



RESEARCH ARTICLE

OPEN ACCESS

COMPUTATIONAL AERODYNAMIC INVESTIGATION OF SWEEPBACK WINGS WITH BIO-INSPIRED LEADING-EDGE TUBERCLES

V T Gopinathan^{*1}, Benadic Richard A², Hariharan V³, Meivarma J P⁴, Sivabalan S⁵

^{1, 2, 3, 4, 5}Department of Aeronautical Engineering, Hindusthan College of Engineering & Technology, Coimbatore 641032, India

¹<http://orcid.org/0000-0002-1484-9684>, ²<http://orcid.org/0009-0001-4238-399X>,

³<http://orcid.org/0009-0006-1769-9999>, ⁴<http://orcid.org/0009-0002-6643-9561>, ⁵<http://orcid.org/0009-0008-8118-6308>

E-mail: *gopinathanvt@gmail.com, benadicrichard05@gmail.com, hariharan13082004@gmail.com, meivarma2003@gmail.com, bsiva2696@gmail.com

ARTICLE INFO

Article History

Received: March 04, 2026

Reviewed: April 04, 2026

Accepted: May 15, 2026

Published: September 30, 2026

Keywords:

Bio-Inspired Design,
Tubercles,
Sweptback Wing,
CFD,
Stall Delay,
Counter Flow Vortices.

ABSTRACT

Aerodynamic effectiveness plays a significant role in enhancing the performance and stability of aircraft wings, particularly at low Reynolds numbers (Re), where early flow separation limits lift generation. In this study, a computational investigation was conducted using ANSYS FLUENT to examine the aerodynamic effects of bio-inspired leading-edge (LE) tubercles on a sweptback wing with a 35° sweep angle. The NACA 2412 airfoil was selected as the wing profile. The tubercled structure consists of a sinusoidal wave modification along the leading edge of the wing, inspired by the Humpback Whale (*Megaptera Novaeangliae*) flipper, characterized by an amplitude-to-wavelength ratio (η). Three different configurations were considered in this work: the conventional Baseline 2412 model and two modified models, HUMP 2412 A with $\eta = 0.25$ and HUMP 2412 B with $\eta = 0.5$. Simulations were performed at an operating Reynolds number (Re) of 1.5×10^5 . The sinusoidal tubercled geometry modifies the local pressure distribution and introduces streamwise counter-rotating vortices along the spanwise direction near the LE. These vortices act as a passive flow-control mechanism by energizing the boundary layer and increasing momentum exchange between the free stream and near-wall region. As a result, the flow remains attached over a longer chordwise distance, effectively delaying stall to higher angles of attack (AoA). The tubercled configurations demonstrate improved lift characteristics and reduced drag in the pre-stall and near-stall regions compared to the Baseline 2412 model. The higher-amplitude case, HUMP 2412 B ($\eta = 0.5$), generates stronger vortical structures and exhibits enhanced post-stall performance. Overall, the study confirms that LE tubercles improve aerodynamic efficiency by increasing lift, reducing drag, delaying flow separation, and enhancing the lift-to-drag ratio in sweptback wings operating at low Re. The findings highlight the effectiveness of bio-inspired tubercled structures as a passive aerodynamic performance enhancement technique.



Copyright ©2026 by authors and Galileo Institute of Technology and Education of the Amazon (ITEGAM). This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

I. INTRODUCTION

The Humpback whale (HW) (*Megaptera novaeangliae*) capability has been known for its unique morphology of its elongated pectoral flippers. Morphological investigations have shown that the flippers possess a high aspect ratio, wing-like planform with rounded tubercles distributed along the leading edge. The observations demonstrated that these flippers function as active hydrodynamic control surfaces. At higher swimming speeds, the flippers enabled sharply executed banked turns and vertical directional changes [1]. The HW is widely known for its unique maneuverability even with its large body. A typical feature contributing to this capability is its elongated pectoral flippers, which play a crucial role during complex swimming maneuvers.

The cross-sections show a rounded leading edge and a sharply tapered trailing edge; both features commonly associated with lift-generating foils. The maximum thickness location varies along the span, reaching from 49% of the chord near the tip to 19% at mid-span. Moreover, the thickness-to-chord ratio observed values between 0.20 and 0.28 [2]. Experimental studies on finite wing models have demonstrated that these tubercles delay stall to higher Angle of Attack (AoA), increase maximum lift, and reduce drag. The improved performance is due to the generation of streamwise vortices that energize the boundary layer and modify spanwise flow, they weakening tip vortices and enhancing effective spanwise flow. Such passive flow-control mechanisms are useful to sweptback wings, where strong spanwise flow and leading-edge vortex separation dominate at high AoA Aerodynamics. In highly swept configurations or heavily loaded wings are operating at reduced aerodynamic efficiency, these leading-edge tubercles offer a potential means of improving lift characteristics and delaying stall without the need for complex active control systems [3]. Numerical investigations have evaluated the aerodynamic performance of wings with and without tubercled leading edges at large Reynolds numbers. At an AoA of 10° , wings equipped with tubercles validate a 4.8% increase in lift, a 10.9% reduction in induced drag, and a 17.6% improvement in lift-to-drag ratio compared to without leading-edge configurations. While a moderate increases form drag was observed, the reduction in induced drag compensated for this effect, resulting in overall performance enhancement. Importantly, tubercles showed no aerodynamic impact at 0° AoA. The findings suggest that tubercles, delay stall and extend the operational envelope of lifting surfaces, particularly at higher AoA where boundary layer separation dominates.

By reducing wing tip vorticity and modifying flow separation behaviour, leading-edge tubercles provide a passive mechanism for improving lift generation and maneuverability [4]. Water tunnel experiments were conducted to evaluate the aerodynamic effects of sinusoidal LE protuberances on finite span wings with rectangular, swept LE, and flipper-like planforms based on a NACA 634-021 profile. Tests were performed at Reynolds numbers up to 4.5×10^5 and angles of attack up to 30° . The lift and drag characteristics of modified wings were compared with baseline configurations. For most planforms, the addition of LE protuberances resulted in drag values that were greater than or comparable to the baseline across the tested AoA range. Even though some modified wings showed variations in maximum lift, the span efficiency factor decreased for all leading edge modified models, with larger amplitudes causing greater reductions. The results indicate that aerodynamic benefits of protuberances are strongly dependent on planform geometry, amplitude and Wavelength [5]. The application of leading-edge tubercles on foils has shown significant aerodynamic benefits, particularly in post stall conditions. Experiments and simulations consistently reveal the formation of streamwise counter-rotating vortices. Several mechanisms have been proposed, including vortex lift generation, boundary layer momentum exchange and variation in effective AoA. Parametric studies indicate that tubercle amplitude significantly affects stall behaviour, where wavelength influences the lift gradient near stall. The Amplitude to Wavelength (A/λ) ratio is considered a key parameter for vortex strength and aerodynamic performance. At higher AoA they help delay flow separation and improve lift behaviour. Numerical studies show that tubercles modify pressure distribution by dividing large low-pressure regions into smaller zones [6].

Sinusoidal leading-edge tubercles have been shown to enhance aerodynamic performance under specific flow conditions, particularly near and beyond stall. Experimental and numerical investigations identified the formation of strong streamwise counter-rotating vortices between tubercle peaks. These vortices created due to well defined pressure gradients near the leading edge, which generate surface vorticity that is stretched, tilted, and diffused in a highly dimensional manner. Boundary layer separation initiates within the trough regions because of larger adverse pressure gradients, while delayed separation occurs near the tubercle peaks. The primary streamwise vortices increase in circulation downstream due to continued boundary-layer vorticity along the shear layer. Although peak vorticity magnitude decreases the downstream flow. The study also discovered unsteady vortex behaviour near the trailing edge at higher AoA. Both Experimental and Computational Fluid Dynamics (CFD) results showed strong agreement in vorticity distribution and vortex evolution. Aerodynamic evaluation demonstrated slightly improved lift performance for the tubercled NACA 0021 wing compared to the smooth baseline under the investigated conditions. The findings support the concept that tubercles modify pressure distribution, delay separation locally, and enhance vortex driven flow control mechanisms [7]. This study investigates about the execution of sinusoidal leading-edge modifications on a NACA 2412 airfoil. In this three-dimensional CAD models, conventional and modified airfoils were developed, and CFD simulations were conducted. It helps to evaluate aerodynamic performance. Multiple modified configurations with varying amplitudes and wavelengths which were analyzed and compared with the baseline NACA 2412 profile.

The results demonstrate that the inclusion of sinusoidal leading-edge geometries directly influences aerodynamic efficiency. Performance improvements were found to depend strongly on amplitude and wavelength parameters. The modified airfoils exhibited up to a 5% increase in aerodynamic efficiency compared to the baseline model. Additionally, the modified configurations maintained higher efficiency near the point of flow separation, confirming the beneficial impact of sinusoidal leading-edge modifications [8]. Experimental investigation was done for wing and blade geometries which were modified with leading-edge bumps inspired by humpback whale tubercles. The objective is to evaluate performance of reduction in lift coefficient before stall and capturing detailed velocity fields using particle image velocimetry (PIV). This result indicates the performance improvements for all tested tubercle configurations and detailed flow-field analysis reveals that the modified leading edges influence vortex formation, separation behaviour and contributing to improve the aerodynamic characteristics. The study also proposes a simplified mathematical model that represents tubercles as delta wings, and this model shows good agreement with experimental observations even with simplified tubercle geometries, supporting their practical implementation in engineered lifting surfaces [9]. Experimental investigation was done for four tapered swept-back wings designed using two distinct configuration rules. Each configuration includes a baseline wing and a modified wing with leading-edge tubercles based on the SD7032 airfoil profile. The airfoil and tubercles were oriented either streamwise or normal to the leading edge. This Results indicates that the baseline swept-back wing with streamwise airfoil alignment shows limited sensitivity to Reynolds numbers above $Re=8.2 \times 10^4$. The overall surface flow topology remains largely similar across different airfoil and tubercle orientations. The tubercles aligned normal to the leading edge at higher angles of attack (above 20°), both modified wings show improved stall characteristics compared to their baseline models, achieving lift enhancement and drag reduction.

But performance between 7° and 20° shows reduced L/D relative to the baseline wings. Flow visualization reveals complex vortex structures generated by each tubercle, including saddle and node formations influenced by sweep angle. It shows increased drag at moderate angles is linked to complex separation behind the tubercles [10]. Experimental investigation was done on engineering design, particularly from the humpback whale (*Megaptera novaeangliae*), whose leading-edge tubercles enhance maneuverability. Inspired by this feature, the present study investigates aerodynamic modifications produced by leading-edge tubercles on cambered airfoils. While most prior research focused on symmetrical airfoils, this work examines the cambered NACA 24xx airfoil series. In these three airfoils were analyzed using ANSYS CFD: NACA 2408, 2410, 2412 airfoils. For these simulations were conducted at 65 m/s to represent light aircraft flight conditions. In that Independent variable included airfoil thickness, angle of attack (AoA), tubercle size, and wavelength, while lift and drag were evaluated as performance metrics. And the results show that overall lift improvements were limited, and many configurations experienced drag increases, resulting in small changes in lift-to-drag (C_l/C_d) ratio. However, NACA 2410 demonstrated significant improvement, particularly at $AOA \leq 5^\circ$, achieving up to 24% enhancement in C_l/C_d compared to its baseline [11]. Aerodynamic performance of two swept wings based on the NACA 0021 airfoil was investigated, one with a smooth leading edge and the other with leading-edge tubercles.

In that force measurements and wake surveys were conducted to compare lift, drag, and spanwise flow behaviour between 0° and 8° angles of attack (AoA) and tubercles were decreased drag by 7–9.5% which results in a 2–6% improvement in lift-to-drag (L/D) ratio. The maximum L/D ratio increased by 3% at 6° AoA. But beyond 8° AoA, tubercles caused lift reduction and significant drag increase, leading to decreased aerodynamic efficiency [12]. For Improving aerodynamic efficiency experimental investigation was done on swept-back wings which can be achieved by enhancing lift or reducing drag. Bio-inspired modifications, particularly sinusoidal leading-edge tubercles derived from humpback whales, have shown promising flow-control characteristics at low Reynolds numbers. The present study evaluates the effect of tubercles on 30° swept-back wings using NACA 0015, 4415 airfoils. Six configurations were analyzed: two baseline smooth leading-edge wings and four modified “HUMP” models with amplitude-to-wavelength ratios (η) of 0.1 and 0.24. And the CFD simulations were conducted for angles of attack (AoA) ranging from 0° to 20° to analyze lift coefficient (C_l), drag coefficient (C_d), pressure gradients, and boundary-layer behaviour in both pre- and post-stall regimes. This results in tubercles enhancement of lift-to-drag (L/D) ratio in the pre-stall region ($0^\circ < AOA < 10^\circ$), particularly when aligned normal to the leading edge. Modified wings exhibit improved stall behaviour and lift enhancement, especially for the symmetric airfoil. Higher amplitude tubercles produce increased C_L and moderate C_D reduction before stall.

Flow visualization reveals asymmetric vortex structures along the span due to sweep effects. Flow separation occurs earlier in trough regions, while peak regions maintain attached flow at higher AoA. These spanwise vortices modify laminar separation bubble (LSB) distribution and contribute to performance gains. Overall, tubercled swept-back wings demonstrate significant potential for improved aerodynamic performance through optimized geometric parameters [13]. Despite the continuous improvement in aerodynamic design, conventional smooth leading-edge wings still experience early flow separation and stall at higher angles of attack. This flow separation leads to the formation of laminar separation bubbles and large vortical structures over the suction surface, which reduce lift and increase drag, particularly in low Reynolds number applications such as unmanned aerial vehicles (UAVs). Recent studies inspired by humpback whale flippers suggest that leading-edge tubercles can modify the flow structure by generating streamwise vortices that help energize the boundary layer and delay stall. However, the aerodynamic behaviour of tubercled wings strongly depends on geometric parameters such as amplitude and wavelength ratio. Therefore, it is necessary to investigate how different tubercle configurations influence the flow characteristics and aerodynamic performance of wings. In this study, numerical simulations are carried out to analyze the effects of leading-edge tubercles on the aerodynamic characteristics of a Swept back wing, NACA 2412 used as wing profile and to compare the results with the conventional smooth leading-edge baseline model.

II. NUMERICAL METHODOLOGY

The numerical methodology in this study is used to evaluate the aerodynamic performance of the Baseline and the HUMP Models configurations. A 3D computational domain is created and discretized using an unstructured mesh to accurately represent the flow field around the wing models. The near wall region to properly capture the boundary layer behaviour over the wing surface. The simulations are performed using a Reynolds Averaged Navier-Stokes (RANS) approach with an appropriate Turbulence model to predict aerodynamic characteristics. Boundary conditions and solver settings are defined to represent realistic flow conditions around the wing. The obtained numerical results are used to evaluate lift and drag characteristics and to support further aerodynamic analysis was illustrated in Figure 1.

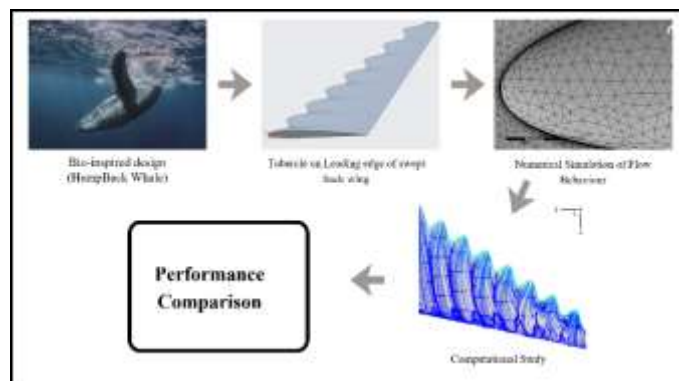


Figure 1: Analysis methodology of the proposed work.
Source: Authors, (2026).

II.1 WING GEOMETRY

The geometry of swept back wing is used for this proposed work which is used in different kinds of flight vehicles. The six tapered swept back wings (Baseline 2412, HUMP 2412 A, HUMP 2412 B) are modelled by considering two different airfoils and amplitude to wavelength (A/λ) ratio. The Hump model consists of the tubercles at the LE while baseline wing model has a smooth LE. The NACA 2412 airfoil is widely used in aerodynamic studies because of its well-documented performance and availability of reliable experimental validation data. It has a moderate camber (2%) and thickness (12%), which provides stable aerodynamic characteristics suitable for both experimental and computational investigations. Previous studies report a maximum lift coefficient of approximately 1.4-1.5 and a stall angle around $14-16^\circ$, making it a good reference airfoil for validation. Due to these well-established aerodynamic characteristics, NACA 2412 is commonly selected as a baseline model for CFD validation and comparison with modified airfoil designs. Therefore, it is used in this study to evaluate the aerodynamic performance of sinusoidal leading-edge modifications against a validated conventional airfoil [8]. The NACA 2412 airfoils are selected and analyzed at low Re , to achieve the performance comparison of tubercles over cambered wings. The geometric parameters for governing the performance of tubercle configurations are wavelength (λ), amplitude (A) and the ratio of amplitude to wavelength, i.e., $\eta = (A/\lambda)$. The Previous studies about sinusoidal leading-edge airfoils show that the aerodynamic performance strongly depends on the amplitude–wavelength ratio of the serrations. Large amplitudes combined with small wavelengths can increase noise reduction but due to loss of effective lifting surface it may reduce lift. In contrast, configurations with smaller amplitudes and relatively larger wavelengths helps to maintain better aerodynamic lift characteristics as the same time still delaying stall. Based on these conclusions, In the recent studies to investigate the influence on the aerodynamic performance of the modified airfoil, amplitude ratios of 0.25 and 0.5 are selected. These ratios provide a balanced configuration to analyze the trade-off between flow control, lift performance, and stall behaviour compared with the baseline model [14]. These geometric parameters would retain the high-priority in the course of design perspective with modified airfoils. The geometry of spanwise ordinates (Z) is used for the variable chord length which is given by the following wave equation.

$$c(Z) = A \cos\left(\frac{2\pi Z}{\lambda}\right) + \bar{c} \quad (1)$$

The Baseline and modified wings are designed with NACA 2412 airfoil cross sections respectively. It has a root chord of 200 mm and tip chord of 60 mm, sweep angle about 35° and semi-span is 300mm. The corresponding mean aerodynamic chord ($\bar{c}$) is determined as 140 mm. The modified wings are concerned by implementation of tubercles along the stream wise cross section of the baseline models. The two wavelengths ($\lambda = 20$ mm and 40 mm) are chosen with one amplitude ($A = 10$ mm) after the cautious inspection of various related works. The chosen relative amplitude & wavelength of tubercles on the modified wings in the present work fall within the range of values associated with HW flippers. The Computer Aided Design (CAD) of baseline and tubercled swept back wings with two different η values are presented in Figures 3 and 4 respectively. In this article, the thickness to chord (t/c) value is fixed at 0.12 based on the pectoral flippers existing in the HW as a novel effort compared with the previous studies.

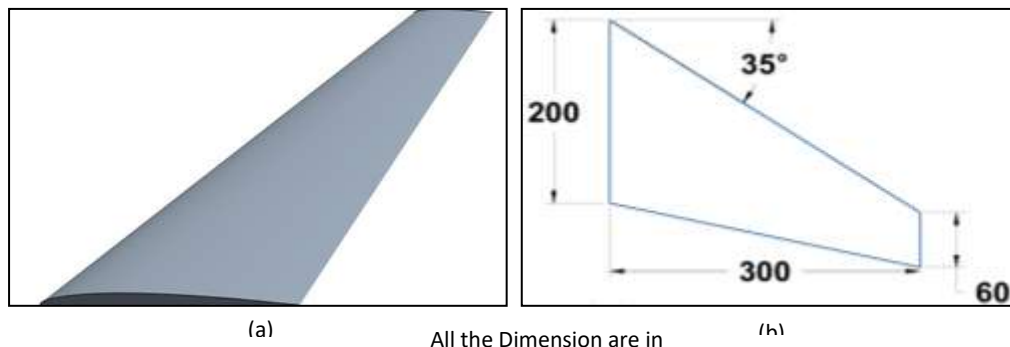


Figure 2: CAD model of baseline wing profiles (NACA 2412) (a) Baseline NACA 2412, (b) Dimensions of CAD model. Source: Authors, (2026).

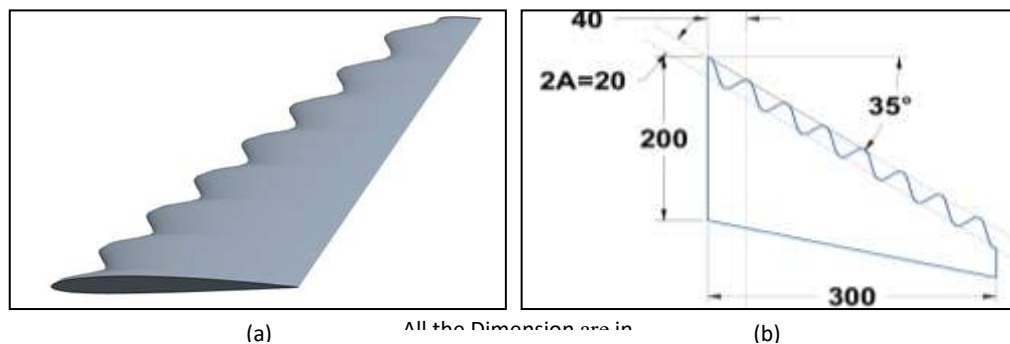


Figure 3: CAD model of baseline wing profiles with tubercles (NACA 2412) (a) HUMP 2412 A, (b) Dimensions of CAD model. Source: Authors, (2026).

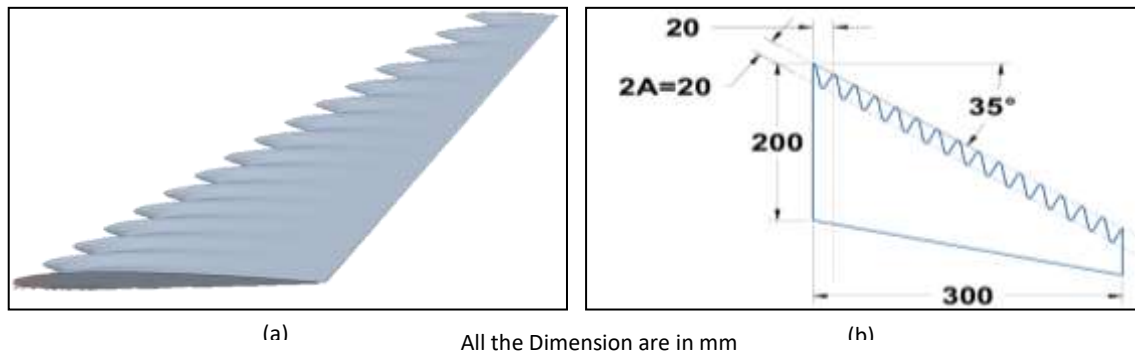


Figure 4: CAD model of baseline wing profiles with tubercles (NACA 2412) (a) HUMP 2412 B, (b) Dimensions of CAD model.
Source: Authors, (2026).

II.2 COMPUTATIONAL MESHING

The Computational meshing and Numerical simulations were performed using ANSYS Fluent 2022 R1. This is widely used for solving complex fluid flow problems. Computational Meshing was carried out to Baseline 2412 model and the modified HUMP 2412 A and HUMP 2412 B Models. A Three-Dimensional(3D) unstructured mesh was generated for the Baseline 2412, HUMP 2412 A, and HUMP 2412 B models using a C-type (Bullet Domain) computational domain. This type of domain was selected to accurately capture the flow development around the leading edge and wake region. The mesh was created using face sizing applied to the overall domain, while edge sizing with Number of Divisions was used along the wing surface to obtain better resolution of the geometric features. A global growth rate of 1.1 was maintained throughout the domain to ensure smooth variation in cell size. The tetrahedral mesh method was adopted to achieve flexible and uniform mesh distribution, especially around the complex hump leading edge regions.

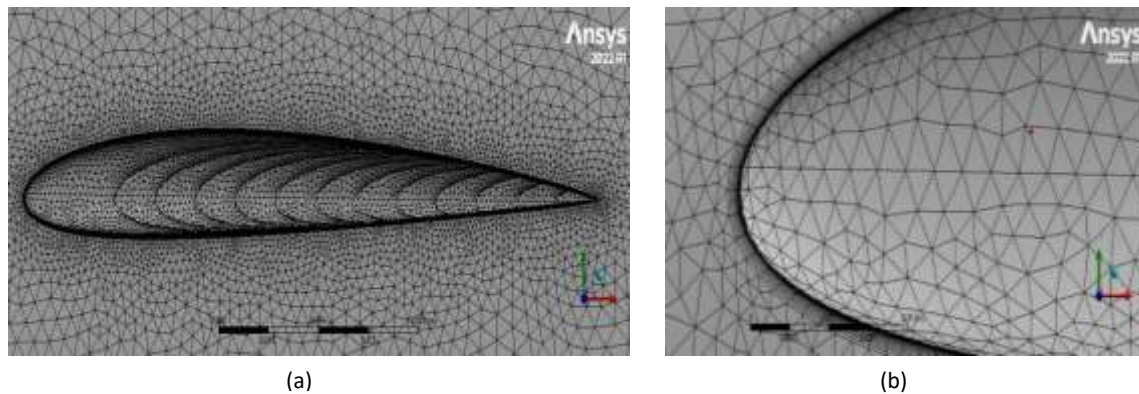


Figure 5: Prism layer formation in baseline and HUMP airfoil surfaces. (a) HUMP 2412 B airfoil surface. (b) Baseline airfoil surface.
Source: Authors, (2026).

To improve mesh quality, bias sizing was applied along the root and tip chord regions, which helped achieve good skewness and orthogonal quality. Special attention was given to the near-wall region to properly resolve the boundary layer effects. The mesh was constructed based on a target y^+ value of 1, suitable for Reynolds Averaged Navier-Stokes (RANS) simulation at a Reynolds number of 1.5×10^5 . Inflation layers were applied on the wing surface with a first layer height of 1.6×10^{-5} m, a total of 20 layers, and a growth rate of 1.2. This ensured accurate prediction of near-wall flow behaviour and aerodynamic parameters. The overall meshing approach provided a smooth transition from the wall region to the far-field domain and ensured reliable numerical accuracy for all configurations. This meshing approach, the Total number of elements generated was approximately 1.8×10^6 for the Baseline 2412 model and 2×10^6 elements for Both HUMP 2412 A and HUMP 2412 B configurations. This mesh setup was sufficient to perform accurate numerical simulation, particularly in the wing surface and near-wake regions. The applied inflation layers to resolved the boundary layer thickness based on the target y^+ value, allowing precise prediction of near-wall flow behaviour. In addition, a fine triangular surface mesh was formed over the wing surface, which helped capture detailed velocity and pressure distributions along the wing and in the surrounding flow region, ensuring stable Aerodynamic results. A grid independence study was performed for the Baseline model at 0° angle of attack using 3- Different Total Number of Elements to evaluate the effect of Mesh in lift and drag coefficients and the results are presented value in Table.1 to mesh-independent aerodynamic results. Unstructured mesh generation plays an important role in accurately simulating complex aerodynamic geometries in Computational Fluid Dynamics (CFD). Among the available techniques, the octree advancing front method provides an efficient and automated approach for generating high quality surface and volume meshes. This method allows the mesh size to vary smoothly across the computational domain while accurately capturing complex geometric features. It also minimizes user intervention by automatically controlling grid spacing and mesh refinement. Therefore, this approach is widely used for aerodynamic simulations to ensure reliable and computationally efficient flow analysis [15].

Table 1: The results of the grid-independency study of the baseline wing at $Re=1.5 \times 10^5$.

Mesh Case	Number of Elements	Lift Coefficient (C_l)	Drag Coefficient (C_d)
Coarse	1568054	0.2036	0.0213
Medium	1651674	0.2197	0.0235
Fine	1875679	0.2350	0.0254

Source: Authors, (2026).

II.3 NUMERICAL SIMULATION

The numerical simulation was carried out by first determining the freestream velocity using the Reynolds number relation. For a Re of $=1.5 \times 10^5$, mean chord length of 0.140 m, air density of 1.225 kg/m^3 , and dynamic viscosity of $1.82 \times 10^{-5} \text{ kg/m}\cdot\text{s}$ (sea level conditions), the inlet velocity was calculated as 17.5 m/s. The solver was configured in ANSYS Fluent 2022 R1 using a pressure-based, absolute velocity formulation.

$$\frac{\partial \bar{U}_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} + U'_j \frac{\partial U'_i}{\partial x_j} = \bar{f}_i - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} \quad (3)$$

Where, $\bar{f}_i$ - vector expressing the forces, $\bar{U}_j$, $\bar{p}$ and ρ representing the mean flow quantities of velocity, pressure and density respectively. A steady RANS approach with the $k-\omega$ SST turbulence model was employed, and turbulence intensity was specified as 5%. The $k-\omega$ SST turbulence model was selected in the present study to solve the steady incompressible RANS equations. This model is widely used for aerodynamic simulations because it can accurately predict boundary layer behaviour and flow separation. Similar to previous studies, the SST model provides better accuracy near the wall region. Therefore, it is suitable for analyzing the aerodynamic characteristics of the baseline and modified wing models [16]. The solution method was set to coupled scheme with second-order discretization for pressure and momentum equations to improve accuracy. Hybrid initialization was used prior to iteration. The residual convergence criterion was set to 1×10^{-6} , with a maximum of 5000 iterations to ensure solution stability. Report definitions were created to compute the lift coefficient (C_l) and drag coefficient (C_d) for performance evaluation [17].

III. RESULT AND DISCUSSION

The results and discussion section presents, The baseline airfoil and the modified HUMP models aerodynamic performance in different flow conditions. The numerical results are estimated over a range of angle of attack (AoA) from 0° to 20° at a Reynolds number of 1.5×10^5 . The justification of the computational results is carried out through the comparison of lift coefficient (C_l), drag coefficient (C_d), wall shear stress distribution, and streamline flow patterns between the baseline and modified configurations. These analyze helps to understand the effect of the bio-inspired sinusoidal leading-edge modification on flow behaviour, separation characteristics, and overall aerodynamic performance.

III.1 WALL SHEAR STREAMLINE PATTERN-BASELINE MODEL

The wall shear streamlines pattern obtained for the baseline NACA 2412 wing are shown in the Figure 6. At lower angles of attack (0° - 5°), the flow remains mostly attached over the suction surface, with only a small Laminar Separation Bubble (LSB) forming near the trailing edge [18]. As the angle of attack increases (10° - 15°), the LSB region expands along the chordwise direction and becomes more prominent across the span of the wing. At higher angles of attack (around 20°), a larger separated flow region is observed on the suction side, indicating the development of strong vortical structures and increased flow instability. These observations agree with earlier studies where the smooth baseline wing exhibited spanwise LSB formation and delayed reattachment, confirming that the present numerical simulation captures the expected wall shear and separation behaviour accurately [19].

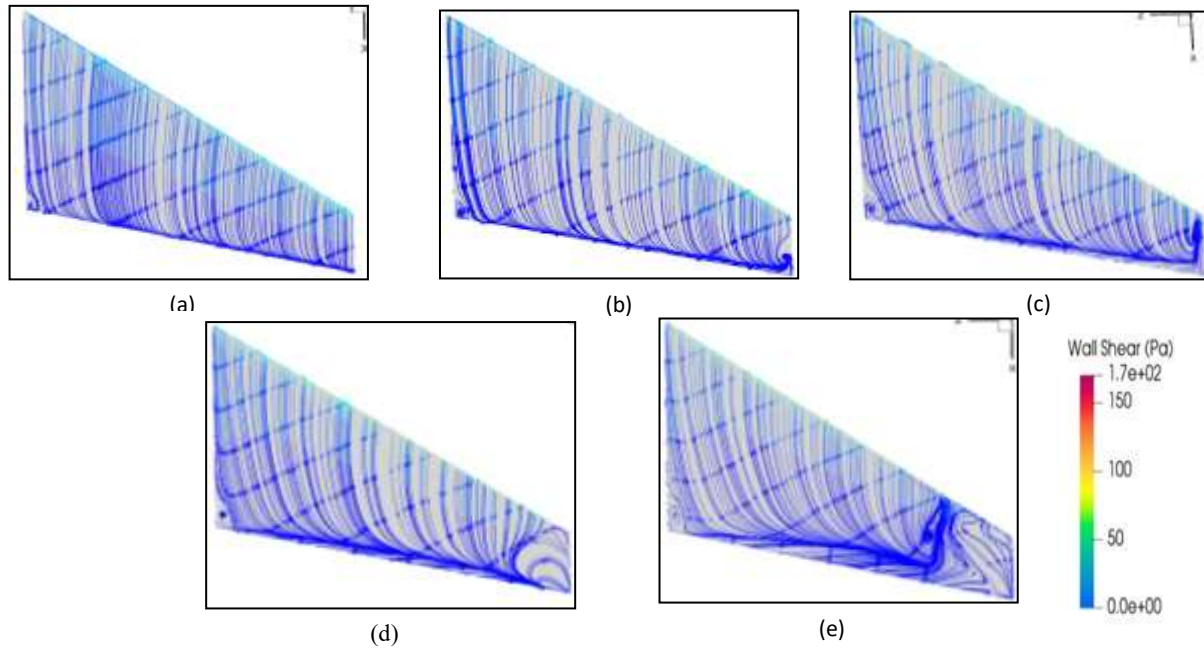


Figure 6: Wall shear streamlines field over suction side of the Baseline 2412 at different AoA. (a) $\alpha=0^\circ$, (b) $\alpha=5^\circ$, (c) $\alpha=10^\circ$, (d) $\alpha=15^\circ$, (e) $\alpha=20^\circ$.
Source: Authors, (2026).

III.2 WALL SHEAR STREAMLINE PATTERN - MODIFIED WING MODELS

The wall shear streamline patterns over the suction surface of the modified wings (HUMP 2412 A and HUMP 2412 B) at different angles of attack are presented in Figures 7 and 8. In contrast to the smooth baseline wing, the modified wings show a more complex surface flow pattern due to the presence of sinusoidal LE tubercles. These geometric variations generate multiple localized vortical structures along the spanwise direction. The flow behaviour over tubercled airfoils is strongly influenced by the pressure gradients near the leading edge. These pressure gradients generate surface vorticity, which develops into streamwise vortices between the tubercle peaks. The interaction of these vortices forms a horseshoe shaped separation region behind the trough of each tubercle. This vortex structure helps control the boundary layer and modifies the separation behaviour over the airfoil surface. As a result, tubercled airfoils can show slightly improved aerodynamic performance compared with conventional smooth airfoils [7]. At lower angles of attack (0° - 5°), the flow remains mostly attached over the suction surface, but small separation regions begin to appear behind the trough regions of the tubercles. This behaviour is consistent with previous studies, where early separation behind troughs occurs due to locally increased adverse pressure gradients [20]. As the AoA increases (10° - 15°), the streamlines clearly show the formation of multiple streamwise vortices generated from the crest and trough regions of the tubercles. These vortices energize the boundary layer and help maintain partial flow attachment over several sections of the wing. Compared with the baseline configuration, the modified wings exhibit a more distributed separation pattern instead of a large continuous separation region [21].

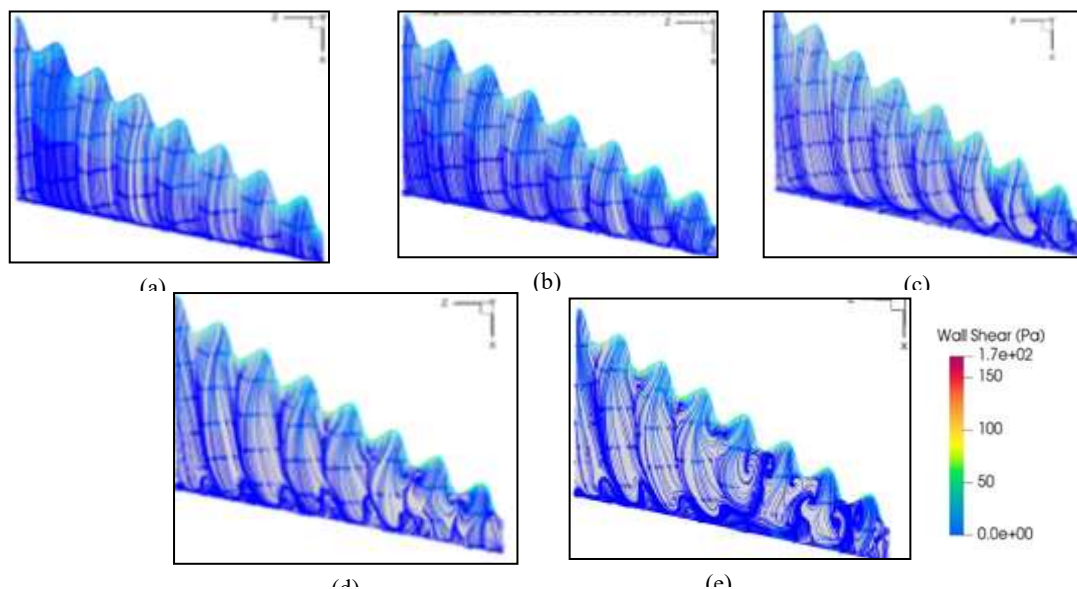


Figure 7: Wall shear streamlines fields over suction side of the HUMP 2412 A at different AoA. (a) $\alpha=0^\circ$, (b) $\alpha=5^\circ$, (c) $\alpha=10^\circ$, (d) $\alpha=15^\circ$, (e) $\alpha=20^\circ$.
Source: Authors, (2026).

At higher AoA (around 20°), stronger vortex structures and localized recirculation zones become visible, particularly near the trailing edge and trough regions. However, the presence of these vortices helps delay large-scale separation by promoting momentum exchange within the boundary layer. Between the two modified configurations, the larger amplitude-wavelength ratio ($\eta = 0.5$) produces stronger and more organized vortical structures than the $\eta = 0.25$ configuration, which indicates a greater influence on flow control and separation behaviour. These observations agree with earlier numerical and experimental investigations of tubercled wings, which report that sinusoidal leading edges generate streamwise vortices that modify surface flow topology and improve stall characteristics [22].

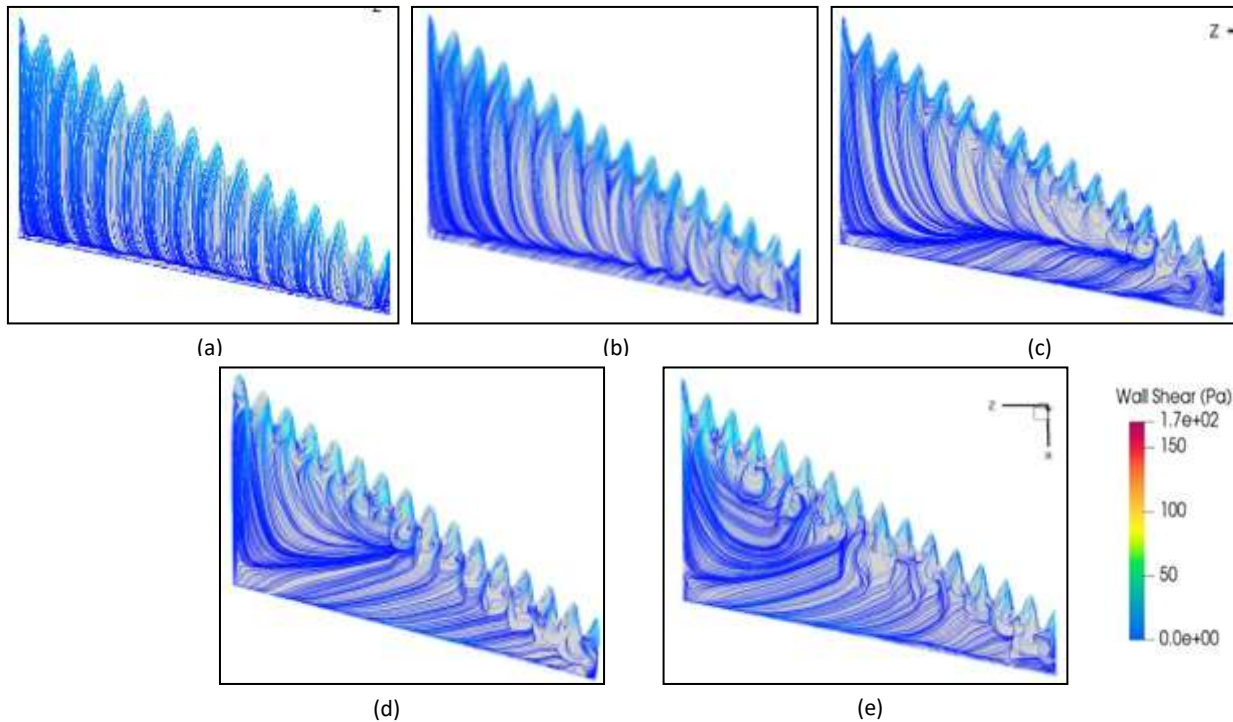


Figure 8: Wall shear streamlines fields over suction side of the HUMP 2412 B at different AoA. (a) $\alpha=0^\circ$, (b) $\alpha=5^\circ$, (c) $\alpha=10^\circ$, (d) $\alpha=15^\circ$, (e) $\alpha=20^\circ$.

Source: Authors, (2026).

III.2.1 Velocity Streamline Pattern For Baseline Model

The velocity streamline patterns provide a clear understanding of the flow behaviour over the suction surface of the baseline wing. In the present study, the streamline contours of the NACA 2412 baseline model are examined at an angle of attack of 15° and at three different spanwise locations (150 mm, 160 mm and 170 mm from the root). The streamline visualization helps to identify the flow separation region, vortex formation, and the development of the laminar separation bubble (LSB) near the suction surface.

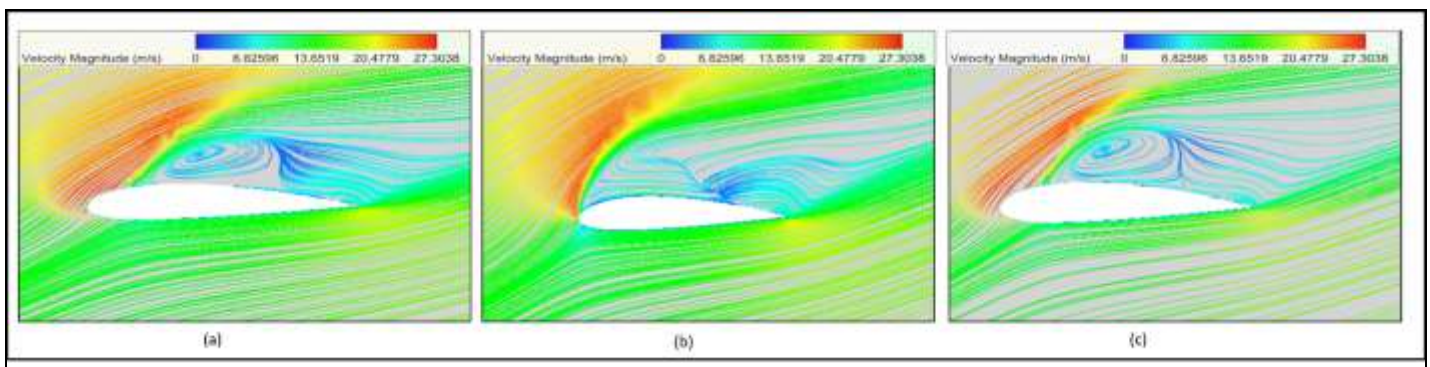


Figure 9: Streamline fields over NACA 2412 at different span wise locations at $a=15^\circ$. (a) at 150mm. (b) at 160mm. (c) at 170mm.

Source: Authors, (2026).

From the streamline contours shown in Figure 9, the flow structure over the suction surface changes slightly along the spanwise direction. At the 150 mm location (Fig. 9a), the flow starts to separate from the leading edge due to the increase in adverse pressure gradient. A primary recirculation zone can be observed above the suction surface, indicating the formation of a laminar separation bubble. The separated flow region extends towards the mid-chord region before it gradually reattaches to the surface. At the 160 mm spanwise location (Fig. 9b), the separation bubble becomes slightly stronger and the vortex structure appears more prominent. The streamlines indicate that the separated flow region increases in size compared with the previous section.

The recirculation zone forms a closed vortex structure above the suction surface, which is a typical indication of boundary layer separation at higher angles of attack. At the 170 mm location (Fig. 9c), the separation region continues to develop and the vortex core shifts slightly downstream along the chord. The streamline curvature becomes more noticeable, showing stronger flow recirculation near the suction side. This behaviour suggests that the flow separation becomes more dominant towards the outer span region of the wing. Overall, the streamline patterns clearly indicate that at $\alpha = 15^\circ$, a significant portion of the suction surface experiences separated flow. The formation of the laminar separation bubble and the associated vortex structures confirm that the baseline wing approaches stall conditions at this angle of attack. Similar flow behaviour has also been reported in previous studies on low Reynolds number airfoils, where the adverse pressure gradient leads to boundary layer separation and the development of recirculating vortices over the suction surface. These observations provide a useful reference for comparing the modified (HUMP) wing configurations, where the introduction of LE modifications is expected to influence the separation behaviour and improve the flow control characteristics.

III.2.2 Velocity Streamline Pattern For Modified WING Models (HUMP 2412 A AND HUMP 2412 B)

The velocity streamline patterns of the modified wing models (HUMP 2412 A and HUMP 2412 B) at $\alpha = 15^\circ$ clearly show how the presence of tubercles changes the flow behaviour along the span. From the figures, it can be observed that the flow structure varies significantly between the peak, mid, and trough regions. In the HUMP 2412 A model ($\eta = 0.25$), the peak region shows comparatively better flow attachment, where the streamlines follow the suction surface smoothly up to a longer chordwise distance before separating. The separation bubble formed in this region is smaller and shifted slightly downstream. In the mid region, a moderate recirculation zone is visible near the mid-chord, indicating partial separation. However, in the trough region, the flow detaches earlier and a larger recirculation bubble is formed due to the stronger adverse pressure gradient. This spanwise variation confirms that separation is not uniform, but distributed along different regions of the wing [23]. For the HUMP 2412 B model ($\eta = 0.5$), the effect of the tubercles becomes more pronounced because of the increased amplitude. The streamline contours show stronger vortical motion near the LE, especially around the peak regions. In these regions, the flow remains attached for a longer distance compared to the trough locations. The trough region again shows earlier flow separation and a well-defined recirculation zone. Compared to HUMP 2412 A, the higher amplitude model generates stronger streamwise vortices, which help in mixing higher energy flow into the boundary layer. As a result, the separated zones are more controlled and localized rather than spreading over the entire suction surface.

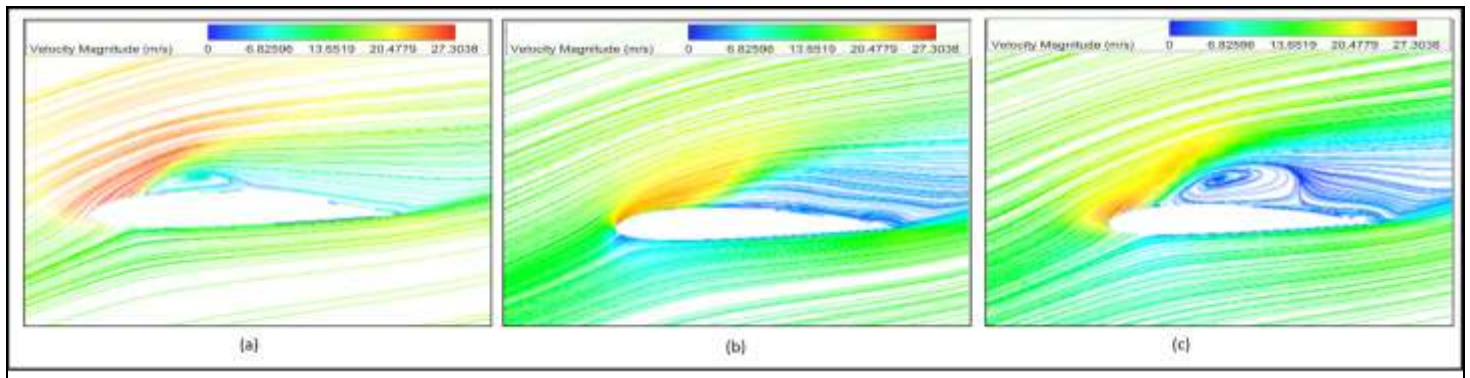


Figure 10: Streamline fields over HUMP 2412 A at different span wise locations at $\alpha = 15^\circ$. (a) Peak region of HUMP 2412 A, (b) Mid region of HUMP 2412 A, (c) Trough region of HUMP 2412 A.
Source: Authors, (2026).

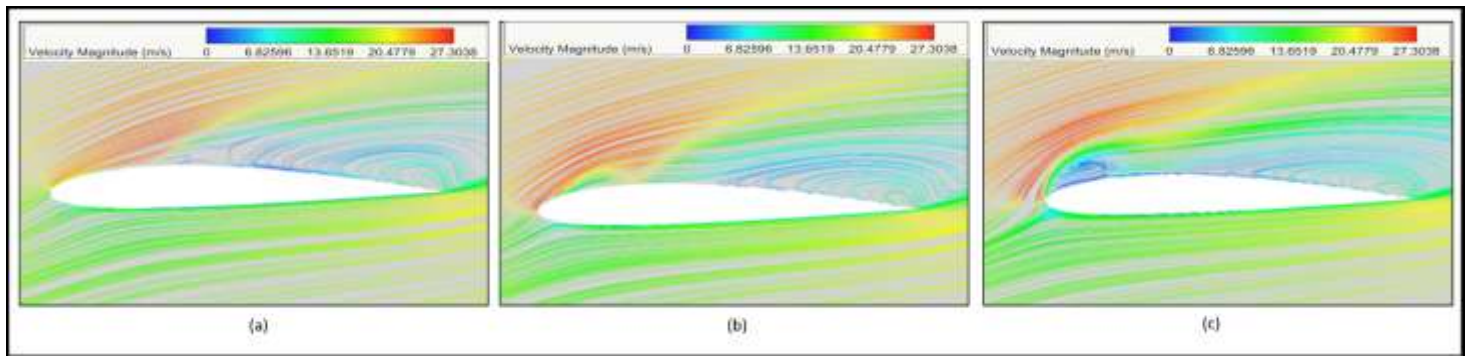


Figure 11: Streamline fields over HUMP 2412 B at different span wise locations at $\alpha = 15^\circ$. (a) Peak region of HUMP 2412 A, (b) Mid region of HUMP 2412 A, (c) Trough region of HUMP 2412 A.
Source: Authors, (2026).

Overall, the streamline results indicate that the modified wing models do not completely eliminate flow separation at higher angle of attack, but they redistribute and control it more effectively than a smooth wing. The presence of tubercles introduces streamwise vortices along the LE. These vortices energize the boundary layer by transferring momentum from the outer flow towards the near-wall region. This mechanism delays large-scale separation and improves flow attachment, particularly near the peak regions.

Therefore, the implementation of leading-edge tubercles enhances the overall flow characteristics by promoting better flow control, delaying stall, and improving aerodynamic stability at higher AoA.

III.3 EFFECT OF TUBERCLES ON AERODYNAMIC COEFFICIENTS

The variation of lift coefficient (C_l) and drag coefficient (C_d) with angle of attack (AoA) for the baseline and modified wing models is presented in Figures 12 and 13. The results are obtained for a Re of 1.5×10^5 over the AoA range of 0° – 20° . From the C_l vs AoA plot, it can be observed that the lift coefficient of all the wing configurations increases gradually with the increase in angle of attack in the pre-stall region. The baseline NACA 2412 wing shows a nearly linear increase in C_l up to about 14° – 15° AoA, after which the lift starts to decrease due to the onset of stall. The maximum lift coefficient of the baseline model is comparatively lower than the modified wing models. In contrast, the HUMP 2412 A ($\eta = 0.25$) and HUMP 2412 B ($\eta = 0.5$) models produce higher lift values across most of the AoA range. Among the modified wings, HUMP 2412 B shows the highest lift coefficient and reaches the maximum C_l around 15° AoA, indicating improved lifting performance. The increase in lift for the modified wings can be attributed to the presence of sinusoidal leading-edge tubercles, which help to energize the boundary layer and delay large scale flow separation [24].

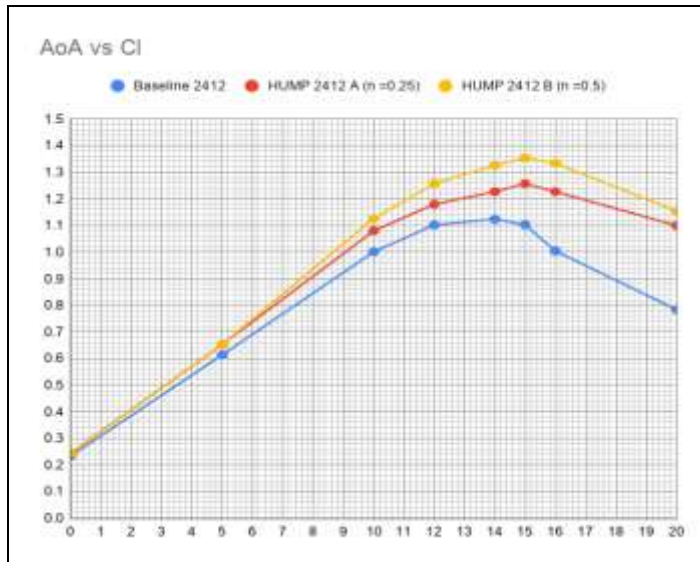


Figure 12: Comparison of C_l vs. α at different AoA for Baseline and Hump wings.
Source: Authors, (2026).

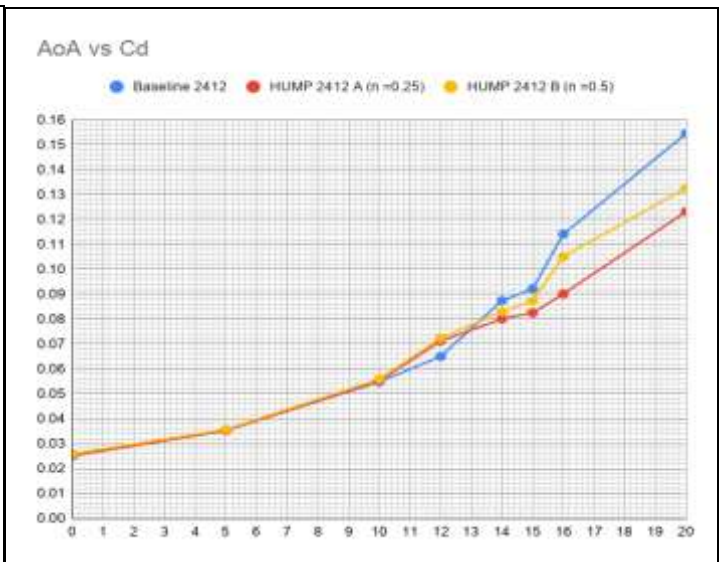


Figure 13: Comparison of C_d vs. α at different AoA for Baseline and Hump wings.
Source: Authors, (2026).

The C_d vs AoA results show that the drag coefficient increases with increasing angle of attack for all the models. At lower AoA, the drag values of the baseline and modified wings are nearly similar. However, as the AoA increases beyond 10° , the drag coefficient rises more rapidly due to stronger flow separation and vortex formation over the suction surface. Although the modified wings show slightly higher drag compared to the baseline model at certain AoA, the increase in lift obtained from the tubercled configurations compensates for this effect. The results indicate that the introduction of sinusoidal leading-edge modifications improves the aerodynamic performance of the wing by enhancing lift and delaying the stall characteristics, especially in the moderate to high angle of attack region. The HUMP 2412 B model ($\eta = 0.5$) demonstrates comparatively better aerodynamic performance among the tested configurations.

III.4 EFFECT OF TUBERCLES ON BOUNDARY LAYER SEPARATION

The boundary layer separation characteristics of the baseline NACA 2412 model and the modified HUMP 2412B configuration are compared at angles of attack $\alpha = 5^\circ$ and 15° , based on the velocity vector and boundary layer profiles shown in Figures 14–18. At $\alpha = 5^\circ$, the baseline model exhibits a favorable pressure gradient over a major portion of the chord from the leading edge. The velocity vectors indicate smooth flow development along the suction surface up to nearly mid-chord. However, beyond this region, an adverse pressure gradient develops toward the trailing edge. The closer view of the boundary layer shows the presence of a point of inflection and gradual reduction of wall-tangential velocity, which eventually leads to a small separation zone near the trailing edge. The appearance of backflow in this region confirms the onset of boundary layer separation due to excessive adverse pressure gradient. At the higher angle of attack, $\alpha = 15^\circ$, the baseline airfoil shows much earlier separation. The velocity vectors clearly indicate that flow separation begins close to the leading edge, forming a large separated region over the suction surface. This early separation is associated with strong adverse pressure gradients and significant momentum loss within the boundary layer, which contributes to rapid lift deterioration and stall behaviour [25].

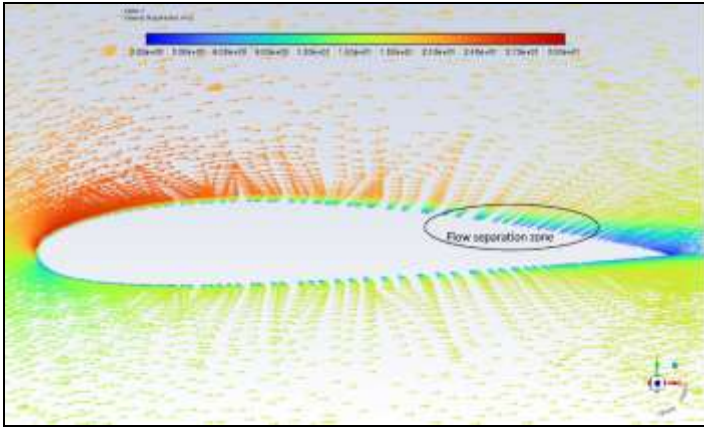


Figure 14: Velocity vector with boundary layer profile for NACA 2412 model at $\alpha=5$.
Source: Authors, (2026).

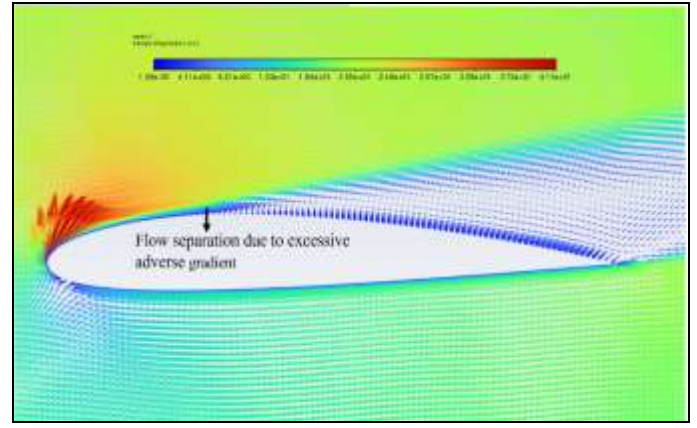


Figure 15: Velocity vector with boundary layer profile for NACA 2412 model at $\alpha=15$.
Source: Authors, (2026).

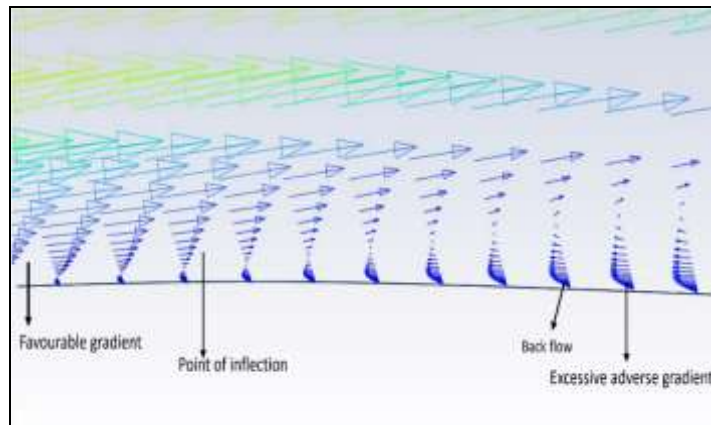


Figure 16: Closer view of separation zone of baseline NACA 2412 model.
Source: Authors, (2026).

For the HUMP 2412B model at $\alpha = 15^\circ$, the separation pattern is modified due to the presence of leading-edge tubercles. In the peak region, the velocity vectors show comparatively less adverse pressure gradient and a delayed separation zone located farther downstream when compared to the baseline case. This behaviour is mainly attributed to the downwash effect over the peak region, which stabilizes the boundary layer and reduces the severity of separation. In contrast, the trough region of the HUMP 2412B model exhibits earlier local separation, starting close to the leading edge which is shown in Figure 17 and 18. This occurs because the upwash effect behind the trough increases the effective local angle of attack and strengthens the adverse pressure gradient. As a result, the boundary layer in the trough region thickens and becomes more prone to separation [26]. However, unlike the baseline model where separation spreads rapidly over the entire span, the tubercled configuration distributes separation in a controlled and localized manner. These results demonstrate that the leading-edge tubercles alter the boundary layer development by creating spanwise variations in pressure gradient. Although localized separation occurs behind the troughs, the peak regions experience delayed separation, which prevents sudden large-scale stall. Therefore, the tubercled configuration improves flow control by transforming abrupt separation into a more gradual and distributed process, enhancing aerodynamic stability at higher angles of attack.

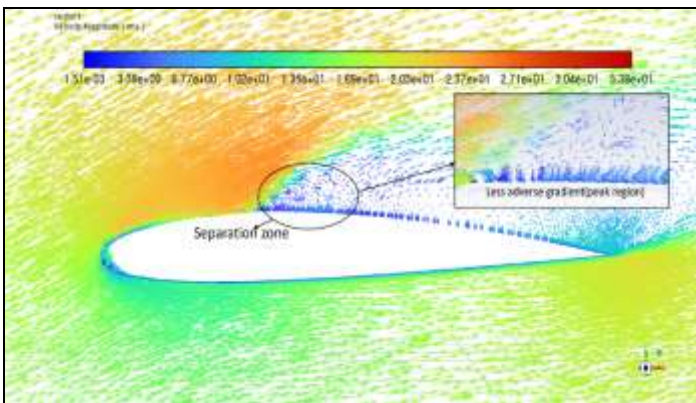


Figure.17: Velocity vector profile of peak region of HUMP 2412B model at $\alpha=15$.
Source: Authors, (2026).

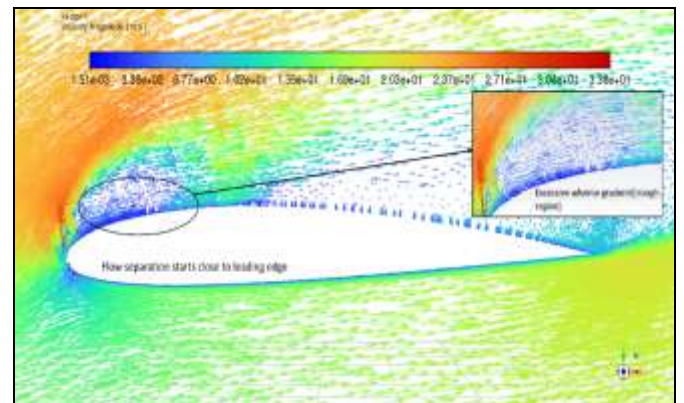


Figure.18: Velocity vector profile of trough region of HUMP 2412B model at $\alpha=15$.
Source: Authors, (2026).

III.5 FURTHER APPLICATIONS OF HW TUBERCLES

The bio-inspired concept of humpback whale (HW) leading-edge tubercles can be effectively incorporated into modern engineering systems to enhance performance and operational stability. It is well established that tubercles generate pairs of streamwise, counter-rotating vortices, which energize the boundary layer and modify near-wall flow behaviour. While most studies focus on aerodynamic lift enhancement and stall delay, these vortical structures also contribute to boundary layer thinning, resulting in improved heat transfer performance reported to increase heat transfer rates by up to 25% in certain applications. In wind turbine technology, the integration of tubercles on blade leading edges has demonstrated reductions in torsional frequencies while maintaining the same planform area. The combined reduction in aerodynamic loads and structural frequencies can positively influence fatigue characteristics, thereby improving the service life of horizontal axis wind turbine blades. Beyond aerospace and energy systems, tubercle geometry has shown promising potential in marine applications. For instance, incorporating leading-edge tubercles on hydrofoils can generate favorable balancing forces, improve stability and enable higher sailing speeds in hydroplane and yacht designs. Furthermore, the implementation of tubercles on inverted wings, such as those mounted on the rear deck of race cars, has been reported to enhance handling stability and acceleration performance by improving flow attachment and downforce characteristics. Overall, the passive flow control capability of leading-edge tubercles makes them a promising design modification for aerodynamic, hydrodynamic, thermal, and energy-based engineering applications.

IV. CONCLUSIONS

In this study, the aerodynamic performance of a baseline wing (NACA 2412) and two modified tubercled wing models (HUMP 2412 A with $\eta = 0.25$ and HUMP 2412 B with $\eta = 0.5$) was numerically investigated at a Re of 1.5×10^5 for angles of attack ranging from 0° to 20° . The CFD simulations were performed using the SST $k-\omega$ turbulence model to capture the flow behaviour over the wing surface. The results were analysed using wall shear contours, velocity streamline patterns, and aerodynamic coefficients (C_l and C_d). The wall shear results of the baseline wing showed the formation of a laminar separation bubble on the suction side, which becomes larger as the angle of attack increases. In contrast, the modified tubercled wings altered the surface flow structure and created spanwise variations in the separation and reattachment regions. The streamline analysis indicated that the tubercled leading edge generates localized vortex structures, which help in controlling the flow separation, especially around the peak regions of the tubercles. The aerodynamic coefficient results showed that the modified wings produce higher lift compared to the baseline configuration. In particular, the HUMP 2412 B model ($\eta = 0.5$) demonstrated the highest lift values and delayed stall behaviour. Although the drag coefficient slightly increased for the modified models at higher angles of attack, the lift enhancement and stall delay indicate improved aerodynamic performance. Overall, the implementation of leading-edge tubercles modifies the flow characteristics over the wing surface, improves lift generation, and delays flow separation. These findings suggest that tubercled wing configurations can be beneficial for low Reynolds number aerodynamic applications such as unmanned aerial vehicles and small aircraft wings.

V. AUTHOR'S CONTRIBUTION

Conceptualization: V T Gopinathan, Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Methodology: Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Investigation: Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Discussion of results: V T Gopinathan, Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Writing – Original Draft: V T Gopinathan, Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Writing – Review and Editing: V T Gopinathan, Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S

Resources: Benadic Richard A, Hariharan V, Meivarma J P, Sivabalan S.

Supervision: V T Gopinathan.

Approval of the final text: V T Gopinathan.

VI. REFERENCES

- [1] R. K. Edel and H. E. Winn, "Observation of underwater locomotion and flipper movement of the Humpback Whale Megaptera Novaeangliae," *Mar. Biol.*, vol. 48, pp. 279–287, 1978.
- [2] F. E. Fish and J. M. Battle, "Hydrodynamic design of the humpback whale flipper," *J. Morphol.*, vol. 225, pp. 51–60, 1995.
- [3] E. F. Frank, W. W. Paul, M. M. Mark, and E. H. Laurens, "The tubercles on humpback whales' flippers: application of bio inspired technology," *Integr. Comp. Biol.*, vol. 51, pp. 203–213, 2011.
- [4] P. Watts and F. E. Fish, "The influence of passive, leading edge tubercles on wing performance," in *Proc. 12th Int. Symp. Unmanned Untethered Submersible Technol. (UUST)*, Lee, NH, 2001.
- [5] D. Custodio, C. W. Henoch, and H. Johari, "Aerodynamic characteristics of finite span wings with leading-edge protuberances," *AIAA J.*, vol. 53, pp. 1878–1893, 2015.
- [6] M. D. Bolzon, R. M. Kelso, and M. Arjomandi, "Tubercles and their applications," *J. Aerosp. Eng.*, vol. 29, pp. 1–10, 2015.
- [7] K. L. Hansen, N. Rostamzadeh, R. M. Kelso, and B. B. Dally, "Evolution of stream wise vortices generated between leading edge tubercles," *J. Fluid Mech.*, vol. 788, pp. 730–766, 2016.
- [8] T. Islam, M. M. H. Mehedi, M. S. B. Zaman, M. R. Ahmed, and M. E. Hoque, "Numerical investigation on modified NACA 2412 airfoil with sinusoidal leading edge and the effect of its amplitude and wavelength," *Mech. Eng. Renew. Energy*, 2021.
- [9] G. Moscato, J. Mohamed, and G. P. Romano, "Improving performances of biomimetic wings with leading edge tubercles," *Exp. Fluids*, vol. 63, no. 146, 2022.

- [10] Z. Wei, T. H. New, and Y. D. Cui, "Aerodynamic performance and surface flow structures of leading-edge tubercled tapered swept-back wings," *AIAA J.*, vol. 56, no. 1, pp. 423–431, 2018.
- [11] A. C. Hernanz and T. Janshon, "Investigating the Tubercle Effect on the NACA 24xx airfoil series: Investigation Using Ansys Fluent," AIAA Student Member Paper, 2021.
- [12] M. D. Bolzon, R. M. Kelso, and M. Arjomandi, "Force measurements and wake surveys of a swept tubercled wing," *J. Aerosp. Eng.*, vol. 30, no. 3, p. 04016085, 2017.
- [13] V. T. Gopinathan, J. B. R. Rose, and M. Surya, "Investigation on the effect of leading edge tubercles of sweptback wing at low reynolds number," *Mech. Ind.*, vol. 21, p. 621, 2020.
- [14] T. P. Chong et al., "Aeroacoustic and Aerodynamic Performances of an Airfoil Subjected to Sinusoidal Leading Edges," in *Proc. AIAA Aviat. Forum*, 2015.
- [15] H. McMorris and Y. Kallinderis, "Octree-advancing front method for generation of unstructured surface and volume meshes," *AIAA J.*, vol. 35, pp. 976–984, 1997.
- [16] A. Skillen, A. Revell, A. Pinelli, U. Piomelli, and J. Favier, "Flow over a wing with leading-edge undulations," *AIAA J.*, vol. 53, pp. 464–472, 2015.
- [17] V. T. Gopinathan, J. B. R. Rose, V. Gokul, and K. Kamalahasan, "Numerical investigation of the effect of leading edge Tubercles at low Reynolds number," in *Proc. Int. Heat Mass Transf. Conf. (IHMTTC)*, 2017, pp. 1055–1059.
- [18] M. D. Bolzon, R. M. Kelso, and M. Arjomandi, "Force measurements and wake surveys of a swept tubercled wing," *J. Aerosp. Eng.*, vol. 30, p. 04016085, 2017.
- [19] Z. Wei, T. H. New, L. Lian, and Y. N. Zhang, "Leading-edge tubercles delay flow separation for a tapered swept-back wing at very low Reynolds number," *Ocean Eng.*, vol. 181, pp. 173–184, 2019.
- [20] M. D. Bolzon, R. M. Kelso, and M. Arjomandi, "Parametric study of the effects of a tubercle's geometry on wing performance through the use of the lifting-line theory," in *Proc. 54th AIAA Aerosp. Sci. Meet.*, San Diego, CA, USA, 2016.
- [21] K. Bang, J. Kim, and S. Lee et al., "Hydrodynamic role of longitudinal dorsal ridges in a leatherback turtle swimming," *Sci. Rep.*, vol. 6, p. 34283, 2016.
- [22] D. Wang et al., "Impact of Leading-Edge Tubercles on Airfoil Aerodynamic Performance and Flow Patterns at Different Reynolds Numbers," *Energies*, vol. 17, no. 21, p. 5518, 2024.
- [23] R. Bardera et al., "CFD Study of the Effect of Leading-Edge Tubercles on Wing Aerodynamics," *Elsevier*, 2024.
- [24] P. V. Badia et al., "Dynamic Stall on Airfoils with Leading-Edge Tubercles," *Exp. Fluids*, 2025.
- [25] S. Hu, "Effect of the Leading-Edge Tubercles on the Aerodynamic Flow Control," *ASCE*, 2025.
- [26] O. Usta, S. Öksüz, and F. Çelik, "Effect of Leading-Edge Tubercles and Surface Corrugations on the Performance and Cavitation Characteristics of Twisted Hydrofoils," *Ocean Eng.*, vol. 335, p. 121663, 2025.