Hydrodynamic Characteristics of Twin-Rudders at Small Attack Angles

Jialun Liu\textsuperscript{1} and Robert Hekkenberg\textsuperscript{2}

\textbf{ABSTRACT}

RANS simulations are implemented to analyse the hydrodynamic characteristics of twin-rudders, i.e. Flat plate rudders, NACA rudders, and Wedge-tail rudders. The study mainly focuses on small attack angles. Results show that the NACA series is the most efficient profile while the Wedge-tail rudder has the highest rudder effectiveness.

\textbf{KEY WORDS}

2D rudder simulations; Flat plate rudders, NACA rudders; Wedge-tail rudders

\textbf{INTRODUCTION}

Rudders are crucial to ship manoeuvrability for initializing and correcting manoeuvres. The main determinants of rudder forces and moments are the rudder area, force coefficients (lift and drag), angle of attack, and incidence flow velocity. A twin-rudder configuration is regarded as a common solution in the case that the rudder size is limited due to shallow water, especially for inland vessels. Rudders are most frequently used at small angles of attack within 15 degrees of course keeping and initial turning. Considering the frequency of occurrence of rudder angles, it is valuable to have a high lift to drag ratio at small attack angles for good manoeuvring performances at low cost.

However, general methods of calculating twin-rudder forces are based on adding correction coefficients to the lift and drag curves of the single rudder. In fact, performances of twin-rudders cannot be simply regarded as a duplication of the single rudder. The interaction between the two rudder blades has to be taken into account. Furthermore, the angle of attack of individual blades also varies under the same rudder angle. Regarding these impact factors, rudder profiles and angles of attack are tested through systematic experiments to verify the determinants. Due to the high cost of model testing, this paper applies Reynolds-Averaged Navier-Stokes (RANS) simulations.

In order to get an accurate estimation of twin-rudder forces and moments in manoeuvring simulations, lift and drag curves are needed. These are obtained for three types of twin-rudders: Flat plate rudders, NACA rudders, and Wedge-tail rudders. The hydrodynamic characteristics of the twin-rudder system in two-dimensional steady-state incompressible flow are analysed through the finite volume method with the k-\omega SST turbulence model. Commercial packages POINTWISE and ANSYS ICEM are applied for unstructured and structured grid generation respectively. ANSYS FLUENT is used as the solver of the Navier-Stokes equations.

To begin with, impact factors in the determination of a twin-rudder system are discussed, i.e. the rudder profile, the lateral spacing between the rudders, and the diversity of attack angles for each plate. In the following section, computational methods applied in this paper are presented through a discussion of mesh generation and turbulence model selection. Due to the lack of twin-rudder experimental results, the method is first validated by classic single rudder profile NACA0012. Multiple cases are carried out with three types of twin-rudder systems with fixed lateral spacing of one rudder chord length c. Results of twin-rudder configurations are compared with single rudders to show the impacts of the number of rudders and profiles. Finally, conclusions of the hydrodynamic characteristics of twin-rudder configurations are drawn. Suggestions are proposed for further research.

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**TWIN-RUDDER CONFIGURATIONS**

**Profile Selection**

To start study on characteristics of a twin-rudder system, a first choice has to be made of the profile for each rudder. Considering the impact factors of the ship type and the navigation environment, there is no universal rudder suitable for all conditions. Profiles are generally classified into different families differing mainly in the maximum relative thickness, which is 20% to 35% of the total length from the leading edge (Thieme 1965). Molland and Turnock (2011) presented an overview of rudder types. This paper compares characteristics of common rudder families as shown in Figure 1, i.e. Flat plat rudders, NACA series, and Wedge-tail rudders.

![Figure 1: Tested single rudder profiles](image)

**Flat Plate Series**

Flat plat rudders are thin rectangular blocks in 3D. The main determinant factor in 2D is the ratio of the rudder thickness $t$ to the rudder chord length $c$. This parameter is principally determined by the requirements of the structural strength from classification societies, for instance Det Norske Veritas (2014). Flat plate rudders achieve high lift efficiency at small attack angles in straight-ahead motion (Thieme 1965), but also stall at relatively small angles of attack. These rudders are not common for modern seagoing ships, but they are widely installed in inland vessels. In this paper, flat plate rudders of $t/c = 0.05$ with round edges are tested.

**NACA Series**

For the objective of economics as discussed by Kim, Kim, Oh, and Seo (2012), the NACA series is most widely used by seagoing ships with no specific requirements. Molland and Turnock (2011) compared the performances of NACA00 series and the low drag series of NACA65 or NACA66, proposing that NACA00 series can be more suitable for rudder applications over a large range of angles while the NACA65 or NACA66 series may be more applicable for high-speed vessels. In this paper, symmetric NACA0025 is applied as representative of the NACA series.

**Wedge-tail rudders**

Wedge-tail and Fishtail (Schilling) profiles are widely used by inland vessels to improve the rudder effectiveness at slow speed in shallow water. To improve the performances of existing rudders, an approach is to attach a wedge tail to the NACA series. Based on the Wedge-tail rudders, Fishtail profiles have better smoothed geometry than the original wedges. However, little information is publicly available regarding the fishtail geometry. Van Nguyen and Ikeda (2014) discussed the effects of Reynolds number, trailing edge thickness, and maximum thickness on the fishtail rudder hydrodynamic characteristics. Commonly, compared with NACA profiles, Wedge-tail and Schilling rudders are superior in extending the stall angle. Tails of Wedge tail and Schilling rudders can also generate high lift coefficients but with extra drag (Molland & Turnock 2011; Thiemann & Thieme, 1959; Thieme, 1965). Because no uniform smoothing methods are found for the Fishtail rudders, only Wedge-tail rudders are discussed in this paper. The Wedge-tail rudder presented is based on the NACA0025 profile concaving at 0.95 $c$ with a tail wedge thickness of 0.1 $c$.

For twin-rudder systems, both rudders are commonly set with the same type of symmetric rudders. For asymmetric profiles, the twin rudders are mirrored in the chord direction. This paper only tests symmetric profiles. At a later stage, more consideration is needed for the relative position of the twin rudders, i.e. the lateral spacing and the diversity of attack angles.
Lateral Spacing

Lateral spacing is the distance between the twin rudder blades. It determines the percentage of rudder area in the propeller stream and the gap between the leading edges of each rudder under large attack angles. As the effective incidence speed largely affects the rudder performances, it is suggested to have a reasonably small lateral spacing to ensure both rudders are still in the propeller slipstream, like the single rudder. On the other hand, in order to reduce the crash stopping distance, the rudders can be simultaneously set at 75° outward to reduce the gap between the leading edges of the twin rudders. A smaller lateral spacing leads to a smaller gap achieving a better performance of stopping. Baudu (2014) indicated that the stopping distance decreases by 50% with respect to the conventional reverse engine stopping. Lateral spacing of 1.0 c is set assuming both rudders are turning with pivot points at 0.25 c. The rudder configurations at straight ahead and crash stopping are shown in Figure 2. In this paper, only straight ahead cases are reviewed.

![Figure 2: Rudder configurations at straight (left) and crash stopping (right) for twin-rudders](image)

Difference of Attack Angles

At cruising speed, ships use small rudder angles to keep a steady course. Rudders are operated in parallel at the same attack angle. When frequent hard manoeuvring is needed, for instance at port area, ships sail at relatively slow speed with large rudder angles. In that case, the difference of attack angles between the inner rudder and the outer one can be as large as 35° (Baudu 2014), which is illustrated in Figure 3. The attack angle difference may affect the complex interactions among rudders and propeller as well as the hydrodynamic characteristics; however, little information about the effects is found. This paper focuses on the small attack angels, as they are most frequently applied in practice. The difference of attack angles is zero.

![Figure 3: Difference of attack angles at cursing (left) and manoeuvring (right)](image)
In order to present the impacts of the number of rudders and the profile on the twin-rudder systems, six cases are tested here for RANS simulations as shown in Table 1.

Table 1: List of tested cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: FP0050</td>
<td>Single Flat plate rudder with t/c = 0.05</td>
<td></td>
</tr>
<tr>
<td>Case 2: NACA0025</td>
<td>Single NACA0025 rudder</td>
<td></td>
</tr>
<tr>
<td>Case 3: Wedge0025</td>
<td>Single Wedge-tail rudder based on NACA0025r</td>
<td></td>
</tr>
<tr>
<td>Case 4: T-FP0050</td>
<td>Twin Flat plate rudders with t/c = 0.05</td>
<td>All the twin-rudder cases are set with lateral spacing of 1.0 c. The tested angles of attack are in range of 0 to 25° at an interval of 5°.</td>
</tr>
<tr>
<td>Case 5: T-NACA0025</td>
<td>Twin NACA0025 rudders</td>
<td></td>
</tr>
<tr>
<td>Case 6: T-Wedge0025</td>
<td>Twin Wedge-tail rudders based on NACA0025r</td>
<td></td>
</tr>
</tbody>
</table>

**COMPUTATIONAL METHODS**

**Mesh Generation**

To start Computational Fluid Dynamics (CFD) calculations, mesh is generated to represent the physical domain in a discrete form on which the governing equations can be resolved numerically. There is no universal mesh suitable for all cases, but the rule of thumb is to refine the mesh in regions where high gradients of fluid characteristics exist. To capture the boundary layers and the interactions, for a twin-rudder system, a fine mesh is needed around each rudder profile and between the twin rudders.

A structured C-type grid of NACA0012 is first generated for the model calibration and validation as shown in Figure 4. A grid independence study is carried out to determine the required number of cells and the domain size. The number of cells is around 500,000 with boundary layers to capture the viscous effects. The initial height of the boundary layer is 4.46E-6 c to ensure the $y^+$ smaller than 1 for the $k-\omega$ SST turbulence model. The domain has a radius of 30 c round the profile and a length of 60 c after the profile to ensure the results are not influenced by the location of far field boundaries.

![Figure 4: Structured mesh around single NACA0012 (left) and detail close to the profile (right)](image)

Considering the complex geometry of Wedge-tail rudders and twin rudder configurations, an unstructured mesh is applied for all tested cases to be able to compare the results under the same strategy of mesh. An unstructured mesh is generated also for NACA0012 to show the order of the relative error caused by the unstructured mesh as shown in Figure 5. The domain is simplified to a rectangular space with a length of 90 c and a width of 60 c. Boundary layers are set as the same size as the structured mesh.

To define the angle of attack, velocity components are specified for a single rudder while the geometries are modified for twin rudders. Each single rudder case has only one mesh but twin rudder cases have different meshes for different angle of attack. Examples of mesh for twin NACA0025 at an angle of attack of 0 and twin Wedge-tail rudders at an angle of attack of 25° are given in Figure 6.
Figure 5: Unstructured mesh around single NACA0012 (left) and detail close to the boundary layers (right)

Figure 6: Unstructured mesh around twin NACA0025 at an angle of attack of 0 (left) and twin Wedge-tail rudders at an angle of attack of 25°

Model Validation

As a primary study, quick assessment with sufficient accuracy is needed. In order to achieve observations on effects of mesh on solutions, several cases of NACA0012 with a sharp leading edge with a structured mesh (Figure 4) and unstructured mesh (Figure 5) are carried out through commercial CFD code ANSYS Fluent 15.0. Throughout this work, the k-ω SST turbulence model is applied. Detailed model settings are presented in Table 2. Residuals are expected to drop by at least four orders to minimize convergence error. In the simulations, the automatic stopping criterion is set at $10^{-5}$. An additional convergence check is done for force coefficient behaviour.

Table 2: Model settings for CFD calculations

<table>
<thead>
<tr>
<th>Property</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>6 million</td>
</tr>
<tr>
<td>Solver</td>
<td>Pressure-Based Steady</td>
</tr>
<tr>
<td>Materials</td>
<td>Water liquid</td>
</tr>
<tr>
<td>Viscous Model</td>
<td>k-ω SST</td>
</tr>
<tr>
<td>Pressure-Velocity Coupling</td>
<td>Coupled</td>
</tr>
<tr>
<td>Gradient</td>
<td>Least Squares Cell Based</td>
</tr>
<tr>
<td>Pressure</td>
<td>Second Order</td>
</tr>
</tbody>
</table>
Momentum
Second Order Upwind
Turbulent Kinetic Energy
Second Order Upwind
Specific Dissipation Rate
Second Order Upwind
Convergence Criteria
$10^{-5}$

FLUENT solutions are compared with the computed results by CFL3D (NASA LaRC, USA), FUN3D (NASA LaRC, USA), and NTS (NTS, Russia) from the Langley Research Centre (2014). Relative errors are calculated at related attack angle of $\alpha$ through equation [1].

$$\Delta C_{\alpha} = \frac{C_{\alpha, CFD}}{C_{\alpha, \text{experiment}}} - 1$$

Table 3: Relative errors of NACA0012 with structured mesh against benchmark CFD data in percent

<table>
<thead>
<tr>
<th></th>
<th>$\Delta C_d_0$</th>
<th>$\Delta C_l_5$</th>
<th>$\Delta C_d_5$</th>
<th>$\Delta C_l_{15}$</th>
<th>$\Delta C_d_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL3D</td>
<td>0.37</td>
<td>-1.45</td>
<td>4.85</td>
<td>-1.41</td>
<td>2.57</td>
</tr>
<tr>
<td>FUN3D</td>
<td>0.50</td>
<td>-2.01</td>
<td>3.43</td>
<td>-1.68</td>
<td>0.04</td>
</tr>
<tr>
<td>NTS</td>
<td>0.37</td>
<td>-1.33</td>
<td>3.60</td>
<td>-1.62</td>
<td>4.07</td>
</tr>
</tbody>
</table>

Table 4: Relative errors of NACA0012 with unstructured mesh against benchmark CFD data in percent

<table>
<thead>
<tr>
<th></th>
<th>$\Delta C_d_0$</th>
<th>$\Delta C_l_5$</th>
<th>$\Delta C_d_5$</th>
<th>$\Delta C_l_{15}$</th>
<th>$\Delta C_d_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL3D</td>
<td>2.47</td>
<td>-1.45</td>
<td>13.83</td>
<td>-1.90</td>
<td>18.34</td>
</tr>
<tr>
<td>FUN3D</td>
<td>2.60</td>
<td>-2.01</td>
<td>12.29</td>
<td>-2.17</td>
<td>15.43</td>
</tr>
<tr>
<td>NTS</td>
<td>2.47</td>
<td>-1.33</td>
<td>12.47</td>
<td>-2.11</td>
<td>20.07</td>
</tr>
</tbody>
</table>

Table 3 and Table 4 present the relative errors of structured and unstructured mesh cases. Both meshes have a good accuracy of the lift, while the structured mesh shows a better capability in drag predication than the unstructured mesh. With either type of mesh, the relative error of lift does not change much at various angles of attack. However, the relative error of drag increases with the increase of the angle of attack. The results of the structured and unstructured meshes indicate an under-estimation of lift and an over-estimation of drag. The under-estimation of lift is mainly caused by the numerical diffusion, while the over-estimation of drag is primarily introduced by the assumption of fully turbulent flow. In fact, the flow is transferred from laminar to turbulence. As the main interest of this paper is to estimate the rudder effectiveness, which is determined by the lift coefficient, the accuracy of the unstructured mesh is regarded as sufficient.

RESULTS AND DISCUSSIONS

Six cases of single or twin rudders are tested through CFD simulations. Results are presented in Table 5 and further discussed in the following section. The discussion of the results begins with lift coefficients, drag coefficients, and lift to drag ratios and ends with the pressure distribution of each rudder configuration.

Table 5: List of test results

<table>
<thead>
<tr>
<th>Case</th>
<th>$C_l$</th>
<th>$C_d$</th>
<th>$C_l_5$</th>
<th>$C_d_5$</th>
<th>$C_l_{15}$</th>
<th>$C_d_{15}$</th>
<th>$C_l_{20}$</th>
<th>$C_d_{20}$</th>
<th>$C_l_{25}$</th>
<th>$C_d_{25}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: FP0050</td>
<td>0.000</td>
<td>0.015</td>
<td>0.567</td>
<td>0.017</td>
<td>0.713</td>
<td>0.136</td>
<td>0.720</td>
<td>0.211</td>
<td>0.767</td>
<td>0.293</td>
</tr>
<tr>
<td>Case 2: NACA0025</td>
<td>0.002</td>
<td>0.012</td>
<td>0.472</td>
<td>0.013</td>
<td>0.919</td>
<td>0.018</td>
<td>1.240</td>
<td>0.033</td>
<td>1.169</td>
<td>0.087</td>
</tr>
<tr>
<td>Case 3: Wedge0025</td>
<td>0.001</td>
<td>0.051</td>
<td>0.688</td>
<td>0.051</td>
<td>1.383</td>
<td>0.051</td>
<td>2.048</td>
<td>0.059</td>
<td>1.615</td>
<td>0.179</td>
</tr>
<tr>
<td>Case 4: T-FP0050</td>
<td>0.002</td>
<td>0.026</td>
<td>0.813</td>
<td>0.029</td>
<td>1.600</td>
<td>0.037</td>
<td>2.248</td>
<td>0.060</td>
<td>2.380</td>
<td>0.147</td>
</tr>
<tr>
<td>Case 5: T-NACA0025</td>
<td>0.002</td>
<td>0.026</td>
<td>0.813</td>
<td>0.029</td>
<td>1.600</td>
<td>0.037</td>
<td>2.248</td>
<td>0.060</td>
<td>2.380</td>
<td>0.147</td>
</tr>
<tr>
<td>Case 6: T-Wedge0025</td>
<td>-0.001</td>
<td>0.107</td>
<td>1.155</td>
<td>0.107</td>
<td>2.313</td>
<td>0.110</td>
<td>3.463</td>
<td>0.123</td>
<td>3.287</td>
<td>0.347</td>
</tr>
</tbody>
</table>
Lift Coefficients

Figure 7 demonstrates that twin-rudder systems have higher lift coefficients than single rudders. The increase of lift from the single rudder to the correspondent twin-rudder system varies with the angle of attack. Figure 7 also shows that the twin-rudder configuration of NACA0025 increases the stall angle. Wedge-tail rudders achieve the highest lift coefficients in both single and twin configurations, while Flat plate rudders get the lowest ones. Due to the flow separation and no reattachment at the trailing edge (Figure 15), the lift of the flat plate does not increase much after an angle of attack of 5°. On the contrary, the flow around Wedge-tail profiles separates at the leading edge and reattaches at the trailing wedges (Figure 17), which increases the pressure difference between the two surfaces. Thus, the single Wedge-tail rudder indicates high lift performance compared to other single and twin-rudder configurations.

![Figure 7: Lift coefficient](image)

Drag Coefficients

Figure 8 shows that the rudder profile significantly affects the drag coefficients. The single and twin Flat plate rudders induce more drag than other configurations due to a larger flow separation effects. The wedge tail not only increases the lift coefficients but also raises the drag curves. After all, the NACA profile shows the best performance with the lowest drag coefficients.

![Figure 8: Drag coefficient](image)

Lift to Drag Ratios

Figure 9 shows the lift to drag ratios of various rudder configurations. First, NACA profiles in both single and twin rudder cases have the highest lift to drag ratio, which means they are more efficient and economical than other configurations. Flat plate rudders’ ratios sharply drop after an attack angle of 5° and remain at a low value, because their lift coefficients do not
increase much while their drag coefficients grow quickly. Due to the wedges, Wedge-tail rudders have lower ratios than the NACA profiles. Among all, the NACA rudders have the highest lift to drag ratios.

![Figure 9: Lift to drag ratio](image)

**Static Pressure**

To understand the mechanism of the lift and drag generation, pressure distributions around single rudders and twin rudders are presented in Figure 15 to Figure 17 and Figure 18 to Figure 20 respectively. The wedge tails trap the flow along the lower surface resulting in two high-pressure zones. More specifically, one is right on the leading edge, the other one is at the concave zone near the trailing edge. The pressure difference of the Wedge-tail rudder between the upper surface and the lower surface is much higher than that of the NACA profile, which is also clearly shown by Figure 10. The twin-rudder system constrains the flow and highly increases the velocity between the upper rudder and the lower rudder, resulting in a zone of low pressure as shown in Figure 18 to Figure 20. Comparing Figure 11 and Figure 12 to Figure 10, the pressure distribution of the upper rudder is more significantly affected than the lower one.

![Figure 10: Pressure coefficients of NACA0025 (left) and Wedge0025 (right) at an angle of attack of 15°](image)

![Figure 11: Pressure coefficients of T-NACA0025 upper (left) and lower (right) rudder at an angle of attack of 15°](image)
Figure 12: Pressure coefficients of T-Wedge0025 upper (left) and lower (right) rudder at an angle of attack of 15°.

Figure 13 and Figure 14 compare the lift and drag coefficients of each rudder in single and twin configurations of NACA0025 and Wedge0025. The lift coefficient of each rudder in the twin-rudder system is smaller than that of the single rudder except the lower rudder in the twin-rudder configuration after about 20°. The drag coefficient of the lower rudder increases while that of the upper rudder decreases.

Figure 13: Comparison of lift coefficients of single rudder and twin rudder system

Figure 14: Comparison of drag coefficients of single rudder and twin rudder system
CONCLUSIONS

Computational Fluid Dynamic (CFD) simulations are performed for six single/twin rudder configurations of Flat plate rudders, NACA rudders, and Wedge-tail rudders. After the validation against other experimental data, steady state simulations are carried out in incompressible viscous water with k-ω SST turbulence model in unstructured 2D mesh. Simulations for each case are presented for six angles of attack ranging from 0 to 25° at an interval of 5°. The lift coefficients, drag coefficients, and lift to drag ratios are compared. Visualization of the pressure coefficients on the rudder surfaces and the pressure distribution around the rudders are presented. Conclusions from the results provide insight in the hydrodynamic characteristics of twin-rudders for small attack angles.

- 2D RANS simulations of rudders underestimate the lift coefficients while overestimate the drag coefficients. The relative error of lift does not change much with an increase of attack angles. The relative error of drag increases as the increase of the angle of attack.

- The accuracy and convergence of the simulation are influenced by the mesh structure. Even though the structured mesh is superior in accuracy to the unstructured mesh, an unstructured mesh is applied in this paper as it is more suitable for complex geometry and is more convergence-friendly than the structured mesh with acceptable accuracy.

- Among the tested cases, the NACA profile is the most efficient one. It induces the lowest drag and ranks highest lift to drag ratio in both single and twin configurations. Thus, NACA profiles are suggested for rudders that do not have strict requirements in lift.

- Wedge-tail rudders can provide high lift but also cause high drag. At the same angle of attack, Wedge-tail rudders have the highest rudder effectiveness, i.e. the highest lift force. Thus, Wedge-tail rudders are proposed for ships, which sail in constrained waterways, such as inland vessels, port boats, and other ships that need good manoeuvrability.

- Compared with the NACA rudders and Wedge-tail rudders, Flat plate profiles are not efficient as ship rudders. As many inland vessels are still operating with Flat plate rudders, more research is suggested to discuss the effectiveness of the rudder replacement.

This paper presents an initial study of the hydrodynamic characteristics of twin-rudders at small attack angles. More tests are needed to concern the other impact factors, such as the Reynolds number, the lateral spacing, and the difference of attack angles, which are the authors’ further topics.

REFERENCES


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Figure 15: Pressure distribution around FP0050 at angles of attack in range of 0 to 25° at an interval of 5°

Figure 16: Pressure distribution around NACA0025 at angles of attack in range of 0 to 25° at an interval of 5°

Figure 17: Pressure distribution around Wedge0025 at angles of attack in range of 0 to 25° at an interval of 5°
Figure 18: Pressure distribution around T-FP0050 at angles of attack in range of 0 to 25° at an interval of 5°

Figure 19: Pressure distribution around T-NACA0025 at angles of attack in range of 0 to 25° at an interval of 5°

Figure 20: Pressure distribution around T-Wedge0025 at angles of attack in range of 0 to 25° at an interval of 5°