



Numerical Investigation on Aerodynamic Characteristics of Bio-Inspired Nose Airfoil NACA 4415

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Abstract: It is widely believed that bionic airfoils can influence aerodynamic performance. Therefore, this study focuses on analyzing the effect of a bio-inspired nose on the NACA 4415 airfoil. This study uses roughtoothed dolphins and spinner dolphins as modifications of the airfoil, which are then tested at $Re = 1.6 \times 10^5$ using Computational Fluid Dynamics (CFD). From the simulation results, it was shown that the baseline NACA 4415 has the best aerodynamic performance across all Angles of Attack (AoA). The average percentage increase in C_d for the spinner dolphin is lower, at 40.399% compared to the baseline. On the other hand, the roughtoothed dolphin shows a higher percentage increase in C_d with an average of 51.479% compared to the baseline. While in the C_l data, the rough-toothed dolphin has a larger average percentage decrease, at -10.472%, whereas the spinner dolphin achieves an average decrease of only -5.194% compared to the baseline. Therefore, it can be concluded that the rough-toothed and spinner dolphin modifications do not enhance the aerodynamic performance of the NACA 4415 airfoil at AoA. However, at low AoA, the roughtoothed dolphin modification performs comparably to the baseline NACA 4415 airfoil.

Keywords: aerodynamic; airfoil; bio-inspired; C_l ; C_d



SDGs Problem Solving

This research focuses on engineering innovation through aerodynamic optimization and CFD simulation to improve airfoil performance. It directly supports technological advancement, industrial efficiency, and sustainable infrastructure development, making SDGs Chapter #9 the most aligned.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

The development of aerodynamic technology plays an important role in the aviation, renewable energy, and modern transportation industries (Coder and Somers, 2020; Krishnan, Al-Obaidi and Hao, 2023; Lagemann et al., 2024). One of the main components in an aerodynamic system is the airfoil, which is the cross-sectional shape of a wing or blade designed to produce lift while minimizing drag (Albers and Schröder, 2021). The performance of an airfoil greatly affects the efficiency, stability, and overall performance of aircraft, wind turbines, and uncrewed aerial vehicles (UAVs). In the aviation industry, selecting the right airfoil profile can improve fuel efficiency and extend flight range (Diecke, 2023). Meanwhile, in wind turbines, optimal airfoil design plays a role in increasing the conversion of wind energy into electrical energy more effectively (Koca et al., 2022). Therefore, research on airfoils continues to be carried out by utilizing experimental methods in wind tunnels and numerical simulations based on Computational Fluid Dynamics or CFD (Hoseinzadeh et al., 2020).

Research related to airfoil modification can generally be categorized into two main approaches, namely passive flow control and active flow control (Özkan, 2022). Active flow control is a flow control method that involves an external energy supply, such as the use of synthetic jets, blowing, or suction to modify the flow pattern around the airfoil surface (Kim, Essel and Sullivan, 2022). This method allows for adaptive flow control, but requires a complex additional system and extra energy consumption. In contrast, passive flow control operates without an external energy source, relying instead on geometric modifications or the addition of passive elements to the airfoil surface. Examples include the addition of vortex generators, gurney flaps, dimples, or biomimetic structures inspired by nature (Genest and Dumas, 2023; Algan, Seyhan and Sarioğlu, 2024). The main advantages of this approach lie in its simplicity, low cost, and its ability to improve aerodynamic performance without sacrificing energy efficiency. Therefore, passive flow control is widely chosen in various studies, especially those that emphasize improving performance while maintaining system efficiency and reliability (Salehin et al., 2025).

To date, many studies on passive flow control have been conducted. Fan et al., investigated a bionic airfoil by introducing tubercles along its leading edge at a low Reynolds number of $Re = 2 \times 10^4$. Their study concluded that applying a bionic design in the form of tubercles effectively enhances hydrodynamic performance, particularly by delaying stall and maintaining higher lift at large angles of attack (Fan et al., 2022). He et al., also studied airfoils that imitate the herringbone pattern of birds at Reynolds number $Re = 2 \times 10^4$, the results of which show that the herringbone pattern modification can delay stall from Angles of Attack (AoA) 10 to AoA 16 (He et al., 2026). Then, Xiao et al., have studied bionic airfoils, Riblet, Seagull, and Teal at a low Reynolds number of 1×10^5 and compared them with the NACA4412 airfoil. The results of the study indicate that the bionic airfoil and the NACA 4412 airfoil exhibit a similar type of nonlinear correlation, and the dimensions and shape of their minimum reduced-order models demonstrate good agreement (Xiao et al., 2023).

Previous studies have extensively examined the effects of bionic airfoil modifications on aerodynamic performance. It is well established that different airfoil types and modification forms can significantly influence the characteristics of the surrounding fluid flow. Based on this, the present study focuses on investigating modifications of the NACA 4415 airfoil by altering the leading edge

inspired by the nose shapes of several marine animals, as previously conducted by Bomagami et al. and Rasheed et al., who examined the aerodynamic effects of marine animal-inspired airfoil nose modifications (Rasheed et al., 2024; Navya et al., 2025). As a differentiator, the modifications used in this study refer to the nose morphology of the roughtoothed dolphin and spinner dolphin. While most previous studies were conducted at low Reynolds numbers, this study uses a higher Reynolds number, namely $Re = 1.6 \times 10^5$. The modified airfoil was then tested at various angles of attack (AoA) to analyze its effect on aerodynamic performance. Overall, this research is focused on assessing the impact of modifications on the performance changes of the NACA 4415 airfoil at $Re = 1.6 \times 10^5$.

2. METHODOLOGY

2.1. Airfoil Configuration

The NACA 4415 airfoil was employed as the reference model in this study, as shown in Figure 1. It is classified as a four-digit NACA airfoil with a 4% maximum camber positioned at 40% of the chord and a maximum thickness of 15% of the chord length. This airfoil was chosen because it is known to have good aerodynamics at certain AoA, as well as good stability against changes in AoA (Hayuningtyas, Nugroho and Jalaali, 2023). To enhance aerodynamic performance, implementing a bio-inspired airfoil design can increase lift and reduce drag (Saputra et al., 2016). Therefore, the spinner dolphin and roughtoothed dolphin modifications were chosen in this study. Both modifications were made by varying the cavity length of the airfoil, with the spinner dolphin having a diameter of 20 mm, a radius of 68 mm, and an angle of 5° . While the roughtoothed dolphin has a diameter of 20 mm, a radius of 64.28 mm, and an angle of α of 5° (Julian et al., 2024).

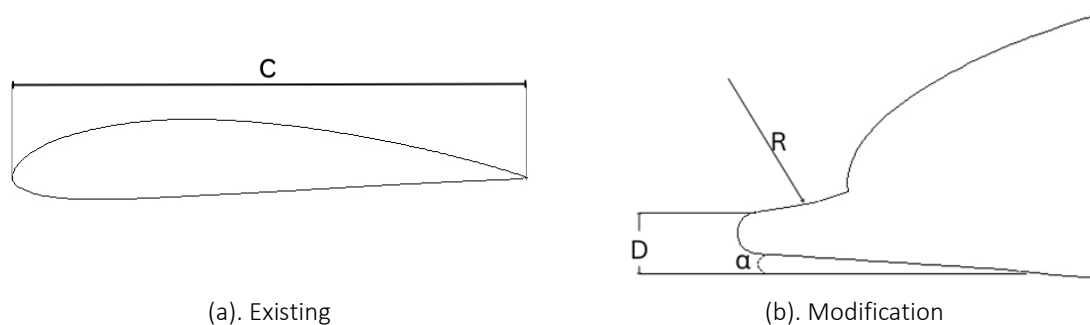


Figure 1. The NACA 4415 airfoil

2.2. Governing Equation

The main equation used in this study refers to the Reynolds Averaged Navier Stokes (RANS) equation. The RANS equation is a modification of the Navier-Stokes equation adapted for CFD calculations. The RANS equation consists of two basic equations, namely the continuity equation and the momentum equation. Equations (1) and (2) (Xiao et al., 2023) describe the RANS equations, where the first represents the continuity equation and the second denotes the momentum equation for fluid motion. Additionally, Equations (3) to (5) outline the k- ϵ - ω turbulence model, incorporating turbulent kinetic energy, laminar kinetic energy, and dissipation rate (Walters and Lylek, 2004).

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

$$\frac{\partial \rho}{\partial \tau} (\rho u_i) + \frac{\partial}{\partial x_i} (\rho u_i u_j) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial u_j} + \frac{\partial u_i}{\partial u_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial u_i} \right) \right] + \frac{\partial}{\partial x_i} (-\rho u_i u_j) \quad (2)$$

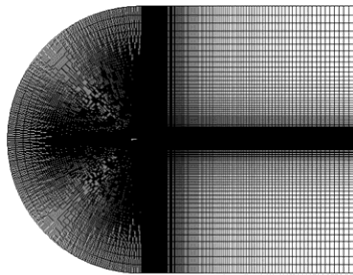
$$\frac{D(\rho k_t)}{Dt} = \rho (P_{kt} + R_{BP} + R_{NAT} - \omega k_t - D_T) + \frac{\delta}{\delta x_j} \left[\left(\mu + \frac{\rho \alpha_T}{\sigma_k} \right) \frac{\delta k_t}{\delta x_j} \right] \quad (3)$$

$$\frac{D(\rho k_L)}{Dt} = \rho (P_{kL} + R_{BP} + R_{NAT} - D_L) + \frac{\delta}{\delta x_j} \left(\mu \frac{\delta k_L}{\delta x_j} \right) \quad (4)$$

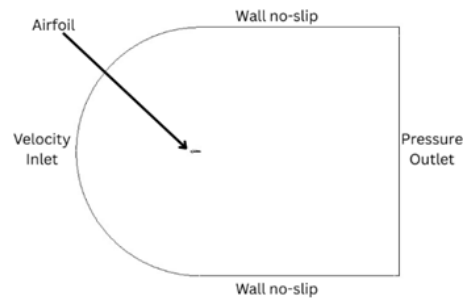
$$\frac{D(\rho \omega)}{Dt} = \rho \left[C_{\omega 1} \frac{\omega}{k_T} P_{kT} + \left(\frac{C_{\omega R}}{f_W} - 1 \right) \frac{\omega}{k_T} (R_{BP} + R_{NAT}) \right] + \frac{\delta}{\delta x_j} \left[\left(\mu + \frac{\rho \alpha_T}{\sigma_\omega} \right) \frac{\delta \omega}{\delta x_j} \right] - C_{\omega 2} \omega^2 + C_{\omega 3} f_\omega \alpha_T f_W^2 \frac{\sqrt{k_T}}{d^3} \quad (5)$$

2.3. Mesh and Boundary Condition

The mesh was constructed using quadrilateral elements with a structured mesh pattern and local refinement around the airfoil, as shown in Figure 2a. The goal of this mesh was to accurately capture the boundary layer and the flow transition area, with element spacing that favors low y^+ values as required by the transition turbulence model. The number of elements was adjusted through grid sensitivity tests to ensure that the simulation results were not affected by the mesh size. The applied boundary conditions included an inlet with $Re = 1.6 \times 10^5$, an outlet with zero pressure, the airfoil surface as a no-slip wall, and upper and lower boundaries that were considered symmetric to reduce wall disturbances, as shown in Figure 2b.



(a). Mesh



(b). Boundary condition

Figure 2. Mesh and boundary condition

2.4. Coefficient Lift (Cl) and Coefficient Drag (Cd)

Lift and drag are two crucial elements when discussing aerodynamics. An airfoil will function well with a good drag-to-lift ratio. Lift has a vector perpendicular to the direction of the freestream flow and is the main component that allows the airfoil to generate flight power. Meanwhile, the drag force has a vector parallel to the direction of the freestream velocity. Lift and drag can be calculated using equations 6 and 7 (Alom, Borah and Saha, 2018).

$$CD = \frac{FD}{\frac{1}{2}\rho A(V-u)^2} \quad (6)$$

$$CL = \frac{FL}{\frac{1}{2}\rho A(V-u)^2} \quad (7)$$

2.5. Y-Plus (Y⁺)

In CFD simulations, particularly in turbulent flows, the dimensionless parameter y^+ is used to measure the distance of the first cell from the wall surface to the flow boundary layer. The ideal y^+ value depends on the turbulence model used. Using y^+ as a mesh verification method is more efficient because it can improve local accuracy without increasing the total number of elements, thus saving time and computational resources. The calculation method for the y^+ value is explained in equation 8 (Nichols, 2010).

$$Y^+ = \frac{\vartheta \times y}{\nu} \quad (8)$$

Verification simulations on the NACA 4415 airfoil aimed to evaluate the accuracy of the numerical model and the impact of mesh changes on the agreement of the results with experimental data. Three mesh variations were used: fine with 200,000 elements, medium with 150,000 elements, and coarse with 100,000 elements, all using quadrilateral elements and structured patterns to maintain the quality of the airfoil surface as shown in Figure 3. The y^+ value was calculated, with the fine and medium meshes adjusted to achieve a value of approximately 1. In contrast, the coarse mesh had a value of approximately 0.5 to allow for a more accurate transitional turbulence model. This method is effective in representing the characteristics of the flow boundary layer.

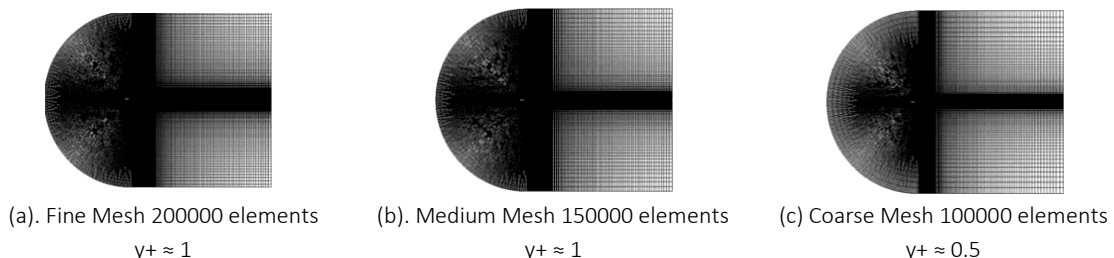


Figure 3. Mesh types

Table 1. Simulation results of Y⁺

	k-kl-omega				
	Number of Elements	Cd		Cl	
Fine	200000	0.024217	19%	1.401135	-4%
Medium	150000	0.024227	19%	1.350139	2%
Coarse	100000	0.027884	7%	1.375177	-6%
(Saliveros, 1988)	eksperimen	0.03		1.3	

The simulation results in Table 1 show that the coarse mesh with 100,000 elements produces the most accurate Cl and Cd values compared to the fine and medium meshes, with a smaller error rate. This indicates that a low y^+ value in the coarse mesh plays a more important role in improving

accuracy than simply the number of mesh elements. Furthermore, using this coarse mesh also reduces computational requirements because the fewer elements speed up the simulation process.

3. RESULTS AND DISCUSSION

3.1. Validation

To validate the computational results, the pressure coefficient distributions obtained from the present study using three different mesh resolutions were compared with the experimental data reported by Saliveros (Saliveros, 1988) and the numerical results presented by Liu et al., (Liu et al., 2020) as shown in Figure 4. The comparison indicates that all mesh configurations capture the overall trend of the reference datasets, with the locations of the maximum and minimum pressure coefficients occurring at nearly identical chordwise positions.

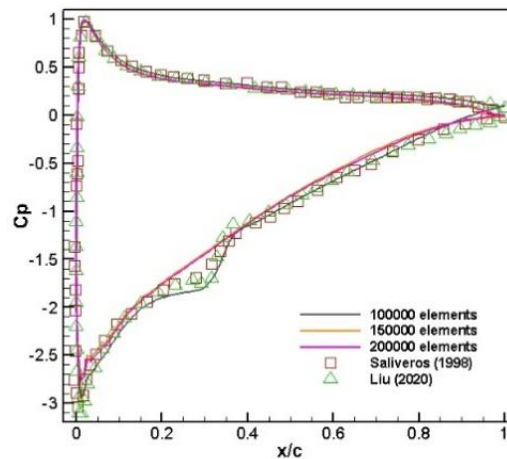


Figure 4. C_p distribution of baseline NACA 4415

The top surface has a strong suction peak next to the leading edge ($x/c = 0$), with C_p values close to -3.0 or a little lower. This very strong negative peak is common for cambered airfoils like the NACA 4415. It means that the flow is speeding up a lot across the top surface right after the stagnation point. The steep change in C_p at the leading edge shows that the airfoil's curvature and camber cause quick changes in pressure. This strong suction peak makes lift much more effective. The comparison of the three mesh densities shows that all the simulations accurately show the leading-edge suction peak, with only small differences. The 200,000-element mesh gives results that are a little smoother and more consistent, especially when it comes to the steep pressure gradient. This shows that mesh refinement improves numerical accuracy.

On the bottom surface, the C_p values at the leading edge are positive, around $+1$. This shows the stagnation area, where the flow velocity is close to zero and the static pressure is at its highest. As the flow moves over the lower surface, the pressure slowly drops, and C_p gets closer to zero at the trailing edge. The relatively smooth pressure recovery on the bottom surface indicates consistent connected flow, free from significant adverse pressure gradient effects.

The C_p distribution on the top surface shows a gradual pressure recovery after the strong suction peak, from about $x/c = 0.05$ to 0.4 . The curve goes up steadily (C_p gets less negative), which means that the fast flow is slowing down as it moves downstream. There is a slight change in slope near the

mid-chord ($x/c = 0.3-0.4$), which could mean that there is a transition zone or that the boundary layer is growing slowly. The absence of abrupt discontinuities in C_p suggests that the flow primarily remains connected over the chord length under the conditions analyzed.

From the middle of the chord to the trailing edge ($x/c \approx 0.4-1.0$), the C_p values for both the top and bottom surfaces get closer to zero. This convergence means that the pressure is balanced at the trailing edge, which meets the Kutta requirement. The smooth merging of pressure distributions at $x/c = 1$ proves that the simulation is physically realistic. The small differences between the three mesh densities in this area don't matter, which shows that the solution doesn't depend on the mesh, especially between 150,000 and 200,000 elements.

The numerical results show a strong link to the experimental or previously published data along the entire chord (Saliveros, 1988; Liu *et al.*, 2020). The suction peak's amplitude, the way pressure recovers, and the behavior at the trailing edge all match up very closely with the reference data points. There are small differences in the middle of the chord and next to the suction peak. These could be caused by differences in turbulence models, numerical methods, or errors in the experiments. Still, the overall consistency backs up the computational method and shows that the chosen mesh densities are enough to accurately show the aerodynamic properties of the baseline airfoil.

The gradual increase from 100,000 to 200,000 elements shows that the data is smoother and more in line with reference data, especially in areas with steep pressure gradients. The difference between 150,000 and 200,000 elements is small, which means that mesh convergence is almost reached at 150,000 elements. This means that the cost of computing and the accuracy of the solution are in perfect balance.

Among the three simulations, the coarse mesh exhibits the closest agreement with both the experimental and numerical reference data, demonstrating a superior ability to reproduce key flow features, including local pressure gradient variations associated with boundary-layer transition. Contrary to the common assumption that finer meshes yield better accuracy, coarse meshes with $y^+ \approx 0.5$ adapt more effectively to boundary-layer transitions, enhancing the performance of the $k-k_l-\omega$ turbulence model. This supports previous findings that meshes with optimal y^+ and efficient element counts can produce accurate results, making the coarse mesh the most suitable choice for further analysis.

3.2. Analysis

The primary aerodynamic parameters obtained in this study are the drag coefficient (C_d) and lift coefficient (C_l), as presented in Figure 5. Figure 5a illustrates the variation of C_l with angle of attack (AoA). At low AoAs, no significant differences are observed among the three airfoil configurations, with the spinner dolphin modification exhibiting a lift trend nearly identical to that of the baseline NACA 4415 airfoil. However, beyond an AoA of 6° , the baseline airfoil shows a more pronounced increase in lift, ultimately stalling at an AoA of 19° , whereas the spinner dolphin and rough-toothed dolphin airfoils stall earlier at AoAs of 15° and 13° , respectively. The lower C_l values observed for the modified airfoils are consistent with previous studies on leading-edge geometric modifications,

which have reported that such alterations can modify the pressure distribution near the leading edge, reduce the suction peak, and consequently decrease lift at moderate to high angles of attack. These findings indicate that bio-inspired nose designs do not necessarily enhance lift performance, despite their potential benefits in flow control.

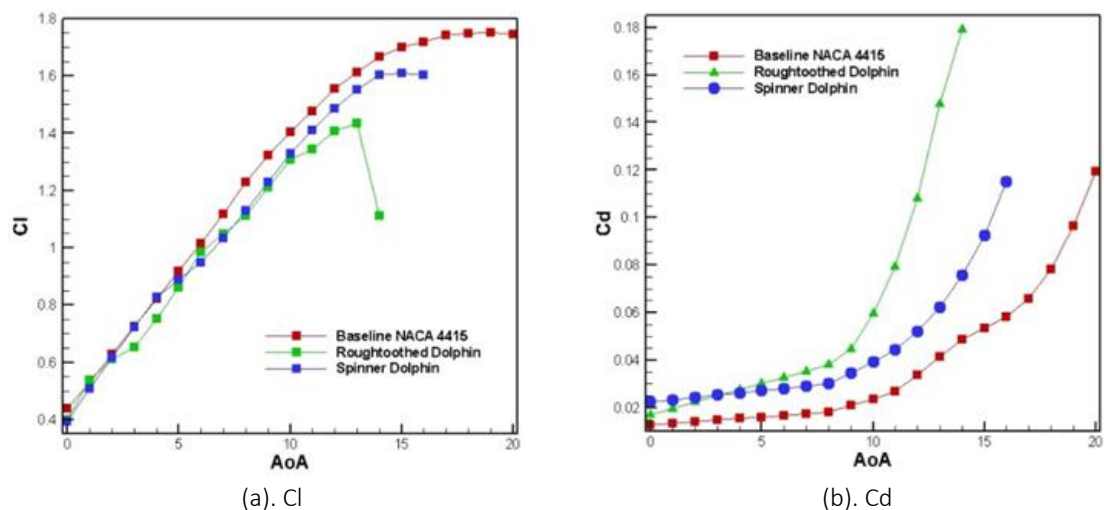


Figure 5. The drag coefficient (C_d) and lift coefficient (C_l) against AoA

The drag coefficient (C_d) results are presented in Figure 5b. The baseline NACA 4415 airfoil consistently exhibits lower drag than the two modified airfoils across the entire range of angles of attack (AoA). At low AoAs, the drag values of all three airfoils are comparable; however, beyond an AoA of 6°, the roughtoothed dolphin configuration shows a pronounced increase in drag, whereas the spinner dolphin airfoil maintains a trend closer to that of the baseline. The higher drag coefficients observed for the modified airfoils are consistent with findings from previous studies on leading-edge geometric modifications, which have reported that such alterations can disturb near-wall flow and modify pressure distributions around the leading edge, leading to increased pressure and friction drag at moderate to high AoAs. These results suggest that bio-inspired nose designs may incur a drag penalty despite their potential benefits in flow control or separation management.

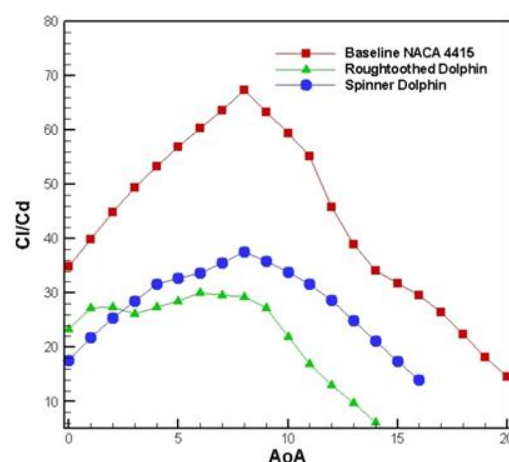


Figure 6. Lift-to-drag ratio against AoA

Figure 6 shows the lift-to-drag ratio (Cl/Cd) versus angle of attack (AoA) data for three airfoil types: Baseline NACA 4415, Roughtoothed Dolphin, and Spinner Dolphin. The NACA 4415 airfoil shows the best overall performance with the highest Cl/Cd value, especially at angles of attack around 4-5°, indicating high aerodynamic efficiency, and is suitable for applications requiring maximum lift with minimal drag. However, incorporating the rough-toothed and spinner dolphin modifications resulted in a decrease in the aerodynamic performance of the NACA 4415 airfoil, as indicated by the significantly lower lift-to-drag ratio compared to the baseline model.

The baseline NACA 4415 airfoil performs well at low angles of attack (0°–4°), with Cl/Cd starting in the mid-30s and getting better as the angle of attack rises. On the other hand, the rough-toothed dolphin's arrangement starts with Cl/Cd values just above 20 and rises slowly as the angle of attack rises. The spinner dolphin arrangement is better than the rough-toothed one in this first area. It starts at about 17–18 and rises more steeply into the low 30s at about 4°–5°. This means that even though changes to the surface that mimic living things might change how the flow behaves, the standard airfoil is still more aerodynamically efficient at lower incidence angles.

When the angle of attack (AoA) rises into the moderate range (5°–9°), all three designs show higher Cl/Cd values, which means they are better at making lift compared to drag. The baseline NACA 4415 works best at about 8°, when the Cl/Cd ratio goes up to almost 67. This peak is the best operating state for getting the best aerodynamic efficiency before flow separation effects start to happen. The spinning dolphin configuration reaches its highest point in this area, which is about 8°. However, its highest point is a little lower, between 37 and 38. The rough-toothed dolphin's shape reaches a maximum of about 6°–7°, which is not very high. The differences show that the baseline airfoil shape is better at keeping beneficial pressure gradients and delaying a big increase in drag compared to the biomimetic changes in this aerodynamic situation.

When the angle of attack goes up even more (over 9°) beyond the apex area, all designs show a drop in Cl/Cd . This drop is linked to an increase in pressure drag and the start of flow separation, which lowers lift efficiency. The baseline airfoil has a steady drop from its highest point, but its Cl/Cd ratios are always better than those of the other two designs up to 20°. For example, the baseline design keeps a Cl/Cd ratio of 45 at about 12°, but the spinning dolphin's ratio drops to about 28, and the rough-toothed dolphin's ratio drops even more, to about 13–15. The big drop in the rough-toothed dolphin example shows that flow separation happened earlier or was worse, which caused more drag and less aerodynamic efficiency.

The difference in performance gets even bigger when the angle of attack is higher (14°–20°). The rough-toothed dolphin's configuration shows a huge drop, with Cl/Cd ratios falling below 10 at around 15°. This means that the dolphin is not very aerodynamic and that there is likely a lot of flow separation. In this range, the spinning dolphin configuration works better than the rough-toothed version, keeping Cl/Cd ratios up to about 16°, but it is still much worse than the baseline airfoil. At the same time, the baseline NACA 4415, which has been steadily getting worse, is still more efficient at higher angles, which suggests that it has better stall characteristics and is more stable in the air.

Then, the percentage data of Cl and Cd from the addition of airfoil modifications are presented, which can be seen in Table 2. In the Cd data, the average percentage increase in Cd for the spinner dolphin is lower, which is 40.399% compared to the baseline. In contrast, the roughtoothed dolphin

shows a higher percentage increase in C_d with an average of 51.479% compared to the baseline. Meanwhile, in the C_l data, the roughtoothed dolphin has a larger average percentage decrease, which is -10.472%, while the spinner dolphin only reaches an average decreased of -5.194% compared to the baseline.

Table 2. Average percentage addition in C_d and C_l of modification roughtoothed and spinner dolphin

AoA	C_d		C_l	
	Roughtoothed Dolphin	Spinner Dolphin	Roughtoothed Dolphin	Spinner Dolphin
0	26.5551%	43.958%	-9.854%	-11.347%
1	32.6615%	43.199%	1.654%	-4.350%
2	37.3439%	42.499%	-2.762%	-1.969%
3	41.0485%	41.852%	-11.230%	-0.606%
4	44.0526%	41.251%	-9.257%	0.620%
5	46.5377%	40.692%	-6.566%	-3.398%
6	48.6277%	40.170%	-3.226%	-7.161%
7	50.4097%	39.683%	-6.553%	-7.961%
8	51.9473%	39.226%	-10.526%	-8.858%
9	53.1306%	39.193%	-9.056%	-7.519%
10	60.3677%	39.966%	-7.265%	-5.676%
11	66.3374%	39.910%	-9.790%	-4.766%
12	68.5362%	34.703%	-10.447%	-4.564%
13	71.9235%	33.503%	-12.491%	-3.993%
14	72.7033%	35.448%	-49.717%	-4.012%
15		41.994%		-5.569%
16		49.532%		-7.163%
AVERAGE	51.479%	40.399%	-10.472%	-5.194%

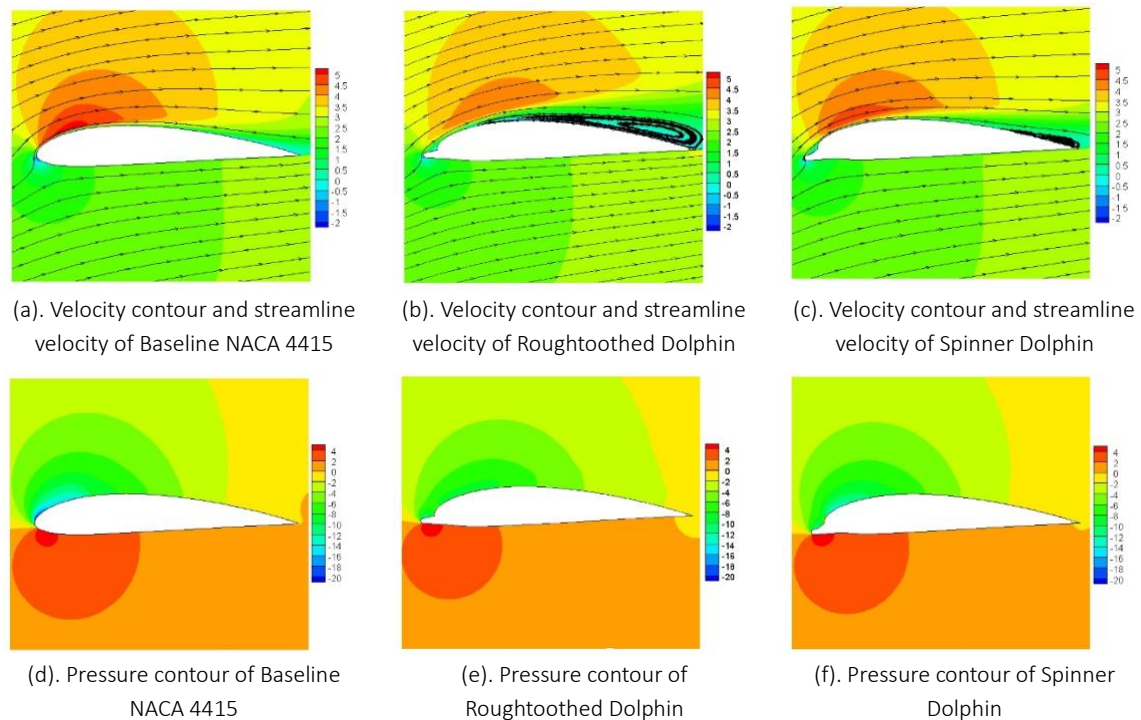


Figure 7. Velocity contour, streamline velocity, and pressure contour at AoA 13

The final data presented are the velocity contour, streamline velocity, and pressure contour of the three airfoils taken at AoA 13, which can be seen in [Figure 7](#). Velocity data indicate that the roughtoothed dolphin type enhances lift near the trailing edge of the airfoil, like the spinner dolphin type. However, at streamline velocity, the roughtoothed dolphin causes a larger recirculation zone when compared to the other two airfoil models. In the pressure contour, the roughtoothed dolphin type can reduce stagnation on the airfoil when compared to the baseline. The spinner dolphin type only reduces pressure on the lower side of the airfoil.

4. CONCLUSION

From the results of this study, non-dimensional parameters successfully reduce the computational load by determining the right first layer thickness so that it does not require too many meshes. From the simulation results, the baseline NACA 4415 is still superior in its aerodynamic performance because it has the highest Cl and low Cd throughout its AoA. The aerodynamic performance of the baseline NACA 4415 is followed by the roughtoothed dolphin modification, which has a higher lift and lower drag compared to the spinner dolphin. Therefore, it can be concluded that the rough-toothed and spinner dolphin modifications do not enhance the aerodynamic performance of the NACA 4415 airfoil at high angles of attack (AoA). However, at low AoA, the rough-toothed dolphin modification performs comparably to the baseline NACA 4415 airfoil.

REFERENCES

- Albers, M. and Schröder, W. (2021) 'Lower drag and higher lift for turbulent airfoil flow by moving surfaces', *International Journal of Heat and Fluid Flow*, 88, p. 108770. Available at: <https://doi.org/10.1016/j.ijheatfluidflow.2020.108770>.
- Algan, M., Seyhan, M. and Sarioğlu, M. (2024) 'Effect of aero-shaped vortex generators on NACA 4415 airfoil', *Ocean Engineering*, 291, p. 116482. Available at: <https://doi.org/10.1016/j.oceaneng.2023.116482>.
- Alom, N., Borah, B. and Saha, U.K. (2018) 'An insight into the drag and lift characteristics of modified Bach and Benesh profiles of Savonius rotor', *Energy Procedia*, 144, pp. 50–56. Available at: <https://doi.org/10.1016/j.egypro.2018.06.007>.
- Coder, J.G. and Somers, D.M. (2020) 'Design of a slotted, natural-laminar-flow airfoil for commercial transport applications', *Aerospace Science and Technology*, 106, p. 106217. Available at: <https://doi.org/10.1016/j.ast.2020.106217>.
- Diecke, S. (2023) 'Electric Aircraft Performance Analysis Utilizing Simplified Approaches for Airfoil and Propulsion Chain Design', *AIAA AVIATION 2023 Forum*. American Institute of Aeronautics and Astronautics (AIAA AVIATION Forum). Available at: <https://doi.org/10.2514/6.2023-3665>.
- Fan, M. et al. (2022) 'Numerical and experimental investigation of bionic airfoils with leading-edge tubercles at a low-Re in considering stall delay', *Renewable Energy*, 200, pp. 154–168. Available at: <https://doi.org/10.1016/j.renene.2022.09.123>.
- Genest, B. and Dumas, G. (2023) 'Numerical Investigation into Single and Double Gurney Flaps for Improving Airfoil Performance', *Journal of Aircraft*, 60(6), pp. 1832–1846. Available at: <https://doi.org/10.2514/1.C037304>.
- Hayuningtyas, R.S.R., Nugroho, F.F. and Jalaali, B. (2023) 'Simulasi Numerik Karakteristik Aerodinamika Pada Airfoil Naca 4415 Dengan Mempertimbangkan Ground Effect', *Vortex*, 4(1), pp. 5–14. Available at: <https://doi.org/10.28989/vortex.v4i1.1339>.

- He, H. et al. (2026) 'Flow over airfoil model covered by bio-inspired herringbone riblets', *European Journal of Mechanics - B/Fluids*, 115, p. 204365. Available at: <https://doi.org/10.1016/j.euromechflu.2025.204365>.
- Hoseinzadeh, S. et al. (2020) 'A detailed experimental airfoil performance investigation using an equipped wind tunnel', *Flow Measurement and Instrumentation*, 72, p. 101717. Available at: <https://doi.org/10.1016/j.flowmeasinst.2020.101717>.
- Julian, J. et al. (2024) 'Effect of airfoil modification on performance improvement of NACA 4415 with bio-inspired nose', *AIP Conference Proceedings*, 3090(1), p. 040002. Available at: <https://doi.org/10.1063/5.0231138>.
- Kim, M., Essel, E.E. and Sullivan, P.E. (2022) 'Effect of varying frequency of a synthetic jet on flow separation over an airfoil', *Physics of Fluids*, 34(1), p. 015122. Available at: <https://doi.org/10.1063/5.0077334>.
- Koca, K. et al. (2022) 'Experimental study of the wind turbine airfoil with the local flexibility at different locations for more energy output', *Energy*, 239, p. 121887. Available at: <https://doi.org/10.1016/j.energy.2021.121887>.
- Krishnan, A., Al-Obaidi, A.Sh.M. and Hao, L.C. (2023) 'A comprehensive review of innovative wind turbine airfoil and blade designs: Toward enhanced efficiency and sustainability', *Sustainable Energy Technologies and Assessments*, 60, p. 103511. Available at: <https://doi.org/10.1016/j.seta.2023.103511>.
- Lagemann, E. et al. (2024) 'Towards extending the aircraft flight envelope by mitigating transonic airfoil buffet', *Nature Communications*, 15(1), p. 5020. Available at: <https://doi.org/10.1038/s41467-024-49361-3>.
- Liu, Y. et al. (2020) 'Numerical study of the effect of surface grooves on the aerodynamic performance of a NACA 4415 airfoil for small wind turbines', *Journal of Wind Engineering and Industrial Aerodynamics*, 206, p. 104263. Available at: <https://doi.org/10.1016/j.jweia.2020.104263>. (Accessed: 27 October 2025).
- Navya, B. et al. (2025) 'Effect of Bio-Inspired Nose on Flow Separation Control Over a NACA 6 Series Airfoil', *International Research Journal on Advanced Engineering Hub (IRJAEH)*, 3(04), pp. 1702–1709. Available at: <https://doi.org/10.47392/IRJAEH.2025.0244>.
- Nichols, R. (2010) *Turbulence Models and Their Application to Complex Flows*. Birmingham, USA: University of Alabama at Birmingham. Available at: <https://www.nasa.gov/wp-content/uploads/2025/09/turbulence-guide-v4-01.pdf?emrc=90c0ad>.
- Özkan, M. (2022) 'Active and Passive Flow Control Methods Over Airfoils for Improvement in Aerodynamic Performance', in T.H. Karakoc, C.O. Colpan, and A. Dalkiran (eds) *New Frontiers in Sustainable Aviation*. Cham: Springer International Publishing, pp. 19–33. Available at: https://doi.org/10.1007/978-3-030-80779-5_2.
- Rasheed, D. et al. (2024) 'Aerodynamics Investigation on Bio-Inspired Surface Design by Use of Shark-Skin Surface on the Aircraft Wing for Drag Reduction', in A. Singh, D.P. Mishra, and G. Bhat (eds) *Recent Trends in Thermal and Fluid Sciences. INCOME 2023*, Singapore: Springer Nature, pp. 81–90. Available at: https://doi.org/10.1007/978-981-97-5373-4_8.
- Salehin, Md.N. et al. (2025) 'Passive flow control devices for road vehicles: A comprehensive review', *Engineering Science and Technology, an International Journal*, 62, p. 101953. Available at: <https://doi.org/10.1016/j.jestch.2025.101953>.
- Saliveros, E. (1988) *The aerodynamic performance of the NACA-4415 aerofoil section at low Reynolds numbers*. Thesis. University of Glasgow. Available at: <https://eleanor.lib.gla.ac.uk/record=b1332067> (Accessed: 21 October 2025).
- Saputra, A. et al. (2016) 'Modifikasi Airfoil Sayap Pesawat Conceptual Transport RM-001', *Indept: Industrial Electronics of Aviation*, 6(1), pp. 48–55.
-

- Walters, D.K. and Leylek, J.H. (2004) 'A New Model for Boundary Layer Transition Using a Single-Point RANS Approach', *Journal of Turbomachinery*, 126(1), pp. 193–202. Available at: <https://doi.org/10.1115/1.1622709>.
- Xiao, Q. et al. (2023) 'Study on Nonlinear Correlation in Modal Coefficients of the Bionic Airfoil', *Machines*, 11(1), p. 88. Available at: <https://doi.org/10.3390/machines11010088>.

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