



Numerical Investigation of Flow Characteristics Around Rudder with Sacrificial Anodes

Hasan İslam Çopuroğlu¹, Mehmet Zeki Şener², Emre Peşman², Yücel Özmen³

¹Osaka Metropolitan University Graduate School of Engineering, Department of Marine System Engineering, Sakai (Osaka), Japan

²Karadeniz Technical University Sürmene Faculty of Marine Sciences, Department of Naval Architecture and Marine Engineering, Trabzon, Türkiye

³Karadeniz Technical University Faculty of Engineering, Department of Mechanical Engineering, Trabzon, Türkiye

To cite this article: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen. Numerical investigation of flow characteristics around rudder with sacrificial anodes. *J Nav Architect Mar Technol.* 2026;228:55-63.

Received: 07.07.2026 - **Revision Requested:** 22.07.2026 - **Last Revision Received:** 18.08.2026 - **Accepted:** 08.09.2026 - **Publication Date:** 30.09.2026

Abstract

Cathodic protection is a method for protecting steel structures immersed in water from electrochemical corrosion. In the maritime industry, this protection is achieved by installing zinc or magnesium galvanic anodes on the hull and underwater components of ships, such as rudders, propellers, and shafts. Although sacrificial anodes effectively prevent corrosion, their presence may alter the flow characteristics around protected components. In this study, the effects of anode shape on the hydrodynamic characteristics of a rudder with a National Advisory Committee for Aeronautics 0018 cross-section were numerically investigated. Three cases were considered: a bare rudder without an anode, a rudder fitted with a rectangular (flat bar) anode, and a rudder fitted with a semi-elliptical (disc) anode. The volumes of both anodes were kept identical for a fair comparison of their hydrodynamic effects. All cases were analyzed at a Reynolds number of 15000 and rudder angles of attack of 0°, 10°, 20°, and 30°. Three-dimensional, time-dependent numerical simulations were performed using computational fluid dynamics (CFD). The numerical methodology was validated against experimental data, and the Realizable k-ε turbulence model was selected because it showed better agreement. The numerical results were evaluated in terms of the flow lines around the rudders, pressure coefficient distributions, and lift and drag coefficients. The results indicate that the anode shape has a noticeable influence on the flow characteristics around the rudder. The rectangular anode generated larger reverse flow regions and stronger flow disturbances than the semi-elliptical anode, resulting in higher drag coefficients. In contrast, the semi-elliptical anode produced smoother pressure coefficient distributions and smaller reverse flow regions. Moreover, oscillations in both lift and drag forces became more significant at higher angles of attack, particularly at 20° and 30°, which may increase the possibility of vibration. Overall, the results suggest that semi-elliptical anodes provide more favorable hydrodynamic performance than rectangular anodes while maintaining the cathodic protection function.

Keywords: Cathodic protection, rudder hydrodynamics, CFD

1. Introduction

The surfaces of metals in contact with seawater corrode over time. This is an electrochemical corrosion process caused by the transfer of electrons. Cathodic protection is a method

used to protect steel structures immersed in water from electrochemical corrosion. It can be employed for many steel structures. Today, this method is still used to prevent corrosion on the wetted surfaces of ship hulls and underwater components such as rudders, propellers, and shafts.

Address for Correspondence: Asst. Prof. Hasan İslam Çopuroğlu, Osaka Metropolitan University Graduate School of Engineering, Department of Marine System Engineering, Sakai (Osaka), Japan

E-mail: hasan.marine@omu.ac.jp

ORCID ID: orcid.org/0000-0001-5486-1277

Cathodic protection is a technology that was developed by Davy [1]. At present, this method is still utilized by placing zinc or magnesium galvanic anodes on the hull and components of ships. These anodes are bolted or welded directly to the hull or ship components. Zinc hull anodes of suitable design can provide useful current outputs for periods of eight to ten years in seawater [2]. In addition, various zinc alloys can offer unique performance in cathodic protection [3]. Furthermore, coatings can also be beneficial for protection. It has been reported that coatings provide the most effective protection when they are used in combination with an anode protection system [4].

Anodes can be classified based on their shape, size, material, mounting method, and method of securing to the surface to be protected. Anodes can have various shapes depending on their application. The selection of the shape of an anode depends on several factors, such as the shape of the surface to be protected, the availability of space, accessibility, and ease of installation. However, different anode shapes may cause different levels of resistance on the surface to be protected. Flat or block-shaped, cylindrical or semi-cylindrical, tear-drop, bracelet, and disc-shaped anodes are among the widely used anode shapes [5].

In the maritime sector, rudders are used to change the course of a ship and facilitate its manoeuvring by generating hydrodynamic forces depending on the ship's cruising speed. Parameters such as the geometric shape of the rudder section, the rudder angle, and the rudder clearance significantly affect the hydrodynamic force generated by the rudder. Therefore, it is beneficial to examine the flow around the rudder and evaluate the effects of these parameters. Nakano et al. [6] investigated the flow and noise characteristics around a National Advisory Committee for Aeronautics (NACA) 0018 airfoil at various angles of attack in an experimental study and determined that the angle of attack affects noise generation. Gim and Lee [7] experimentally observed the flow around a rudder with a NACA 0018 cross-section and a plate attached to its end and determined the effects of the attached plate on the flow. Lee et al. [8] examined the flow characteristics and pressure distributions around the rudder and stated that there is an interaction among the hull, rudder, and ship propeller. Fakorede et al. [9] studied the impact of ice accretion on the aerodynamic coefficients of a wind turbine airfoil.

However, since no anodes were used in any of these studies, the effects of the anodes on the flow around the rudder could not be observed. Rudders made of metal are among the components on which anodes are used to prevent corrosion. Since the flow around the rudder is important, the effects of anodes on the flow should be investigated.

1.1. Aim of the Study

In this study, the effects of various anode shapes on the flow around the rudder were examined. The examined rudder has a NACA 0018 cross-section. Two different anode shapes were placed on the rudder, and three cases were considered. The first case was a bare rudder without an anode. The second case was a rudder with a flat bar anode, and the third case was a rudder with a semi-elliptical (disc) anode. The turbulent water flows around these three rudders were numerically investigated using the commercial software package ANSYS FLUENT 16. The aim was to examine the effects of the anodes on the flow characteristics around the rudder for the three cases by performing three-dimensional, time-dependent numerical simulations. The results were evaluated in terms of the flow lines around the rudders, the pressure distributions on the rudder surfaces, and the lift and drag force coefficients of the rudders.

2. Numerical Study

2.1. Governing Equations

Continuity equation of three-dimensional time-dependent motion of an incompressible fluid in Cartesian coordinates can be shown as,

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

Momentum equation can be shown as,

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \rho}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j}(-\rho \overline{u'_i u'_j}) \quad (2)$$

In this study, Smagorinsky, Realizable k-ε and Standard k-ω turbulence models in FLUENT commercial package based on finite volume approach were used. The numerical results obtained from these two different turbulence models were compared with the experimental data in the literature and the sensitivity of the turbulence models were tested. Since the results obtained from Realizable k-ε turbulence model are more compatible with the experimental data, all the other solutions of the study were conducted with Realizable k-ε turbulence model. The modelled transport equations for k and ε is,

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (3)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (4)$$

In these equations, G_k produces turbulent kinetic energy production due to the average velocity gradient; G_b refers to turbulent kinetic energy production due to buoyancy. σ_k and σ_ε are the turbulent Prandtl numbers, S_k and S_ε are the source terms. The constants for the turbulence model are $C_{1\varepsilon}=1.44$, $C_2=1.9$, $\sigma_k=1.0$

2.2. Computational Domain and Boundary Conditions

The computational domain and boundary conditions are shown in Figure 1. Water was utilized as a fluid at a temperature of 15 °C. The rudder has a cross-sectional area of NACA 0018. It has a chord length of 0.1 m and a width of 0.3 m. The Reynolds number calculated according to the chord length is $Re=15000$.

In this study, three cases were considered. The first case is a rudder without an anode. The second case is a rudder with a rectangular prism anode, and the third case is a rudder with a semi-elliptical anode. The volumes of the rectangular prism anode and the semi-elliptical anode are equal. The anodes are located at the transverse and longitudinal midsections of the rudder. The geometries of all cases are shown in Figure 2.

The mesh structure in the flow field was generated with increasing mesh density around the rudders, as shown in Figure 3. Calculations were conducted using different numbers of tetrahedral mesh elements to obtain mesh-independent solutions. Approximately 2.8 million mesh elements were used to achieve mesh-independent solutions. A time step of 0.001 s was used for the transient simulations, and the Courant number was maintained below 1. The SIMPLEC algorithm was employed for pressure-velocity coupling. The Least Squares Cell Based method was used for gradient calculation. The Second Order scheme was used for pressure, while the Second Order Upwind scheme was used

for momentum, turbulent kinetic energy, specific dissipation rate, and energy. The first-layer height of the mesh elements around the rudder was determined according to the criterion of ($y^+ < 2$). The convergence criterion was defined as non-normalized residuals of less than 10^{-6} . In addition, all cases were analyzed at four different rudder angles: 0°, 10°, 20°, and 30°.

2.3. Validation

Since validation is one of the most essential criteria in CFD analysis, a validation study was performed. Validation is necessary to ensure the reliability and accuracy of the numerical results. In this study, the validation was performed by comparing the CFD results with the experimental study conducted by Gim [10] (2013). Figure 4 shows the comparison between the numerical and experimental results. The Realizable $k-\varepsilon$, Standard $k-\omega$, and Smagorinsky turbulence models were used for validation. It should be noted that the validation case has a twin-rudder configuration, whereas the present study investigates a single rudder with different anode geometries. Therefore, this validation does not directly validate the present single-rudder configuration or the hydrodynamic effects of the anodes, but provides support for the capability of the numerical methodology and turbulence model to predict the flow characteristics around a NACA 0018 rudder. It was observed that all turbulence models predicted the average velocity profiles behind the twin rudders close to the experimental data, but the Realizable $k-\varepsilon$ model produced slightly better results than the Standard $k-\omega$ and Smagorinsky models. Therefore, the Realizable $k-\varepsilon$ turbulence model was employed in all subsequent numerical simulations.

A grid independence study was conducted using different mesh densities. The grid independence assessment was performed for the 0° case, which was used to determine the mesh density for the subsequent simulations. The normalized velocity values (U/U_0) at the selected Y/C location were compared for the different mesh configurations, as shown in Figure 5. The results showed that the normalized velocity

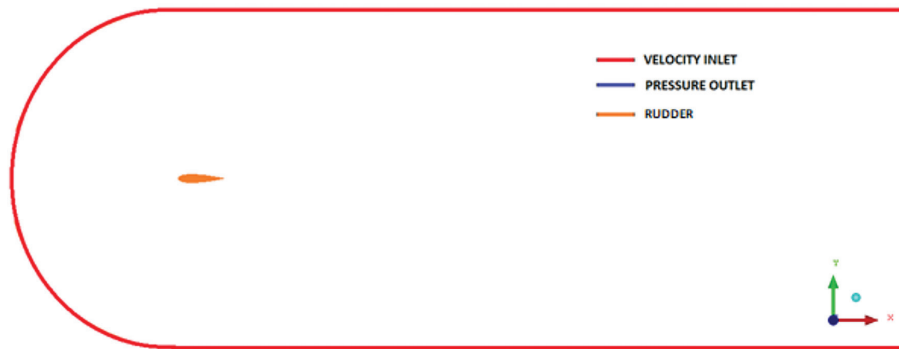


Figure 1. Flow area and boundary conditions.

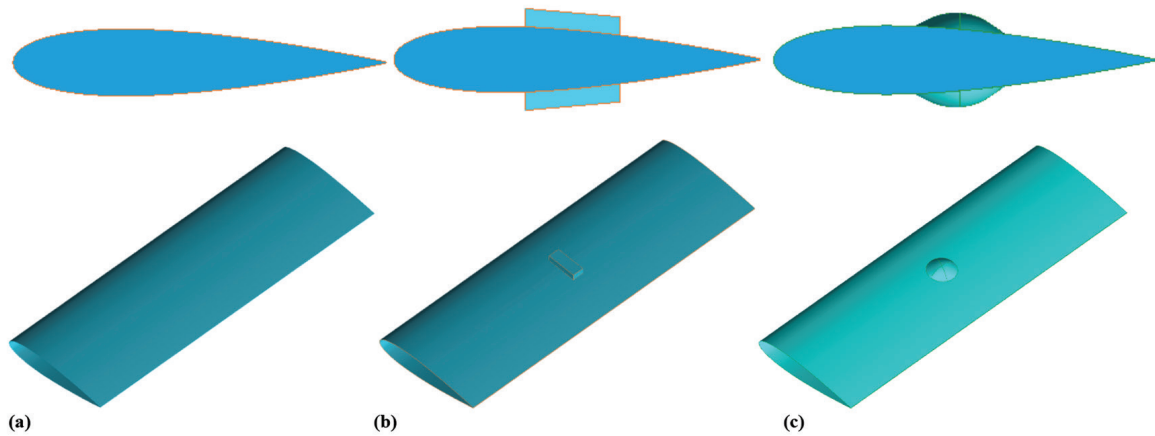


Figure 2. Rudder types: (a) without anode, (b) with rectangular anode (c) with semi elliptical anode.

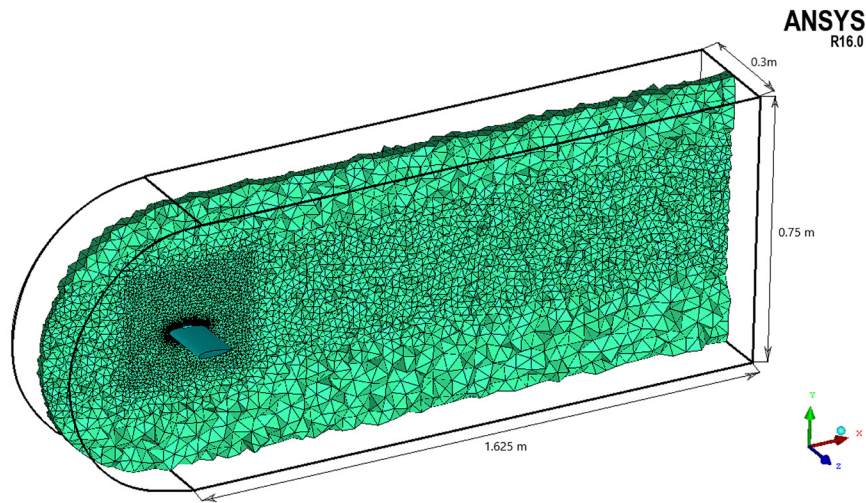


Figure 3. Numerical domain dimensions and three-dimensional mesh structure.

values became sufficiently insensitive to further mesh refinement. Therefore, the mesh consisting of approximately 2.8 million tetrahedral elements was selected for the subsequent numerical simulations.

3. Results

In this study, the effects of the rectangular and semi-elliptical anode shapes on the rudder were numerically investigated. Three-dimensional, time-dependent numerical simulations were performed for the anode and non-anode cases at different angles of attack. The results obtained from these analyses are presented as flow lines around the rudder surface, pressure coefficient distributions at the midsection of the rudder surfaces, and lift and drag coefficients of the rudders. Based on these findings, the effects of the anodes on the flow characteristics were determined for different angles of attack.

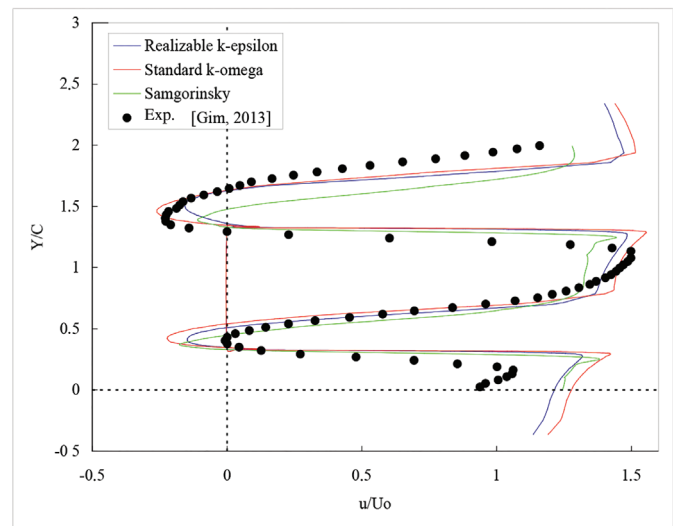


Figure 4. Average velocity profiles behind double rudders.

Figure 6 shows the flow lines around the rudder at different angles of attack. At angles of attack of 0°, 10°, and 20°, the size of the reverse flow regions formed at the midsection of the rudder increases due to the anode shape. At an angle of

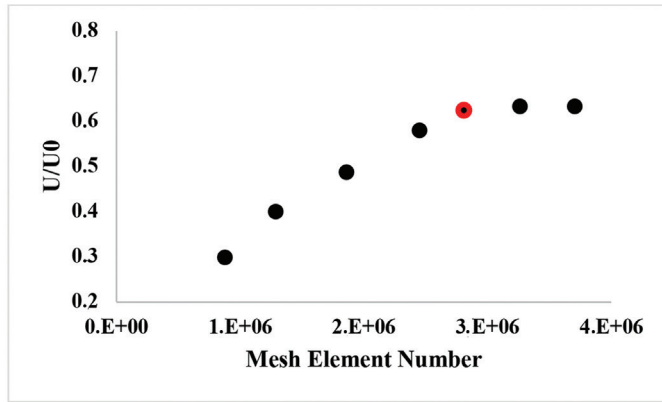


Figure 5. Grid independence study based on normalized velocity values.

attack of 30°, the effect of the anode shape on the reverse flow regions becomes negligible. In addition, the cases without anodes have the smallest reverse flow regions, whereas the cases with rectangular anodes have larger reverse flow regions than the others because the sharp edges of the anodes promote flow separation. Therefore, it can be inferred that the cases with anodes exhibit more complex and larger reverse flow regions.

When the changes in the lift and drag coefficients were examined at 0°, the lift coefficient was almost zero for all cases (Figure 7a). At an angle of attack of 10°, the highest lift coefficient was obtained for the rudder with the semi-elliptical anode (Figure 7b). At an angle of attack of 20°, it can be said that the rudder with the semi-elliptical anode and the rudder without an anode have higher lift forces than the rudder with the rectangular anode (Figure 7c). At an angle of attack of 30°, although the highest lift coefficient was obtained for the rudder with the rectangular anode, the rudder with the semi-elliptical anode and the rudder without

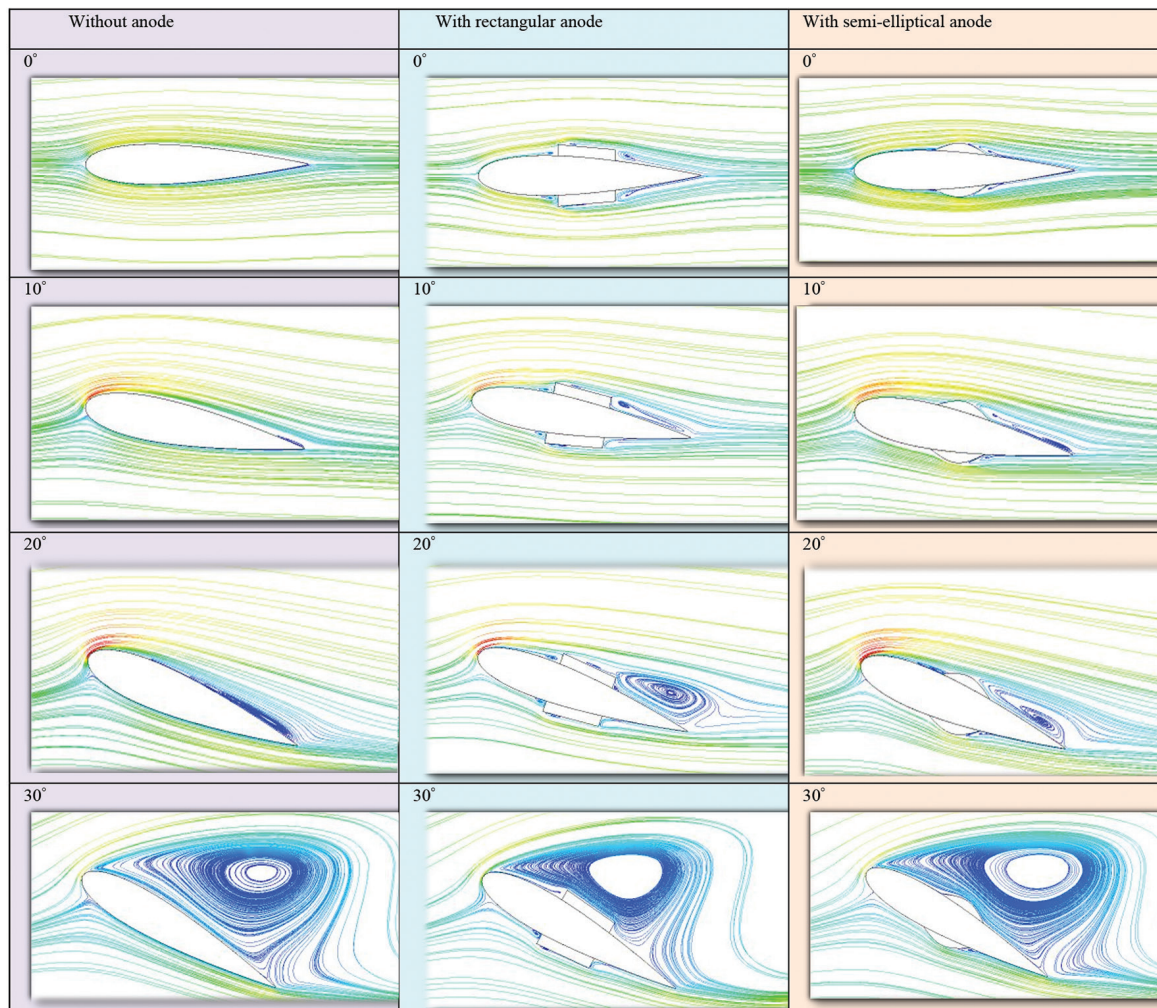


Figure 6. Velocity magnitude lines around the rudders.

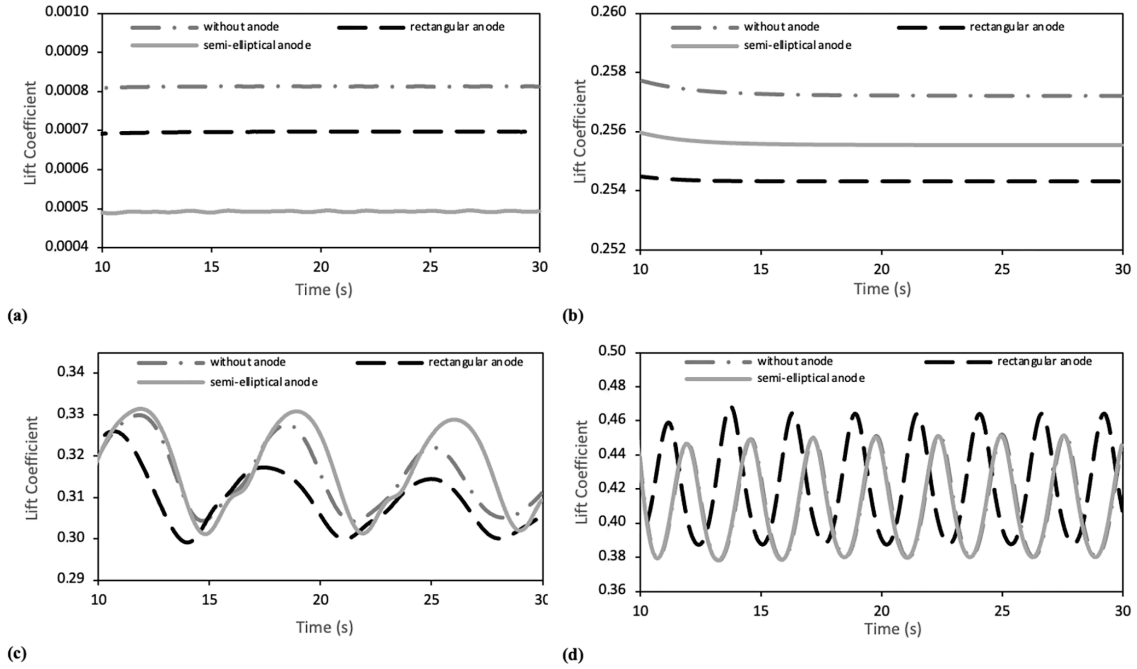


Figure 7. Lift coefficients of the various cases. (a) Rudder with different anode types at the angle of 0° , (b) rudder with different anode types at the angle of 10° , (c) rudder with different anode types at the angle of 20° , (d) rudder with different anode types at the angle of 30° .

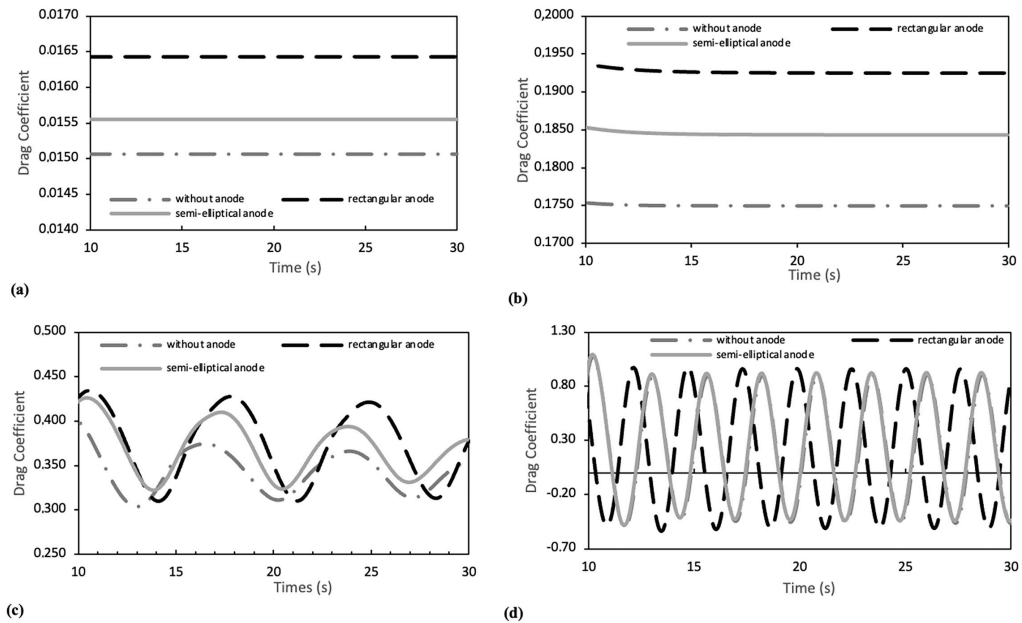


Figure 8. Drag coefficients of the various cases. (a) Rudder with different anode types at the angle of 0° , (b) rudder with different anode types at the angle of 10° , (c) rudder with different anode types at the angle of 20° , (d) rudder with different anode types at the angle of 30° .

an anode exhibited almost the same lift coefficient values (Figure 7d). On the other hand, the lift forces at angles of attack of 20° and 30° exhibited significant oscillations, which can cause vibration, an undesirable phenomenon.

Furthermore, the cases at 30° exhibited a higher oscillation frequency.

The rudder with the rectangular anode exhibited the highest drag coefficient overall (Figure 8a). Since the drag force

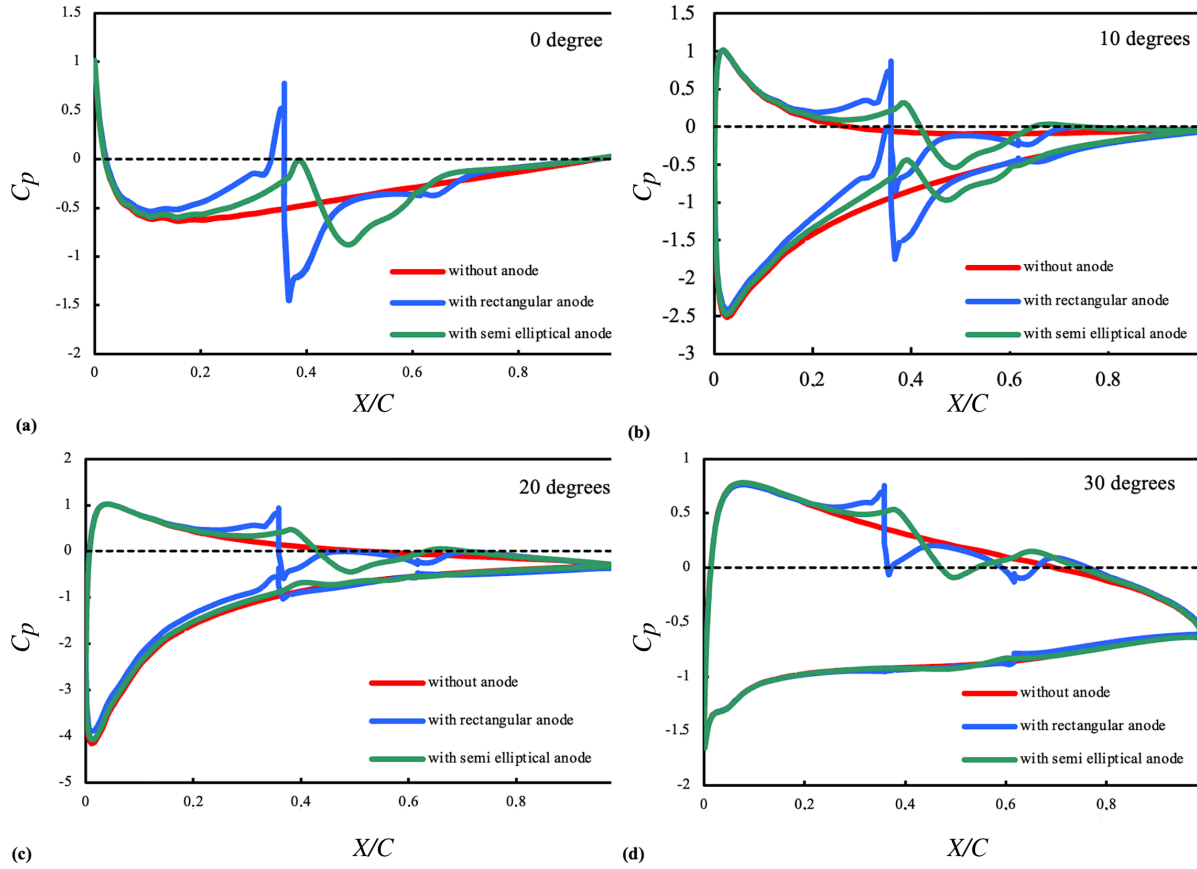


Figure 9. Pressure coefficients on the rudders' surface cases for (a) 0°, (b) 10°, (c) 20°, (d) 30°.

Table 1. Average values of the lift coefficients.

Cases	Rudder without anode	Rudder rectangular anode	Absolute difference	Percentage change	Rudder with semi-elliptical anode	Absolute difference	Percentage change
0°	0.00079	0.00067	-0.00012	-15.19%	0.00048	-0.00031	-39.24%
10°	0.25614	0.25334	-0.00280	-1.09%	0.25463	-0.00151	-0.59%
20°	0.33524	0.32284	-0.01240	-3.70%	0.33612	+0.00088	0.26%
30°	0.46737	0.47383	+0.00646	1.38%	0.46678	-0.00059	-0.13%

Table 2. Average values of the drag coefficients.

Cases	Rudder without anode	Rudder rectangular anode	Absolute difference	Percentage change	Rudder with semi-elliptical anode	Absolute difference	Percentage change
0°	0.01507	0.01643	+0.00136	9.02%	0.01555	+0.00048	2.85%
10°	0.17500	0.19261	+0.01761	10.06%	0.18447	+0.00947	5.41%
20°	0.34235	0.37298	+0.03063	8.95%	0.36906	+0.02671	7.80%
30°	0.24237	0.25425	+0.01188	4.90%	0.24860	+0.00623	2.57%

is a resistance force that increases the fuel consumption of ships, lower drag forces are beneficial for energy efficiency. In addition, similar to the lift forces, the cases at 20° and 30° exhibited oscillating drag forces, which can cause vibration of the rudder (Figure 8c, d).

These inferences can also be observed from the flow lines shown in Figure 6. The reverse flow regions are significantly larger in the cases at 20° and 30°. These flow patterns are caused by the oscillations of the drag and lift forces.

The average values of the lift and drag coefficients are presented in Tables 1 and 2. These values were obtained from the simulation results between the 10th and 30th seconds. At an angle of attack of 30°, a large and highly unsteady vortex structure develops around the rudder, with vortices separating from the tip region and being shed downstream. This vortex shedding results in strong fluctuations in the pressure distribution and consequently produces significant oscillations in the lift and drag forces. The negative instantaneous drag coefficient values observed in Figure 8d occur during these force oscillations and do not indicate a negative mean drag force. The mean drag coefficient remains positive for all three cases, as shown in Table 2. The percentage changes relative to the case without an anode are also presented. It is important to note that the drag forces increase significantly, whereas the lift forces decrease when anodes are installed. In particular, the drag force increases by up to 10% with the rectangular anode. This observation is also consistent with the findings of Fakorede et al. [9], who reported that ice accretion on wind turbine airfoils reduces the lift force and increases the drag force.

Plots of the pressure distribution are key to identifying flow separation and other adverse flow phenomena around the rudder. Therefore, these plots should be analyzed carefully, and the pressure fluctuations should be examined in detail. The pressure coefficients obtained from the midsection of the rudder are shown in Figure 9.

In the midsection of the rudder, it can be observed that a step effect occurs in the pressure coefficient distributions under the influence of the anode shape. For all cases, the pressure coefficients on most of the front surface have positive values since these surfaces are exposed to the water flow. A low-pressure region is formed on the rear surface of the rudders. Negative pressure coefficient values indicate the presence of low-pressure regions. For all cases, the differences between the (C_p) curves are caused by the anodes. It can be seen that the anodes lead to increases in both the minimum and maximum (C_p) peaks. It can also be seen that this effect is more pronounced in the case with the rectangular anode. When (X/C) is between 0.7 and 0.8, the (C_p) curves are similar for all cases, whereas the case with the semi-elliptical anode exhibits smoother curves than the case with the rectangular anode. This effect can also be observed in Figure 6. The case with the rectangular anode has larger reverse flow regions behind the anode.

4. Conclusion

This article focused on the flow patterns and forces around a NACA 0018 foil at a Reynolds number of 15000 to investigate the influence of rectangular and semi-elliptical anode shapes. It should be noted that the Reynolds number

of 15000 used in the present study is considerably lower than that of full-scale ship rudder applications. Therefore, the present results should not be directly extrapolated to full-scale operating conditions. The main objective of this study was to compare the relative effects of rectangular and semi-elliptical anode geometries on the flow characteristics around the rudder under controlled conditions. Further studies at higher Reynolds numbers are required to evaluate the applicability of these findings to full-scale operating conditions. The flow around the foil at various angles of attack for a bare rudder, a rudder with a rectangular anode, and a rudder with a semi-elliptical anode was calculated using the CFD method. The observations and analyses are summarized as follows.

- The CFD method and the turbulence model used in this study showed good agreement with the experimental data in the validation study. Therefore, CFD can be used for similar problems.
- When the flow lines are examined, it can be seen that the use of anodes creates flow disturbances that affect the flow structures behind the rudder and the anodes.
- The shape of the anode is also important for the forces acting on the rudder. The lift and drag forces differ for each case, and regarding the drag force, which contributes to flow resistance, the rudder with the rectangular anode exhibits the highest drag force. Therefore, the use of sharp-edged anodes, such as rectangular anodes, is not recommended from the viewpoint of flow resistance.
- In terms of the lift force, all cases exhibit similar values. However, oscillations in the lift force can be observed after 20°. These oscillations may cause vibration, which is undesirable. In particular, the case with the rectangular anode exhibits higher peak and trough values. This indicates that the variation between the maximum and minimum lift forces is greater. Consequently, the rectangular anode may induce vibration more easily than the other anode configurations.

In general, it can be concluded that avoiding the use of sharp-edged anodes, such as rectangular anodes, may be beneficial in terms of reducing flow resistance and improving manoeuvrability. In future studies, different anode types will be investigated under various Reynolds numbers and angles of attack.

Footnotes

Authorship Contributions

Concept: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen, Design: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen, Data Collection or Processing: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen, Analysis or Interpretation: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman,

and Y. Özmen, Literature Review: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen, Writing: H. İ. Çopuroğlu, M. Z. Şener, E. Peşman, and Y. Özmen.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

NOMENCLATURE

Symbol	Description
u_i	Mean velocity component in the i -direction
u_j	Mean velocity component in the j -direction
k	Turbulent kinetic energy
ε	Turbulent dissipation rate
G_k	Turbulent kinetic energy production due to the average velocity gradient
G_b	Turbulent kinetic energy production due to buoyancy
σ_k	Turbulent Prandtl number for k
σ_ε	Turbulent Prandtl number for ε
S_k	Source term for k
S_ε	Source term for ε
C_2	Model constant
C_L	Lift coefficient
C_D	Drag coefficient
C_p	Pressure coefficient
Re	Reynolds number
U_0	Freestream velocity
X/C	Normalized longitudinal position
Y/C	Normalized transverse position
y^+	Dimensionless wall distance
U_∞	Freestream velocity
Y_M	Contribution of the fluctuating dilatation in compressible turbulence

References

- [1] Sir H. Davy, "Recollections of the development of my mind and character," *Philosophical Transactions of the Royal Society*, vol. 114, pp. 151-242, 1824.
- [2] J. A. H. Carson, "Zinc as a self-regulating galvanic anode for ship hulls," *Corrosion*, vol. 16, no. 10, pp. 491t-496t, 1960.
- [3] J. A. H. Carson, W. L. M. Phillips, and J. R. Wellington, "A laboratory evaluation of zinc anodes in sea water," *Corrosion*, vol. 16, no. 4, pp. 171t-177t, 1960.
- [4] T. Tezdogan, and Y. K. Demirel, "An overview of marine corrosion protection with a focus on cathodic protection and coatings," *Brodogradnja : An International Journal of Naval Architecture and Ocean Engineering for Research and Development*, vol. 65, no. 2, pp. 49-59, Jun 2014.
- [5] TheNavalArch, "Ship corrosion: cathodic protection and sacrificial anodes," Accessed: Jul 7, 2025. [Online]. Available: <https://thenavalarch.com/ship-corrosion-cathodic-protection-sacrificial-anodes/>
- [6] T. Nakano, N. Fujisawa, Y. Oguma, Y. Takagi, and S. Lee, "Experimental study on flow and noise characteristics of NACA 0018 airfoil," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 95, pp. 511-531, 2007.
- [7] O. S. Gim, and G. W. Lee, "Flow characteristics and tip vortex formation around a NACA 0018 foil with an endplate," *Ocean Engineering*, vol. 60, pp. 28-38, 2013.
- [8] Y. G. Lee, J. W. Yu, B. H. Kang, and K. R. Pak, "A numerical study on the flow around a rudder behind low-speed full ship," *Journal of Ship and Ocean Technology*, vol. 12, no. 2, pp. 41-52, 2008.
- [9] O. Fakorede, H. Ibrahim, A. Ilinca, and J. Perron, "Experimental investigation of power requirements for wind turbines electrothermal anti-icing systems," in *Wind Turbines - Design, Control and Applications*, IntechOpen, 2016.
- [10] O. S. Gim, "Assessment of flow characteristics around twin rudders with various gaps using PIV analysis in uniform flow," *Ocean Engineering*, vol. 66, pp. 1-11, 2013.