the point of stall where the thrust now decreases. Stall occurs in lower J values earlier and they start decreasing at this point where as stall occurs later for higher dynamic pressure flow (higher J values) as seen in the figure 4.1. and continues to follow its trend to increase. This forms the intersection point which seems to be more coincident. However, this point appears to be less significant for the study. A similar inflexion point at 55- 60 degrees for pushing thrusters is also seen, described later in chapter 6.

It is also interesting to see the thrust force in the sailing direction, as it is a component of thrust produced in the direction of the propeller rotation axis and will have an effect on the straight sailing force of the ship. The effect of changing the steering angle and J values on thrust produced in sailing direction is shown in figures 4.3 and 4.4 below. Obviously for straight inflow conditions, i.e. a steering angle of zero degrees the thrust in sailing direction is equal to the thrust in propeller rotation axis. As the thruster is steered there is a decrease in the thrust in the sailing direction, as the thrust vector rotates about the steering axis. After some degree of steering of the unit, the thrust in sailing direction becomes negative which means that the lift produced by the propeller is less than the drag force acting on the propeller, this is explained later by flow visualizations in chapter 4.

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**FIGURE 4.3 THRUST IN SAILING DIRECTION AT VARIOUS STEERING ANGLES, FOR DIFFERENT J VALUES.**

**FIGURE 4.4 THRUST IN SAILING DIRECTION AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES.**
4.2.2 Side Force:

The side force is caused due to hydrodynamic forces of lift and drag due to the steering angles and is illustrated in detail in chapter 5. The effect of changing the steering angle and J values on side force is shown in figures 4.5 and 4.6 above. It is mainly due to blocking of incoming flow due to the presence of the thrusters housing including the shank, skeg and pod. The propeller rotation direction governs the sign of this side force in positive and negative steering angles. The side force increases with steering angles due the increase of lift forces on the thrusters unit and decreases around 75 degrees as shown in figure 4.5 above, which is due to stall at this degree.

4.2.3 Propeller Shaft Torque:

Figures 4.7 and 4.8 above show the propeller shaft torque required for the propeller rotation for various steering angles and J values. Previously the open water characteristics of the thruster were shown in Figure 3.2, where the propeller shaft torque was decreasing for increasing advance coefficients for straight inflow conditions. Similarly, over here in Figures 4.7 and 4.8 a decrease in propeller shaft Torque values is seen for an increase in the J values.
In figure 4.8 the propeller torque for positive and negative steering angles is observed to be quite same. The torque behaviour is quite similar to thrust behaviour as can seen in figures 4.7, 4.8 and 4.1, 4.2 respectively. Later in chapter 6, an important comparison with the behaviour of shaft torque for a pushing unit will be done in detail.

4.2.4 Hydrodynamic Steering Moment:

Figures 4.9 and 4.10 shows behaviour of hydrodynamics steering moments. The loads due to hydrodynamic forces become significant at higher steering angles; however they are quite linear with increasing advance coefficients. As discussed earlier in section 1.3 these moments are due to the thrust eccentricity moment and the side force moment. In general there is a rapid increase in Fy side force at higher degrees of steering angles and hence the side force moment becomes larger than the thrust force moment as shown in figure 4.9, 4.11, 4.13. The dominance of thrust eccentricity moment in the steering moment is seen more around initial steering degrees and later increases rapidly due to the side force moment.

The oblique inflow created by steering of the thruster causes a thrust eccentricity. The thrust vector shifts away from the propeller rotation axis resulting in this thrust eccentricity which then acts eventually on the steering shaft. Eccentricity of Fx is almost zero until plus, minus 15 degree, hence the yFx side force moment is zero in this range as shown in figure 4.11. The
thrust eccentricity moment increases with increase in steering angle and it is due to that fact that the thrust is higher for lower propeller inlet velocities as seen in section 4.2.1.

![Figure 4.13 Side Force Moment at Various Steering Angles for Different J Values.](image1)

![Figure 4.14 Side Force Moment at Various J Values, for Different Steering Angles.](image2)

The steering moment produced by the side force moment is partly counter-balanced by the thrust force moment and the remainder has to be withstood by the Steering motor. The Pod, shank, skeg partly block the incoming fluid flow and the blockage increases with increase in steering angles which adds to increase in Fy force. This results in a general increase of side force moment and this is shown in figure 4.13. The side force moment is non-zero at zero degree as seen in figure 4.14 above. This is due to difference in inflow pressure on the left and right side of the skeg, shank and pod caused by the propeller blade passing in front of them, leading to a side force with some eccentricity from the steering shaft. The thrust force moment is zero in straight inflow conditions as seen in figure 4.12. This shows the side force moment contributes to the total Mz steering moment for pushing thrusters also as shown in figure 4.10. This steering moment is absent in the pushing type of thruster in straight inflow conditions and is discussed in chapter 6.
STEERING TORQUE DETERMINATION OF PULLING OPEN THRUSTERS
CHAPTER 5

CONTRIBUTION OF THE VARIOUS THRUSTER PARTS TO THE MOMENT

The numerical model is first validated with experimental data and was analyzed to investigate forces and moments for the whole thruster unit. However, it can also give a force analysis for the individual components of the thruster unit, unlike experiments which are limited to measurements of whole units. A study of such an individual behaviour of the thruster parts, shank, skeg, pod and propeller can lead to better understanding of the forces and contribute to improving the design. Before considering the contribution of the individual parts a general idea of the flow field behaviour around the propeller in general is quite important, to understand the physics behind the graphical representations of the forces to follow in coming sections.

5.1 General flow field:
Consider the thruster geometry as shown in the Figure 5.1 below. For ease of expressing the flow visualizations, let us consider the blade position numbers as 1,2,3,4 with the first blade being one which is at the bottom in every quarter rotation and the second being in the next quarter as shown in clockwise direction and so on.

![Figure 5.1 Blade Position Number](image-url)

5.1.1 Flow field around the propeller
Consider a cylindrical sheet of 0.7 Radius used to form a cutting plane as shown in figure 1.3. This is a significant radius, and is often used as representative for the propeller as briefly described in section 1.4.1. A pressure contour is plotted on the cylinder surface and then it is unwrapped into a 2D plane for various steering angles as shown in Figure 5.2. The cylindrical plane is a surface of revolution and it is unwrapped into a flattened surface by employing the m-theta warping tool in the commercial code [7]. The figure below shows the flattened surfaces for various steering angles with blade numbering used as mentioned in figure 5.1.

In figure 5.2 the flow can be imagined to be coming from right to left. In reality, the propeller is rotating in a clockwise sense when looking from front. The leading edge of each aerofoil can be observed where the pressure is the highest in that particular aerofoil section. Also the pressure difference can be noticed between the front and back of the aerofoils, which creates the required lift force. For the positive steering angles, the top blade in the number
three position has an orientation, which acts as a set of airfoils to the incoming flow. Hence, this blade position produces the highest thrust over other blade positions, which can be seen from figure below, where the pressure difference for the third blade position for positive steering angles is higher than other three. However, in contrast, now consider negative steering angles where the bottom blade i.e. blade position number 1, produces most of the thrust again due to the orientation as a set of airfoils to the incoming flow. Moreover, from this figure one can also study the blade area at various steering angles where cavitation may start occurring by setting the vapour pressure as a lower limit for absolute pressure.
5.1.2 Flow field around the Shank

The gearing system for controlled transmission of propulsion power and the gearing system for steering of the thruster body is partly housed in the shank. But this housing adds to form or pressure drag and skin friction drag. The skin friction drag is caused by viscous drag in the boundary layer around the thruster shank body. The form or pressure drag is due to the shape of the shank. To reduce the form drag the shank is shaped hydro dynamically in the shape of an airfoil for each horizontal section which has symmetric camber as it is not intended to produce lift force. A steering angle of the thruster can now be considered as an angle of attack for the shank and different angles will have different thrust and side force values resulting in some hydrodynamic steering moment as mentioned earlier.

In figure 5.3 the pressure contour and streamlines around the shank are shown for the simulations performed at 16 knots and low pitch of 0.965. The shank when at zero degree steering angle, has very less or no lift (here side force) created because we have the same velocities on both sides of the shank body and thereby no considerable pressure difference. At an angle to the flow a lift force and drag force are created resulting in a considerable side force contribution to total side force of the thruster unit. This shank lift force increases until stall occurs at approximately 60 to 75 degrees as observed in the graphical representations of figure 5.11 which shows side forces for various steering angles. The shank has least pressure drag at zero degree due to the hydrodynamic orientation to the flow. This is also evident from figure 5.10 which shows forces (thrust) in the sailing direction as positive. The pressure drag for the shank (or negative thrust) is least at zero degrees and increases with increasing angle, as it obstructs the flow as a blunt body. However, it is interesting to realize here that since we are interested to understand steering moment behaviour, the thrust in local direction has to be considered. In that sense, considering equation 5.3 the shank drag reduces with an increase in steering angle as seen in figure 5.6. The magnitude of this drag force is described later in section 5.2.1

As seen in figure 5.3 the flow field is not symmetric for positive and negative steering angles. The inflow to the shank is different due to the spinning of the blades. For negative angles the shank airfoil sections are oriented in a negative angle of attack to the flow and hence does have a heavy recirculation already at small angles. A early recirculation was observed around minus 30 degrees already for negative steering angles, unlike for the positive steering angles. For the shank a negative steering angle to the flow is comparable to a flow past a blunt body.
5.1.3 Flow field around the Skeg

As mentioned in the introduction of the thruster parts the skeg is an additional device used to contribute to the anti-steering moments along with the steering motor. A skeg is generally used under a ship hull to improve directional stability and creates an anti moment to rolling motion of the ship. On this thruster it is used to counteract the hydrodynamic steering moment Mz.
The flow field around the skeg is quite similar to that of the shank. However, since the skeg is at the bottom, the spinning of the flow now results in a positive angle of attack with the inflow to airfoil sections of the skeg, in the minus steering angles unlike the shank. Again in contrary to shank, in the positive steering angles the flow starts recirculating quite earlier. The skeg produces hardly any change in the thrust force as the thickness of airfoil is very small compared to chord and has a symmetric camber, this is evident in figure 5.6 and 5.9. However, it creates a lot of side force, around 20 to 30 % of the total side force as shown in figure 5.11 and 5.13. Due to the eccentricity of this force from the steering shaft, the Skeg produces an anti moment, this is discussed later in section 5.3.

5.1.4 FLOW FIELD AROUND POD

The flow field around the Pod is generally quite hydro dynamically smooth and has no considerable effects. The flow past the Pod only creates recirculation zones around 60 to 70 degrees, which are still smaller in scale as seen for the skeg and shank. The flow around the pod is symmetric in both steering angles. This is due to the fact that the spinning effect of the propeller blades is having no effects on the inflow to the pod unlike the skeg and shank.
5.2 Contribution of various Thruster parts to Moment

In the previous chapter it was mentioned about the steering moment of various cases and it was also discussed how the side force plays a significant role in the same. In this section another idea is expressed of how various parts contribute to the forces and moments of the thruster system. Also, now that we are introduced to the flow field around the various parts of the thruster it would be better to relate to the physical flow phenomena and the graphical analysis of forces and moments. As described earlier in section 1.4.2 the steering moment, $M_z$ is a moment to keep the thruster at its particular angular position against the external Hydrodynamic forces and some internal forces. This torque is provided by the motor. The steering moment $M_z$ considering only the hydrodynamic forces is given by a cross product:

$$M_z = M_{\text{thrust}} + M_{\text{Side force}} = F_x r_y - F_y r_x$$  \hspace{1cm} (5.1)

Here,

$F_x$ is the Thrust in local direction.
$F_y$ is the Side force in lateral direction to $F_x$. 

**FIGURE 5.5 FLOW FIELD AROUND POD AT 16 KNOTS, LOW PITCH, AT VARIOUS STEERING ANGLES**
$r_y$ is the Thrust eccentricity from steering shaft axis.
$r_x$ is the Side force eccentricity from steering shaft axis.

The steering moment $M_z$ is thus a function of thrust, side force and the respective eccentricities. So each of these components are analyzed here separately for each part of the thruster unit.

**5.2.1 THRUST**

In figure 5.6 the thrust force is given in the thruster local coordinate system and this system moves along with the thruster unit at the various steering angle. The thrust is given by a thrust coefficient which is non-dimensionalized as mentioned previously, but now for each thruster component.

The thrust Coefficient is given by, $K_{F_x} = \frac{F_x}{\rho n^2 D^4}$

![Figure 5.6 Non-Dimensionalized Thrust Component Contribution at 16 Knots, Low Pitch](image)

It can be seen in Figure 5.6 that the thrust coefficient $K_{F_x}$ increases with the steering angle. The propeller produces the thrust and other parts are responsible for the drag and the whole represents the total thrust as shown. A similar trend is seen across in all the simulation (not shown) done for various ship speeds and Pitch by Diameter ratios.
A physical reason for the increase in thrust force with steering angles is as follows:

\[ \alpha = \Theta - \beta \]
\[ \alpha = \Theta - \tan \left( \frac{V_a}{U} \right) \]
\[ \alpha = \Theta - \tan \left( \frac{J}{\pi} \right) \]

The thrust of the propeller is calculated by an integration of lift and drag forces over the span of the propeller blade. The lift force depends on the fluid density, area, the inflow velocity and the lift coefficient \(C_p\). Further, the lift coefficient ‘\(C_p\)’ increases with \(\alpha\), until stall occurs. Hence, the thrust increases with decrease in \(J\) value in equation 5.2. Now it is discussed here referring to figure 5.8 that this \(J\) value decreases with an increase in steering angle. During operation as the steering thruster is rotated, \(V_a\), a cosine component of inlet velocity as shown in figure 5.8 decreases for an increase in steering angle. Hence, the advance velocity \(V_a\) or non-dimensionalized advance coefficient \(J\) decreases with increasing steering angle. Thus, the thrust increases as shown in Fig. 5.6 for increasing steering angles due this change of angle of attack. However, this thrust value also depends on the value of drag and is subjective to different cases.

A similar behaviour is seen under straight inflow conditions. This is evident from the open water characteristics shown in figure 3.2 where \(K_t\) increases with decreasing \(J\) i.e. with a reduction in advanced speed \(V_a\). This again because of the increase in angle of attack due to the change in \(V_a\) as can be deduced from figure 5.7 above.
It can be clearly seen in figure 5.6 that as expected, the propeller contributes a major part to the thrust force and other parts don’t add much to the thrust. However, an attempt is made to understand in the following figure 5.9, which shows the percentage contribution of each thruster component to the total thrust to understand the scale to which other components affect the thrust force.

At any particular steering angle the total thrust of the unit is represented by 100% and a contribution of other components can be seen. It should be noted that the magnitude of the total force however should be obtained from the figure 5.6. Some nice conclusions can be deduced for the thrust as mentioned ahead. First it is similarly clear as it was from the earlier
way of representing the data in figure 5.6 that the propeller contributes almost all the thrust. However, at zero degrees the propeller contributes something around 115% of the total and loses 10% of total because of the shank. This is due to the skin friction drag and form drag of the shank. The form drag is given by:

\[ F_d = 0.5 \rho v^2 C_d A \]  
(5.3)

The form drag increases by the square of the incoming flow velocity. Under straight inflow conditions the velocity is the highest of all steering angles and hence the higher contribution of the shank drag at 0 Deg. Around minus 20 to 30 degrees the shank contributes to 5% of loss of the total thrust. As seen in flow visualizations for the shank in Figure 5.3 this is due to the early recirculation past the shank for negative steering angles. In Appendix C- visuals section it can be seen that the reason for the shank to produce the thrust around 75 degrees is the low pressure zone created due to a recirculation in front of the shank and the high pressure behind the shank and this also reduces the thrust of the whole unit.

The thrust shown in Figure 5.6 is in the local thrust direction. However, it can be also interesting to see in figure 5.10 below that the thrust in the sailing direction now goes below zero after some steering angle. The thrust also decreases with increase in steering angle as expected, and it is maximum at zero degrees. Also it is interesting to see that the thrust coefficient goes negative after 30 degree in this case. This is due to the fact that drag created by the propeller is larger than the lift and hence no thrust will be created in the sailing direction.

5.2.2 SIDE FORCE

Figure 5.11 shows quantities which are non- dimensionalized component contributions to the side force. Also the non- dimensionalized thrust force is added to study the changes in the side forces w.r.t the main force. The side force as discussed earlier is due to hydrodynamic forces of lift and drag which are a function of the steering angles. The side force increases with steering angle due the increase of lift forces on the thruster unit and decreases around 75 degrees as shown in Figure 5.11 below. This is due to stall.
It can be seen that when the steering angle is 30 degrees, the side force produced by the shank almost equals to thrust at zero degree and when steering angle is only 15 degrees the total side force equals the thrust at zero degree, which shows how steeply a typical thruster side force increases.

Figure 5.12 above shows how the shank contributes to the side force due to the hydrodynamic lift force and thus the side force increases with increase in steering angle. However, it decreases with introduction of stall.
The above graph in figure 5.13 shows a percentage contribution of each thruster component to the total side force, to see the relative importance to which other components contribute the side force. Similar to the total thrust, the side force of the unit is represented by 100% and a contribution of other components at any particular steering angle can be seen. As the shank contribution does not vary much w.r.t. the steering angle, it can be said that shank contributes to around 35% of side forces from 15 degree to 90 degree.

It seems as if the propeller shank gives an important contribution for the steering moment as it is contributing heavily to the thrust and side force. However, it can be seen in a later section that the eccentricity of the shank forces is quite small and so it doesn’t contribute to the steering moment much.

**5.3 Hydrodynamic Steering Moment**

Figures 5.14 and 5.15 show the behaviour of the hydrodynamic steering moments at various steering angles. The total steering moment shows a increase with increase in steering angles. As discussed earlier in section 5.2 these moments are due to the thrust eccentricity moment and the side force moment. In general there is a rapid increase in the Fy side force at larger steering angles and hence the side force moment becomes larger than the thrust force moment which is shown in figure 5.18.
The steering moment or torque provided by the steering motor is a moment to keep the thruster at its particular angular position against the external Hydrodynamic forces and some internal forces. The rotation of the propeller at oblique angles causes eccentric forces. The moment is mainly produced due to propeller as seen in figure 5.14. The Skeg and motor create an anti-moment to the moment produced by the propeller. A percentage based contribution at any particular degree is shown below in Figure 5.15. All moments are shown as a percentage of the motor steering moment required to balance the total hydrodynamic moment. The propeller moment contribution is significant and this is counter acted mainly by the skeg. As discussed in 5.2.2, the shank has higher forces of thrust and side force but rather contributes very less to the steering force moment, which is notable in the Figure 5.14 and 5.15. This is due to the fact that these forces pass through the steering shaft about which the moment acts. The remainder i.e. a total of 100% has to be counteracted by the steering motor. There is however an exception at zero degrees and is discussed in detail in chapter 6 when we compare with pushing thrusters which have no steering moments at straight inflow conditions.
5.3.1 Mz balance

Until now the moment contribution was considered for different thruster parts, but now in figure 5.16 contribution based on moments is considered. Steering moment Mz produced by side force Fy is counter-balanced by the thrust force Fx and the remainder has to be withstood by the Steering motor. This is also evident from the equation 5.1 which stated:

\[ M_z = yFx - xF_y \]

Eccentricity of Fx is almost zero until plus, minus 15 degree, hence the yFx side force moment is almost zero in this range. The thrust eccentricity moment increases with increase in steering angle and this is due to that fact that the thrust force (Fx) is higher for lower propeller inlet velocities. The Pod, shank, skeg partly block the incoming fluid flow and the blockage increases with increase in steering angles which adds to the increase in Fy force. This results in an increase of the side force moment.

Figures 5.17 and 5.18 describe the contribution of the various parts to the side force and thrust force moments. As seen in figure 5.17 the Skeg and the propeller mainly contribute to yFx and hence reduces Mz as mentioned in equation above. Further it is seen in figure 5.18 that the Skeg reduces xFy but the Propeller adds to xFy. In both cases the skeg contributes an anti moment to the hydrodynamic steering moments produced.
FIGURE 5.17 NON-DIMENSIONALIZED THRUST MOMENT COMPONENT CONTRIBUTIONS, AT 16 KNOTS, LOW PITCH

FIGURE 5.18 NON-DIMENSIONALIZED SIDE FORCE MOMENT COMPONENT CONTRIBUTION AT 16 KNOTS, LOW PITCH
CHAPTER 6

PUSHING V/S PULLING THRUSTER

Generally azimuthal thrusters are classified into two types depending on the mounting of the propeller and housing. As discussed earlier, when the thruster housing is located upstream of the propeller it is considered to be of pushing type thruster, while it is pulling or tractor type when the thruster housing is located downstream of the propeller. As mentioned in Hydrodynamic Aspects of Steerable Thrusters by J. Dang and H. Laheij [10], a pushing mode thruster is used for low speeds while pulling mode is used for fast vessels. Using the pushing type at relative high speeds, results in cavitation and vibration problems. A pushing versus pulling thruster is compared with respect to hydrodynamic load behaviour in the following sections.

A numerical study for various steering cases of a Pushing Ducted type thruster was carried out in CFD Analysis of Transient behaviour of Azimuthal thrusters by D.W. Suikkerbuijk previously at Wärtsilä [11]. It is compared here with the present study of a Pulling thruster for force and moments using non-dimensional numbers. However, the available pushing thruster under study is with a duct and it would be limited to compare hydrodynamics behaviours for all forces and moments. In figure 6.1 the CAD model used for simulations is shown. The Pulling thruster parts are as described earlier; the pushing unit parts considered in study by Suikkerbuijk for simulations are Pod, Shank, Propeller and duct. Notice the absence of skeg which is used in present pulling unit.

![FIGURE 6.1 PULLING THRUSTER (L) PUSHING THRUSTER (R) [11]](image)

6.1 COMPARISON OF HYDRODYNAMIC STEERING MOMENTS

As the study is mainly about steering hydrodynamics, first a comparison of the steering moment is done. Figure 6.2 shows the behaviour of hydrodynamics steering moments at various steering angles and advance coefficients for the pulling and the ducted pushing thruster under study. The hydrodynamic moments rise very steeply and become significant at higher steering angles for both type of thrusters. It is also quite interesting to see in Figure 6.2, the presence of a non-zero moment even in straight inflow conditions i.e. zero degree steering conditions. On the contrary there is no steering moment present under straight inflow conditions for the pushing type of thruster.
A possible explanation for this non-zero steering moment for the pulling thruster is as follows. Consider figure 6.3 which was shown earlier in section 5.3, where the individual contributions of thruster parts are considered. During the rotation of the propeller there is a force interaction of blades with the shank and skeg via the medium of the fluid. As seen in figure 6.3 the propeller does not contribute to any steering moment here. This is because the blade loading is even for all four blades, due to a more or less similar pressure difference on all the blades, as seen in the pressure contour, as shown in figure 6.4 below. However, at positive steering angles, the blade in position ‘3’ passes the shank and produces most of the thrust among all blades. As there is a difference between forces produced by each blade, the mean thrust produced has an eccentricity away from the propeller rotation axis, which causes a moment about the steering shaft. Similarly, an uneven blade loading is seen at negative steering angles. This results in a moment by the propeller at various steering angles which is significant as seen in figure 6.3 below.
At zero degree, it is in fact the Skeg, Shank and Pod which contribute to the steering moment. This is due to difference in flow pressure on left and right side of the skeg, shank and pod caused by the non-symmetric propeller blade passing position on either side.

Thus, the pulling type of propeller always has a hydrodynamic steering moment loading even in straight inflow conditions. This loading is of a cyclic nature as shown in figure 6.5a. As the thruster is used also for main propulsion, the steering shaft and transmission system in line will be subjected to a cyclic loading for a considerable time during the straight course journey. This Mz Moment about the vertical axis will cause a cyclic cantilever load on the skeg about its mechanical joint. This needs to be taken into account in the design of the transmission system and the skeg to avoid failure due to fatigue. A normalized amplitude with the mean steering moment, for 1st and 2nd blade frequencies is shown in figure 6.5B. The fluctuation of the steering moment increases with an increase of advance velocities.
In case of the pushing type of thruster, the housing is the leading member to the inflow and then the flow passes the propeller which does not involve this kind of interaction. Thus the pushing type of thruster has less or no steering moment at zero degrees as seen in figure 6.2.
Figure 6.6 a and b shows the behaviour of the hydrodynamic steering moments at a range of J values for a pulling and ducted pushing thruster. The steering moments are quite linear for both thruster types at higher advance coefficients as seen in figure 6.6. For the pushing type thruster, possibly due to the presence of the duct the flow is symmetric for positive and minus steering angles unlike for open pulling thrusters as shown above. However, a comparison of open pushing type versus open pulling type would be interesting for comparing symmetry behaviour and can be a part of further investigation.

6.2 COMPARISON OF THRUST FORCE

The effect of changing the steering angle and J values on the thrust produced in pulling and pushing type is shown in figures 6.7 and figure 6.8 below.

![Graph showing non-dimensionalized thrust at various steering angles for different J values](image)

**FIGURE 6.7 NON- DIMENSIONALIZED THRUST AT VARIOUS STEERING ANGLES FOR DIFFERENT J VALUES**

In figure 6.7 it is seen that with an increase in steering angle there is an increase in thrust produced in both thrusters. This is owing to the increase in angle of attack due oblique inflow to the thruster unit. Incase of a Pulling unit it is related to the angle of attack for the propeller blade sections. However, incase of a ducted pushing thruster the angle of incidence is the same for the propeller due to straight inflow as oriented by the duct. Rather the increase of thrust is due to the increase in angle of attack for the duct section.

There is an inflexion point in the figure 6.7 for both the thrusters. All thrust values for different J intersect at around 55-60 degree for both thrusters. It seems to be a bit coincident. However, a possible reason is as follows. This happens before the point of stall where the thrust now decreases. Stall occurs later for higher dynamic pressure flow (higher J values) and continues to follow its trend to increase, where as stall occurs in other lower J values earlier and they start decreasing here. This forms the intersection point. However, this point seems to be less significant for the study.
The trend of the thrust force is linear as seen in figure 6.8 for both thrusters. The forces are indeed symmetrical for positive and negative steering angles for the pulling type. However, for the Pushing type, the difference between Kt values increases for positive and negative steering angles, with increase in J values, as well with increase in steering angles. This is because the housing is in front of the propeller which causes the mass flow rate to increase on one side of housing than another. This pattern inverts in the mirrored steering condition. However, the rotation of the propeller is in the same direction. This results in the difference of thrust between positive and negative steering angles for a pushing thruster (even without a duct).

6.2.1 Recovery of Rotational loss
As mentioned in report Literature review on steering behavior of thrusters that in the Pulling type of thruster [13], generally many theories state that, the presence of a housing behind the propeller leads to some recovery of rotational losses. The propeller leaves rotating fluid behind in its wake which creates an angle of attack for an equally cambered skeg and shank as shown in the streamlines of figure 6.9. A inflow at an angle can be observed for the skeg and the shank. This creates a lift force whose component may act in the thrust direction. Thus the rotation loss is reduced.
However, as mentioned in Hydrodynamic Aspects of Steerable Thrusters by J. Dang and H. Laheij [10], the housing is in the high speed slipstream of the propeller and this will result in higher friction losses compared to the pushing unit. In this particular case of pulling thruster, the skeg, shank and pod produce more friction than the thrust produced by them and this leads to no recovery of rotational loss in total. This is shown in figure 6.10 where the thrust forces produced by each of them is negative at zero steering angle. It is important to note that the thruster used on this ship is used for main propulsion also. The recovery of rotational losses is considerable in straight inflow conditions i.e. zero degree of steering angle.
6.3 COMPARISON OF THE SIDE FORCE

The effect of changing the steering angle and J values on the side force produced by the pulling and pushing type is shown in figures 6.11 and figure 6.12 below. The trend of side force is quite similar for both types. Irrespective of the presence of the duct the side force would be similar in trend, for a pushing type of thruster, as it is a basically a force considering projected area which is blocking the inflow. For the same reason the pulling and pushing force would have a very similar trend as evident in figure 6.11. Figure 6.12 shows near symmetry for positive and negative steering angles for both type of thrusters.
FIGURE 6.12b NON-DIMENSIONALIZED SIDE FORCE AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES (FOR COMPARING MAGNITUDES)
CHAPTER 7

CONCLUSION

Determining and understanding the behaviour of hydrodynamic loads acting on the pulling thruster is important for the mechanical design and analysis of the transmission system for the main propulsion and for the steering of the thruster. The purpose of the thesis was to perform analysis and provide insights in the occurring physical phenomena for the open pulling thruster operating under oblique inflow conditions. Also a hydrodynamic load comparison with a ducted pushing thruster is performed.

A numerical model was used to perform the hydrodynamic calculation. Using RANS to simulate the turbulence, open water test simulations were performed with a quasi-steady method and the Manoeuvring tests were performed with a transient method. During post processing the numerical data was compared with available experimental model scale data for various operating conditions. The results showed an acceptable agreement to do further analysis of steering moment behaviour.

The behaviour of the steerable thruster has been analyzed for different inflow speeds and pitch settings at varying steering angles, even for mirrored conditions. The magnitude of various moments and forces were found to be mostly symmetrical at all the steering cases in the matrix considered. The flow field was found to be not symmetrical for steering angles larger than a certain threshold, this was due to inflow angle and the spinning direction of the propeller rotation. In general, the various hydrodynamic forces were found to be increasing with an increase in steering angles. The thrust force increased due to an increase in angle of attack, the side force increased due to an increase in projected area to inflow. The steering moment increased due to an increase in this two former forces and the eccentricity of these forces about the steering shaft. The contribution of individual parts of the thruster for different forces and moments was also analyzed. The side force moment created by the propeller is balanced mainly by anti moments created by skeg and the steering motor. The side force was found to be increasing steeply with steering angles. The actual loads on the propeller vary during a rotation due to the interaction effects with the housing downstream of the propeller. It is found by Fourier analysis that with an increase in steering angles and ship speed, there is an increase in the blade passing amplitudes of propeller thrust and torque and steering torque.

The pulling thruster under study was compared with a pushing thruster with respect to hydrodynamic loads. It is found that the non dimensional magnitudes are comparable for thrust and side force, whereas due to the eccentricity of these forces the non dimensional magnitudes differ considerably for steering moments. The steering moments in both cases rise very steeply with steering angles and are significant at higher steering angles. Also, it is found that in case of a pulling thruster there is a non-zero fluctuating steering moment present at zero degrees unlike for the pushing unit. As the ship sails in straight conditions for a longer duration of the journey, such a force has to be taken in account for the mechanical design of the transmission system and the skeg to avoid failure due to fatigue. Considering the frictional losses, the recovery of rotation losses behind the propeller from the housing was analyzed to be absent in the pulling thruster under study in straight inflow conditions.

Thus, a numerical effort is made to analyse the hydrodynamic forces of the open pulling thrusters. Further design and developments could be possibly made considering such factors to improve overall performance of pulling type thrusters.
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[18] Some Unsteady Propulsive Characteristics of a Podded Propeller Unit under Maneuvering Operation, Liu, Pengfei; Islam, Mohammed; Veitch, Brian
Appendix A

Performance measurement tests

In the towing tanks model tests of ships are generally done for various analyses, a few tests relevant for the topic are mentioned below:

a. Towing tests
The ship model is towed by the measuring carriage only and there is no propulsion system to propel the model. The model is free to move vertically but motion is prevented sideways. A number of runs at different speeds are done to measure the total resistance of the ship which is recalculated to find the full-scale resistance. These model to full scaling errors, if any, are needed to be considered while validating the numerical model for full scale.

b. Self propulsion tests and open water tests.
To get a clear difference the tests are compared below:

<table>
<thead>
<tr>
<th>Self Propulsion Test</th>
<th>Open water Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>The model of ship is driven by a measuring carriage and its own propeller.</td>
<td>Similarly, the model of ship is driven by a measuring carriage and its own propeller at low shaft speed.</td>
</tr>
<tr>
<td>The speed of the model(by carriage) is kept constant</td>
<td>The speed of the model(by carriage) is varied</td>
</tr>
<tr>
<td>The Rpm of propeller is increased until ship model speed equals the carriage speed. At this point the thrust equals resistance.</td>
<td>The Rpm of Propeller is kept constant</td>
</tr>
<tr>
<td>At this equilibrium speed the values of Rpm,torque,thrust are measured</td>
<td>The values of torque, thrust are measured and efficiency is calculated.</td>
</tr>
<tr>
<td>Tests are carried out to find wake fraction, thrust deduction factor, to confirm early ship power and speed requirements and to check if the propulsor is able to absorb the delivered power</td>
<td>Tests are carried out to find the open water characteristics</td>
</tr>
</tbody>
</table>

Thus Self propulsion test is clearly distinguished from Open water test and the former is used for getting early ship power and speed requirements.
Appendix B

FORCES AND MOMENTS FOR HIGH PITCH/DIAMETER OF 1.142, AT VARIOUS STEERING ANGLES AND J VALUES

Thrust:

FIGURE B.1 THRUST AT VARIOUS STEERING ANGLES, FOR DIFFERENT J VALUES.

FIGURE B.2 THRUST AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES.

FIGURE B.3 THRUST IN SAILING DIRECTION AT VARIOUS STEERING ANGLES, FOR DIFFERENT J VALUES.

FIGURE B.4 THRUST IN SAILING DIRECTION AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES.
Side Force:

Propeller Shaft Torque:

Hydro dynamic Steering Moment:
FIGURE B.11 THRUST MOMENT AT VARIOUS STEERING ANGLES, FOR DIFFERENT J VALUES.

FIGURE B.12 THRUST MOMENT AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES.

FIGURE B.13 SIDE FORCE MOMENT AT VARIOUS STEERING ANGLES FOR DIFFERENT J VALUES.

FIGURE B.14 SIDE FORCE MOMENT AT VARIOUS J VALUES, FOR DIFFERENT STEERING ANGLES.
Appendix C

VISUALS

FIG C.1 FLOW FIELD AROUND THRUSTER UNIT AT 16 KNOTS, LOW PITCH, AT VARIOUS STEERING ANGLES: ZX PLANE (+Y)
FIG C.2 FLOW FIELD AROUND THRUSTER UNIT AT 16 KNOTS, LOW PITCH, AT VARIOUS STEERING ANGLES: ZX PLANE (-Y)
Appendix D

Correlations

(Appendix to Multiple Sections)

D.1 Various Speeds and corresponding Advance Coefficient J Values

<table>
<thead>
<tr>
<th>Speed [knots]</th>
<th>*Speed [m/s]</th>
<th>J [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>6.17</td>
<td>0.561</td>
</tr>
<tr>
<td>14</td>
<td>7.20</td>
<td>0.655</td>
</tr>
<tr>
<td>16</td>
<td>8.23</td>
<td>0.748</td>
</tr>
<tr>
<td>18</td>
<td>9.26</td>
<td>0.842</td>
</tr>
</tbody>
</table>

*1 knot = 0.5144 m/s

D.2 Pitch Deflection and corresponding Pitch/Diameter Ratio

<table>
<thead>
<tr>
<th>Pitch Deflection [ Deg ]</th>
<th>P/D [-]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.965</td>
<td>Low Pitch, results in low power transmitted to fluid.</td>
</tr>
<tr>
<td>3.7</td>
<td>1.142</td>
<td>High Pitch, results in high power transmitted to fluid.</td>
</tr>
</tbody>
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Appendix E

Maneuvering Tests Results at Other Speeds
Experimental v/s CFD

(Appendix to Section 3.4.1)

FIGURE E.1 MANOEUVRING TESTS RESULTS – CFD V/S EXPERIMENTAL (SPEED 12 KNOTS)

PITCH / DIAMETER : 1.142 , J : 0.561

FIGURE E.2 MANOEUVRING TESTS RESULTS – CFD V/S EXPERIMENTAL (SPEED 14 KNOTS)

PITCH / DIAMETER : 1.142 , J : 0.655
STEERING TORQUE DETERMINATION OF PULLING OPEN THRUSTERS

FIGURE E.3 MANOEUVRING TESTS RESULTS – CFD V/S EXPERIMENTAL
(SPEED 18 KNOTS)

PITCH / DIAMETER : 1.142, J : 0.842