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Effect of Bio-Inspired Nose on Flow Separation Control Over a NACA 6 Series Airfoil

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Abstract
Flow separation poses a challenge in NACA 6 series airfoils, impacting lift, drag, and stall characteristics. To *address this here, the Concept is about investigating the effect of a bio-inspired nose on flow separation control. Drawing inspiration from nature, the bio- inspired nose aims to optimize aerodynamic performance. This study aims to understand the impact of this design alteration through systematic numerical simulations, considering varying Reynolds numbers and angles of attack. The outcomes of this study could offer valuable insights into bio-inspired design applications for flow separation control in NACA 6 series airfoils. The potential improvements in aerodynamic performance hold promise for advancing the design and efficiency of airfoils used in various aerospace applications, including unmanned aerial vehicles and aircraft. This research aligns with the ongoing quest for innovative and nature-inspired solutions in aerodynamics, contributing to the evolution of high-performance airfoil design.*

Keywords: *Bio-Inspired Nose Airfoil; Flow Separation Control; NACA 6 Series Airfoil; Stall Characteristics.*

1. Introduction

The NACA 6 series airfoils are widely used in aerospace applications due to their excellent lift and drag characteristics. However, like many airfoils, they can experience flow separation under certain conditions, leading to a drop in aerodynamic performance and an increase in drag. Flow separation happens when the boundary layer of air detaches from the airfoil's surface, disrupting smooth airflow. This not only increases drag but also reduces lift, making it a critical challenge in aircraft design.[1] Aerodynamics plays a key role in optimizing aircraft performance, and even small changes to an airfoil's shape can make a significant difference. Managing flow separation is particularly important, as it affects lift, drag, and overall efficiency. The NACA 6 series airfoils, despite their popularity, are not immune to this issue. Flow separation is a critical aerodynamic phenomenon that significantly impacts the performance of airfoils, leading to increased drag, loss of lift, and premature stall. These effects are particularly detrimental in applications such as aircraft wings, wind turbine blades, and unmanned aerial vehicles (UAVs), where maintaining optimal aerodynamic efficiency is crucial. The NACA 6-series airfoils, widely used in aerospace due to their favorable lift-to-drag characteristics, still suffer from flow separation at high angles of attack (AoA), limiting their operational range.[1] Traditional flow control techniques, such as vortex generators, slats, and flaps, have been employed to mitigate separation, but these methods often introduce mechanical complexity, weight penalties, and increased maintenance. In recent years, bio-inspired designs have emerged as a promising alternative, leveraging millions of years of evolutionary optimization in natural flyers and swimmers. Cetaceans (e.g., humpback whales, dolphins) exhibit unique morphological adaptations—such as tubercles on their flippers—that delay stall and enhance hydrodynamic efficiency by manipulating flow structures. Similarly, avian species like owls and eagles possess specialized wing features that minimize turbulence and noise while improving lift at high AoAs.[2] In recent years, engineers and researchers have looked to nature for inspiration. Biological systems have evolved highly efficient ways to navigate complex airflows, offering new ideas for improving aerodynamic performance. One promising approach is bio-inspired nose modifications for airfoils. By mimicking natural features found in certain organisms, these modifications aim to reduce flow separation and enhance aerodynamic efficiency.[1] This study explores how bio-inspired nose modifications influence key aerodynamic parameters such as lift, drag, and stall behavior. Using computational simulations and experimental testing, This Research aim to quantify the impact of these modifications and better understand the flow patterns around the airfoil. Flow visualization techniques will help reveal how these changes affect separation control, potentially leading to more efficient and effective airfoil designs.[3]

2. Method

2.1. Design

The leading-edge profile of NACA 63-415 (Figure) was adjusted to incorporate a bio-inspired nose design resembling that of a whale's flipper by introducing a forward-facing step and a trough on the underside of the airfoil. The forward-facing step generates a low-pressure area due to the multiple accelerations of airflow over the upper surface at low angles of attack. The trough on the bottom creates a vortex and a low-pressure zone on the upper surface, which helps postpone flow separation at higher angles of attack.[1]

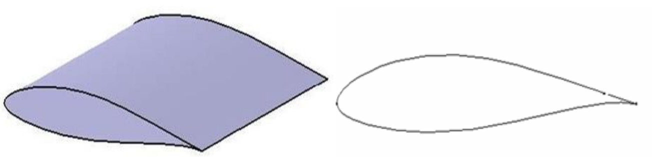

Figure 1 Design of NACA 63-415 airfoil (A)

To develop various nose designs inspired by nature, the NACA 63-415 airfoil with a chord length of 100 cm has been selected as the baseline model. A square grid is established close to the leading edge of the airfoil, where circles of varying diameters are illustrated at different positions, as depicted in Figure .[1] The dimensions of the square grid are set to half of the maximum thickness of the NACA 63-415 airfoil, while the circles have a diameter of 1.875mm (the leading edge circle diameter of the NACA 63-415 airfoil was considered as the maximum). To shape the cetacean species' nose, as illustrated in Figure , an ellipse is employed to connect the nose circle and the upper surface of the airfoil (which is tangent to both). Additionally, a tangent line is drawn to link the nose circle with the lower surface of the airfoil. This bio-inspired nose design for the NACA 63-415 airfoil was created using CATIAV5R24 software, Figure 4. As depicted in Figure , six regions are emphasized on the grid, taking inspiration from various cetacean species represented in **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.** .[1] The B region results in a longer nose with a shallow cavity, similar to the NACA 63-415-Rough-toothed dolphin depicted in **Error! Reference source not found.**. The A region produces a shorter nose with a shallow cavity, represented by the NACA 63-415-Bottlenose dolphins. The D region leads to a longer nose with a medium-depth cavity, as shown in **Error! Reference source not found.**, NACA 63-415-Spinner dolphin. The C region results in a shorter nose with a medium-depth cavity, illustrated in **Error! Reference source not found.**, NACA 63-415-Beluga whale. The F region generates a longer nose with a deeper cavity NACA 63-415-Indus dolphin. Conversely, the E region produces a shorter nose with a deeper cavity NACA 63-415-Northern bottlenose whale. Altering the leading edge of an airfoil to mimic a whale's flipper, particularly with the addition of tubercles, can significantly impact aerodynamic performance.

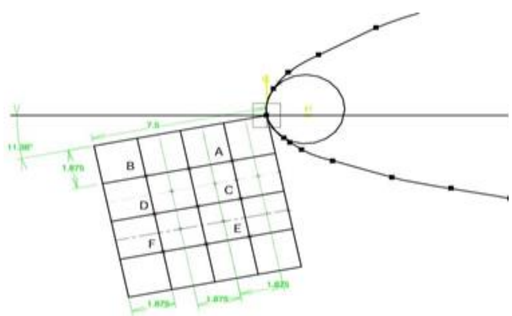

Figure 2 Design of Square Grid

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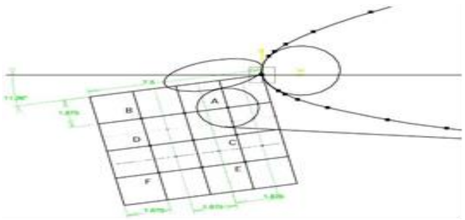

Figure 3 Design of Circle and Ellipse to Create the Shape of Bottle Nose Dolphin

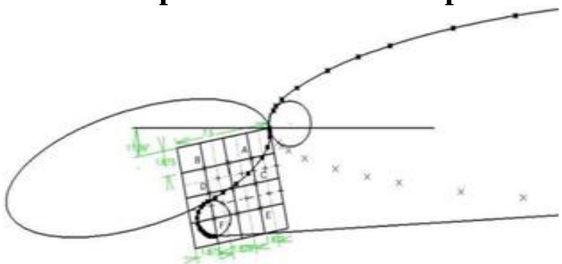

Figure 4 Design of Circle and Ellipse to Create the Shape of Indus Dolphin

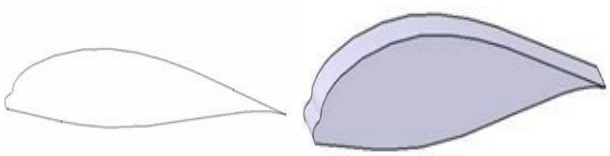

Figure 5 Design of Bio Inspired Airfoil B (Beluga Whale)

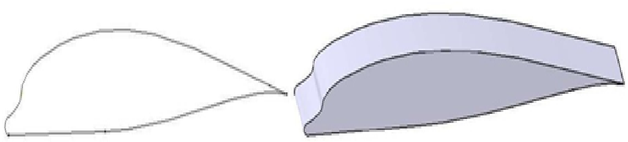

Figure 6 Design of Bio inspired Airfoil C (Baiji)

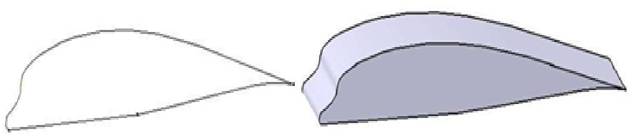

Figure 7 Design of Bio inspired Airfoil D (Bottle nose dolphin)

2.2. Analysis

Analysis has been carried out in ANSYS-FLUENT software. The aerodynamic properties such as coefficient of lift, coefficient of drag, aerodynamic efficiency (C_l/C_d) and also the vortex generation have been analyzed for different bio-inspired nose NACA63-415 airfoils. The computational domain for the NACA 63-415 airfoil is designed to ensure accurate aerodynamic simulations. The leading edge of the airfoil is positioned 12.5 times the chord length (C) from the inlet, while the outlet extends 20 times the chord length (C) downstream to capture wake effects. The top and bottom boundaries are symmetrically placed around the airfoil to maintain a balanced flow field and minimize numerical inaccuracies, Figure 8 [5-8].

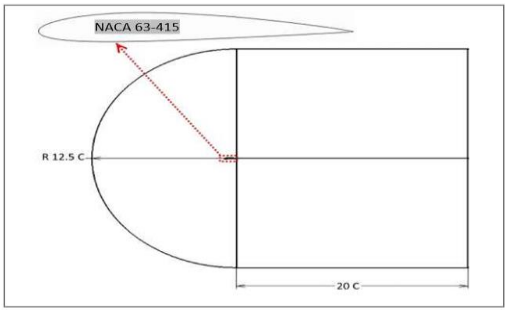

Figure 8 Computational Domain

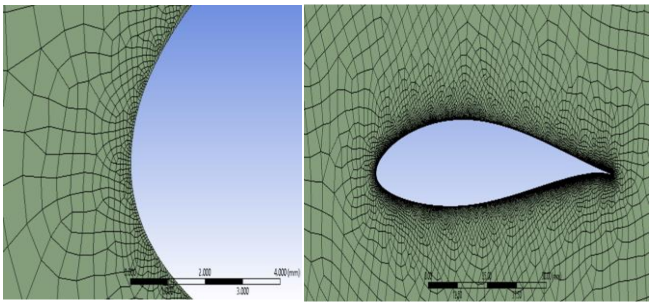

Figure 9 Meshing of NACA 63-415 Airfoil

The mesh metrics indicate good overall quality for analyzing additional airfoils. Inflation settings include a transition ratio of 0.27–0.28, growth rate of 1.2, and 2–5 boundary layers, providing adequate near-wall resolution. Mesh density ranges from 63,956–134,887 nodes and 62,825–133,183 elements, indicating medium to fine resolution. Sizing parameters include a minimum size of 0.25–2.0 mm, max face size of ~61.15 mm, and a curvature normal angle of 18°, ensuring sufficient refinement in curved regions. The mesh uses a fine relevance center, curvature-based sizing, and smooth inflation transitions. Minimum mesh quality is maintained above 0.3 for numerical stability and

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accuracy, Figure 9 & 10..

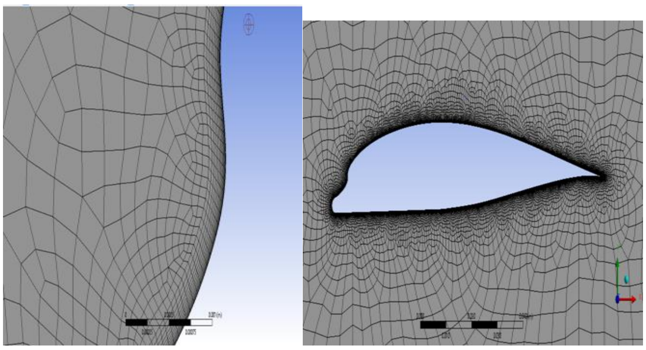

Figure 10 Meshing of Baiji Inspire NACA 63-415 Airfoil

The conditions for the simulation are two-dimensional, steady, incompressible, and characterized by low subsonic flow. A velocity inlet, wall with a no-slip condition (representing the airfoil), and pressure outlet conditions are employed for the simulation. A C-type multi-block structured grid is utilized for the calculations. It was observed that the Transition 4 equation provides superior flow predictions compared to the other models across all angles of attack. The pressure coefficient for the NACA 63-415 airfoil, obtained through ANSYS simulations, was compared. The coefficients of lift and drag for the NACA 63-415 airfoil at various angles of attack were derived from the ANSYS simulations [9-10].

3. Results and Discussion

3.1. Results

NACA 63415 airfoil has been modified with the bio-inspired nose and other 6 cases are analyzed using Ansys– Fluent at low speed. Figure 22, shows the variation of coefficient of drag at different angle of attacks for base airfoil (NACA 63415) and bio–inspired NACA 63415 airfoils. These bio– inspired airfoils have different nose length. As here at zero angle of attack it has more drag for airfoil D and less for the unmodified airfoil, but when AOA is changing the drag of airfoil D is less than the drag of unmodified airfoil. Airfoil B, C, D modified airfoils possess less drag as AOA increases as compared to all the modified and unmodified airfoils. So, the bioinspired airfoils with longer nose possess less drag, Figure 11 to Figure 20.

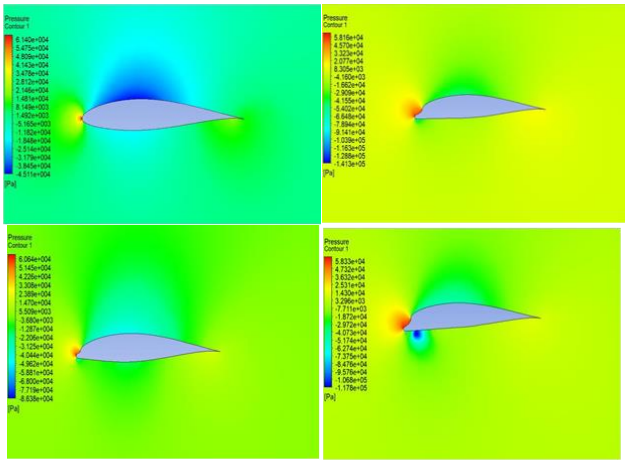

Figure 11 Pressure Contour of NACA 63-415 And Bio-Inspired Nose Airfoils At 0° Angles of Attack

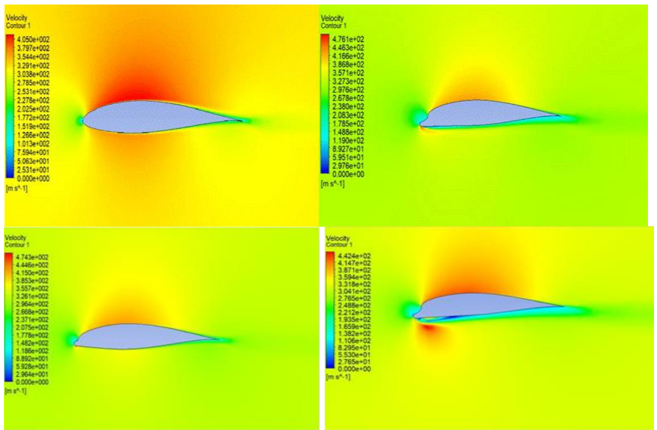

Figure 12 Velocity Contour of NACA 63-415 and Bio-Inspired Nose Airfoils at 0° Angles of Attack

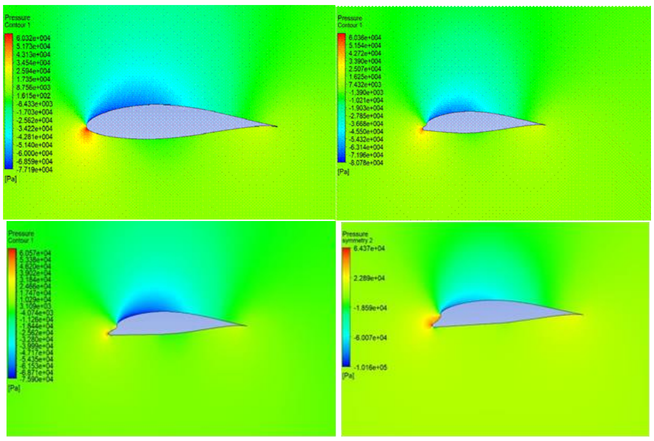

Figure 13 Pressure Contour of NACA 63-415 and Bio-Inspired Nose Airfoils at 4° Angles of Attack

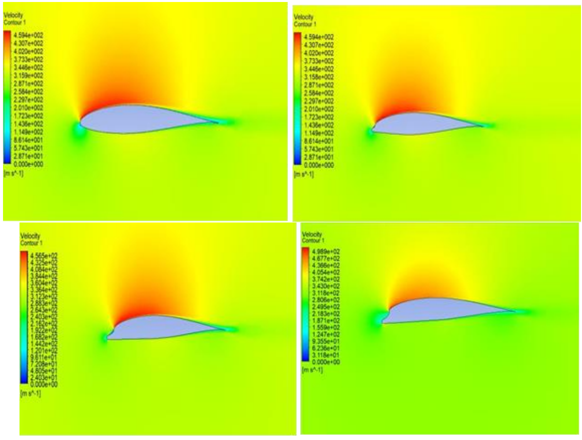

Figure 14 Velocity Contour of NACA 63-415 and Bio-Inspired Nose Airfoils At 4° Angles of Attack

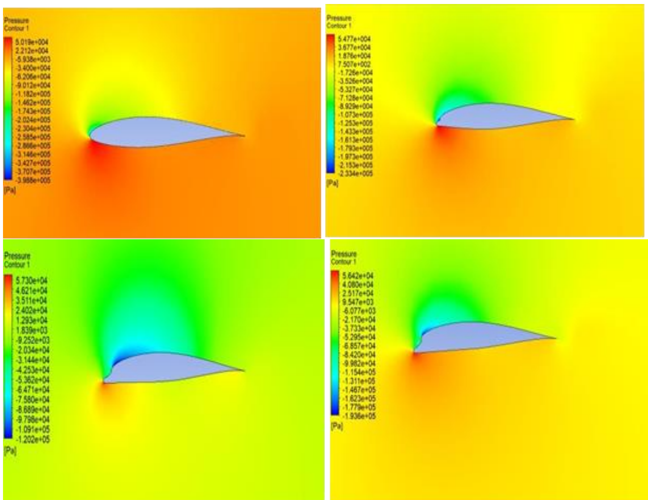

Figure 15 Pressure Contour of NACA 63-415 And Bio-Inspired Nose Airfoils At 12° Angles of Attack

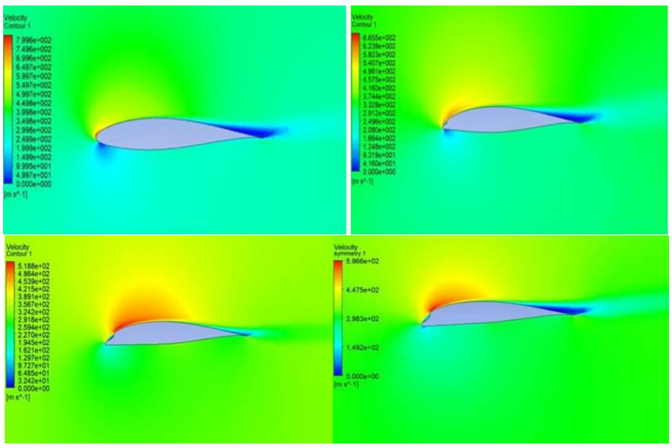

Figure 16 Velocity Contour of NACA 63-415 and Bio-Inspired Nose Airfoils At 12° Angles of Attack

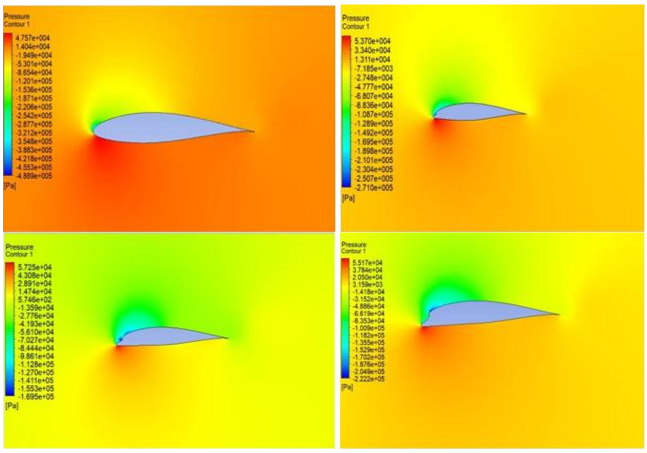

Figure 17 Pressure Contour of NACA 63-415 and Bio-Inspired Nose Airfoils At 14° Angles of Attack

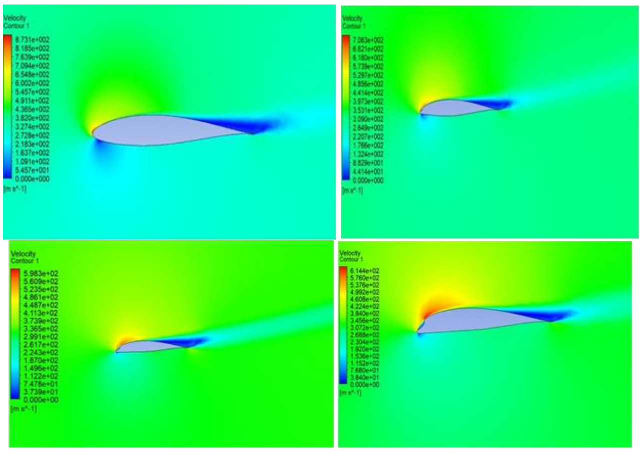

Figure 18 Velocity Contour of NACA 63-415 and Bio-Inspired Nose Airfoils At 14° Angles of Attack

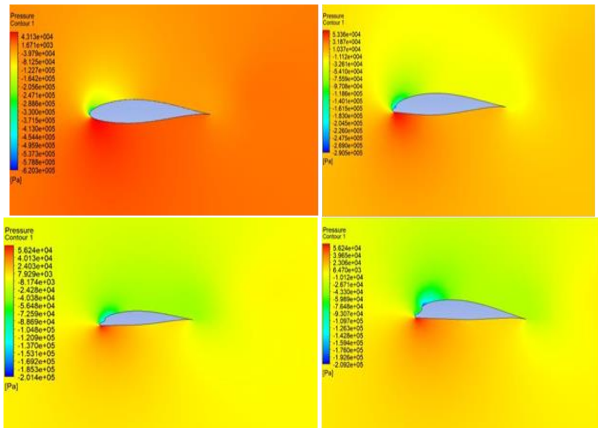

Figure 19 Pressure contour of NACA 63-415 and bio-inspired nose airfoils at 18° angles of attack

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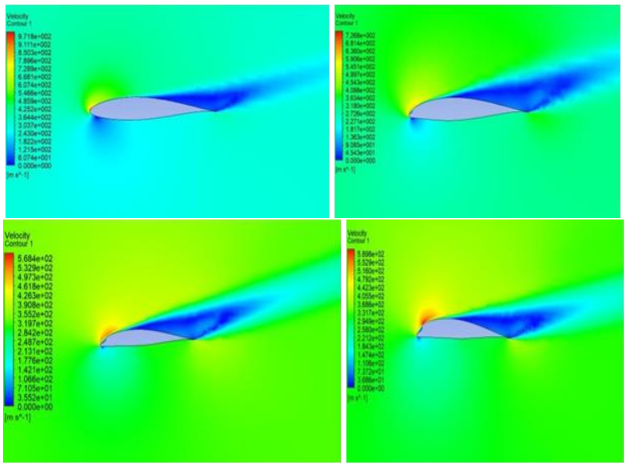

Figure 20 Velocity Contour of NACA 63-415 and Bio-Inspired Nose Airfoils at 18° Angles of Attack

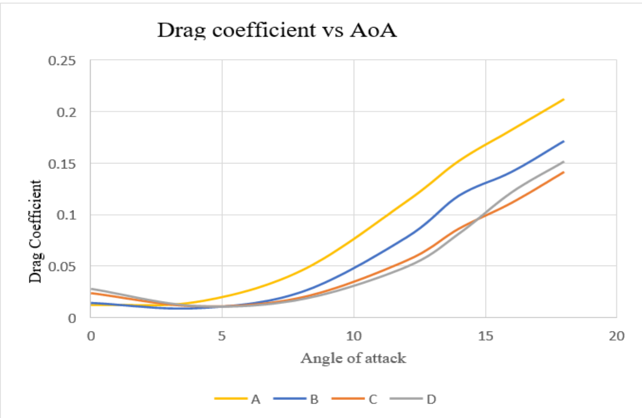

Figure 21 CD vs AOA for NACA 63-415 and bio-Inspired Airfoil

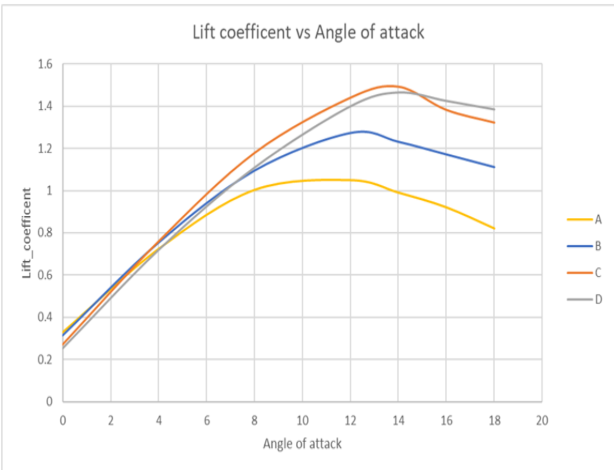

Figure 22 CL vs AOA for NACA 63-415 and Bio-Inspired Airfoil

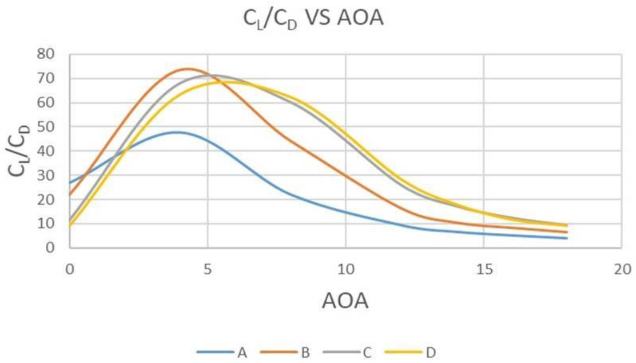

Figure 23 CL/CD vs AOA for NACA 63-415 and Bio-Inspired Airfoil

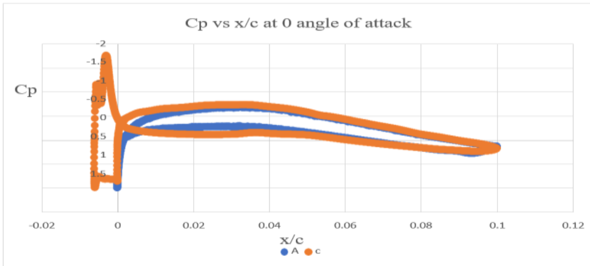

Figure 24 Cp vs x/c for NACA 63-415 and Bio-Inspired Airfoil C At 0 AOA

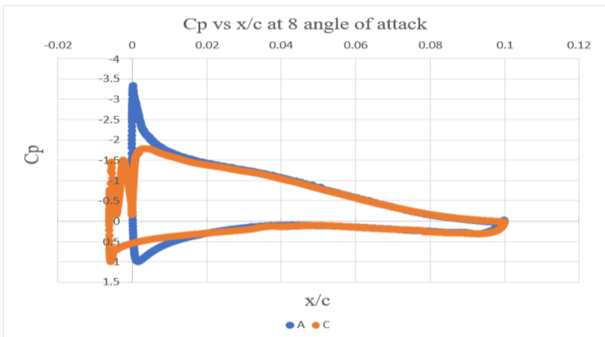

Figure 25 Cp vs x/c for NACA 63-415 and Bio-Inspired Airfoil C at 8 AOA

3.2. Discussion

Figure 21 illustrates the relationship between drag coefficient (C_D) and angle of attack (AOA) for the baseline NACA 63-415 airfoil and bio-inspired designs. At 0° AOA, the baseline airfoil has the lowest drag, while bio-inspired variants show higher drag due to design modifications. However, as AOA increases, the drag for bio-inspired airfoils—especially those with longer noses (Airfoils B, C, and D)—becomes lower than the baseline, indicating delayed flow separation and improved aerodynamic performance at higher AOAs.[1] **Error! Reference source not found.** shows the variation of lift coefficient (CL) with AOA. At 0° AOA, the baseline airfoil generates slightly more lift than the bio-inspired versions. With increasing AOA, the bio-inspired airfoils outperform the baseline, particularly the long-nose designs (B, C, and D), which produce significantly higher lift. This is due to enhanced flow attachment and stabilization of the low-pressure region, making them ideal for take off and high-speed maneuvering. **Error! Reference source not found.** presents the lift-to-drag ratio (C_L/C_D) as a function of AOA. Long-nose bio-inspired airfoils (B, C, and D) exhibit markedly higher aerodynamic efficiency across most AOAs. While differences are minor at low AOA, the efficiency advantage becomes clear as AOA increases. Among them, Airfoil C stands out as the most efficient, offering the best lift-drag balance. **Error! Reference source not found.** plots the pressure coefficient (Cp) distribution along the chord at 0° AOA for the baseline and bio-inspired Airfoil C. While both airfoils show similar overall pressure trends, the bio-inspired design introduces subtle changes near the leading edge, leading to smoother airflow and improved stability due to energized boundary layers.**Error! Reference source not found.** shows Cp distribution at 8° AOA for the same airfoils. Airfoil C exhibits a more favorable pressure gradient on the upper surface, maintaining attached flow and enhancing lift, while the baseline airfoil shows signs of early flow separation. These results highlight the aerodynamic advantages of the bio-inspired design at higher AOAs.[4] In summary, bio-inspired airfoils, especially those with extended noses (B, C, D), consistently outperform the baseline in terms of lift and drag across various AOAs. Among all, Airfoil C offers the highest efficiency, combining superior lift with reduced drag, making it the most effective design for enhanced aerodynamic performance. The results section of the study on the effect of bio-inspired nose on flow separation control over the NACA 63-415 airfoil reveals several key findings:

- **Drag Reduction:** The bio-inspired designs demonstrated a reduction in drag across various angles of attack (AOA) compared to the unmodified NACA 63-415 airfoil. As seen in the results, airfoils with longer bio-inspired noses, such as designs B, C, and D, showed the most significant decrease in drag as AOA increased. At zero AOA, drag was initially higher in modified airfoils compared to the baseline. However, as the AOA increased, modified designs began to outperform the baseline model, indicating effective drag reduction at operational angles.
- **Lift Enhancement:** At zero AOA, the lift coefficient for the unmodified airfoil was higher. However, as the AOA increased, the bio-inspired designs, especially those with longer noses (designs B, C, D), produced greater lift than the baseline model. The increase in lift with AOA suggests that the bio-inspired nose designs effectively enhance aerodynamic performance, particularly in conditions where higher lift is necessary, such as takeoff or high-speed maneuvers.
- **Efficiency (Lift-to-Drag Ratio):** As shown in **Error! Reference source not found.**, Bio-inspired airfoils with longer noses demonstrated improved aerodynamic efficiency by achieving a higher lift-to-drag ratio across varying AOAs. The improved efficiency is attributed to the enhanced flow attachment and delayed separation caused by the modified leading-edge structures, allowing for a more favorable balance between lift and drag.

  Optimal Design: By analyzing the parameters and outcomes from all the airfoils like pressure distribution as shown in **Error! Reference source not found.** and **Error! Reference source not found.** and ratios of coefficient of lift to drag as shown in **Error! Reference source not found.** and among the bio-inspired modifications, airfoil C emerged as the most efficient design, providing the best combination of increased lift and reduced drag.

Conclusion

The study concludes that incorporating bio-inspired nose designs significantly improves flow separation control in the NACA 63-415 airfoil. Designs with longer noses, such as airfoil C, offer the highest lift and lowest drag across a range of angles of attack, thereby enhancing aerodynamic performance. The results indicate that bio-inspired designs hold promise for applications requiring enhanced lift and reduced drag, including unmanned aerial vehicles and other aerodynamically sensitive platforms. Future work could explore further optimization of these bio-inspired features to enhance performance across differed-nt operating conditions and environments. In conclusion, this study demonstrates that bio-inspired nose designs on the NACA 63-415 airfoil effectively enhance aerodynamic performance by improving flow separation control. Inspired by natural forms, the modified airfoil designs achieve greater lift and reduced drag, particularly at higher angles of attack, where traditional airfoil shapes often face performance limitations. The findings suggest that bio-inspired modifications can significantly enhance stability and efficiency, providing smoother airflow and delaying separation. Among the tested designs, airfoil C emerged as the most effective, showcasing the potential for these biomimetic shapes to optimize lift-to-drag ratios and fuel efficiency. The implications of this study extend to practical applications in aerospace, especially for UAVs and other performance-sensitive aircraft, where enhanced aerodynamic control is critical. Future work could build on these findings by exploring more variations in bio-inspired shapes and testing under different environmental and operational conditions to fully leverage the benefits of nature-inspired aerodynamic solutions.

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References

[1]. Mohamed Arif Raj Mohamed, Ugur Guven and Rajesh Yadav, "Flow separation control of NACA-2412 airfoil with bio-inspired nose". Aircraft Engineering and Aerospace Technology, Vol. 91 No. 7 and 2019, pp. 1058-1066.

[2]. W. YANG, "Aerodynamic performance of owl-like airfoil undergoing bio-inspired flapping kinematics", Chinese journal of Aeronautics,13 January 2021 https://doi.org/10.1016/j.cja.2020.10.017

[3]. Humberto Bocanegra Evans, Ali M. Hamed, Serdar Gorumlu, Ali Doosttalab, Burak Aksak, Leonardo P. Chamorro, Luciano Castillo," Experimental Investigation of the Effect of Bio-Inspired Wavy Leading-Edges on Aerodynamic Performance and Flow Topologies of the Airfoil. ", Published on 29t feb 2024. https://doi.org/10.3390/aerospace11030194 .

[4]. Lishu Hao, Yongwei Gao, Binbin Wei, Ke Song, "Numerical Simulation of Flow over Bionic Airfoil", International Journal of Aerospace Engineering Volume 2021, Article ID 5556463, 17 pages https://doi.org/10.1155/2021/5556463 Research..

[5]. McCullough, G.B. and Gault, D.E. (1948), "An experimental investigation of an NACA 631- 012 airfoil section with leading-edge suction slots", NACA technical note 1683, August.

[6]. H. Demir, B. Kaya, "Investigation of the aerodynamic effects of bio-inspired modifications on airfoil at low Reynolds number", Journal of mechanical engineering and sciences ISSN: 2289-4659 e-ISSN: 2231-8380 VOLUME 17, ISSUE 4, 2023, 9715–9724

[7]. Md AkhtarKhan, Chinmaya Padhy, "Aerodynamic and experimental analysis of bio-mimic corrugated dragonfly aerofoil". INCAS BULLETIN, Volume 12, Issue 2/ 2020.

[8]. James Julian, Waridho Iskandar, Fitri Wahyuni, "Leading Edge Modification of

NACA 0015 and NACA 4415 Inspired by Beluga Whale", International Journal of Marine Engineering Innovation and Research, Vol. 8(2), Jun. 2023. 222-231 (pISSN: 2541-5972, eISSN: 2548-1479)

[9]. Boris A Mandadzhiev, Michael K Lynch, Leonardo P Chamorro, Aimy A Wissa, "An experimental study of an airfoil with a bio-inspired leading edge device at high angles of attack", IOP Publishing Ltd 17 August.2017,

[10]. Chowdhury, M. S., Mau, M. M., Shayok, M. I., Mallick, R. B., & Ali, M. (2019, July). "Effect of backward facing step on the aerodynamic characteristics of NACA 0015 airfoil". In AIP Conference Proceedings, 2121(1), p. 050008). AIP Publishing LLC.