Short Paper

INVESTIGATION OF HYDRODYNAMIC PERFORMANCE OF HIGH-SPEED CRAFT RUDDERS VIA TURBULENT FLOW COMPUTATIONS, PART I: NON-CAVITATING CHARACTERISTICS

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Key words: high-speed craft rudder, non-cavitating hydrodynamic characteristics, turbulent flow computation, computational fluid dynamics.

ABSTRACT

This paper focuses on the numerical analysis of non-cavitating hydrodynamic characteristics of practical rudders used for high-speed crafts, which is valid in the low-speed region. The force and moment acting on rudder are calculated by integrating the shear force and pressure force on the rudder surface, which are obtained from the turbulent flow calculation around rudder. The non-cavitating hydrodynamic characteristics of NACA rudders, as well as rudders using simple profiles, are computed and then compared. Three non-dimensional coefficients, the lift, drag and stock moment coefficient of rudder, are evaluated to investigate the influences of profile shape and profile thickness. The influences of rudder’s geometrical parameters on the stall characteristics are also discussed. According to the predicted results, the location of maximum thickness is the most important factor to influence the non-cavitating hydrodynamic characteristics. For all studied rudders, the thicker rudder generates larger stock moment despite of the profile difference.

INTRODUCTION

For high-speed crafts, cavitation is an inevitable phenomenon occurred at propeller and rudders. The cavitating characteristics of rudder are valid for the high-speed region, while the non-cavitating characteristics of rudder are applicable in the low-speed region. The presented paper focuses on the non-cavitating hydrodynamic characteristics, where cavitation is neglected. The cavitating characteristics of rudder are also very important for high-speed craft rudders, and are definitely different from the non-cavitating characteristics. The cavitating performances of rudders will be discussed in the second part of this study and presented in a separate paper, where the turbulent cavitating rudder flow is computed through the coupling of Rayleigh-Plesset equation to take the influence of cavitation effect into account. Many experimental and numerical analyses are conducted in the past to investigate the performance of low aspect ratio NACA foils both in fields of aerodynamics and hydrodynamics. Experimental measurements of a family of all-movable, low aspect ratio control surfaces in free-stream at various Reynolds number have been performed [10]. A relevant experiment to investigate the force and moment characteristics of six high-speed rudders with aspect ratio of 1.5 and different section shapes under cavitating conditions can be found in [2]. Furthermore, a series of rudders with a geometric aspect ratio of 1.5 but widely varying section shapes was constructed to determine the effect of section shape on the cavitating performances while operating in the propeller slipstream [5]. However, few works for other profile shapes are observed. Recognizing the need for providing useful information in the rudder design and the proper selection of rudder gears, further investigations on the performance of high-speed rudders are essentially
necessary. As mentioned in [8], the model experiments produce accurate hydrodynamic forces at model-scale Reynolds numbers, but are poor to give maximum lift due to the scale effect. One popular approach used to analyze the rudder flow problems is the potential flow calculation. However, it failed to give any stall condition due to neglecting viscosity, which leads to turbulence and flow separation.

The purpose of this paper is to analyze the non-cavitating hydrodynamic performances of NACA rudders, as well as rudders using simple profiles. A numerical method based on computational fluid dynamics (CFD) is applied to predict the non-cavitating hydrodynamic characteristics of rudder. The force and moment acting on a rudder are calculated by integrating the shear force and pressure force on the rudder surface, which are obtained from the turbulent flow calculation around rudder. Therefore, viscous effects, such as flow separation, can be taken into account. Therefore, the stall phenomenon can be reasonably predicted, which cannot be predicted by the potential methods. Through the calculated results, valuable information can be concluded for the rudder design, which compromises between the hydrodynamic performance and the manufacturing cost.

GOVERNING EQUATION AND TURBULENCE MODEL

The steady and incompressible Reynolds-averaged Navier-Stokes equation and continuity equation are used as the governing equation to describe the flow around rudder:

\[
\frac{\partial (U_i U_j)}{\partial x_j} = \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] - \frac{\partial \left( \bar{u}_i u_j \right)}{\partial x_j}
\]

(1)

\[
\frac{\partial U_j}{\partial x_j} = 0
\]

(2)

\[
\bar{u}_i u_j = -\nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + \frac{2}{3} \delta_{ij} k
\]

(3)

where \( U_i, P \) denotes the mean velocity and the mean pressure, respectively, \( u' \) the fluctuating velocity component, \( \rho \), the density, \( \nu \) the fluid viscosity, \( \nu_t \) the turbulent viscosity, and \( x_i \) the Cartesian coordinate. A two-equation turbulence model, i.e. the \( k - \epsilon \) model [4] is used in the numerical computations:

\[
\frac{\partial (k U_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \epsilon
\]

(4)

\[
\frac{\partial (\epsilon U_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \nu + \frac{C_{\epsilon 1} k}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + c_{\epsilon 1} P_k \frac{\epsilon}{k} - C_{\epsilon 1} \frac{\epsilon^2}{k}
\]

(5)

\[
P_k = -u_i u_j \frac{\partial U_i}{\partial x_j}
\]

(6)

\[
\nu_t = C_{\mu} \frac{k^2}{\epsilon}
\]

(7)

where \( k \) denotes the turbulent kinetic energy, and \( \epsilon \) the dissipation rate of \( k \). The constants in the above equations are given in Table 1. Because this paper focuses on the non-cavitating performance of rudders for high-speed crafts, the computations are performed for turbulent flow at Reynolds number (Re) equal to \( 10^6 \). The effect of transition from laminar to turbulence is neglected, which means that the flow is fully turbulent along the wall. The wall function approach is adopted to bridge the viscous sublayer near wall, where the equations (4) and (5) are no more valid. The shear stress on solid wall \( \tau_w \) is computed as follows, where \( \mu_p \) denotes the local velocity component parallel to the wall of the first grid point from wall, \( y \) the distance to wall and \( \mu_e \) the effective viscosity (\( \equiv \mu + \mu_t \)):

\[
\tau_w = \mu_e \frac{u_p}{y}, \text{ if } y^+ \leq 20
\]

(8)

\[
\tau_w = \mu_e \frac{\rho k}{\sqrt{C_{\mu} \epsilon}}, \text{ if } y^+ > 20
\]

(9)

\[
y^+ = \frac{y \sqrt{\tau_w}}{\nu}
\]

(10)

NUMERICAL METHOD

All the vector quantities such as position vector, velocity, and moment of momentum, are expressed in Cartesian coordinates system. A second order finite volume method is utilized to discretize the governing equation into a system of algebraic equations. The governing equations are first expressed in an integral form over a control volume \( V \) bounded by the control surface \( A \) with outward normal vector \( \hat{n} \). The integral
form of generic function $\phi (= 1, U_i, k)$ and $\varepsilon$ is given as follows:

$$\int_A \phi (\overrightarrow{u} \cdot \overrightarrow{n}) dA = \int_A \Gamma^\phi (\nabla \phi \cdot \overrightarrow{n}) dA + \int_V q^\phi dV \quad (11)$$

where $\overrightarrow{u}$ denotes the velocity vector at cell interface, the diffusion constant $\Gamma^\phi$ and the source term of $q^\phi$. The value of $\phi$ is then expressed in terms of the neighboring nodal values. The number of neighboring points and mathematical form depend on the order of the approximation scheme. Here a deferred correction approach [3] is adopted to approximate the convection term, where a central difference scheme is blended with an upwind difference. Then the governing equation is discretized into a system of algebraic equations as follows:

$$a^c_i \phi^c_i = \sum_i a^i \phi^i + S^c \quad (12)$$

where the subscript $c$ denotes the considered cell node, the subscript $i$ the neighboring cells, $a$ the linearized coefficient and $S$ the linearized source term. The resulted algebraic equations are solved by the SIP method [9]. The SIMPLE algorithm [6] is applied to compute velocity and pressure updates. The pressure interpolation at cell faces follows a special treatment [7] is adopted to obtain a non-oscillating pressure field. Please reference [1] for more details.

**DESCRIPTION OF RUDDERS**

The geometric definition of rudder used in this paper is shown in Figure 1. It consists with the one used in [10]. The mean chord length ($c_m$), taper ratio ($T_r$), and aspect ratio ($A_r$) of rudder are defined in Eq. (1) to (3):

$$c_m = \frac{c_t + c_r}{2} \quad (13)$$

$$T_r = \frac{c_t}{c_r} \quad (14)$$

$$A_r = \frac{h}{c_m} \quad (15)$$

where $c_t$ and $c_r$ denote the chord length at the tip and the root of the rudder, respectively. The height of the rudder is represented by $h$. The angle intersects between the quarter chord axis and Z-axis is known as the sweep angle $\beta$. The geometric aspect ratio and taper ratio of the rudders are 1.5 and 1.0, respectively. All rudders are with zero sweep angles.

Six rudder shapes: NACA 00 series, NACA 16 series, NACA 66 series, wedge shapes, ellipse shapes and rectangle shapes, with different geometric parameters were evaluated. The first two profile series are widely used for rudders due to their smooth pressure distributions along the rudder surface, which could significantly reduce the vibration of rudder caused by an unsmoothed pressure distribution. The third one is often used as the basic profile for propeller blades. It is investigated in order to validate the differences between the rudder profile and propeller profile. For small crafts, such as boats, in order to minimize the manufacturing cost of rudder, rudders of simple shapes are often employed, which fall into the category of the latter three. The name of studied shapes is expressed by alphabetic characters and numeric digits, where the alphabetic characters denote the profile shape, and the numeric value after the alphabetic characters gives the maximum thickness of the profile, e.g. Rectangle08 means the rectangle rudder with a maximum thickness of 8% chord length. All rudders are geometrically symmetrical about their nose-tail line. For rectangle and wedge type rudders, the trailing edge doesn’t converge to a single point and have a finite end thickness. Because the slope nears the trailing edge changes drastically, a significant pressure change near the trailing edge is expected, which deteriorates the convergence of the turbulence model with wall function employed. Hence, small geometrical simplifications near the leading edge and trailing edge are made, as shown in Figure 2, in order to obtain a better numerical convergence in the turbulence model. This geometrical
simplification could influence the pressure distribution along the profile, especially near the trailing edge. Because the pressure near trailing edge has only little contribution to the total force calculation, the pressure change due to the geometry change near the trailing edge has quit limited influence on the lift and drag, which are calculated through the integral of stresses along the profile. This approach has been justified in [1], in which a similar approach was adopted.

GRID TOPOLOGY

The arrangement of the computational domain, Figure 3, is created with the strategy described in [1]. The upstream part of the computational domain is a half cylinder with radius $R$ and height $T$, whereas the downstream part is a rectangular block with length $R$, width $2R$ and height $T$. Since the rudders are assumed to be symmetrical about their root section in the numerical computation, only one half of rudder is modeled. In order to avoid unfavorable effects of the artificial outlet boundary, $R$ and $T$ are specified as $5$ cm. The computational domain is divided into 400,000 cells based on a C-H topology, Figure 4. The local grid quality can influence the discretization error significantly. Therefore, the grid lines in the horizontal planes near rudder surface were clustered with elliptic smoothing to keep the grid lines almost orthogonal in order to reduce the interpolation errors due to grid skewness.

CONSTANT MAXIMUM THICKNESS

The influence of the rudder shape is examined in this section. Six rudder profiles, including Ellipse08, Rectangle08, Wedge08, NACA 0008, NACA 1608 and NACA 6608 are considered with a constant maximum thickness of 8% chord length, Figure 5. The drag coefficient ($C_D$), the lift coefficient ($C_L$), and the stock moment coefficient about the axis at 25% chord length from the leading edge ($C_{M,0.25}$) of these rudders are shown in Figures 6-8, respectively. Generally speaking, the $C_D$ of the Rectangle08 rudder is much greater than the other rudders. Besides, the drag produced by the Wedge08 rudder is also larger than those of NACA series. The $C_D$ of the Ellipse08, NACA 0008, NACA 1608 and NACA 6608 rudders are almost in the same order of magnitude. This is due to that the streamlining shape has a considerable effect on the drag reduction. The differences of $C_D$ between the NACA series rudders are quite small. Obvious differences are only observed at large angles of attack (before the stall angle). Among these rudders, the ones with convex end seem to produce lower drag for large angles of attack. The results demonstrate that the streamlining of section shape is an important factor that affects the drag coefficient.

In Figure 7, the $C_L$ curve of the Rectangle08 rudder deviates significantly from the other rudders with the increasing angle of attack. With the angle of attack $\alpha = 10^\circ$ for instance, the $C_L$ of the Rectangle08
rudder is 29.3% smaller than that of the NACA 0008 rudder. The Wedge08 rudder with the maximum thickness at the trailing edge seems to stall earlier among all rudders except the Rectangle08. The Ellipse08 rudder, which has a convex end and the maximum thickness located at the chord middle point, generates smaller lift when compared to the NACA rudders. Rudder is a kind of hydrofoil that should operate over a wide range of angle of attack, and the location of maximum thickness of the rudder section should be designed close to the leading edge in order to deliver large lift. The maximum thickness of NACA 1608 and NACA 6608 section are situated near the middle chord. This is why they yield lower lift than the NACA 0008 rudder. Therefore, they are not favorable for applications with large variation in angle of attack, and this explains why they are preferred in the propeller blade design, where small operation range of angle of attack are expected. The NACA 0008 rudder provides the largest maximum lift coefficient ($C_{L, max}$) and stall angle ($\alpha_{stall}$), whereas the Rectangle08 rudder offers the smallest ones. The $C_{L, max}$ and the $\alpha_{stall}$ for all rudders are summarized in Table 2, where $x_{max}$ denotes the location of maximum thickness. Figure 8 demonstrates the required turning moment for each rudder. The Wedge08 rudder with an unusual location of maximum thickness at the trailing edge shows the most unfavorable performance (the largest moment) in $C_{M, 0.25}$ for all angles of attack. This is due to that the high-pressure region of this rudder, which is generally corresponding to the location of maximum thickness, is found most distant from the stock location than other rudders. The same mechanism leads to that the NACA 0008 rudder produces the smallest $C_{M, 0.25}$, because its maximum thickness is located very close to the rudder stock. From the predicted results, both the location of maximum thickness and the shape at trailing edge play an important role on the rudder performance.

<table>
<thead>
<tr>
<th>Rudder</th>
<th>$C_{L, max}$</th>
<th>$\alpha_{stall}$ (°)</th>
<th>$x_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipse08</td>
<td>0.53</td>
<td>15.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Rectangle08</td>
<td>0.32</td>
<td>11.2</td>
<td>–</td>
</tr>
<tr>
<td>Wedge08</td>
<td>0.45</td>
<td>11.8</td>
<td>1.0</td>
</tr>
<tr>
<td>NACA 0008</td>
<td>0.88</td>
<td>21.0</td>
<td>0.3</td>
</tr>
<tr>
<td>NACA 1608</td>
<td>0.56</td>
<td>15.0</td>
<td>0.5</td>
</tr>
<tr>
<td>NACA 6608</td>
<td>0.54</td>
<td>14.4</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Fig. 6. $C_D$ of rudders with different profile shapes.

Fig. 7. $C_L$ of rudders with different profile shapes.

Fig. 8. $C_{M, 0.25}$ of rudders with different profile shapes.
Figures 9 and 10 depict the drag-lift ratio (C_D/C_L) and moment-lift ratio (C_M,0.25/C_L) curves for the rudders. Again, the NACA 0008 rudder shows its superior performance on C_D/C_L and C_M,0.25/C_L compared with the other rudders. The Rectangle08 rudder, which has a zero slope on the profile shape along the downstream direction, produces the largest C_D/C_L and C_M,0.25/C_L. The Wedge08 rudder gives lower C_D/C_L and C_M,0.25/C_L than that of the Rectangle08 one but obviously greater than the other rudders. Therefore, a foil-shaped rudder not only produces lower C_D but also offers greater C_L, higher C_L, max and larger α_stall. The calculated results indicate that the location of maximum thickness is the most important factor that influences the rudder performance.

**PROFILE THICKNESS**

In this section, rudders of four common profile shapes: NACA 00 series, ellipse, rectangle and wedge with various profile thickness are analyzed. Figure 11, Figures 12 and 13 describe the computed C_D, C_L and C_M,0.25 curves of the NACA0008 rudders (NACA 0008, NACA 0012, NACA 0015 and NACA 0018). As shown in the figures, the differences of drag and lift coefficient between the NACA 00XX rudders are quite small for most angles of attack. Hence, no notable difference on C_D/C_L curves is observed in Figure 14. The thicker profile results in a slight increase in C_L, max but a decrease in C_D/C_L.
NACA00 rudder gives larger $C_{L,max}$ and greater $\alpha_{stall}$ without much increase in drag force. This is because the effective angle of attack of thicker rudder is smaller than that of thinner one, so that the thinner rudder produces larger $C_L$ at a fixed angle of attack and stalls at a smaller angle of attack than that of thicker one. However, the thicker rudder required a larger moment. The $C_{M,0.25}/C_L$ curves of the rudders deviate from each other with the increase of angle of attack, Figure 15.

The $C_D$, $C_L$ and $C_{M,0.25}$ curves of three ellipse rudders (Ellipse08, Ellipse09 and Ellipse11) were shown in Figures 16-18, respectively. For $\alpha < 10^\circ$, the $C_D$ curves are quite similar among the ellipse rudders. But after $\alpha = 10^\circ$, Ellipse08 rudder experiences larger drag than the other ellipse rudders. Figure 17 depicts that the thinner ellipse rudder produces larger lift for a fixed angle of attack. Nevertheless, the thinner one seems to still stall at a smaller angle of attack than the thicker one. The $C_{L,max}$ of the Ellipse11 rudder is 28.3% larger than that of the Ellipse08 rudder, whereas the $\alpha_{stall}$ is 31.4% greater than that of the Ellipse08 rudder. However, the Ellipse11 rudder requires larger turning moment for all attack angles. The predicted results show that only 3% increase in profile thickness for ellipse rudder will result in about 28% to 31% increase in $C_{L,max}$ and $\alpha_{stall}$, respectively, but at the same time the moment coefficient $|C_{M,0.25}|$ increases by 36.9%. For most angles of attack, the difference in $C_D/C_L$ curves,
Figure 19, is somewhat small. Besides, the $C_{M,0.25}/C_L$ curves, Figure 20, significantly differ from each other with the increasing angle of attack. The $C_D$, $C_L$, and $C_{M,0.25}$ curves of the rectangle rudders are illustrated in Figures 21-23. The thicker rectangle rudder (Rectangle08) produces a drag increase by 200% when compared to the drag generated by the thinner one (Rectangle04). Before $\alpha = 5^\circ$, the lift gradient of the two rudders are almost identical. After $\alpha = 5^\circ$, the slope of lift curve for the thicker rectangle rudder decreases severely. The Rectangle08 rudder generates a lower $C_{L,\text{max}}$ and smaller $\alpha_{\text{stall}}$ than that of the Rectangle04 one, which is different from the trend given by the NACA 00 rudders. The effective angle of attack of rectangle rudders does not decrease with the increasing profile thickness, because the profile slope significantly influences the effective angle of attack of rudders. When compared with the Rectangle08 rudder, the Rectangle04 rudder gives a decrease of 71.9% in $C_{L,\text{max}}$ and an increase of 31.2% in $\alpha_{\text{stall}}$. As illustrated in Figure 23, the Rectangle08 rudder has a worse characteristic on turning moment than the thinner one. The $C_D/C_L$ and $C_{M,0.25}/C_L$ curves of the rectangle rudders are given in Figures 24 and 25, respectively. Although the performance of the Rectangle08 rudder is more favorable than that of the Rectangle04 rudder, the thinner one may fail to provide sufficient structure strength.

Three wedge rudders (Wedge08, Wedge12 and...
Wedge14) are also computed to compare their non-cavitating hydrodynamic performances on lift, drag and moment, Figures 26-28. The Wedge08 rudder experiences larger $C_D$ than two other thicker ones, while the drag coefficient of the Wedge14 rudder is almost the same as that of the Wedge12 rudder. Because the geometric difference near the leading edge between these two rudders is quite small, it explains the small deviation in the drag coefficient. The Wedge08 rudder gives a larger lift gradient but a smaller $C_{L,\text{max}}$ and $\alpha_{\text{stall}}$ than that of the Wedge12 rudder, as shown in Figure 26. The Wedge12 rudder yields larger $C_L$ than the Wedge14 rudder for the most angles of attack, while the latter one produces a lower $C_{L,\text{max}}$ and a smaller $\alpha_{\text{stall}}$. As observed among the performance of NACA 00 rudders, the thicker rudder should provide a larger $C_{L,\text{max}}$ and also a greater $\alpha_{\text{stall}}$, which is not found in the wedge rudders. Through the geometry simplification of the Wedge12 and Wedge14 rudders, the thickness distribution on profile is slightly different from the original shape. The maximum thickness between the Wedge12 and Wedge14 rudders is only differ by 2% of the chord length. For small variation in the maximum thickness, the simplified geometry may not reflect the correct influence of the maximum thickness. Hence, the comparisons between the Wedge08 and Wedge12 rudders or the comparison between the Wedge08 and Wedge14 rudders are more appropriate to illustrate the influence of profile.

Fig. 21. $C_D$ of rectangle rudders with different thicknesses.

Fig. 22. $C_L$ of rectangle rudders with different thicknesses.

Fig. 23. $C_{M,0.25}$ of rectangle rudders with different thicknesses.

Fig. 24. $C_D$ vs. $C_L$ of rudders with different thicknesses.
thickness for wedge rudders. The thicker wedge rudder demands a larger $C_{M,0.25}$ than those thinner ones. This tendency is also found in other rudder shapes mentioned above. For instance, $|C_{M,0.25}|_{\text{max}}$ of the Wedge12 rudder is 39.9% greater than that of the Wedge08 rudder. The $C_{D}/C_{L}$ curves are depicted in Figure 29, and the thinner wedge rudder offers smaller $C_{D}/C_{L}$ values. The $C_{M,0.25}/C_{L}$ values, Figure 30, of the Wedge12 and Wedge14 rudders are much larger than that of the Wedge08 rudder. Therefore, the thinner wedge rudder shows a better hydrodynamic performance compared with that of thicker one. The $C_{L,\text{max}}$ and $\alpha_{\text{stall}}$ of the above discussed rudders are given in Table 3.

![Fig. 25. $C_{M,0.25}$ vs. $C_{L}$ of rudders with different thicknesses.](image1)

![Fig. 26. $C_{D}$ of wedge rudders with different profile thicknesses.](image2)

![Fig. 27. $C_{L}$ of wedge rudders with different profile thicknesses.](image3)

![Fig. 28. $C_{M,0.25}$ of wedge rudders with different thicknesses.](image4)

<table>
<thead>
<tr>
<th>Rudder</th>
<th>$C_{L,\text{max}}$</th>
<th>$\alpha_{\text{stall}}$ ($^\circ$)</th>
</tr>
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<tbody>
<tr>
<td>NACA 0008</td>
<td>0.88</td>
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<td>NACA 0015</td>
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</tr>
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<tr>
<td>Ellipse08</td>
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<td>Ellipse09</td>
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<td>Ellipse11</td>
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</table>
CONCLUSION

In the presented work, non-cavitating hydrodynamic performances of different rudders used for high-speed crafts are analyzed using a CFD approach. The three-dimensional, turbulent flow around rudders has been computed by solving the Reynolds-averaged Navier-Stokes equations combined with the $k-\varepsilon$ turbulent model.

For a given maximum thickness, the foil-shaped rudder not only produces lower drag and greater lift at a specified angle of attack before stall but also offers higher maximum lift and larger stall angle. The NACA 00 rudder generates the largest maximum lift coefficient and stall angle among other rudders with the same maximum thickness. The rectangle rudders show the most unfavorable performance, i.e., the smallest lift coefficient gradient and the largest drag coefficient for all angles of attack. The stock moment coefficient of the NACA 00 rudder is also much smaller than other rudder profiles, which is favorable from the maneuvering point of view. The predicted results reveal that both the location of maximum thickness and the shape at trailing edge play important roles on the rudder performance. The profile with a maximum thickness location near to the leading edge is favorable in the rudder design. For the NACA and ellipse rudders, a slight growth in thickness increase the stall angle and gives larger lift without significant increase in the drag force. However, the thicker rectangle rudder produces larger drag and seems to stall at smaller angle of attack than the thinner one. For wedge rudders, the thicker one gives larger stall angle, larger maximum lift and also larger drag. For all the investigated rudder profiles, the thicker rudder yields larger stock moment.

REFERENCES
