

Validated Computational Analysis and Airfoil Optimization for Fixed-Wing UAV using XFLR5 and Boundary-Layer-Resolved CFD

Rebaz Omer Abdalla

Department of Mechanical and Mechatronics, College of Engineering,
Salahaddin University, Erbil, Kurdistan Region, Iraq.

Email: rebaz.abdalla@su.edu.krd

Prof. Dr. Iyd Eqqab Maree

Department of Aviation Engineering, College of Engineering, Salahaddin
University, Erbil, Kurdistan Region, Iraq

Email: iyd.maree@su.edu.krd

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ABSTRACT

This study introduces a validated and systematic framework for the aerodynamic analysis and optimization of airfoils specifically designed for medium-altitude long-endurance (MALE) fixed-wing unmanned aerial vehicles (UAVs). Seven airfoils—CLARK-Y, E-387, RG-15, MH-32, NACA 2415, NACA 23015, and NACA 4415—were evaluated at a Reynolds number of 1×10^6 utilizing XFLR5, which is based on the XFOIL panel method. The NACA 4415 airfoil was identified as the optimal candidate for detailed high-fidelity analysis based on its lift-to-drag performance and stall characteristics. Subsequent Computational Fluid Dynamics (CFD) simulations were performed using ANSYS Fluent, utilizing the standard SST $k-\omega$ model, which assumes fully turbulent flow, alongside the SST-Transition model that integrates transition-sensitive transport equations to address the evolution of laminar-to-turbulent boundary layers. The simulations enabled precise characterization of flow separation, boundary layer development, and post-stall aerodynamic behaviour over a wide range of angles of attack. Numerical results have been validated with experimental data obtained from the 3×5 ft and 7×10 ft subsonic wind tunnels at Ohio State University. The SST-Transition model demonstrated superior predictive accuracy, with deviations remaining within 10% during the pre-stall regime and closely aligning with post-stall trends. XFLR5

showed efficiency in initial airfoil screening; however, it significantly underestimated drag at elevated angles owing to inviscid assumptions. The integrated methodology demonstrates high reliability for selecting and refining airfoil geometries in UAV design, offering improved aerodynamic efficiency, extended endurance, and enhanced flight stability.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have become essential across several sectors due to their versatility, efficiency, and capability to operate in hazardous or inaccessible environments. UAV technology is rapidly advancing due to its many applications in agriculture, surveillance, disaster management, and logistics. The increasing need for enhanced performance, stability, and durability, together with a diverse array of configurations, has led to a growth of innovative UAV designs (Zou et al., 2006). Selecting an airfoil is crucial in the design process since it directly influences lift, drag, manoeuvrability, and flight stability. Certain airfoil configurations excel in generating lift at low speeds, making them suitable for accurate movements and prolonged staying durations. Others excel in high-speed flying and range efficiency (Zhonghua et al., 2021).

UAVs are categorized into various groups according to the configuration of their wings. These include fixed-wing, flapping-wing, ducted-fan, and multirotor systems such as tricopters and quadcopters (Beard et al., 2005, Ehsani et al., 2014). Fixed-wing UAVs, particularly Medium-Altitude Long-Endurance (MALE) variants, must possess optimal aerodynamic efficiency to provide enough lift, minimal drag, and stable flight, dependent upon their mission profile and operational circumstances. Selecting the appropriate airfoil is crucial for optimizing UAV performance (Zhang, 2024).

Previous studies have explored various aspects of UAV wing design and aerodynamic performance. Andrews et al. (2015) developed a conceptual wing weight model that integrated finite-element structural analysis with a nonplanar vortex-lattice aerodynamic solver. This enabled the rapid and precise estimation

of the weight of both conventional and nonplanar wing configurations. Kuntjoro et al. (2012) used superelement modelling to analyze the static stress and deflection of a fighter wing. They compared practical and theoretical methodologies, including traditional finite element analysis and superelement finite element analysis with NASTRAN software. The findings indicated that all strategies functioned well in conjunction.

Studies specific to UAV aerodynamic efficiency at low Reynolds numbers have also advanced. Alsahlan and Rahulan (2017) developed and enhanced 12 novel airfoils, including ZMR-19 and ZMR-26, for aft-swept flying-wing UAVs using a MATLAB-based tool and a genetic algorithm. They targeted minimal pitching moments and maximal aerodynamic efficiency at low Reynolds numbers. The new airfoils exhibited an improved lift-to-drag ratio compared to the previous models; nevertheless, their performance deteriorated as their thickness increased. Durmuş (2023) Utilised XFLR5 to evaluate MH60, TL54, Eppler 339, and TsAGI 12% airfoils for tailless flying wing UAVs. MH60 and TL54 exhibited the highest aerodynamic efficiency, with maximum lift-to-drag ratios of 33.1 and 32.7, respectively. They also discovered that MH60 and TsAGI had a 12% superior capability in maintaining pitch stability compared to TL54 and Eppler 339. Antonio and Yan (2023) used XFLR5 to examine undercambered airfoils and four distinct tail configurations for a 30 kg UAV capable of transporting a 5 kg payload at low Reynolds numbers. They examined lift, drag, and stability to determine the optimal combination. The findings indicated that the Eppler 216 airfoil with a conventional tail provided the most lift and optimal stability for flight at low altitudes and subsonic speeds.

Experimental and CFD-based methods are increasingly used in aerodynamic validation. Liu and Nishino (2018) used computational fluid dynamics to study oscillating stall cells on the NACA 0012 airfoil. They found that these oscillations are closely related to changes in lift, and they proved this with proper orthogonal decomposition (POD) research. Similarly, Shams et al. (2020) developed a comprehensive methodology for the selection and evaluation of airfoils for a flying wing micro aerial vehicle (FWMAV). Eppler 387 was identified as the most efficient reflexed airfoil according to its aerodynamic efficiency and stability

parameters. Wind tunnel studies were conducted at 20 m/s using a 6-DOF body-axis model to evaluate the aerodynamic performance, control efficacy, and flight stability of the FWMAV. They conducted many successful flying tests despite encountering issues such as left roll induced by propeller impacts.

Despite these efforts, a comprehensive and consistent comparison of various UAV-compatible airfoils using a singular simulation and validation methodology remains absent. Most prior research either examine a single airfoil or use disparate methodologies that complicate comparisons. Furthermore, several studies fail to integrate low-fidelity panel techniques, high-fidelity CFD models, and empirical wind tunnel experiments.

This work aims to address this gap by examining and comparing seven airfoils—CLARK-Y, E-387, RG-15, MH-32, NACA-2415, NACA-23015, and NACA-4415—at a Reynolds number of 1×10^6 , consistent with the operational conditions of MALE UAVs. This work establishes a robust methodology for selecting airfoils by integrating XFLR5, sophisticated computational fluid dynamics (utilizing SST $k-\omega$ and SST-Transition turbulence models), and validating the findings with wind tunnel data from Ohio State University. The objective is to identify the optimal airfoil that achieves a balance among aerodynamic efficiency, stall characteristics, and transitional boundary layer properties. This will enhance the UAV's endurance, control, and overall flying performance.

2. Material and Methods

2.1 Airfoil Selection

This research analyses a Middle Altitude Long Endurance (MALE) UAV. Equivalent UAVs are examined to get technical details. Table 1 presents the UAVs and the planned UAV.

Table (1): Similar Aircraft Technical Specifications and Proposed UAV

Category	1-Scan Eagle	PENGUIN B	PENGUIN C Mk 2 UAS	YANGDA FW-320	YANGDA Sky Whale Mini	SKYLANE-320	Proposed UAV
Max Speed (m/s)	41	36	31	27	33	30	25

Altitude (m)	5950	4000	5000	3500	3500	3800	4290
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The UAV's concept design has been developed based on the assumption of the t/c ratio. For this investigation, the assumption has been established as $t/c > 14\%$. Based on this premise, seven airfoils have been selected. Chosen airfoils are named (CLARK Y, E-387, RG-15, MH-32, NACA 2415, NACA 4415, NACA 23015) Airfoil profiles are given in figure 1.

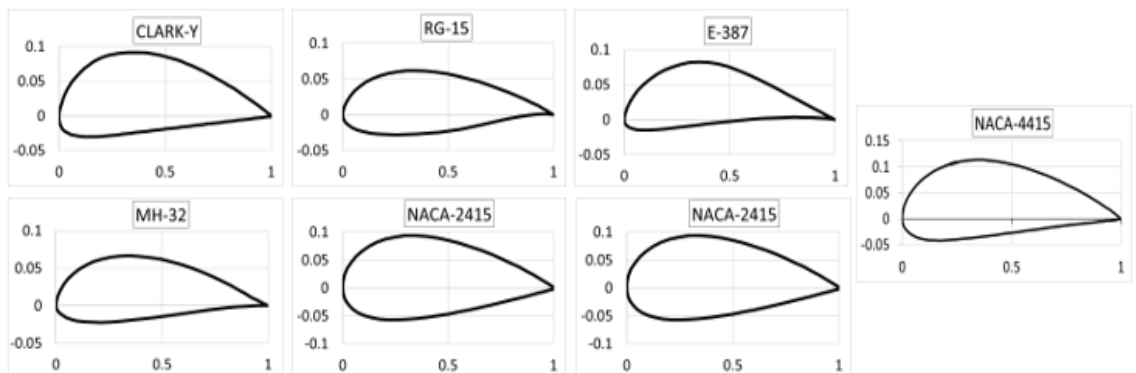


Figure (1): Airfoil Profiles

2.2 Wing Geometry and Reynolds Number

The Reynolds number, a key indicator of flow behavior over the wing, was calculated using Eq. (1):

$$Re = \frac{\rho V C}{\mu} = \frac{V l}{\nu} \quad \text{Eq. (1)}$$

Based on standard sea-level conditions (15°C) and the parameters listed in Table 2, the calculated Reynolds number is approximately 1.0×10^6 . This value was used to evaluate the aerodynamic performance of small-scale UAV configurations. From the UIUC airfoil database of over 170 high-lift airfoils, seven were selected for detailed analysis. A two-dimensional aerodynamic study was conducted using XFLR5 to assess their lift and efficiency characteristics, providing insight into their suitability for fixed-wing UAV applications.

Table (2): Fixed Parameters using Standard Sea-Level Conditions (15°C)

Air density ρ (kg/m ³)	Free stream velocity V(m/s)	Chord length c(m)	Dynamic viscosity μ (kg/m·s)	Kinematic viscosity ν (m ² /s)
1.225	25	0.58	1.7894×10^{-5}	1.46×10^{-5}

2.3 Aerodynamic Analysis by Computational Fluid Dynamics Method

Designing flying things requires precise knowledge of the lift and drag coefficients. Due to the high costs and restricted application of experimental work, numerical approaches have advanced in recent years. The reduced cost, increased speed, and capacity to accurately replicate complex geometries and operating situations make numerical simulations optimal choices for aerodynamic assessments. Comparable to several scholars and institutions, Similar to NASA, we have performed our aerodynamic simulations using the numerical simulation tool Fluent software (Zou et al., 2006).

2.3.1 Aerodynamic Theory and Modeling

Two models, namely SST-transition and k- ω shear stress transport (SST) models, are taken into consideration. For every turbulence model, the lift (CL) and drag (CD) coefficients are calculated for attack angles (AOA) between 0 and 16.2. The results are then compared with data from XFLR5's CL versus AOA and CD vs AOA testing, as well as the wind tunnel experiments performed by Ohio State University (Reuss et al., 1995).

2.3.2 Simulation Assumptions

Prior to proceeding with the 2D simulations, several assumptions are established (Siddiqi and Lee, 2019).

- The flow is considered incompressible due to the UAV's maximum cruise speed being significantly below Mach 0.3. This indicates that the air density remains constant.
- The properties of air under standard conditions are utilised.

- The 2D simulations were set at a Reynolds number of 1×10^6 to match wind tunnel data, using the coupled pressure–velocity scheme and Green–Gauss cell-based gradient option in Fluent.

Two-dimensional (2D) simulations are still a commonly used and computationally effective method, especially in the early phases of UAV design, even though complete three-dimensional (3D) wing modelling provides thorough aerodynamic knowledge. 2D simulations were used in this work to analyze important aerodynamic characteristics as lift, drag, and flow separation as well as to compare against data from wind tunnels. This method yields useful sectional data, but it excludes 3D effects like spanwise flow and wingtip vortices. To expand on these results, future research will use lifting-line theory or full-span 3D CFD.

2.3.3 Turbulence Solver and Governing Equations

The SST $k-\omega$ and SST-Transition turbulence models are used to predict boundary layer evolution, flow detachment, and transition events on airfoil surfaces. The governing transport equations for turbulent kinetic energy, specific dissipation rate, intermittency, and momentum-thickness Reynolds number are numerically solved within ANSYS Fluent as part of the CFD simulation process. The SST model integrates near-wall $k-\omega$ and free-stream $k-\epsilon$ formulations, while the SST-Transition model includes transition-sensitive parameters to improve predictability in low Reynolds number aerodynamic situations. (Sarkar and Bangalee, 2024):

$$\begin{aligned} \text{Turbulent kinetic energy (k):} \quad & \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P_k - \beta^* \rho k + \\ & \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad \text{Eq. (2)} \\ \text{Specific dissipation rate (\omega):} \quad & \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \right. \\ & \left. \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] \quad \text{Eq. (3)} \end{aligned}$$

The SST-Transition model incorporates two additional equations into the SST framework to represent the transition from laminar to turbulent flow (Menter et al., 2006):

$$\text{Intermittency } (\gamma): \frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\gamma \mu_t) \frac{\partial \gamma}{\partial x_j} \right] \quad \text{Eq. (4)}$$

Momentum thickness Reynolds number $Re_{\theta t}$:

$$\begin{aligned} \frac{\partial(\rho Re_{\theta t})}{\partial t} + \frac{\partial(\rho u_j Re_{\theta t})}{\partial x_j} &= P_{Re_{\theta t}} \\ &+ \frac{\partial}{\partial x_j} \left[\sigma_{\theta t} (\mu + \mu_t) \frac{\partial Re_{\theta t}}{\partial x_j} \right] \end{aligned} \quad \text{Eq. (5)}$$

Transition activation adjusts the eddy viscosity: $\mu_t = \gamma \mu_{t,SST}$
 Eq. (6)

2.3.4 Mesh Quality and y^+ Analysis

To ensure accurate near-wall resolution, the mesh was generated with a first-layer height of $y=3.6984 \times 10^{-6}$ m, resulting in a non-dimensional wall distance of approximately $y^+ \approx 0.03$. This satisfies the wall-resolved requirements for SST and SST-Transition turbulence models, where:

$$y^+ = \frac{y \cdot u_\tau}{\nu}$$

Eq. (7)

$$u_\tau \approx U_\infty \cdot \sqrt{\frac{0.0225}{\sqrt{Re_x}}}$$

Eq. (8)

The key flow parameters used for this estimation are summarized in Table 3.

Table (3): Fixed Flow Parameters Used in y^+ Estimation

Reynold number Re	Free stream velocity U_{∞} (m/s)	Kinematic viscosity ν (m ² /s)
1.0×10^6	25	1.46×10^{-5}

the estimated friction velocity was $u_{\tau} = 0.1185\text{m}$, yielding y^+ values below 0.7 across the airfoil surface mostly between 0.03–0.3. With mesh quality above 0.98, the setup follows recommended best practices for accurate low-Reynolds-number simulations (Menter et al., 2006)

3. Result and discussion

3.1 Airfoil Selection Criteria and Initial Screening (XFLR5)

A preliminary aerodynamic assessment was performed on seven chosen airfoils—CLARK-Y, E-387, MH-32, NACA 23015, NACA 2415, NACA 4415, and RG-15—to analyze their performance at a Reynolds number of 1×10^6 across different angles of attack (AoA). This investigation used XFLR5, a computational technique derived from XFOIL, which employs a linear strength panel approach integrated with viscous boundary-layer adjustments. XFLR5 is well designed for aerodynamic assessments at low to moderate Reynolds numbers and has been extensively used in the first phases of airfoil analysis for unmanned aerial vehicles (UAVs).

This current study assessed the drag characteristics of seven airfoils at a Reynolds number of 1×10^6 across several angles of attack (AoA). Figure 2 illustrates that the RG-15 demonstrated the minimal drag between 2° and 4° , indicating efficiency under cruising circumstances. The NACA 4415 exhibited reduced drag throughout a broader angle of attack range, particularly from 4° to 16° , owing to its camber and thickness that facilitate consistent laminar flow and diminish boundary layer separation. Conversely, CLARK-Y and MH-32 exhibited significant drag increases beyond 10° , indicating premature flow separation. The RG-15 has a more pronounced increase in drag at elevated angles of attack compared to the NACA 4415, while the E-387 shows increased drag about 7° ,

most likely due to laminar separation bubbles or premature boundary layer transition, hence diminishing its efficiency.

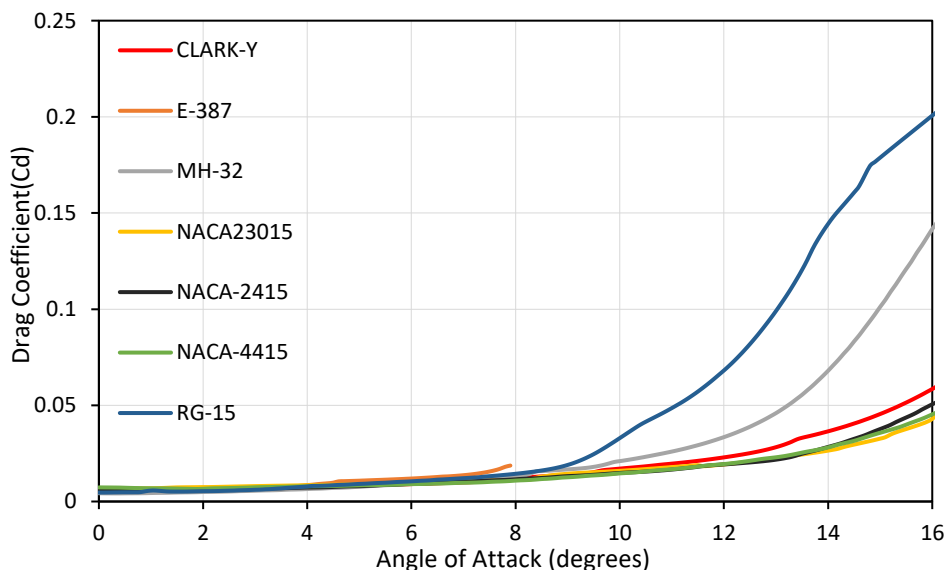


Figure (1): Drag Coefficient with Angle of attack

As illustrated in Figure 3, the NACA 4415 exhibited superior lift performance, owing to its moderate camber and thickness, which facilitate the establishment of suction peaks and prolong flow separation, thereby enhancing aerodynamic stability. The CLARK-Y airfoil demonstrated similar lift performance because to its simple shape and consistent boundary layer properties, making it a suitable choice for UAV applications. The NACA 2415 had a linear lift response but demonstrated suboptimal performance at elevated angles of attack. The E-387 had an unexpected stall, limiting its operating range. Laminar-flow airfoils,

including MH-32 and RG-15, shown premature separation. The NACA 23015 produced moderate lift but was deficient in high-lift performance.

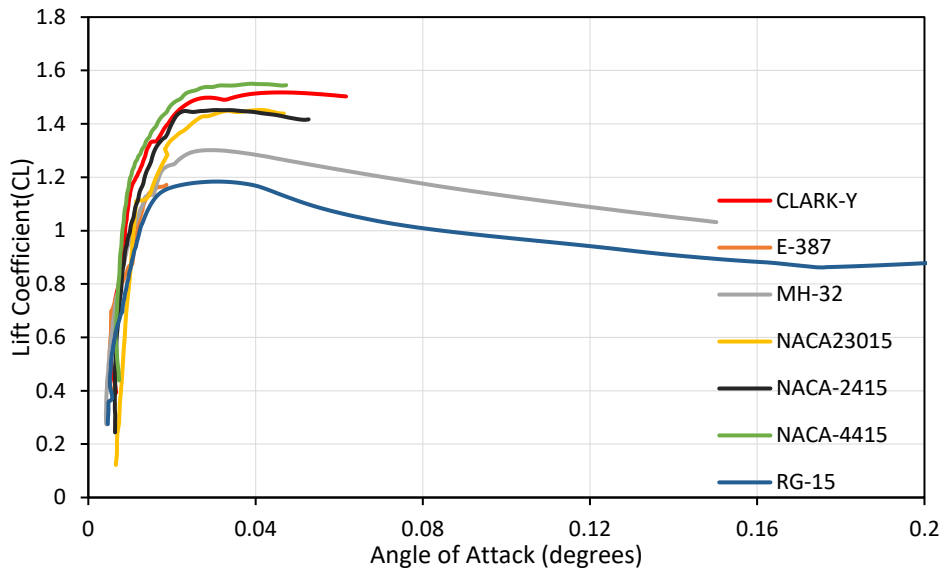


Figure (2): lift coefficient with Angle of attack

Figure 4 illustrates the lift-to-drag ratio (CL/C_d) of seven airfoils at a Reynolds number of 1,000,000 over angles of attack ranging from 0° to 16.2° . The NACA 4415 is distinguished by its constantly elevated CL/C_d ratios and stable, gradual stall characteristics, making it optimal for reliable handling in training and general aviation. Despite the E-387 attaining the greatest peak CL/C_d , it has a significant performance decline and rapid stall beyond its critical angle. CLARK-Y exhibits comparable stall development but decreased sustained efficiency relative to NACA 4415. MH-32 and RG-15 exhibit diminished aerodynamic efficiency and accelerated post-peak drops, limiting their applicability throughout extensive operating ranges. NACA 4415 provides the optimal equilibrium of efficiency, stall delay, and dependable performance under varied situations.

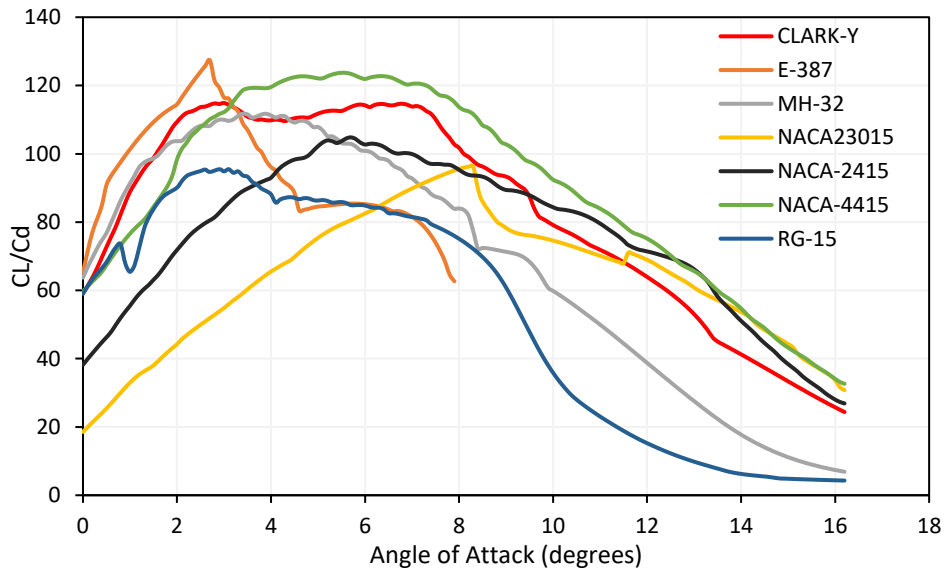


Figure (4): lift-to-drag ratio (CL/Cd) with angle of attack

3.2 Bridging Simulation Domains (Transition to CFD and Experimental Validation)

XFLR5 offers significant preliminary airfoil analysis; nevertheless, its inviscid-core assumption constrains the precision of stall predictions. NACA 4415 proved to be ideal, demonstrating balanced lift, efficiency, and steady stall characteristics. Validation using computational fluid dynamics and wind tunnel tests affirmed its strong aerodynamic performance.

The validation framework consisted of:

- RANS simulations conducted in ANSYS 2D Fluent, using both the SST $k-\omega$ and SST-Transition turbulence models to illustrate various aspects of boundary layer behaviour;
- The 3×5 ft and 7×10 ft subsonic wind tunnels at Ohio State University (OSU) were used to get experimental data for the NACA 4415 airfoil. This data serves as dependable empirical standards for aerodynamic validation. The 3×5 ft tunnel generated a comprehensive dataset, including lift, drag, and the lift-to-drag (CL/Cd) ratio at various angles of attack. The 7×10 ft tunnel provided just lift data, without

measurements for drag or lift-to-drag ratio (Reuss et al., 1995, Somers, 1999);

- A comparative analysis of the lift coefficient (CL), drag coefficient (Cd), and aerodynamic efficiency (CL/Cd) curves derived from models and experimental data.

3.3 Comprehensive Validation of CFD and Semi-Empirical Methods for Predicting Lift Coefficient on the NACA 4415 Airfoil

Three numerical methods were utilised to assess the lift coefficient (CL) of the NACA 4415 airfoil at $Re = 1 \times 10^6$: the SST Transition and SST k- ω turbulence models in ANSYS Fluent, and the XFLR5 (XFOIL-based) solver. Validation was conducted using experimental data from the 3×5 ft and 7×10 ft subsonic wind tunnels at The Ohio State University. Figure 5 illustrates that all methodologies demonstrated uniform CL trends throughout the 0°–16.2° angle of attack range; yet, significant quantitative discrepancies were detected. The SST Transition model exhibited enhanced consistency with the 7×10 wind tunnel data, with deviations confined to within 5% between 6.2° and 10.2°, owing to its precise representation of boundary-layer transition. Conversely, the SST k- ω model consistently underestimated CL by 10–15% over the majority of the range, attributable to its assumption of totally turbulent flow. The XFLR5 solver precisely represented pre-stall behaviour but overestimated lift by 10–15% after stall. The findings align with previous research, which indicated that computational lift estimates correlate well with actual results at low angles but diverge at higher angles owing to unmodeled surface flaws and flow complexity around the airfoil.(Sogukpinar and Bozkurt, 2015) Of all the evaluated

techniques, the SST Transition model provided the most precise and dependable lift predictions when compared to confirmed experimental data.

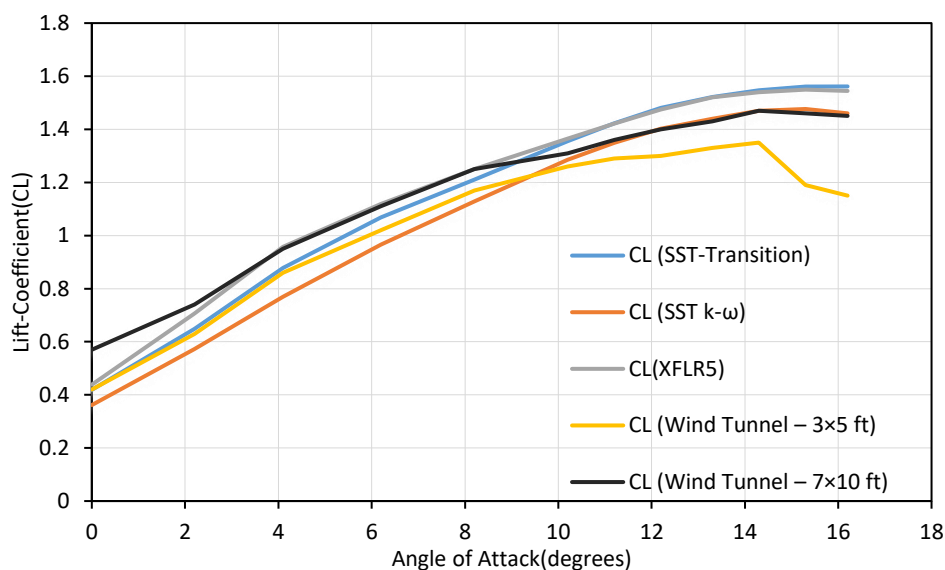


Figure (5): Lift coefficient of the computational and experimental results

3.4 Comprehensive Validation of CFD and Semi-Empirical Methods for Predicting Drag Coefficient on the NACA 4415 Airfoil

Three numerical methodologies were employed to evaluate the drag coefficient (C_d) of the NACA 4415 airfoil at $Re = 1 \times 10^6$: the SST Transition and SST $k-\omega$ turbulence models in ANSYS Fluent, and the XFLR5 (XFOIL-based) solver. These were compared against experimental data from the OSU 3×5 ft subsonic wind tunnel. Figure 6 illustrates that all methods demonstrated the anticipated nonlinear escalation in C_d with rising angle of attack (AoA); nonetheless, significant quantitative variations were seen across the range. The SST $k-\omega$ model consistently overestimated drag, with discrepancies reaching 18% in the pre-stall area, mostly owing to the assumption of totally turbulent boundary layers from the leading edge. Subsequent to the stall, it persisted in overestimating drag while exhibiting insufficient sensitivity to transitional effects. The SST Transition model exhibited the highest agreement with

experimental data, keeping errors below 10% in the pre-stall area and precisely depicting the abrupt increase in drag associated with flow separation

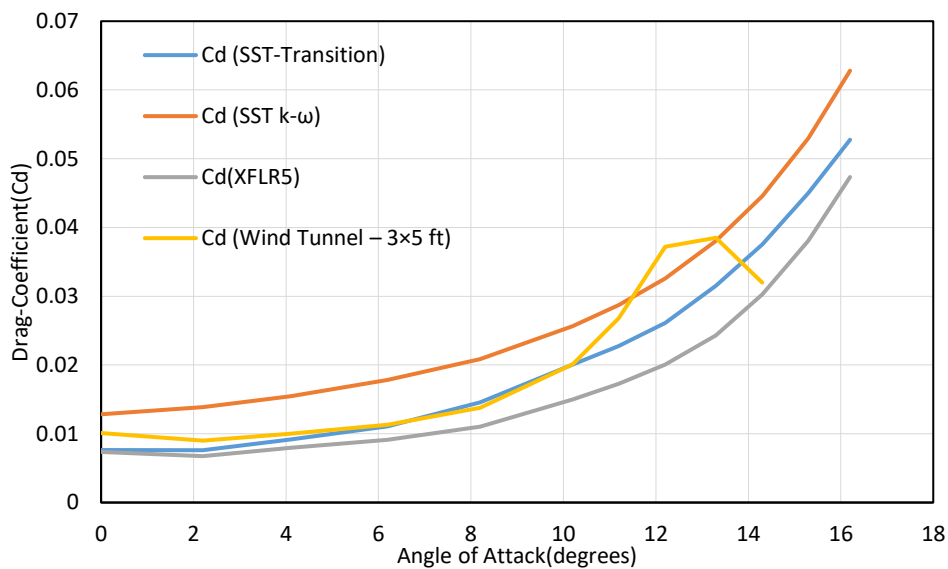


Figure (6): Drag coefficient of the computational and experimental results

The XFLR5 solver, constrained by its inviscid-core formulation and primitive boundary-layer modifications, underestimated drag across the angle of attack spectrum, with variances reaching 15% in the pre-stall area. Following stall onset, it failed to detect the abrupt rise in drag resulting from flow separation and wake turbulence. Conversely, the SST Transition model had the greatest overall accuracy in drag prediction. This finding aligns with other findings, notably those by NASA researchers, indicating that drag predictions—particularly at elevated angles of attack—frequently deviate from experimental outcomes owing to modelling constraints and flow intricacies (Shabur et al., 2020)

3.5 Comprehensive Validation of CFD and Semi-Empirical Methods for Predicting Aerodynamic Efficiency of the NACA 4415 Airfoil

Three numerical methods were used to assess the lift-to-drag ratio (CL/Cd) of the NACA 4415 airfoil at $Re = 1 \times 10^6$: the SST Transition and SST $k-\omega$ turbulence models in ANSYS Fluent, and the XFLR5 (XFOIL-based) solver. The simulations were compared with experimental data from the OSU 3×5 ft subsonic wind tunnel. Figure 7 illustrates that all methodologies demonstrated uniform aerodynamic efficiency patterns over the angle of attack range of 0° – 16.2° , with efficiency increasing to a maximum before subsequently decreasing owing to enhanced drag and flow separation. The SST Transition model produced the most precise findings, indicating a peak CL/Cd of around 97 at 6.2° , closely aligning with the wind tunnel maximum of 90 at the same angle, and sustaining variations within 10% throughout the pre-stall area. The XFLR5 solution achieved the greatest peak efficiency, around 125, owing to its underestimating of drag, while it failed to adequately represent post-stall behaviour. The SST $k-\omega$ model produced the lowest peak, around 55, due to persistently elevated drag and diminished lift predictions. The SST Transition model was determined to be the most dependable among those evaluated methodologies. It is crucial to acknowledge the inherent uncertainties involved with numerical simulations, even when there is a good connection between CFD findings and experimental data. These result from idealised boundary conditions, turbulence model assumptions, and mesh discretisation. In this work, mesh refinement, model validation, and solver sensitivity control were used to reduce these uncertainties. Nonetheless, the residual deviations observed—particularly in the SST $k-\omega$ and XFLR5 predictions—reflect the limitations of simplified modelling approaches and underscore the importance of uncertainty consideration in aerodynamic analysis.

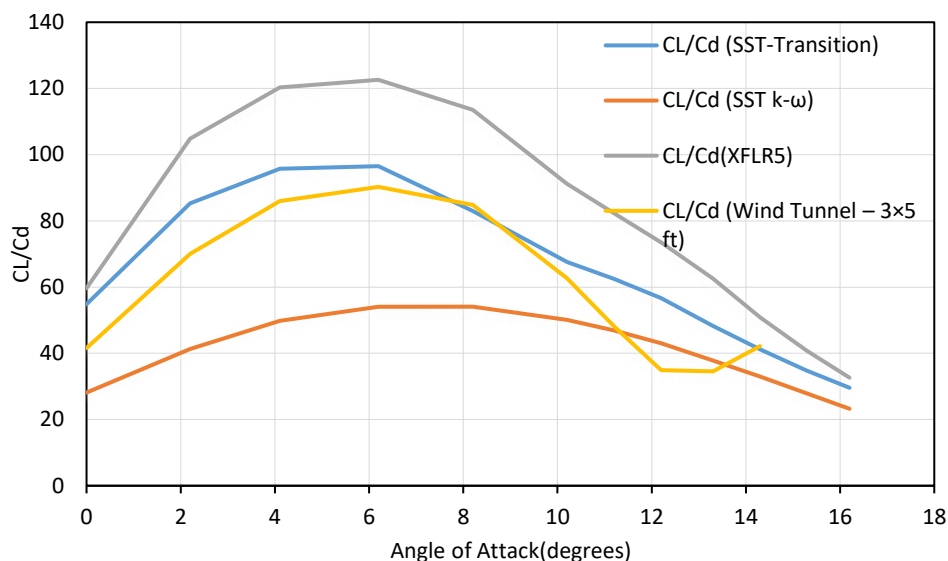


Figure (7): Lift to drag ratio of the computational and experimental results

3.6 Flow Field Dynamics and Transition Behavior (Pressure and Velocity Contour Characterization)

Contours of Static pressure and velocity were produced using the SST-Transition turbulence model, chosen for its proven efficacy in accurately duplicating experimental data over the operational angle of attack (AoA) spectrum. Figure 8 clearly illustrates the transformation of aerodynamic flow structures for angles of $\alpha = 0^\circ$, 8° , and 16.2° . At $\alpha = 0^\circ$, the flow stays entirely connected and symmetrical, with the stagnation point located at the leading edge. The static pressure distribution reveals a high-pressure area at the stagnation point and a gradual pressure recovery throughout both surfaces, while the velocity contour indicates acceleration across the top surface and a stable boundary layer, signifying little drag and consistent aerodynamic loading. At $\alpha = 8^\circ$, a laminar separation bubble develops on the top surface, indicated by a localized low-pressure region and a velocity deficit, subsequently followed by reattachment. This transitional behaviour indicates enhanced lift production accompanied by mild drag increase. At $\alpha = 16.2^\circ$, the flow transitions into profound stall. The

contours indicate an extensive area of flow separation and reversed velocity along the trailing edge, followed by a collapse of the suction peak. The pressure field becomes dispersed, indicating significant performance reduction and a decline in aerodynamic efficiency.

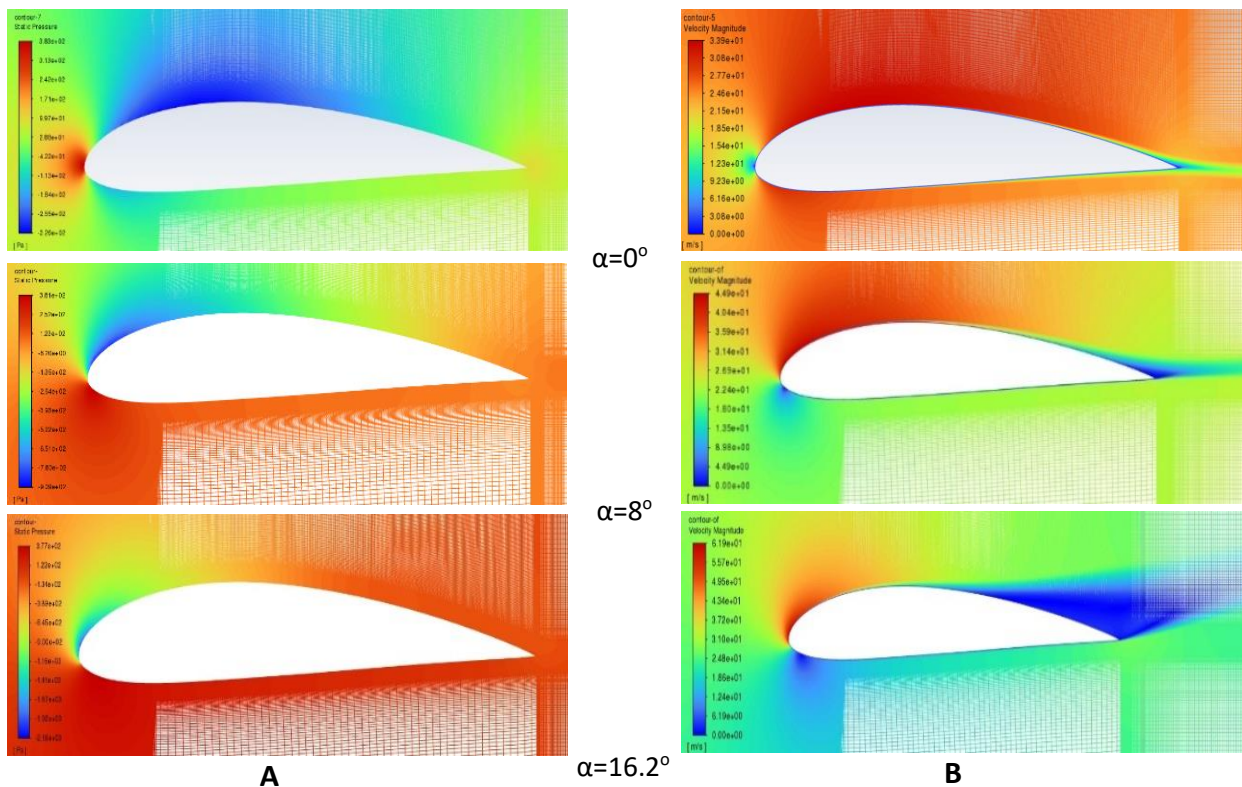


Figure (8): A. Contours of static pressure, B. Contours of velocity

4. Conclusion

This research performed an extensive aerodynamic assessment of seven potential airfoils for medium-altitude long-endurance (MALE) fixed-wing unmanned aerial vehicles (UAVs) functioning at a Reynolds number of 1×10^6 . A robust validation framework was established to evaluate airfoil performance across various flight conditions by integrating low-fidelity XFLR5 panel method predictions, high-fidelity Reynolds-Averaged Navier–Stokes (RANS) simulations, and experimental wind tunnel data from Ohio State University.

The NACA 4415 airfoil consistently exhibited exceptional aerodynamic performance throughout the configurations assessed. The mild camber and advantageous thickness distribution facilitated pronounced suction peaks, smooth pressure recovery, and prolonged boundary-layer separation, yielding elevated lift-to-drag ratios, steady stall characteristics, and aerodynamic efficiency at several angles of attack. These characteristics make it especially appropriate for UAV mission profiles that need prolonged endurance, agility, and consistent control. The comparison between the SST $k-\omega$ and SST-Transition turbulence models was essential to this investigation. The SST $k-\omega$ model yielded conservative estimates predicated on completely turbulent assumptions, but the SST-Transition model more precisely represented laminar-to-turbulent transition, separation onset, and post-stall dynamics. Its tighter alignment with wind tunnel results validated its superior forecasting abilities for transitional flow regimes characteristic of low Reynolds number UAV operations. This study illustrates the effectiveness of integrating transition-sensitive CFD modelling with initial aerodynamic screening to guide airfoil selection. The methodological framework and results confirm NACA 4415 as the superior MALE UAV airfoil and provide a validated, accessible methodology for future aerodynamic design and analysis in realistic flight situations.

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شیکاری حیساباتی په سه‌ندکراو و باشکردنی ئایرفویل بۆ فرۆکه‌ی بئرفۆکه‌وانی بال جیگیر به به‌کاره‌ینانی XFLR5 و CFD ی چینه سنوورییه‌کان

پوخته:

ئهم توێژینه‌وه بریتیه له تاقیکردنه‌وه‌ی باشترین جوړی ئیرفویل بۆ فرۆکه‌ی بئرفۆکه‌وانی بال جیگیر که بتوانیت له به‌رزیه‌کی مامناوه‌ندی بفریت بۆ ماوه‌یه‌کی درێژخایه‌ن، هه‌وت جوړی جیاواز له ئیرفویل تاقیکراوه‌ته‌وه که بریتین له CLARK-Y, E-387, RG-15, MH-32, (NACA 2415, NACA 23015, and NACA 4415) له رېنۆلدزی یه‌ک ملیۆن به‌به‌کاره‌ینانی، به‌رنامه‌ی xflr5 که پشت به میتۆدی پانیلی XFLR5 ده‌به‌ستیت. ئیرفویلی NACA 4415 وه‌ک باشترین ئیرفویل هه‌لبژێردرا بۆ تاقیکردنه‌وه‌ی وردتر، باشترین CL/CD ی هه‌بوو، زۆر به‌هێواشی توشی ستۆل بوو، له‌ توێژینه‌وه‌که‌دا دوو مۆدیلی جیاواز تاقیکرایه‌وه به‌ به‌رنامه‌ی ANSYS Fluent، که (SST k- ω) هه‌موو فلۆکه بریتیه له‌ تۆربلنت به‌لام SST- (Transition) له‌ ناوچه‌ی تۆربلنت بۆ ترانزیشن. ئهم سیموله‌شنه بریتیه له‌ ویناکردنیکی تایبه‌تی فلۆ سپیهره‌هیش و باونده‌ری لێیه‌رو سیفه‌تی ئیروڤدانامیکی پیش‌ستۆل له‌ مه‌ودایه‌کی دیاریکراوی گۆشه‌کان، مۆدیه‌کان راستاندنی بۆ کرا له‌ریگه‌ی داتای تاقیکاری OSU له‌ ویند ته‌نلی (3×5 ft and 7×10 ft)، مۆدیلی (SST-Transition) باشترین نه‌جامی پیشاندا که جیاوازیه‌کان له‌ مه‌ودای 10% مایه‌وه له‌ پیش‌ستۆل و وه‌ دوا‌ی ستۆل‌یش زۆر نزیک بوو له‌ داتای تاقیکاریه‌که، XFLR5 چوستیه‌کی زۆر باشی هه‌یه له‌ هه‌لبژاردنی سه‌ره‌تایی ئیرفویه‌کان به‌لام له‌ گۆشه‌ به‌رزه‌کاندا جیاوازی به‌رچاو هه‌بوو له‌ هاوکۆله‌کی دراگ، ئهم توێژینه‌وه‌یه ده‌کریت پشته‌ی پێه‌به‌ستیت بۆ هه‌لبژاردنی باشترین جوړی ئیرفویل له‌ دیزانی UAV، که باشترین چوستی ئیروڤدانامیکی و مه‌ودایه‌کی زۆری مانه‌وه له‌ ئاسماندا و باشترین جیگیری فرین ده‌دات به‌ فرۆکه‌ی بئرفۆکه‌وانه

دراسة حسابية مُعتمدة لتحليل وتحسين جناح الطائرة بدون طيار ذات التصميم الجناحي، باستخدام برنامج XFLR5 ومحاكاة ديناميكا الموائع المُحللة لطبقة الحدود

المُلخص:

تُقدّم هذه الدراسة إطاراً منهجياً ومُعتمداً لتحليل وتهيئة الأداء الهوائي لجنيحات الطائرات بدون طيار ذات الأجنحة الثابتة المصممة للطيران على ارتفاعات متوسطة ولفترات طويلة (MALE UAVs). تم تقييم سبعة أنواع من الجنيحات — CLARK-Y و E-387 و RG-15 و MH-32 و NACA 2415 و NACA 23015 و NACA 4415 — عند عدد رينولدز قدره $10^6 \times 1$ باستخدام برنامج XFLR5 المبني على طريقة ألواح XFOIL. وقد تم تحديد جناح NACA 4415 كأفضل مرشح لإجراء تحليل دقيق عالي الدقة استناداً إلى أدائه من حيث نسبة الرفع إلى السحب وخصائص الانهيار الهوائي (Stall). تم لاحقاً إجراء محاكاة ديناميكا الموائع الحسابية (CFD) باستخدام برنامج ANSYS Fluent، وتضمنت استخدام النموذج القياسي (SST k- ω) الذي يفترض الجريان المضطرب بالكامل، إلى جانب نموذج (SST-Transition) الذي يدمج معادلات نقل حساسة للانتقال الهوائي لمعالجة تطور طبقات الحدود من الجريان الصفحي إلى الجريان المضطرب. وقد مكّنت هذه المحاكاة من توصيف دقيق لانفصال الجريان، وتطور طبقة الحدود، والسلوك الهوائي بعد الانهيار عبر مجموعة واسعة من زوايا الهجوم. تم التحقق من النتائج العددية من خلال مقارنتها مع بيانات تجريبية تم الحصول عليها من نفق الرياح تحت الصوتي بقياس 5×3 قدم و 10×7 قدم في جامعة ولاية أوهايو. وقد أظهر نموذج (SST-Transition) دقة تنبؤية عالية، حيث بقيت الانحرافات ضمن حدود 10% خلال مرحلة ما قبل الانهيار، وتوافقت بشكل وثيق مع الاتجاهات الهوائية بعد الانهيار. أظهر برنامج XFLR5 كفاءة في الفحص الأولي للجنيحات، إلا أنه قلل بشكل ملحوظ من تقدير قوة السحب عند الزوايا المرتفعة بسبب افتراضاته غير اللزجة (inviscid). تُظهر المنهجية المتكاملة موثوقية عالية في اختيار وتحسين هندسة الجنيحات في تصميم الطائرات بدون طيار، مما يسهم في تحسين الكفاءة الهوائية، وزيادة زمن التحليق، وتعزيز استقرار الطيران.