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Investigating the Impact of Tubercle Modifications on the Performance of the NACA 643-221 Airfoil

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Investigating the Impact of Tubercle Modifications on the Performance of the NACA 643-221 Airfoil

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Abstract. The distinctive tubercles on the leading edge of humpback whale flippers have potential applications in the design of aviation wings. These knobby structures are hypothesized to enhance aerodynamic performance, particularly in low-speed, high-lift conditions, by reducing drag and increasing lift. This study investigates the feasibility of incorporating whale-inspired tubercles into aircraft wing designs to improve flight performance. Through a combination of computational fluid dynamics (CFD) simulations and wind tunnel experiments, the aerodynamic properties of tubercle-equipped wings are compared to those of conventional smooth-wing designs. The findings demonstrate that tubercles contribute to more stable airflow, delay flow separation, and increase lift-to-drag (L/D) ratios. These improvements have significant implications for enhancing aircraft performance and fuel efficiency, particularly during critical phases such as takeoff and landing, potentially leading to the development of more efficient and environmentally sustainable aviation technologies.

Keywords: Whale Tubercles; Aerodynamics; CFD; Lift Force; Sustainable Aviation

1. Introduction

Humpback whales possess distinctive features known as tubercles on the leading edge of their fins as displayed in Fig. 1. These structures are believed to enhance the efficiency of the whales' movement through water by generating turbulence, which reduces drag and increases lift. The exceptional hydrodynamic and aerodynamic properties of whale fins have inspired research into their application in aerodynamic design, particularly for aircraft wings. By improving L/D ratios, reducing fuel consumption, and enhancing overall flight efficiency, the integration of these biological features has the potential to revolutionize aviation. [1]

Figure 1. Humpback Whale

The distinctive knobby structures on the leading edge of humpback whale flippers have inspired the design of the tubercle aviation wing. These tubercles, shown in Fig. 2, typically arranged at regular intervals along the leading edge of the wing, serve a crucial aerodynamic function by modifying airflow patterns to reduce drag and increase lift. This effect is particularly beneficial in low-speed, high-lift scenarios such as takeoff, landing, and high-angle-of-attack maneuvers. [1, 2]

Figure 2. Tubercle Airplane Wing.

The primary advantage of tubercles lies in their ability to regulate airflow over the wing, thereby improving flow control. By generating localized turbulence, the tubercles delay flow separation from the wing surface, a common cause of drag and lift loss, particularly at high angles of attack. This disturbance helps maintain smoother, more stable airflow, ensuring improved aerodynamic control during critical flight phases. As a result, the airflow remains attached to the wing for longer, enhancing performance and maneuverability. [1]

The tubercle wing design is particularly advantageous in scenarios requiring high lift and low speed, such as takeoff, landing, or navigating turbulent air. By maintaining smooth airflow, the design enables the wing to generate greater lift without a significant increase in drag. This efficiency allows the wing to operate effectively at higher angles of attack before experiencing flow separation, thereby improving overall aerodynamic performance and increasing the L/D ratio. Beyond the tubercles, the overall wing design is optimized to balance lift and drag factors, ensuring aerodynamic efficiency. Tubercle wings can be integrated into existing aircraft designs with minimal structural modifications while maintaining a streamlined profile. Depending on the specific requirements of the aircraft—whether a small airplane, cargo plane, or commercial jet—

the size, shape, and spacing of the tubercles illustrated in Fig. 3 can be adjusted to maximize aerodynamic performance.

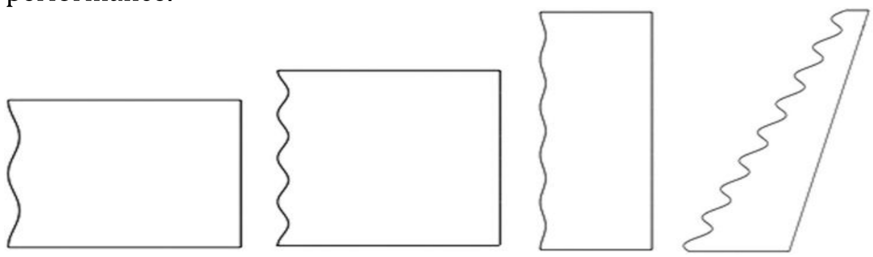


Figure 3. Wing design types.

Extensive research, including wind tunnel tests, has explored the potential of tubercle wings. While the concept remains largely experimental, it holds significant promise for applications in aircraft requiring high lift for takeoff and landing or for operations in turbulence-prone environments. Additionally, tubercle wings could be adapted for drones, unmanned aerial vehicles, and other specialized aircraft to improve flight economy, reduce fuel consumption, and enhance stability. This innovative approach to wing design represents a step toward more efficient and versatile aviation technologies.

The impact of leading-edge tubercles on aerodynamic performance has been extensively studied, with a focus on their effects on lift, drag, and stall behavior. Zhao et al. [3] conducted experiments demonstrating that tubercles enhance airflow control and improve stall characteristics by modifying vortex generation. Similarly, Thomke et al. [4] provided experimental data on lift and drag, emphasizing their potential in aircraft design. Miller et al. [5] explored the effects of tubercles on small aircraft, reporting improvements in stability and control at different speeds and angles of attack. These results align with Ogg and McCroskey [6], who showed that tubercles reduce flow separation and enhance airfoil performance.

Several studies have addressed the application of tubercles in low-speed flight regimes, particularly for UAVs and small aircraft. Oppenheim et al. [7] examined the aerodynamic performance of airfoils with tubercles at low Reynolds numbers, highlighting their effectiveness in improving efficiency under these conditions. Alok Mishra et al. [8] revealed that tubercles significantly enhance L/D ratios and delay stall onset in low-speed scenarios. Additionally, Pengxin Yang, et al. [9] concluded that tubercles positively affect airfoil and wing performance in low-speed flight.

Optimization and theoretical studies have further advanced the understanding of tubercles. Moreau [10] focused on optimizing tubercle geometry to maximize aerodynamic efficiency, demonstrating that tailored designs significantly improve lift and reduce drag. Bartels [11] investigated the integration of tubercles into wing designs, reporting substantial improvements in lift, drag, and stall characteristics. These findings are consistent with patented innovations by Patent US6709119B1 [12] and Patent US6572131B1 [13], which describe methods for incorporating tubercles into aircraft wings to enhance flow control and aerodynamic performance.

Foundational textbooks provide a theoretical framework for understanding tubercle applications in aerodynamics. Anderson's works, including Introduction to Flight [14], Fundamentals of Aerodynamics [15], and Aircraft Performance & Design [16], discuss bio-inspired features like tubercles and their potential to improve aircraft efficiency. Similarly, Bertin's Aerodynamics for Engineers [17] emphasizes the importance of advanced wing designs, including tubercles, for modern engineering challenges.

Bio-inspired design principles have been a recurring theme in tubercle research. Gad-el-Hak [18] explored the future of flow control and emphasized the role of bio-inspired features like tubercles in reducing drag and enhancing stability. New and Ng [19] investigated the morphology of tubercles in aerodynamics and hydrodynamics, highlighting their broad applicability. Atzori et al. [20] contributed complementary insights by studying flow control mechanisms such as uniform blowing and suction on airfoils, which can work in tandem with tubercles.

Studies on geometric parameters and design optimization have demonstrated the importance of tubercle morphology in achieving aerodynamic efficiency. Research on the effects of wavy leading edges [21, 22] showed that precise control over geometric features can significantly enhance aerodynamic performance. Additional insights from NASA technical reports [21] and AIAA publications [22] further validate the potential of tubercles as an innovative solution in modern aerodynamic designs.

This study aims to explore the feasibility and potential advantages of incorporating whale-inspired tubercles into aircraft wing designs. Specifically, the objectives are to analyze the impact of whale tubercles on wing surface aerodynamics, compare the performance of tubercle-equipped wings with that of conventional smooth-wing designs, and provide recommendations for future aviation design based on the study’s findings.

2. Methodology

To evaluate the effectiveness of incorporating whale-inspired tubercles into airplane wing designs, this study will employ a combination of computational simulations and experimental testing.

2.1. Computational Fluid Dynamics (CFD) Simulations

ANSYS Fluent is used to model airflow over wings with and without tubercles. These simulations will provide detailed insights into key aerodynamic parameters, including lift, drag, and airflow patterns, across a range of angles of attack. The CFD analysis enables a comprehensive evaluation of how tubercles influence the aerodynamic performance of the wings.

The baseline and tubercle-equipped wing models illustrated in Fig. 4 were designed using SolidWorks. The tubercle features were incorporated along the leading edge based on the specified amplitude and wavelength parameters as displayed in Fig. 5, following a sinusoidal wave profile. The trailing edge section of the airfoils remained consistent across all models to ensure a controlled comparison.

To maintain experimental validity, the tubercle-equipped models were designed to have the same planform area as the baseline model, ensuring that the aerodynamic differences could be attributed solely to the tubercles. The planform area of both models was set at A = 0.0504 m^2, calculated using Equation (1).

$$A = C \times S \tag{1}$$

where C represents the chord length, and S represents the wing span [8]. This approach ensures that the geometric and aerodynamic parameters remain consistent, allowing for a reliable assessment of the tubercles' impact on wing performance.

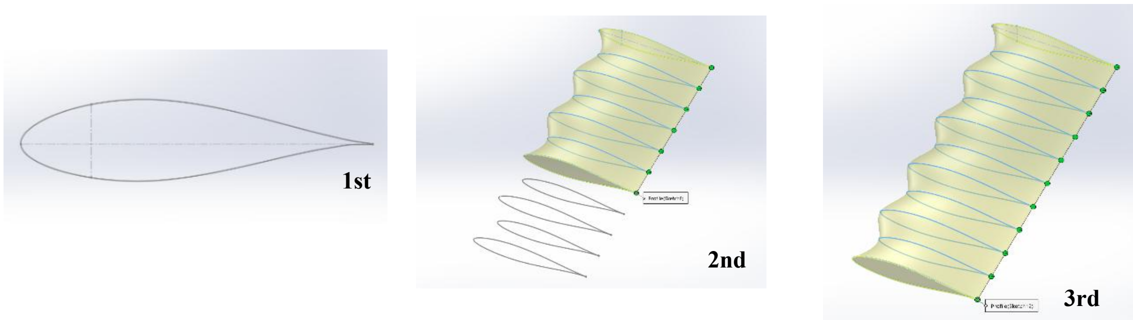


Figure 4. Modelling on SOLIDWORKS.

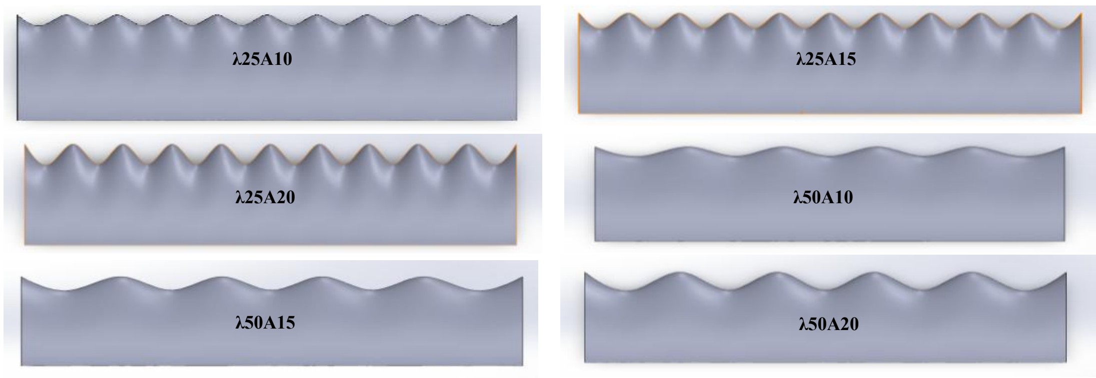


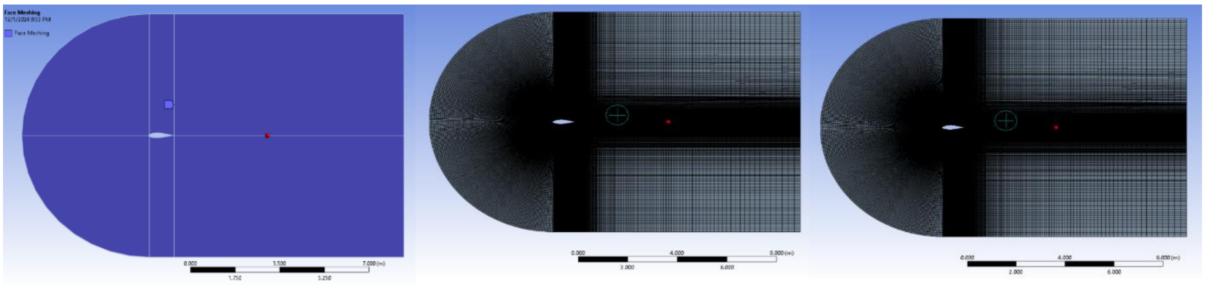
Figure 5. Tubercle Models of various Wavelengths and Amplitudes.

The wing model was imported into ANSYS ICEM CFD as a STEP/IGES file to facilitate the creation of a computational domain representing the control volume. For this study, a project was set up to analyze the airflow over the wing, requiring the definition of a domain to specify the direction and boundaries of the fluid flow.

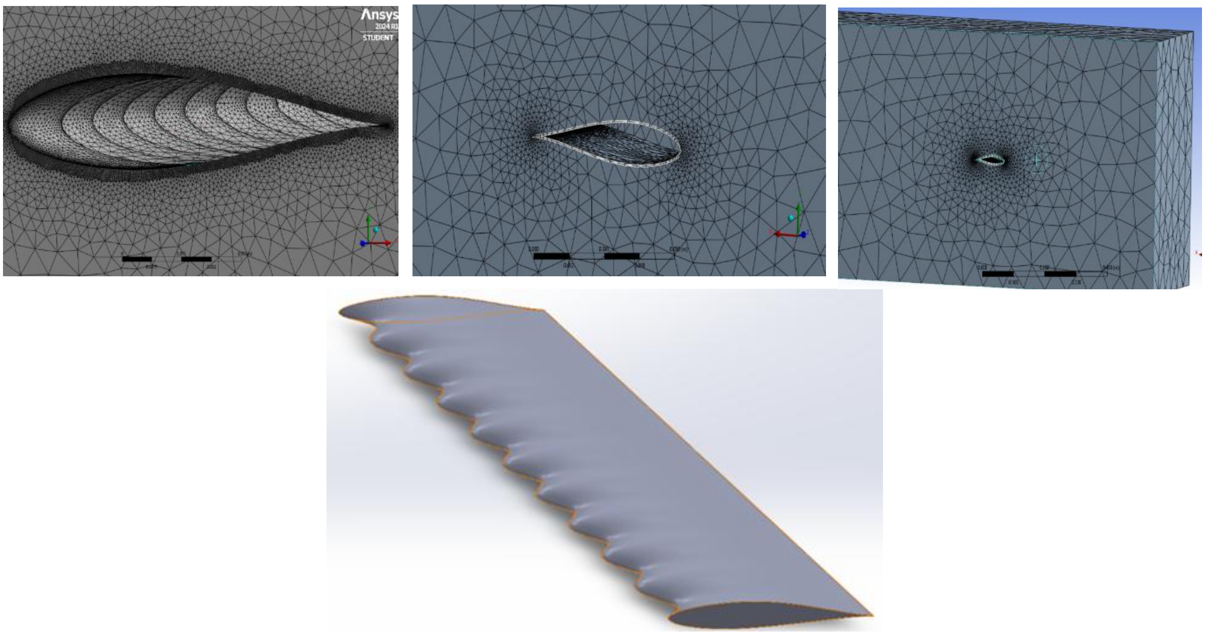
The far-field boundary was positioned at a distance of 8c behind the wing and 7c in front, above, and below the wing, where c represents the mean aerodynamic chord. The mean aerodynamic chord was calculated using Equation (2).

$$C=(S\times 2)/b \tag{2}$$

here, S is the span of the wing area, and b is the planform width [14]. Figure 6 illustrates the performed meshing using ANSYS ICEM CFD 2D and 3D. This domain setup ensures accurate representation of the flow field and minimizes boundary effects, enabling a precise evaluation of the aerodynamic performance of the wing models.



(a)



(b)

Figure 6. Meshing using ANSYS ICEM CFD (a) 2D, (b) 3D.

2.2. Wind Tunnel Testing

Physical prototypes of airplane wings, both with conventional smooth surfaces and tubercle-equipped designs, will be fabricated for experimental testing. The aerodynamic performance of these prototypes will be assessed in a controlled wind tunnel environment, allowing for precise measurement of their behavior under various flight conditions. [14]

Experimental and simulation studies for wind tunnel experiment results on the use of tubercles for NACA 643-221 section wings indicate that the incorporation of wavy leading edges (tubercles) can significantly enhance aerodynamic performance, particularly at high angles of attack. The presence of tubercles reduces airflow separation and increases lift, leading to notable improvements in the L/D coefficient compared to conventional wings. Additionally, enhanced stability was observed in post-stall conditions, demonstrating the tubercles' ability to maintain smoother airflow over the wing surface.

CFD simulations and wind tunnel experiments revealed that the amplitude and wavelength of tubercles play a critical role in optimizing aerodynamic performance. Specific configurations, such as λ25A10 and λ50A10, were shown to deliver superior lift rates compared to other tested models. These findings highlight the importance of precise tubercle geometry in achieving optimal aerodynamic efficiency.

Physical testing was conducted using 3D-printed wing models equipped with tubercles in wind tunnels operating at speeds of up to 45 m/s. The experiments confirmed a reduction in drag and an increase in overall wing efficiency. Furthermore, the tubercle-equipped wings exhibited smoother aerodynamic behavior at high angles of attack, validating their potential for improving performance under challenging flight conditions.

These results underscore the promising role of tubercles in enhancing wing performance, with potential applications in aviation for increased efficiency, stability, and fuel economy.

2.3. Performance Metrics

Key metrics for evaluating the aerodynamic performance of the wing designs include:

- L/D Ratio: A critical measure of aerodynamic efficiency, reflecting the balance between lift generation and drag resistance.
- Flow Separation Points: Locations on the wing surface where airflow detaches, directly impacting drag and lift.
- Pressure Distribution: Analysis of pressure variations across the wing surfaces to understand how tubercles influence airflow stability.

2.4. Data Analysis and Design Parameters

The collected data will facilitate a comparative analysis of tubercle-equipped wings against traditional smooth-wing designs, with an emphasis on performance in high-lift conditions and turbulent airflow. The study will also consider the optimal design parameters for tubercle placement. Drawing from biological research, typical humpback whale flippers exhibit between 9 and 11 tubercles, with aspect ratios ranging from 7.7 to 3.6. These findings illustrated in Fig. 7 and Table 1 will guide the sizing, spacing, and placement of tubercles to ensure a balance between aerodynamic performance and practical implementation within the scope of modern aircraft design. [1]

Table 1. Tubercle Distribution

Tubercle Distribution (C 0.100m & S = 0.250m)				
Model	mm	Amplitude	mm	Wave Length
%10 of span	25	Of chord %10	10	λ25A10
		Of chord %15	15	λ25A15
		Of chord %20	20	λ25A20
%20 of span	50	Of chord %10	10	λ50A10
		Of chord %15	15	λ50A15
		Of chord %20	20	λ50A20

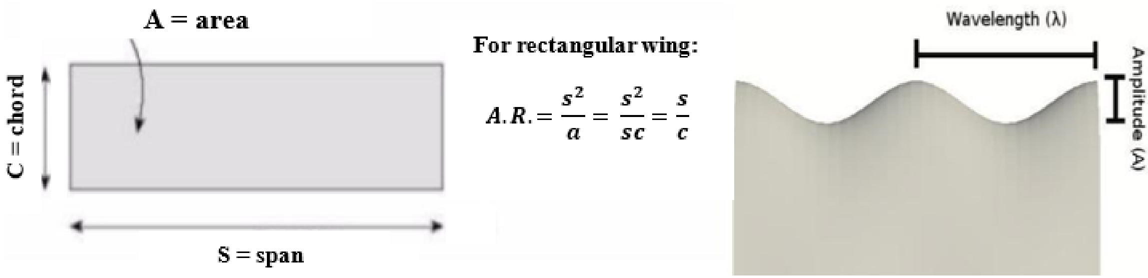


Figure 7. Relation between Span, Chord and Aspect Ratio and figure representing tubercle wavelength and amplitude.

3. Results and Discussion

The results of CFD simulations and wind tunnel experiments will be analyzed to evaluate the aerodynamic performance of tubercle-inspired wing designs in comparison to traditional smooth-wing designs. The comparison focuses on the following key metrics:

1. L/D Ratio: It is anticipated that tubercle-equipped wings will exhibit a superior L/D ratio, particularly during low-speed maneuvers such as takeoff and landing, where strong lift generation is critical. The improved Cl/Cd ratio is expected to enhance the overall aerodynamic efficiency of the wing in scenarios requiring high lift with minimal drag.
2. Flow Separation: At higher angles of attack, traditional wing designs often experience premature flow separation, leading to a loss of lift and an increase in drag. The presence of tubercles is expected to delay flow separation by generating localized turbulence that helps maintain airflow attachment to the wing surface. This improvement is anticipated to result in reduced turbulence, smoother airflow control, and improved wing stability, particularly in post-stall conditions.
3. Pressure Distribution: Tubercles are expected to create a more uniform pressure distribution across the wing surface, improving airflow efficiency and reducing drag. This characteristic ensures better aerodynamic performance by stabilizing pressure gradients and minimizing energy loss across the wing. The tubercle design thus offers a promising alternative to traditional designs in terms of both efficiency and stability.

Although the precise performance of tubercle-equipped wings may vary based on the size, spacing, and shape of the tubercles, preliminary data suggest a significant enhancement in lift generation and a reduction in drag during low-speed flight. The results align with the biological inspiration of the humpback whale’s flippers, which feature unique adaptations for fluid dynamics:

- Flipper Characteristics: Humpback whale flippers range from 0.25% to 0.33% of the whale’s total body length. They are highly mobile at the shoulder joint and exhibit flexibility along their span. The flippers possess a high aspect ratio and a cross-sectional profile closely resembling a 21% thick airfoil.
- Tubercle Geometry: Based on studies by marine biologists, the typical number of tubercles ranges from 9 to 11, with aspect ratios varying between a maximum of 7.7 and a minimum of 3.6. These observations guided the design parameters for the tubercle-inspired wing, ensuring aerodynamic feasibility while maintaining reasonable design scope (Fig. 6).

Figure 8 illustrates the relationship between the angle of attack (AOA) and the drag and lift coefficients. The lift coefficient increases significantly with AOA, peaking at around 15°, while the drag coefficient shows a more gradual increase across the range of AOA values.

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Figure 9 shows a graph depicting the drag force as a function of the AOA. The drag force increases exponentially with AOA, reaching its highest value at 17°, indicating a strong nonlinear relationship.

Figure 10 illustrates the lift force as a function of the AOA. The lift force increases rapidly with AOA, reaching a peak around 15°, before slightly decreasing at 17°, indicating a stall effect.

Figure 11 displays the relationship between the AOA and the L/D ratio. As the AOA increases from 0 to 8 degrees, the L/D ratio also increases, reaching a maximum value at an AOA of around 8 degrees. Beyond this point, further increases in AOA lead to a decrease in the L/D ratio, indicating a deterioration in aerodynamic efficiency.

AOA	Drag coefficient	Lift coefficient
0	0.01174	0.14621
4	0.013675	0.58576
6	0.01569	0.79521
8	0.018675	0.98852
11	0.02684	1.2156
13	0.037184	1.2943
15	0.052646	1.3152
17	0.07283	1.3015

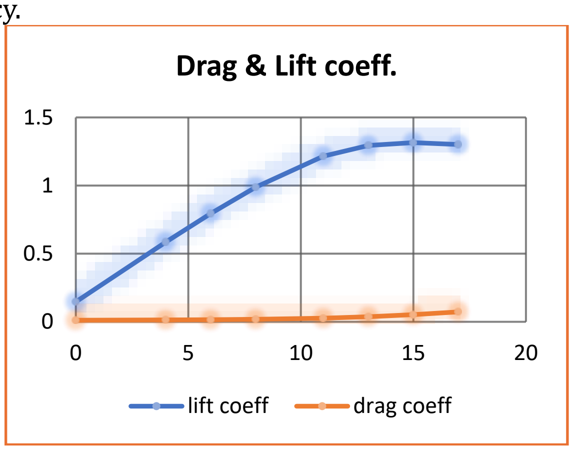

Figure 8. the relationship between the AOA and the drag and lift coefficients.

AOA	Drag force (N)
0	0.8118
4	0.944126
6	1.082
8	1.28648
11	1.84828
13	2.56086
15	3.62823
17	5.02332

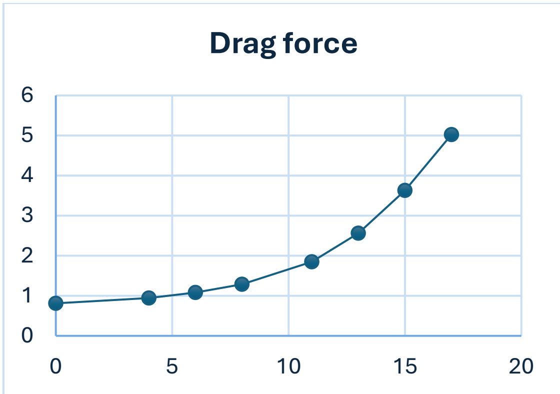

Figure 9. the relationship between the AOA and the drag force.

AOA	Lift force (N)
0	10.1097
4	40.5035
6	54.9868
8	68.3532
11	84.0524
13	89.4993
15	90.9431
17	89.996

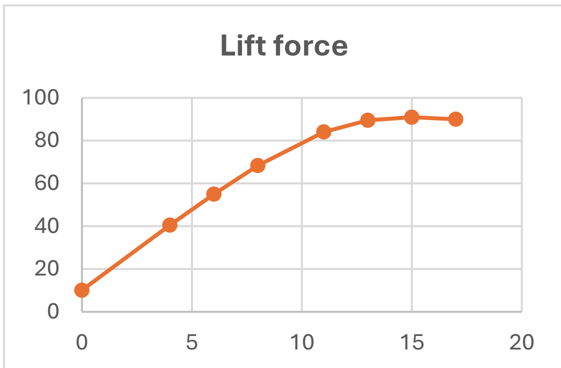

Figure 10. the relationship between the AOA and the drag and lift force.

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AOA	L/D
0	12.4534
4	42.9005
6	50.8195
8	53.135
11	45.4761
13	34.9489
15	25.0654
17	17.9156

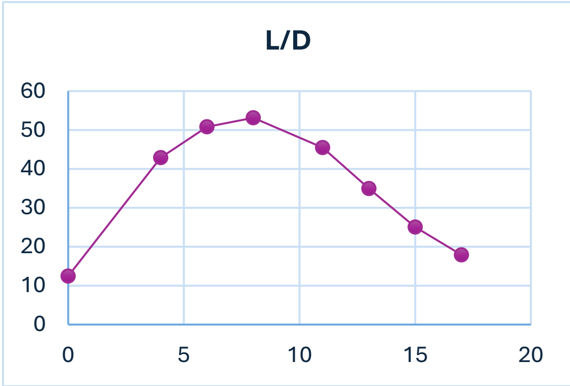

Figure 11. The relationship between the AOA and the L/D ratio

4. Conclusion

This study highlights the significant potential of whale tubercles to enhance the aerodynamic performance of aircraft wings, particularly in low-speed, high-lift scenarios such as takeoff and landing. By reducing drag, improving airflow control, and increasing stability, tubercle-inspired designs offer a promising pathway toward more efficient and fuel-saving wing configurations. The findings suggest that adopting this bio-inspired innovation could lead to substantial improvements in flight performance and sustainability. Future research should focus on optimizing tubercle parameters—such as size, spacing, and orientation—for various aircraft types and flight conditions. Additionally, full-scale testing is essential to validate these results in real-world applications. Further exploration of tubercle-inspired designs on other aircraft components, such as rudders and tail fins, could unlock broader aerodynamic benefits and revolutionize aviation design.

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