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INVESTIGATION OF THE AERODYNAMIC PERFORMANCE OF AIRFOILS WITH DOLPHIN HEAD-SHAPED LEADING-EDGE MODIFICATION

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ABSTRACT

In this study, the aim was to investigate the aerodynamic performance of airfoils with dolphin head-shaped leading-edge modifications. For this purpose, the leading edge of the NACA 4412 and NACA 6409 airfoils was modified to resemble a dolphin head, and analyses were conducted in XFLR5 software. A performance comparison of the lift coefficient, drag coefficient and lift/drag ratio between the original and modified airfoils was made by creating a 3D wing model. As a result of the analysis, the modified 4412 airfoil demonstrated a 15% reduction in minimum drag value and a 11% increase in aerodynamic efficiency. Similarly, the modified 6409 airfoil showed 13% reduction in minimum drag value and a 29% increase in aerodynamic efficiency. The dolphin head shape on the leading edge provided better performance since it led to a very low reduction in lift, while leading to a greater reduction in drag. On the other hand, dolphin head-shaped leading-edge modification provides an advantage in asymmetric airfoils with positive camber. So, changing the airfoils' leading edge to the shape of a dolphin head does not provide an advantage for symmetrical airfoils. Air foils with a leading edge in the shape of a dolphin's head are suitable for use in mini-UAVs due to the advantages they provide at certain angles of attack. *Additionally, the dolphin head-shaped leading-edge modification is impractical at high angles of attack compared to the original airfoils, resulting in a dramatic reduction in the lift/drag ratio.*

INTRODUCTION

The new wing profiles formed based on the aerodynamic forms of living things that fly or swim in nature are called bionic airfoils. In the literature, there are studies on bionic airfoils and how leading-edge modifications of airfoils affect the boundary layer, speed, pressure distribution, drag, and lift coefficients [Hansen, 2012; Rose et al. 2021; Guo et al., 2019; Tian et al.2013; Wu and Liu, 2021]. Salunke et al. [2021] conducted a review study on airfoil parameterization

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and claimed that the combination of Bezier and PARSEC techniques is highly advantageous and covers a wide range of airfoils.

Additionally, the literature contains studies on the use of modified airfoils in wind turbine blades. According to Gu et al. [2012], they conducted a numerical study to demonstrate the superiority of the gull airfoil compared to the NACA 4412 airfoil. Huang et al. [2021] proposed a new bionic airfoil based on the NACA 0018 airfoil, mimicking the outline of *Phocoenoides dalli's* head shape and combining it with changes in the dolphin's locomotion behavior. They claimed that the modified bionic form provides a significant reduction in drag. Furthermore, Huang et al. [2022] conducted a study on a modified form of the S809 airfoil (Dol-Rot 24) on a dolphin head-shaped wind turbine blade to strictly control aerodynamic noise and blade load level. Asli et al. [2015] conducted a numerical study of the wind turbine airfoil (S809) with a leading-edge bump and claimed that it acts as a vortex generator, preventing deep stall at high angles of attack.

In the literature, there are studies based on the structure and shapes of dolphins. Fish [2006] claimed that dolphins reduce drag by regulating the flow over their bodies, maintaining a completely laminar boundary layer. Taposu and Spataru [2000] conducted an experimental study on the DA20G08 dolphin profile at low speeds and concluded that it performs well aerodynamically, particularly at high angles of incidence. Zhang et al. [2014] conducted an experimental study on a bionic airfoil with a soft surface made of sticky silicone rubber to reduce drag. Berbente and Daniala [2007] studied dolphin profiles with a continuous radius of curvature and found that they provide a 9% drag reduction at an average angle of attack. Zorana et al. [2022] studied dolphin airfoils modified from NACA 2415 and concluded that Dolphin 2415 M4 is suitable for general aviation applications. Moreover, Mohamed et al. [2021] claimed that the porpoise nose design delays flow separation and improves aerodynamic efficiency for NACA 4 and 6 series airfoils. In their study, they evaluated the aerodynamic shape of the dolphin's head through modifications to 4-digit NACA airfoils. In contrast to Mohamed et al. [2021], this study made more radical (large-scale) shape changes to the leading edge of the airfoil, but only on its upper surface.

In this study, NACA 4412 and NACA 6409 airfoils were used to show how airfoils with modified dolphin head leading edge affect aerodynamic performance.

METHOD

Schematic displays of the NACA 4412 and NACA 6409 airfoils and their modified dolphin head leading edge forms can be seen in Fig. 1 and Fig. 2, respectively. In both designs, a dolphin head-shaped leading edge was designed along the upper surface of the airfoil, covering approximately 7% of the chord length. This length was chosen because it approximates the ratio of a dolphin's head to its body length.

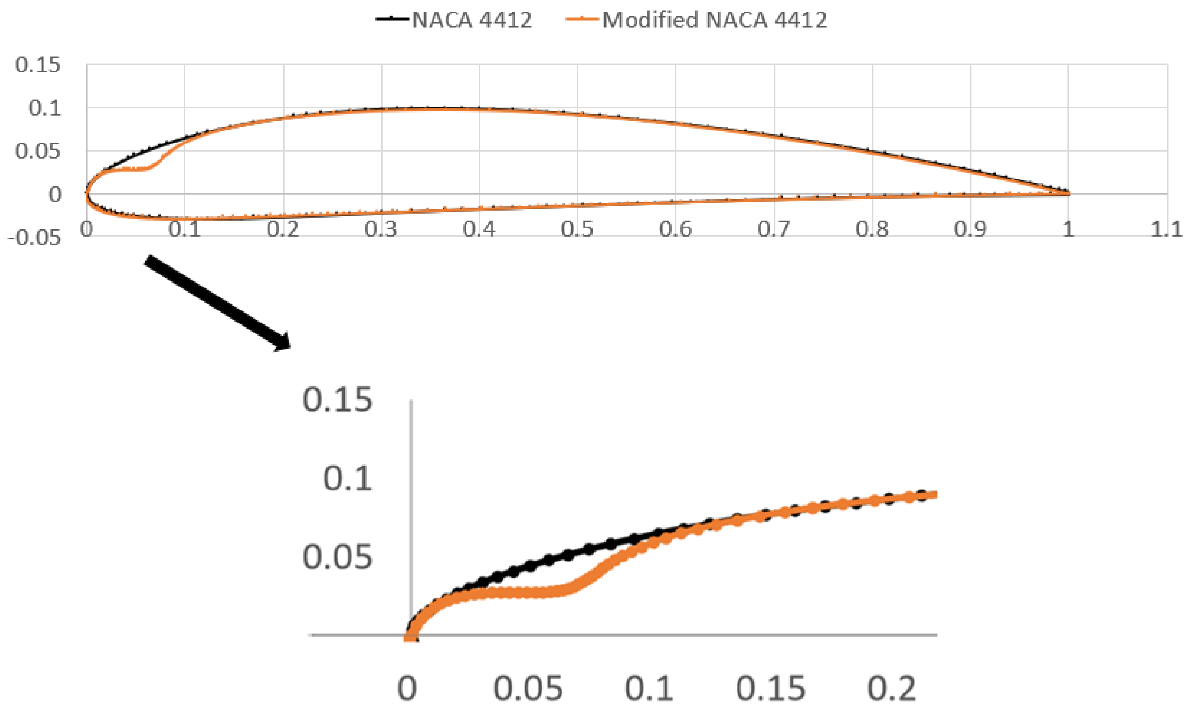

Figure 1. Schematic representation of NACA 4412 with modified form.

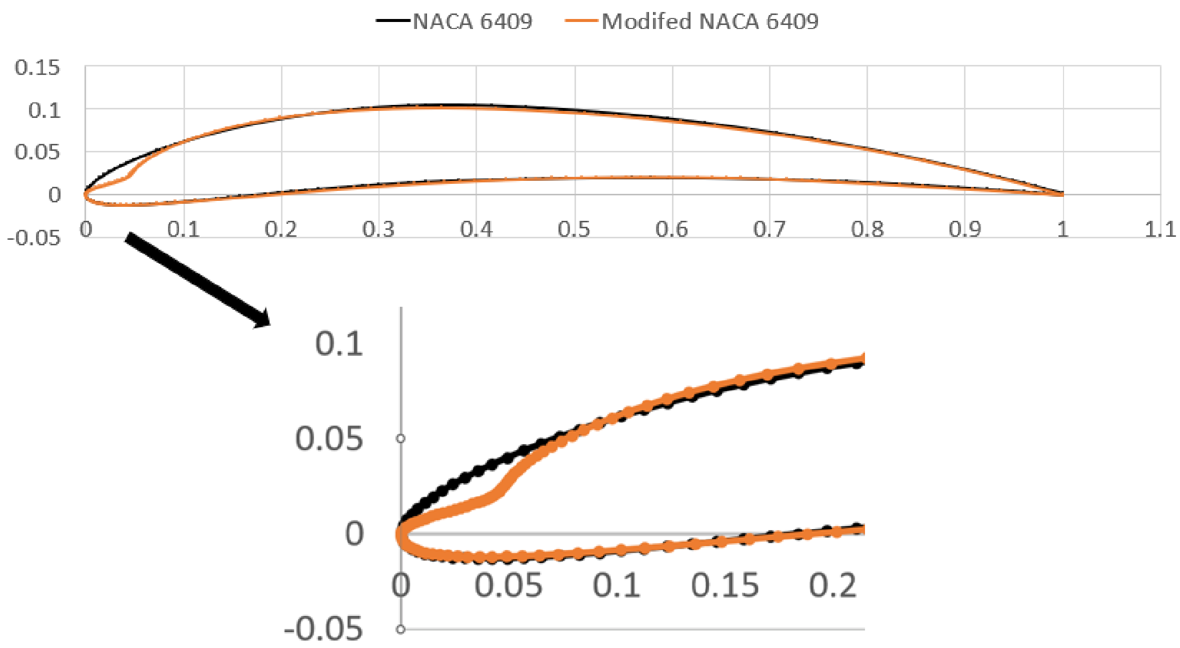

Figure 2. Schematic representation of NACA 6409 with modified form.

In XFLR5, the analysis was performed using a 3D wing design to obtain more realistic results compared to 2D theoretical results. Fig. 3 shows the size and shape properties of the 3D wing design constructed from a modified NACA 4412 airfoil. The analysis results were obtained for changes in angles of attack ranging from -10 to 10 degrees, using ISA sea level conditions as the air characteristics. The analysis was conducted in XFLR5 using approximately 10,000 panels, and the vortex lattice method (VLM2) was used to obtain results for a fixed cruise speed under viscous flow conditions. The analyzes were performed at low Reynolds numbers-100,000 Reynolds number for NACA 4412 and 160,000 Reynolds number for NACA 6409. It has been seen that dolphin head leading edge forms again provides an advantage for different Reynolds numbers, but the results are given for a specific Reynolds number.

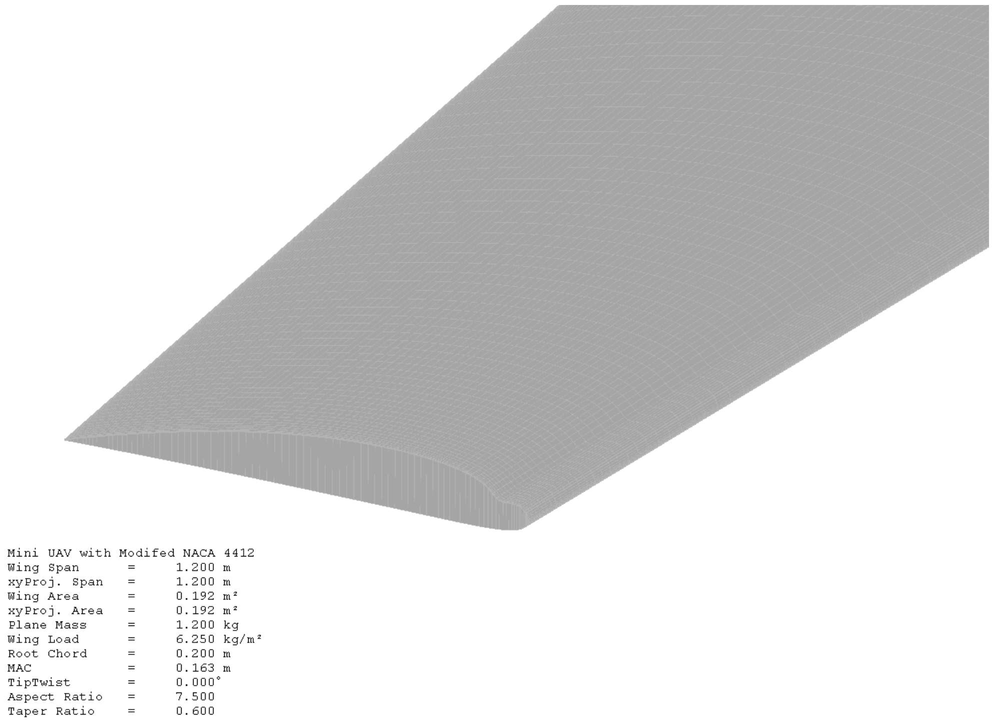

Figure 3. 3D wing model of modified NACA 4412 with dolphin head shaped leading edge.

RESULTS

Aerodynamic analysis was conducted to demonstrate the effect of the proposed modification to the wing design, with a leading edge modified in the shape of a dolphin head. For the 3D wing design, lift coefficient vs. the drag coefficient curve and lift-to-drag ratio vs. angle of attack curve were obtained. As depicted in Fig. 4, the dolphin head-shaped leading-edge modification provides reduction in the drag coefficient at certain angles of attack. The minimum C_D value for NACA 4412 is 0.0217, while for the modified airfoil, this value is 0.0184. Therefore, it can be concluded that the modified airfoil provides approximately15% reduction in minimum drag value.

The comparison of the lift-to-drag ratio (C_L/C_D) curve for NACA 4412 with its modified version is shown on Fig. 4. Due to the dramatic reduction in the drag coefficient, the dolphin head-shaped airfoil provides the best aerodynamic efficiency, as indicated by the maximum lift-to-drag ratio. The maximum C_L/C_D value for NACA 4412 is 18.49, while for the modified form, this value is 20.50, resulting in approximately 11% increase in aerodynamic efficiency based on the maximum lift-to-drag ratio value.

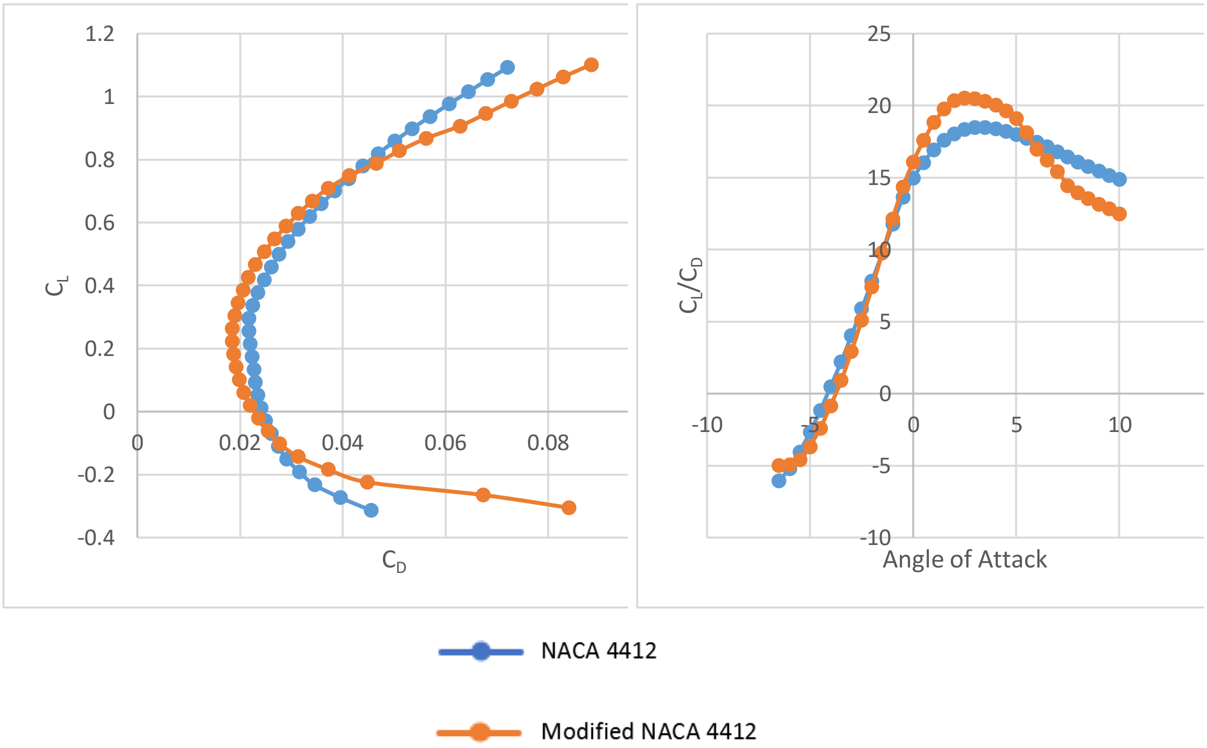

Figure 4. C_L vs C_D curve and lift to drag ratio curve of NACA 4412 with modified version at 100,000 Reynolds number.

Since it is of interest to understand the effect of the dolphin head shape on airfoils with different camber and thickness, analyses were conducted for various NACA series. The drag coefficient curve for NACA 6409 and its modified form is shown on the left side of Fig. 5. Unlike NACA 4412, the drag coefficient values for NACA 6409 are lower up to a certain angle of attack. However, the modified airfoil loses its superiority at high angles of attack ($\alpha > 5$). The minimum C_d value for NACA 6409 is 0.0358, while for the modified airfoil, this value is 0.0316. Therefore, it can be concluded that the modified airfoil provides approximately 13% reduction in minimum drag value.

To evaluate the advantage of the dolphin head-shaped leading-edge modification change in total drag, the lift-to-drag ratio was used as an aerodynamic efficiency criterion. The comparison of lift-to-drag ratio (C_L/C_D) curves of NACA 6409 and its modified version is shown on the right side of Fig. 5. Generally, the modified airfoil form is more advantageous, except for high angles of attack. The maximum C_L/C_D value for NACA 6409 is 18.2, while for the modified form, this value is 23.5. Therefore, it can be concluded that the modified airfoil provides a 29% increase in aerodynamic efficiency according to the maximum lift-to-drag ratio value.

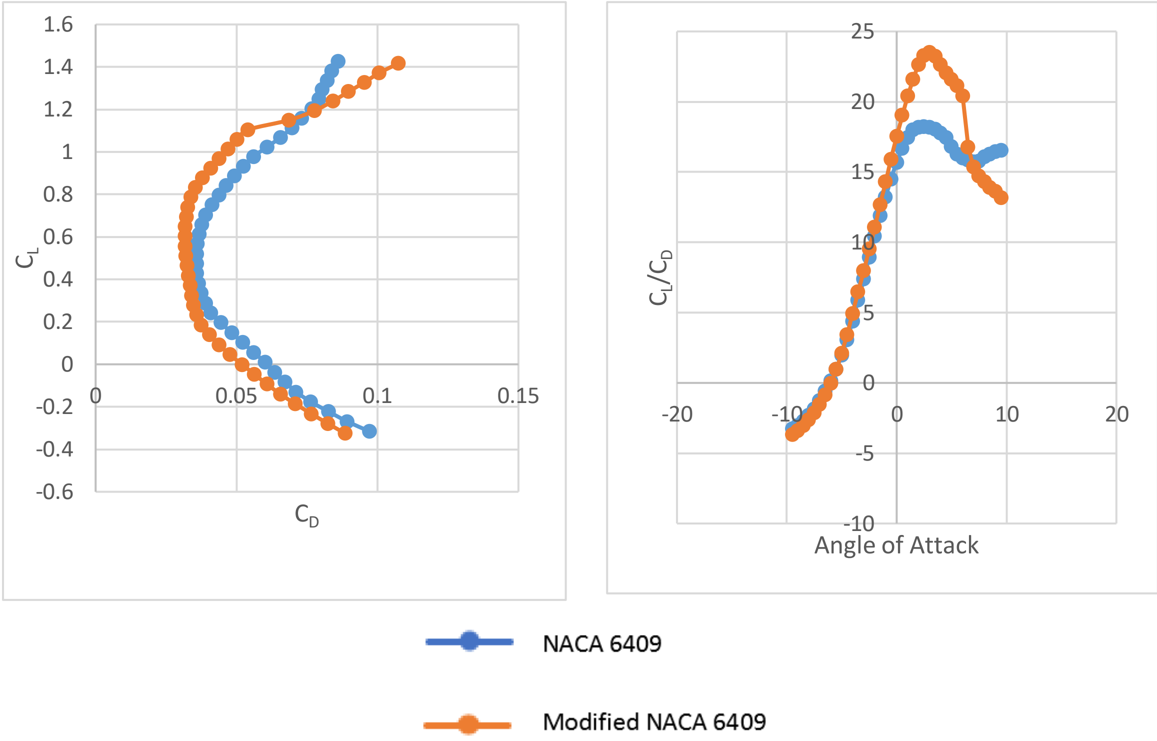

Figure 5. C_L vs C_D curve and lift to drag ratio curve of NACA 6409 with modified version at 160,000 Reynolds number.

Air foils with a leading edge in the shape of a dolphin's head are suitable for use in mini-UAVs due to the advantages they provide at certain angles of attack. During the investigation of how the modification affects airfoil aerodynamics, it was found that the dolphin head-shaped leading-edge modification does not provide an advantage for symmetrical airfoils. Dolphin head-shaped leading-edge modification provides an advantage in asymmetric airfoils with positive camber. Another finding of the study is that the dolphin head modification provides an advantage at certain angles of attack and beyond certain angles of attack the modified form can result in a dramatic reduction in the lift-to-drag ratio.

CONCLUSION

The study aimed to investigate the effect of leading-edge modifications in the shape of a dolphin head on reducing the drag of 4-digit airfoils-NACA 4412 and NACA 6409 at low Reynolds numbers. The 3D wing was analyzed with Vortex Lattice Method, and performance comparison curves were obtained using XFLR5 software. The results showed that the modified NACA 4412 with dolphin head shaped leading edge provided a 15% reduction in minimum drag value and a 11% increase in aerodynamic efficiency-lift to drag ratio and modified NACA 6409 with dolphin head shaped leading edge provided a 29% reduction in minimum drag value and a 13% increase in aerodynamic efficiency. The dolphin head shape on the leading-edge resulted in a slight reduction in lift, while providing better performance due to a greater reduction in drag. On the other hand, changing the airfoils' leading edge to the shape of a dolphin head does not provide an advantage for symmetrical airfoils. Dolphin head-shaped leading-edge modification provides an advantage in asymmetric airfoils with positive camber. In future studies, whether leading-edge modifications in the shape of a dolphin head is useful or not can be supported by CFD data, and what kind of effects on pressure and velocity distributions can be examined.

References

Asli, M., Mashhadi Gholamali, B., & Mesgarpour Tousi, A. (2015). Numerical analysis of wind turbine airfoil aerodynamic performance with leading edge bump. Mathematical Problems in Engineering, 2015.

Berbente, C., & Danaila, S. (2007). On the aerodynamic characteristics of a class of airfoils with continuous curvature at subsonic, transonic and supersonic regimes. University" Politehnica" of Bucharest Scientific Bulletin, Series D: Mechanical Engineering, 69(1), 15-28.

Fish, F. E. (2006). The myth and reality of Gray's paradox: implication of dolphin drag reduction for technology. Bioinspiration & biomimetics, 1(2), R17.

Gu, R., Xu, J. L., & Yang, Y. B. (2012). The investigation of the small bionic wind turbine based on the seagull airfoil. In Advanced Materials Research (Vol. 347, pp. 3533-3539). Trans Tech Publications Ltd.

Guo, C. Y., Zhang, Z. T., Cao, X. X., Wu, T. C., & Su, Y. M. (2019). Numerical and experimental studies of hydrodynamic performance of bionic leading-edge tubercle airfoil. Journal of Hydrodynamics, 31(6), 1240-1249.

Hansen, K. L. (2012). Effect of leading edge tubercles on airfoil performance (Doctoral dissertation).

Huang, S., Hu, Y., & Wang, Y. (2021). Research on aerodynamic performance of a novel dolphin head-shaped bionic airfoil. Energy, 214, 118179.

Huang, S., Qiu, H., & Wang, Y. (2022). Aerodynamic performance of horizontal axis wind turbine with application of dolphin head-shape and lever movement of skeleton bionic airfoils. Energy Conversion and Management, 267, 115803.

Mohamed, M. A. R., Yadav, R., & Guven, U. (2021). Flow separation control using a bio-inspired nose for NACA 4 and 6 series airfoils. Aircraft Engineering and Aerospace Technology.

Rose, J., Natarajan, S. G., & Gopinathan, V. T. (2021). Biomimetic flow control techniques for aerospace applications: a comprehensive review. Reviews in Environmental Science and Bio/Technology, 20(3), 645-677.

Salunke, N. P., Juned Ahamad, R. A., & Channiwala, S. A. (2014). Airfoil parameterization techniques: A review. American Journal of Mechanical Engineering, 2(4), 99-102.

Taposu, I., & Spataru, P. (2000). About the experimental results of a dolphin profile at low speeds. In 18th Applied Aerodynamics Conference (p. 4506).

Tian, W., Liu, F., Cong, Q., Liu, Y., & Ren, L. (2013). Study on aerodynamic performance of the bionic airfoil based on the swallow's wing. Journal of Mechanics in Medicine and Biology, 13(06), 1340022.

Wu, L., & Liu, X. (2021). Dynamic Stall Characteristics of the Bionic Airfoil with Different Waviness Ratios. Applied Sciences, 11(21), 9943.

Zhang, X. P., Wang, Y. H., & Ren, L. Q. (2014). Wind tunnel test for drag reduction of airfoil bionic soft surface. In Applied Mechanics and Materials (Vol. 461, pp. 767-778). Trans Tech Publications Ltd.

Zorana, Z. D., Kostic, I. A., Kostic, O. P., Bengin, A. Č., & Vorotović, G. S. (2022). Initial Development of The Hybrid Semielliptical-Dolphin Airfoil. Thermal Science, 26(3A), 2199-2210.