Effects of X Rudder Area on the Horizontal Mechanical Properties and Wake Flow Field of Submarines

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Abstract. X rudder is particularly important for submarine maneuverability, but its influence on wake flow field remains largely unknown. In this study, the X rudder was scaled down three-dimensionally to 80%, 85%, 90%, 95% and 100% of the original rudder area with unchanged aspect ratio and installation position of rudder shaft. Next, the effects of X rudder area on the horizontal mechanical properties and wake flow field of the submarine with a tail control plane were analyzed using the CFD method. The results showed that when the X rudder area was reduced by 20%, the resistance was not significantly affected, and the yaw torque was still larger than that of cross-shaped rudder submarine. At the rudder angles of 0°, 2° and 5°, the velocity non-uniformity coefficients of S1 were reduced by about 9%, 25% and 71%, respectively, when compared to those of S5.

Keywords: X rudder area; Wake flow field; Resistance; Yawing torque; CFD.

1. Introduction
The area and layout of tail control plane are typically determined according to the best maneuvering effect. However, maneuverability is just one aspect of general submarine performance, so other performance indexes should be comprehensively considered to design a submarine with favorable overall performance [¹]. The current studies regarding X rudder have mainly concentrated upon the hydrodynamic performance and its influence on the submarine maneuverability, while the effect of X rudder on the submarine wake flow field has been neglected [²]. Wake flow field not only affects the basic hydrodynamic performance of submarine but also generates radiation noise. Previous studies have shown that tail control plane is the most important factor influencing the submarine wake flow field [³⁻⁶]. The velocity uniformity of propeller disk can be effectively improved by optimizing the distance between tail rudder and screw propeller. As the tail rudder shifts rearward, the axial velocity non-uniformity of propeller disk becomes poorer, with a critical spacing. Such velocity non-uniformity markedly deteriorates after the distance between tail wing and propeller disk becomes shorter than a critical spacing [⁷,⁸]. Enlightened by the above studies, the influence laws of changes in X rudder area on the submarine wake flow field were explored in this study.

2. Study Object and Mesh Generation
The X rudder area was scaled according to the following principles: for the unchanged aspect ratio λ of rudder, airfoil and relative position of rudderstock, the rudder area was scaled three-dimensionally to
80%, 85%, 90% and 95% of the original rudder area, respectively. We call that plan S1-S5, which corresponds to 5 different rudder areas (A1-A5). The original rudder area A5 is 17052 mm². Subsequently, the tail control plane schemes (Figure 1) of X rudder area were obtained, and the corresponding X rudder areas are listed in Table 1:

![Submarine models with different X rudder areas.](image)

**Table 1.** X rudder areas after scaling.

| Scheme | Ai/A5(i=1,2,3,4,5) |
|--------|---------------------|
| S1     | 80%                 |
| S2     | 85%                 |
| S3     | 90%                 |
| S4     | 95%                 |
| S5     | 100%                |

The mesh section diagram of X rudder and the surface meshes of submarine body are shown in Figures 2 and 3, respectively.

![Sectional meshing diagram of the computational domain.](image)

**Figure 1.** Submarine models with different X rudder areas.

**Figure 2.** Sectional meshing diagram of the computational domain.
3. Effects of X Rudder Area on the Mechanical Properties of Submarine Horizontal Plane

First, the influence of changes in X rudder area on the submarine was analyzed. The reduction of X rudder area was considered equivalent to the reduction of appendage area. Next, the direct sailing status of X rudder submarine at an inflow velocity of 6.5 kn and different rudder angles were simulated through the RANS numerical method and SST k-ω turbulence model. The total resistance and yaw torque under the 5 X rudder area schemes were monitored and reported, in order to explore the relationships of rudder angle with the resistance and yaw torque of the submarine.

Table 2 Relative errors of resistance under different rudder areas.

| Rudder angle (°) | (A5-A1)/A1 | (A5-A2)/A2 | (A5-A3)/A3 | (A5-A4)/A4 |
|-----------------|------------|------------|------------|------------|
| 0               | 5.75%      | 1.49%      | 0.93%      | 0.23%      |
| 2               | 3.05%      | -1.09%     | -1.65%     | -2.33%     |
| 5               | 4.05%      | 1.83%      | 1.01%      | 0.59%      |
| 10              | 8.01%      | 4.51%      | 2.57%      | 1.66%      |
| 15              | 13.68%     | 12.05%     | 6.94%      | 4.86%      |
| 20              | 15.43%     | 11.91%     | 4.62%      | 3.66%      |

Table 3. Relative errors of yaw torque under different rudder areas.

| Rudder angle (°) | (A5-A1)/A1 | (A5-A2)/A2 | (A5-A3)/A3 | (A5-A4)/A4 |
|-----------------|------------|------------|------------|------------|
| 0               | 24.52%     | 50.24%     | 35.47%     | 3.59%      |
| 2               | 46.18%     | 20.12%     | 15.71%     | 7.77%      |
| 5               | 30.33%     | 28.43%     | 14.37%     | 5.75%      |
| 10              | 53.90%     | 30.47%     | 18.50%     | 12.42%     |
| 15              | 53.40%     | 37.89%     | 29.43%     | 18.86%     |
| 20              | 23.16%     | 13.48%     | 4.95%      | 0.95%      |

As shown in Figure 4, the resistance of submarine with cross-shaped rudder tail control plane was...
consistently larger than that of submarine with X rudder tail control plane. Adding insight from Table 2, it could be concluded that the smaller the X rudder area was, the lower the resistance. When the rudder area was reduced by 20%, the total resistance of submarine body was reduced the most. At the rudder angle of 0°, the total resistance of S1 was 5.75%, which was smaller than that of S5. When the rudder angle was adjusted to 20°, the total resistance of S1 was reduced by 15.43% compared to that of S5. When the tail rudder (an important appendage to the submarine) operated at a small rudder angle (within 5°), the overall resistance borne by the submarine body was not evidently affected by the 20% reduction of X rudder area. The decreased X rudder area indicates the reduction of its wetted surface area. At a small rudder angle, the total resistance of X rudder submarine varied mainly due to the frictional resistance. However, when the rudder angle was large, the changes in the total resistance of X rudder submarine were mainly affected by the viscous resistance.

The relationship between the rudder angle and yaw torque is shown in Figure 5. It was found that with the enlargement of rudder angle, the yaw torque of submarine was also increased. At the rudder angle of 15°, the yaw torque coefficient of S1 was about 53% smaller compared to that of S5, indicating that the steering efficiency is significantly influenced by the rudder area. As shown in Table 3, when the X rudder area was scaled to 80% of the original area, the yaw torque coefficient was still larger than that of cross-shaped rudder submarine. Therefore, it can be inferred that the maneuverability margin of X rudder is sufficient, and the influence of X rudder area reduction on the wake flow field of submarine is further determined to provide a reference for the follow-up design of X rudder tail control plane in the low-noise submarine.

4. Effects of X Rudder Area on Submarine Wake Flow Field

The cross-shaped rudder submarine could be rotated on the horizontal plane only if the rudders acted, namely, steering the upper and lower vertical rudders. For the submarine with X rudder tail control plane, however, the 4 rudders should be simultaneously steered to form certain rudder angles. To describe the steering mode of two tail control planes, the cross-shaped rudders and X tail rudders were numbered and their directions were specified (Figures 6 and 7). From the rear view, the rudder blades did clockwise rotation (rightward rotation) around the rudder shaft.

![Figure 6. Specifications for steering direction of tail control plane.](image-url)
In general, the maximum diameter of submarine propeller is 0.35-0.4 times that of submarine body, so the propeller disk area where the propeller works can be defined as the minor-radius area \((r/R \leq 0.4)\) of propeller disk \(^{(9)}\), where \(R\) is the maximum radius of submarine and \(r\) stands for the distance from the measuring point on the propeller disk to the central shaft of submarine body. The circumferential angle \(\theta\) is illustrated in Figure 8, where the circumferential angle of \(0^\circ\) is located rightly above the propeller disk and shows a gradual clockwise growth trend.

**5. Axial Dimensionless Velocity Distribution**

Furthermore, the effect of X rudder area on the wake flow field was analyzed by selecting the axial velocities on the circumferences with \(R = 0.2, 0.3, 0.4\) and \(0.5\). Where \(R\) represents the length of the rudder and \(r\) represents the radial position of the rudder. Afterwards, the wake flow field was simulated under the direct sailing state of submarine horizontal plane at the rudder angle of \(0^\circ, 2^\circ\) and \(5^\circ\). During the simulation, the inflow velocity was set to 6.5 kn, and the RANS numerical method and SST k-\(\omega\) turbulence model were employed. The axial dimensionless velocity was defined as \(V_x/U\), where \(U\) denotes the inflow velocity and \(V_x\) is the axial velocity. The axial velocity distribution curves within the minor-radius zone of propeller disk in the X rudder submarine at different rudder angles are displayed in Figures 9-11. The corresponding uniformity coefficient curves of axial velocity are shown in Figure 12.
Figure 9. Axial velocity distribution in the minor-radius zone of propeller disk at rudder angle of 0°. The circumferential distribution curves of axial velocities under different schemes at the rudder angle of 0° are presented in Figure 9. Through a comparison, it was observed that when $r/R = 0.2$, the axial velocity reached a valley value between two adjacent rudder blades. With the reduction of X rudder area, the valley value was obviously elevated, while the peak value remained unchanged. At the same radius part of propeller disk, the circumferential distribution of axial velocity of X rudder submarine showed a consistent curvilinear trend. Due to the hindering effect of appendage on the velocity, the valley values appeared behind the fairwater and at four rudder wings (0°, 45°, 135°, 225° and 315°). Meanwhile, the valley values at the two X rudder blades circumferentially close to the fairwater were smaller, which was ascribed to the disturbance of horseshoe vortex generated by the fairwater. At $r/R = 0.4$ and 0.5, the axial velocity distribution curves of X rudder area were nearly overlapped. This indicates that after the X rudder area is scaled, the flow field within $r/R \leq 0.3$ range of propeller disk is improved, and the improvement effect is apparent.

Figure 10. Axial velocity distribution in the minor-radius zone of propeller disk at rudder angle of 2°.
The axial velocity distribution curves at the rudder angle of 2° and 5° are shown in Figures 10 and 11, respectively. When the rudder angle was enlarged, the peak value of axial velocity was increased and the valley value was reduced, indicating the range of velocity distribution has been expanded. Consequently, the velocity non-uniformity of wake flow field was intensified. Within 180°-360°, the velocity fluctuated significantly, especially at \( r/R = 0.35 \), and the velocity distribution curve showed a zigzag shape, which was related to the deflection of X rudder angle. When X rudder served as the tail rudder, the angle formed by two adjacent rudder blades imposed adverse disturbance to the flow field after the steering, indicating that the velocity was disturbed the most by the angle between rudder 3 and rudder 4. In addition, the axial velocity curve of S1 was the flattest, suggesting that the reduction of rudder area can exert the "peak clipping and valley lifting" effects.

By comparing the axial velocity distribution graphs at the propeller disk of X rudder submarine under different schemes, it was observed that the axial velocity distribution curves under the 5 rudder area schemes were similar to the geometric sectional shape on the propeller disk at the submarine tail. Due to the hindering effect of rudder wings, the low-velocity inner-radius zone of propeller disk was enlarged with the increase in the rudder area. At the rudder tip and in the region close to the submarine surface (\( r/R = 0.25-0.4 \) and \( r/R = 0.9 \)), the low-velocity zones were generated, and their range was expanded with the increase in the rudder area.

In this study, the RMS was taken as the wake fraction non-uniformity coefficient of flow field to further quantitatively describe the velocity uniformity at the propeller disk. The RMS value was calculated as follows:

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V_{\Delta} = \frac{2}{N} \sum_{i=1}^{N} \left( \frac{U_i - \bar{U}}{\bar{U}} \right)^2 \]

where \( U_i \) is the dimensionless velocity of a sample point on the circumference of propeller disk, \( \bar{U} \) stands for the dimensionless average velocity of sample points and \( N \) represents the number of sample points. The value of \( V_{\Delta} \) reflects the discrete degree of velocity. The greater the \( V_{\Delta} \) values, the higher the degrees of discrete velocity at this radius.
The curve charts of axial velocity non-uniformity coefficients on the propeller disk of X rudder under different schemes are displayed in Figure 12. It was observed that, when $r/R = 0.2-0.9$, the smaller rudder area led to a smaller axial velocity non-uniformity coefficient. At the rudder angle of 0°, the zone with the maximum axial velocity non-uniformity was nearby $r/R = 0.4$, and the axial velocity non-uniformity coefficient at $r/R = 0.2$ of S1 declined by about 9% compared to that of S5. The axial non-uniformity coefficient was firstly increased and then decreased with increasing $r/R$ values. Within $0.7-0.9 R$, the non-uniformity coefficients of S1 and S2 were reduced by about 15%-20% compared to that of S5. When the rudder angle was 2° and 5°, the axial velocity non-uniformity coefficient appeared nearby $r/R = 0.2$. At the rudder angle of 2°, the velocity non-uniformity coefficient of S1 declined by about 25% compared to that of S5. As the rudder angle was enlarged to 5°, the velocity non-uniformity coefficient of S1 was about 71% smaller than that of S5. The analysis of the axial velocity distribution in Figures 8 and 9 supports the explanation of the results. In the steering process, every two rudder blades are mutually interfered, so the larger the rudder area is, the greater the non-uniformity of force borne by the rudder blade surface. This causes the disorder of boundary layer and further affects the inflow velocity uniformity at the propeller disk. It is evident that the enlargement of rudder angle and reduction of rudder area can improve the inflow velocity uniformity of the propeller. Thus, it can be inferred that the wake flow field is obviously improved by reducing the X rudder area.

6. Vortex System Distribution of Tail Control Plane

The flow field uniformity on the propeller disk was greatly correlated with the vortex system distribution generated by the rudder wings. Next, the Q criterion was used to visually express the vortex system distribution on the tail control plane within the rudder area, and $Q = 50$. 

Figure 12. Axial velocity non-uniformity coefficients.
The vortex system distribution on the tail control plane of X rudder submarine at the rudder angle of 0° is shown in Figure 13. It was found that the turbulent boundary layer rolled up due to the adverse pressure gradient formed at the leading-edge stagnation point of X rudder. As a result, a horseshoe vortex was generated at the junction between the X rudder and submarine body, and a tip vortex was generated at the trailing edge of X rudder top. Notably, the former exhibited higher strength and stability with a wider scope of influence than the latter. As the rudder area was enlarged, the horseshoe vortex generated at the junction between the X rudder and submarine body was more apparent, which developed backward along the submarine body surface and then flowed into the propeller disk. However, the tip vortex was nearly parallel to the central longitudinal line of submarine body and developed backward. Due to the influences of horseshoe and tip vortices, the velocity distribution curve of propeller disk was bent. Moreover, the tip vortex generated at the trailing edge of rudder top was distant from the center line of propeller, which mainly affected the zone beyond 0.9 \( R \). Therefore, it can be inferred that the flow field uniformity in the minor-radius zone of propeller disk is mainly affected by the horseshoe vortex generated at the junction between the X rudder and submarine body, while the inflow velocity of propeller is slightly affected by the tip vortex generated at the tip of rudder wing.
The vortex system distributions on the tail control plane at the rudder angles of 2° and 5° are displayed in Figures 14 and 15, respectively. Due to the deflection of rudder angle, the line type at the junction between the rudder wing and submarine body altered more intensely. Moreover, the nearby boundary layer rolled up to a greater extent, owing to the viscosity of submarine body surface and rudder wing surface.

As the rudder angle was increased from 0° to 5°, the horseshoe vortex generated at the junction between the X rudder and submarine body exhibited high strength and good stability. With the shrinkage of line type at the tail segment of submarine body, the horseshoe vortex developed backward along the submarine body surface and converged at the submarine tail, thus changing the velocity distribution and turbulence intensity distribution at the propeller disk. With the increase in the rudder angle, the submarine body surface at the tail segment was evidently separated from the horseshoe vortex. In addition, the tip vortex generated at the tip of X rudder was closely parallel to the central longitudinal line of submarine body and developed backward, which mainly affected the velocity distribution at the outer radius of propeller disk. When the X rudder area was reduced, the area of influence of tip vortex started to shrink in the minor-radius zone of propeller disk, but the inner radius was unaffected.

7. Conclusion
When the X rudder area was scaled three-dimensionally under an unchanged aspect ratio, the rudder...
height and thickness were simultaneously changed. The influence laws of X rudder area on the kinematical mechanical properties of submarine horizontal plane and its wake flow field were explored through the CFD method:

1. Reducing the X rudder area is equivalent to the reduction of its wetted surface area. The total resistance of submarine is not significantly affected at a small rudder angle. When the X rudder area is scaled to 80% of the original area and the rudder angle is 15°, the yaw torque coefficient of S1 is about 53% smaller than that of S5, but the yaw torque is still greater than that of cross-shaped rudder submarine, indicating that the maneuverability margin of X rudder is much larger than that of cross-shaped rudder.

2. With the increase in the rudder angle (within 5°), the inflow velocity uniformity of propeller is significantly improved when the X rudder area is reduced. At the rudder angles of 0°, 2° and 5°, the velocity non-uniformity coefficients of S1 declines by about 9%, 25% and 71%, respectively, when compared to those of S5.

3. The X rudder tail control plane is one of the most important factors that influence the submarine stern wake. The X rudder exerts an impact on the velocity of propeller disk, mainly through the shear flow formed at the boundary layer and the horseshoe vortex generated at the junction between the X rudder and submarine body. When the X rudder area retains at 80%-100% of the original area, the calculation results demonstrate that a smaller X rudder area is better for improving the quality of wake flow field.

Hence, a trade-off should be made between the maneuverability of X rudder and submarine denoising. According to the practical situation, partial X rudder area can be appropriately sacrificed to improve the quality of wake flow, enhance the stealth performance of submarine, and increase the propulsive efficiency of propeller.

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