Airfoil Analysis Report - NACA 4418/NACA2412/SeligS1223

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Project

Cefiro - SAE AeroDesign Standard

Analysis Objective:

The objective of this analysis is to evaluate the aerodynamic performance of the **NACA 4418/NACA2412/SeligS1223** airfoils under conditions representative of the expected flight environment of an aircraft intended for the **SAE AeroDesign Standard Class** competition. This airfoil is considered a potential candidate for the main wing of the aircraft, and its behavior in terms of lift, drag, and overall aerodynamic efficiency is analyzed using XFLR5. The goal is to determine whether the mentioned air foils meet the performance requirements for low-speed, high-lift flight typically encountered during takeoff, climb, and sustained flight in the mission profile defined by the competition.

This study is part of the **preliminary design phase** of the aircraft being developed by **Team Céfiro** from Tecnológico de Monterrey, Campus Guadalajara. By characterizing the airfoil's performance at relevant Reynolds numbers and angles of attack, this analysis contributes to informed decision-making in airfoil selection, which is a critical factor in achieving optimal aerodynamic performance and mission success.

Configuration (XFLR5 Input Parameters and Assumptions)

Wing Geometry:

-Wingspan = 2.4 m

-Aspect ratio = 3.5

-Wing Area = 1.65 m^2

-Wing chord = 0.69 m

Flight Conditions (Based on Guadalajara atmospheric conditions):

-Air desnsity (kg/m^3) = 1.06 kg/m^3

-Dynamic Viscosity (Pa*s)= 1.89*10^-5

-Takeoff airspeed = 15m/s

-Cruise airspeed = 16m/s

-Total Aircraft mass = 25kg (5kg structure + 20kg payload)

Estimated Reynolds:

Take off = $\frac{Air\ Density*\ Speed\ TakeOff\ *Wing\ Chord}{Dynamic\ Viscosity} = \frac{1.06\ kg/m^3\ *\ 15\ m/s\ *\ 0.69m}{1.89*10^{-5}} = 576,870\ R$

Cruise = $\frac{Air\ Density*\ Speed\ Cruise\ *Wing\ Chord}{Dynamic\ Viscosity} = \frac{1.06\ kg/m^3\ *\ 16\ m/s\ *\ 0.69m}{1.89*10^{-5}} = 615,328\ R$

Target Cl for take off and cruise:

To determine the required lift coefficient (Cl) for takeoff and cruise phases, the standard lift equation was used (*Lift Equation | Glenn Research Center | NASA*, 2023) :

$$L = Cl\ *\ \rho\ *\ V^2\ *\ A\ *\ 1/2$$

Based on the mission requirements of the SAE AeroDesign Standard Class, it was assumed that during takeoff, the lift force must exceed the aircraft's total weight at maximum payload capacity by a reasonable margin to ensure safe and effective liftoff. An 8% safety margin was applied to account for surface drag, wind gusts, and imperfect takeoff conditions.

Assumed parameters:

Air density (ρ)= 1.06 kg/m^3 (Guadalajara conditions)

Air speed take off (V) = 15 m/s

Air speed cruise(V) = 16 m/s

Wing Area (A) = 1.646 m^2

Maximum plane weight = 25kg (5kg aircraft + 20kg payload)

Required lift force (W) = $W * g = 25kg * 9.81m/s^2 = 245.25\ N$

Take off Cl estimation :

Applying the 8% safety margin:

$L = 245.25\ N * 1.08 = 264.87$

With this lift force calculated and using the lift equation, it is possible to estimate the needed lift coefficient in take off conditions, solving for Cl:

$$Cl = \frac{264.87N}{1.06*15^2*1.646*1/2} = 1.349 \simeq 1.3$$

Therefore, a Cl ≈ 1.3–1.35 is considered appropriate for takeoff. This value ensures a lift force about 8% greater than the aircraft's total weight, providing a minimal but sufficient safety margin for realistic operating conditions. Slightly higher Cl values may be beneficial under adverse conditions, but for the purpose of preliminary airfoil comparison, Cl = 1.3 is used as a reference.

Cruise Cl estimation:

For steady level flight at 16 m/s:, the following Cl was calculated:

$$Cl = \frac{245.25N}{1.06*16^2*1.646*1/2} = 1.098 \simeq 1.1$$

At Cl = 1.1 , the airfoil generates 245.56 N of lift, which perfectly balances the aircraft weight of 245.25 N. This confirms that Cl = 1.1 is appropriate for cruise, allowing the aircraft to maintain level flight efficiently without excessive drag or excess lift.

Airfoils analyzed:

-NACA 4418

-Selig S1223

- NACA 2412

Simulation Setup:

Reynolds: 610 000

Angle of attack range: -20° to 20°

Analysis type: 2D Airfoil analysis using Direct Foil Analysis (DFA)

Transition model: Natural transition with **N_crit = 7**, simulating typical moderate turbulence levels

Number of panels: 99

Turbulence model: XFLR5 default

Results NACA 4418

Lift Coefficient vs. Angle of Attack (*figure 1.1*)

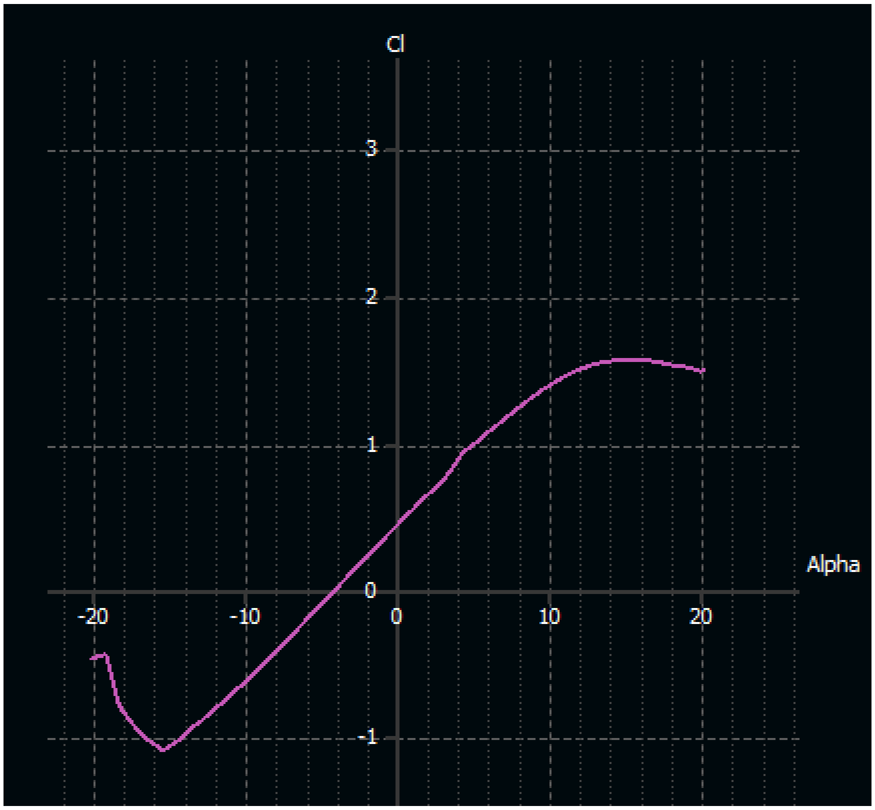

Figure 1.1 (NACA 4418 "Cl vs AoA")

Key findings:

At an angle of attack of 0°, the airfoil generates a lift coefficient (Cl) of approximately 0.45.

The airfoil reaches a Cl of **1.3** at an AoA of **8.5**°, which matches the lift requirement for **takeoff** as estimated in the flight condition analysis.

For **cruise conditions**, a Cl of **1.1** is required. This is achieved at an AoA of approximately **6.4**°.

The NACA 4418 demonstrates a well-defined linear lift region up to approximately **10**°, with stall occurring near **15**°, where the airfoil reaches a maximum lift coefficient (**Cl**) of about **1.57**. After this point, the Cl gradually decreases, forming a smooth post-stall curve, which indicates a **predictable and forgiving stall behavior** a desirable trait for stability and control in low-speed flight regimes.

Drag Polar (Cd vs. Cl) ***(figure 1.2)***

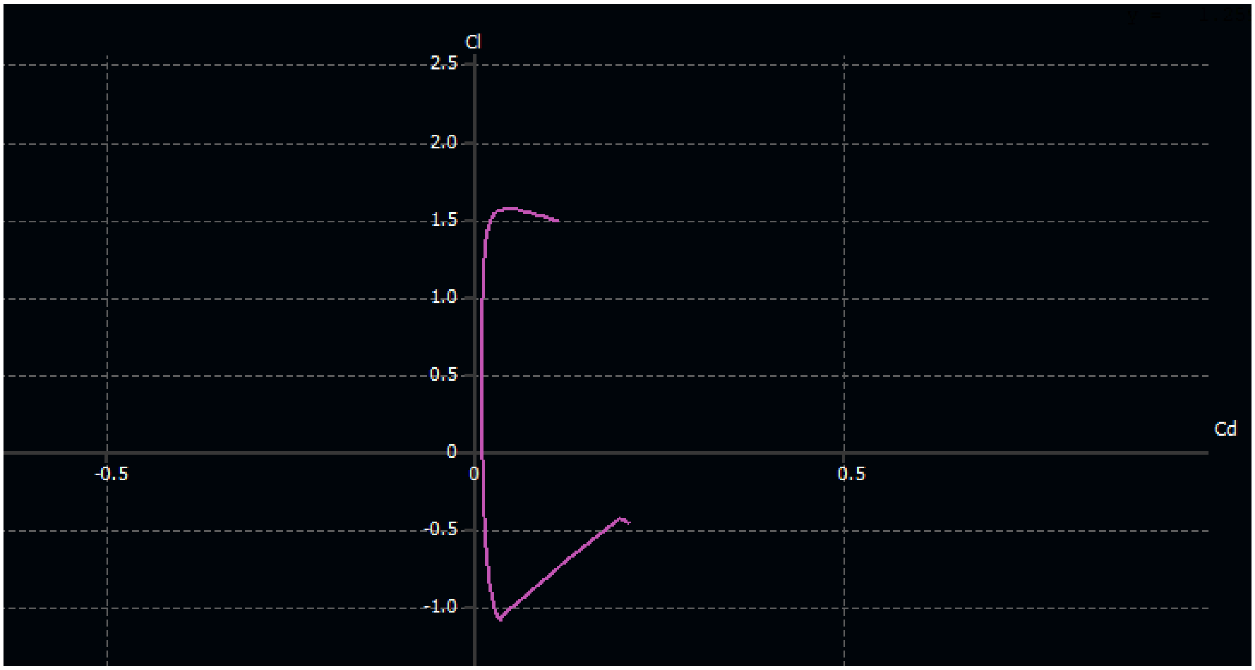

Figure 1.2 (NACA 4418 "Cd vs Cl")

Key findings:

The NACA 4418 airfoil exhibits a high lift-to-drag ratio (Cl/Cd) at low angles of attack, as the lift coefficient increases significantly while drag remains relatively low in the initial range. This behavior is favorable for cruise performance, where efficiency is a key parameter.

The maximum Cl/Cd ratio is achieved around **Cl = 1.55**, corresponding to a moderate angle of attack, making this the most efficient operating point for sustained flight.

Additionally, the drag polar curve displays a **smooth and gradual increase in drag** near stall, rather than a sharp break, indicating a **predictable and forgiving stall behavior**. This makes the NACA 4418 a reliable and stable choice for flight conditions with low Reynolds numbers, as typically encountered in SAE AeroDesign missions.

Efficiency (CL/CD) vs. Angle of Attack (*figure 1.3*)

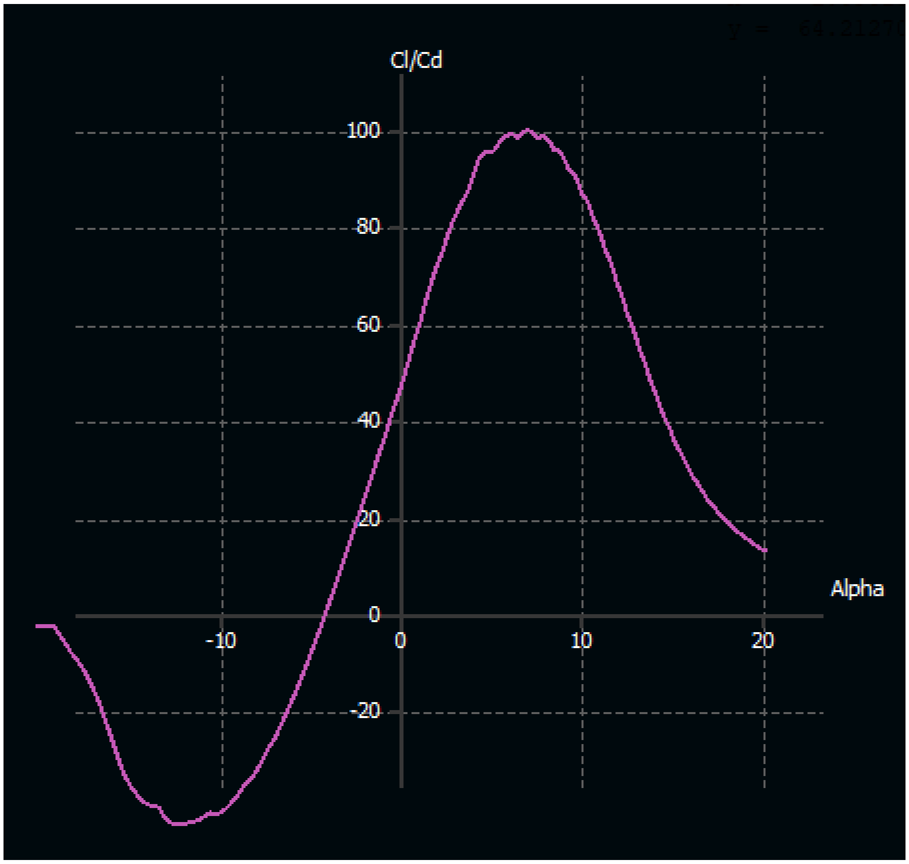

Figure 1.3 (NACA 4418 "Cl/Cd vs AoA")

Key findings:

The maximum aerodynamic efficiency (Cl/Cd) occurs at an angle of attack of approximately **6.8**°, making this the most efficient operating point for cruise or sustained flight.

This aligns closely with the required Cl for cruise (1.1), supporting the airfoil's suitability for this mission phase.

Cl vs. Xtr top (laminar flux on wing upper surface 0-1) (*figure 1.4*)

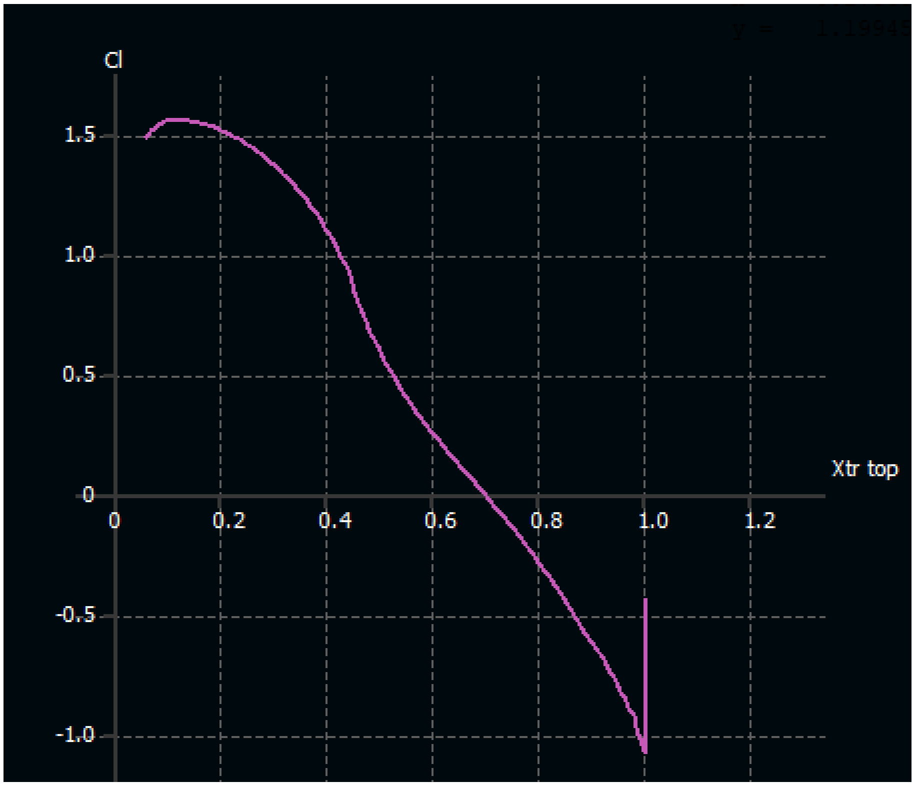

Figure 1.4 (NACA 4418 "Cl vs Xtr top")

Key findings:

At **Cl = 1.3** (takeoff condition), the transition point on the upper surface (**Xtr_top**) is located at approximately **0.34** (i.e., 34% of the chord from the leading edge), indicating early transition to turbulent flow, which slightly reduces efficiency.

At **Cl = 1.1** (cruise condition), **Xtr_top ≈ 0.40**, meaning the laminar flow extends further before transitioning, which reduces skin friction and contributes to better aerodynamic performance.

The **delayed transition** under cruise conditions is beneficial, as it reduces drag and improves overall efficiency.

Cm vs. Alpha (plane tendency to pitch) (*figure 1.5*)

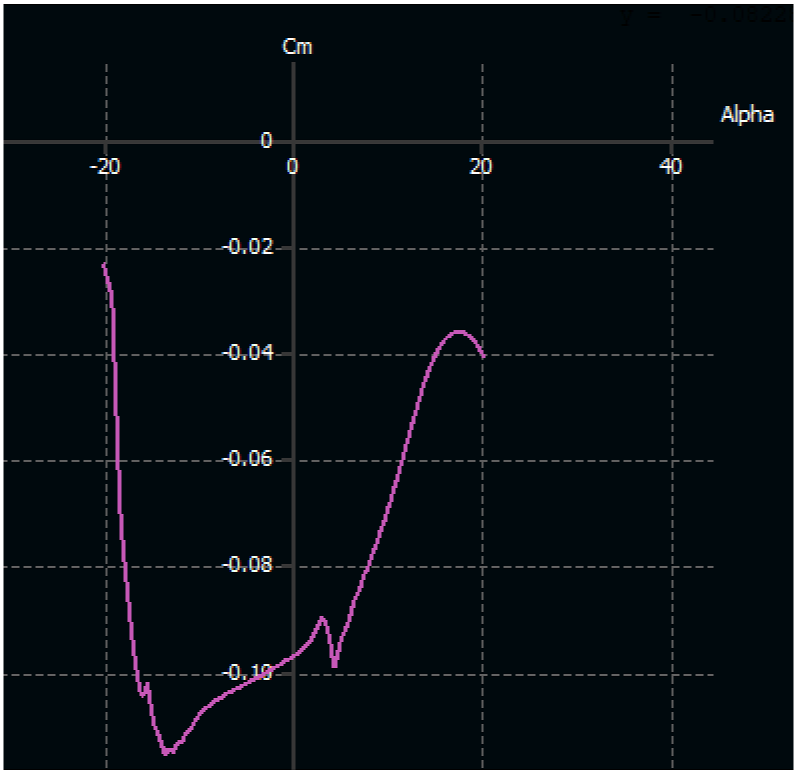

Figure 1.5 (NACA 4418 "Cm vs AoA")

Key findings:

The moment coefficient (Cm) remains negative across the entire angle of attack range, indicating that the NACA 4418 airfoil is inherently stable in pitch. Within the operational AoA range of 6° to 10°, which is being considered for cruise and sustained flight, Cm values remain between −0.089 and −0.068, increasing gradually and linearly.

This smooth and predictable trend suggests favorable longitudinal stability and control characteristics. While this preliminary result supports the airfoil's suitability, further analysis would be required to evaluate how these moment characteristics affect the sizing and airfoil selection of the horizontal stabilizer in the final aircraft configuration.

Results NACA 2412:

Lift Coefficient vs. Angle of Attack (*figure 2.1*)

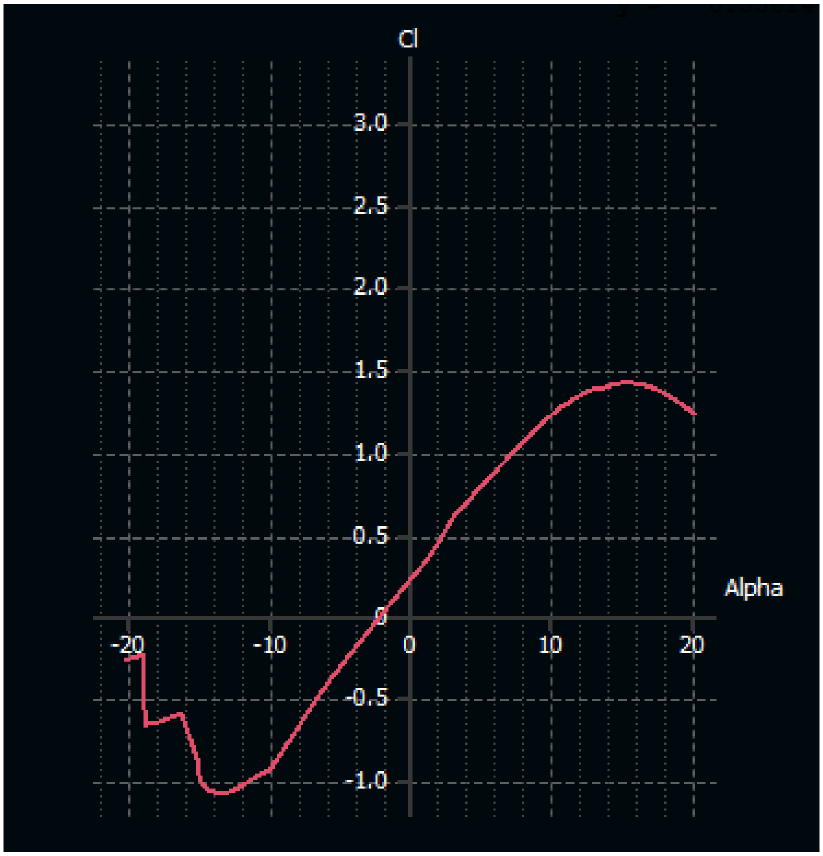

Figure 2.1 (NACA 2412 "Cl vs AoA")

Key findings:

At an angle of attack (AoA) of 0°, the NACA 2412 airfoil generates a lift coefficient (Cl) of approximately 0.23, which is significantly lower than that of the previously analyzed NACA 4418 (Cl ≈ 0.45). This suggests that the 2412 may be less efficient at generating lift at low AoA and could lead to reduced static stability, particularly in level flight or glide conditions.

The airfoil reaches the target Cl of 1.3 (required for takeoff) at an AoA of approximately 11°. This is notably higher than the 8.5° required by the NACA 4418. An AoA of 11° may be difficult to achieve within the aircraft's geometric and structural constraints, and could also result in increased drag and reduced performance during liftoff.

For cruise conditions, the required Cl of 1.1 is attained at an AoA of about 8.3°, compared to 6.4° for the 4418. This indicates that the 2412 operates at less efficient angles during sustained flight, potentially affecting aerodynamic performance and energy consumption.

Despite these limitations, the NACA 2412 exhibits a well-defined linear lift region up to approximately 13° AoA, with stall occurring near 15°, where the airfoil reaches a maximum Cl of 1.42. After stall, the Cl decreases gradually, forming a smooth and predictable post-stall curve, which is a desirable characteristic for stability and control in low-speed flight regimes.

Drag Polar (Cd vs. Cl) (*figure 2.2*)

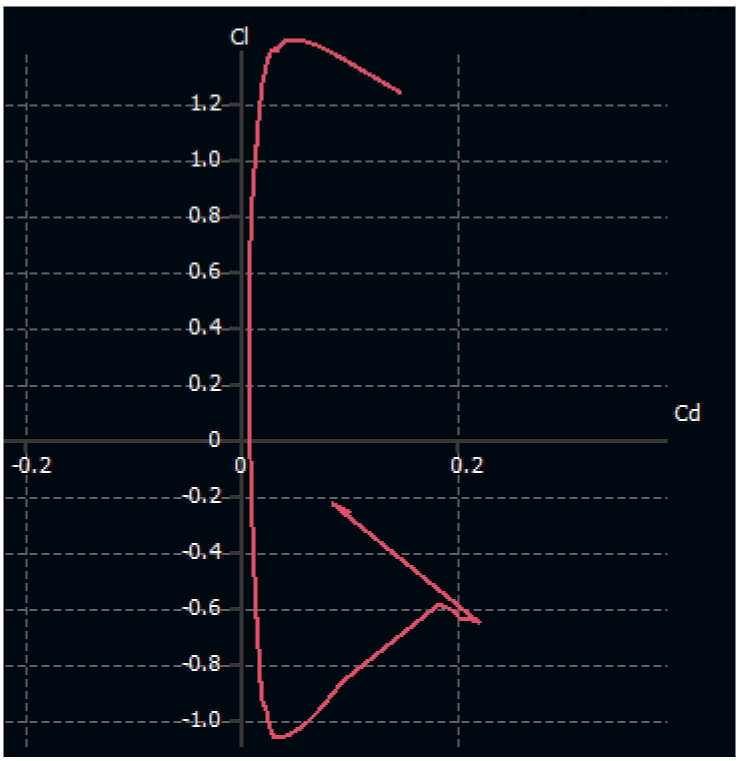

Figure 2.2 (NACA 2412 " Cd vs Cl")

Key findings:

The drag polar curve of the NACA 2412 shows that it achieves a relatively high lift-to-drag ratio (Cl/Cd) at low angles of attack, particularly in the initial region where the lift increases significantly and drag remains low. This trend is favorable for cruise conditions, where aerodynamic efficiency is essential. In this respect, the NACA 2412 performs similarly to the NACA 4418 in the early stages of the lift curve.

However, the maximum Cl/Cd ratio is reached at approximately Cl = 1.42, which corresponds to a relatively high angle of attack. This makes it a less efficient operating point for sustained flight when compared to the NACA 4418, which achieves its peak efficiency at lower AoA, closer to typical cruise requirements.

On the positive side, the drag increases gradually near stall, forming a smooth curve without sudden breaks. This behavior indicates a predictable and forgiving stall characteristic, which is particularly valuable in low Reynolds number regimes. From a control and handling perspective, the NACA 2412 demonstrates stability and reliability, even if its overall efficiency is slightly inferior.

Efficiency (CL/CD) vs. Angle of Attack (*figure 2.3*)

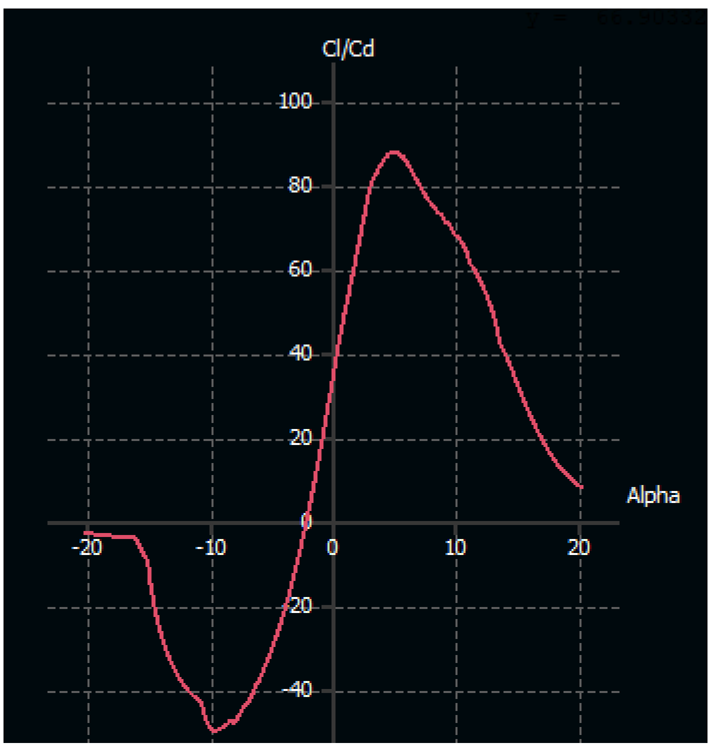

Figure 2.3 (NACA 2412 "Cl/Cd vs AoA")

Key findings:

The maximum aerodynamic efficiency (Cl/Cd) for the NACA 2412 airfoil occurs at an angle of attack of approximately 5°, representing its most favorable operating point in terms of lift to drag ratio. While this efficiency peak is achieved at a lower AoA than the NACA 4418, it comes at the cost of insufficient lift generation.

At this angle, the airfoil does not produce enough lift to satisfy the requirements for either cruise (Cl ≈ 1.1) or takeoff (Cl ≈ 1.3) phases as defined in the mission profile. As a result, despite having good theoretical efficiency, this operating point is not practically useful for the flight conditions of the SAE AeroDesign mission.

Therefore, while the NACA 2412 demonstrates excellent aerodynamic efficiency at low angles of attack, its inability to meet the required lift at that point makes it an unsuitable choice for the intended design. Its efficiency advantage is effectively negated by its lack of performance in the relevant lift range.

Cl vs. Xtr top (laminar flux on wing upper surface 0-1) (*figure 2.4*)

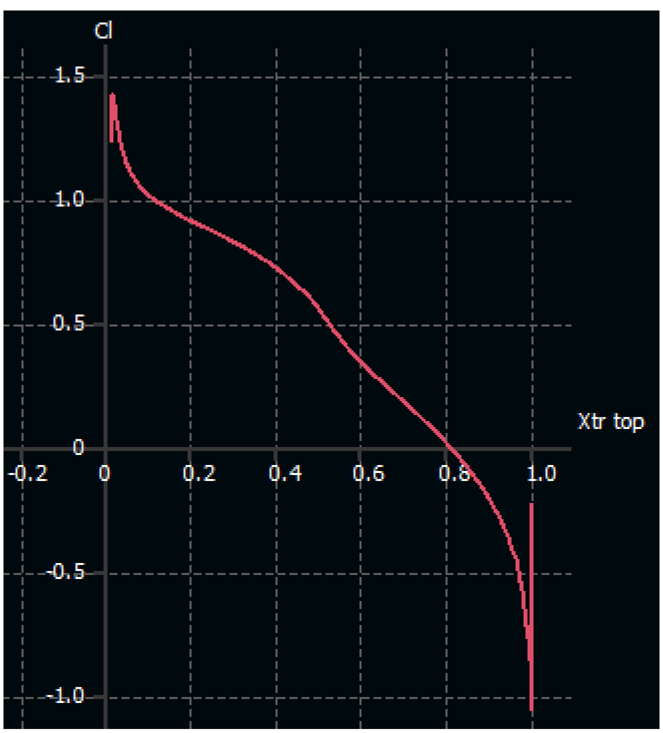

Figure 2.4 (NACA 2412 “Cl vs Xtr top”)

Key findings:

At **Cl = 1.3** (takeoff condition), the transition point on the upper surface (**Xtr_top**) is located at approximately **0.02** (02% of the chord from the leading edge), This indicates an almost immediate transition to turbulent flow, resulting in a significant increase in skin friction and a corresponding reduction in aerodynamic efficiency. In contrast, the NACA 4418 maintains laminar flow up to 34% of the chord (Xtr ≈ 0.34) under the same lift condition, making it far more efficient in this regard

Similarly, at Cl = 1.1, the lift coefficient associated with cruise conditions, the NACA 2412 exhibits an Xtr_top ≈ 0.06, again suggesting near instantaneous transition to turbulence. This implies that the upper surface remains mostly turbulent throughout flight, even at moderate lift conditions, leading to higher drag and reduced performance.

Although the NACA 2412 may perform better in terms of laminar flow at very low lift coefficients, in the operational range required for this aircraft's mission, it fails to retain laminar flow, whereas the NACA 4418 demonstrates much more favorable boundary layer behavior, with Xtr_top values between 0.34 and 0.40. This gives the 4418 a clear advantage in terms of aerodynamic efficiency for both takeoff and cruise.

Cm vs. Alpha (plane tendency to pitch) (*figure 2.5*)

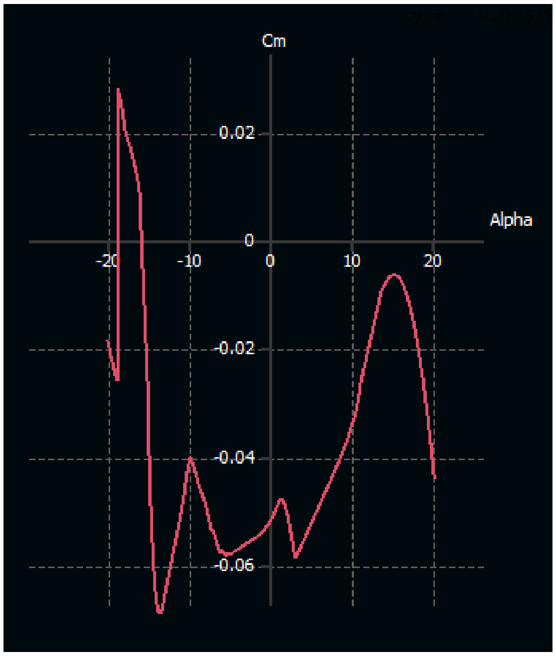

Figure 2.5 (NACA 2412 "Cm vs AoA")

The NACA 2412 exhibits a negative pitching moment (Cm) throughout the analyzed range of angles of attack for this airfoil from 8° to 12°, indicating favorable static longitudinal stability. Compared to the NACA 4418, the 2412 Cm curve remains closer to zero, typically between -0.042 and -0.019, while the 4418 displays more negative values in the range of −0.089 and −0.068.

Although both airfoils exhibit desirable stability characteristics, the NACA 2412 less negative Cm implies that it would require less trimming force from the horizontal stabilizer to maintain equilibrium in pitch. This could potentially result in lower drag and improved efficiency, especially in cruise conditions. However, it must be balanced against the 2412 lower lift performance, which may limit its suitability for the specific mission profile.

Results Selig S1223:

Lift Coefficient vs. Angle of Attack (*figure 3.1*)

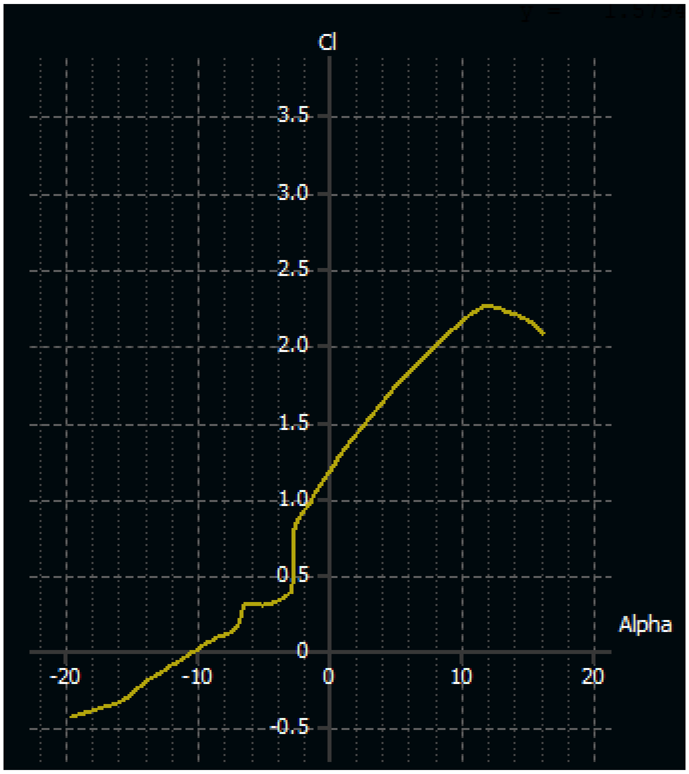

Figure 3.1 (Selig S1223 "Cl vs AoA")

Key findings:

At an angle of attack (AoA) of 0°, the Selig S1223 airfoil generates a lift coefficient (Cl) of approximately 1.18, which is the highest among the three airfoils analyzed (NACA 4418, NACA 2412, and S1223). This high Cl at zero AoA makes it exceptionally favorable for both takeoff and cruise, as it can generate the required lift without requiring any incidence angle.

For the calculated takeoff condition, which requires a Cl of 1.3, this airfoil achieves that at an AoA of just 0.9°, making it by far the easiest airfoil to operate during takeoff among the ones studied.

The lift curve is smooth and gradual, reaching a maximum Cl of approximately 2.25 at 12° AoA. This suggests the airfoil could support higher payloads than the ones considered in the current mission analysis, even though this would mean designing an even more challenging structure for the aircraft. However, stall occurs at that same AoA (12°) and is more abrupt compared to the other airfoils, which could pose a challenge for stability, particularly if the airfoil is used on the main wing attached directly to the fuselage, where smoother stall behavior is typically preferred, also the changes of Cl between AoA are very high which may mean a greater difficulty for the pilot to make smooth adjustments precisely, which on a scaled airplane it's very important.

Drag Polar (Cd vs. Cl) (*figure 3.2*)

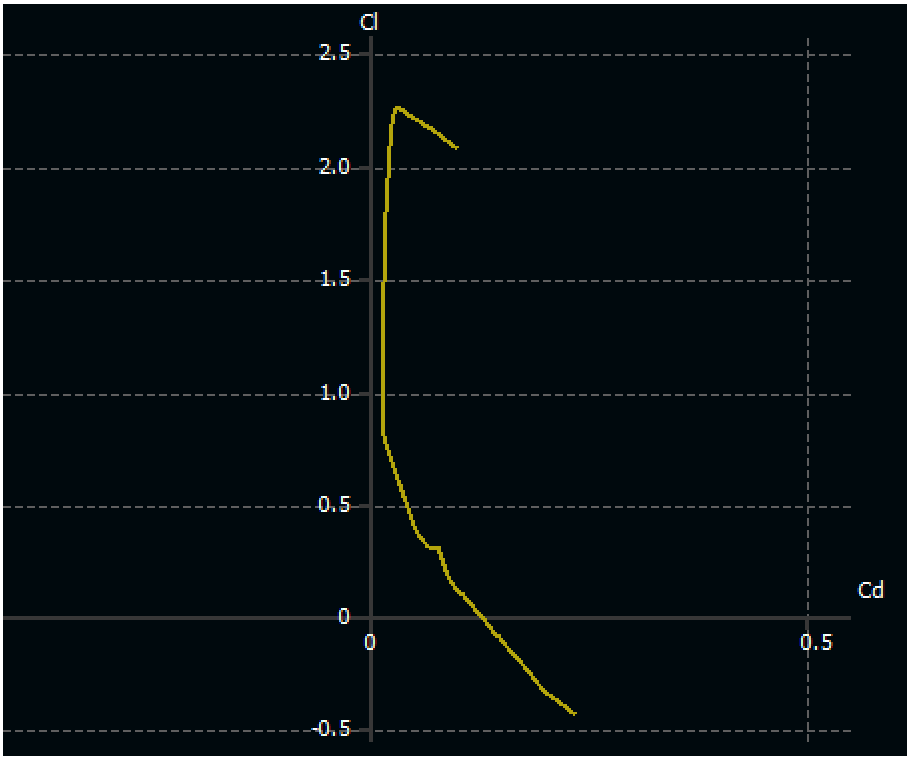

Figure 3.2 (Selig S1223 "Cd vs Cl")

Key findings:

The Selig S1223 airfoil demonstrates a very high lift-to-drag ratio (Cl/Cd) at moderate to high lift coefficients, peaking around Cl ≈ 2.26 with a remarkably low drag coefficient of approximately 0.02. This corresponds to an exceptional aerodynamic efficiency that could be leveraged in missions requiring either increased payload capacity or reduced cruise velocity. However, for the current mission, which requires significantly lower Cl values (around 1.1–1.3), this peak performance may not be fully utilized.

At lower lift coefficients (Cl ≈ 0–0.7), the airfoil exhibits unusually poor aerodynamic efficiency due to disproportionately high drag. While these Cl values are outside the operational envelope for this mission, it is noteworthy that this behavior differs significantly from the other airfoils analyzed, suggesting higher sensitivity and potential volatility in off-design conditions

Efficiency (CL/CD) vs. Angle of Attack (*figure 3.3*)

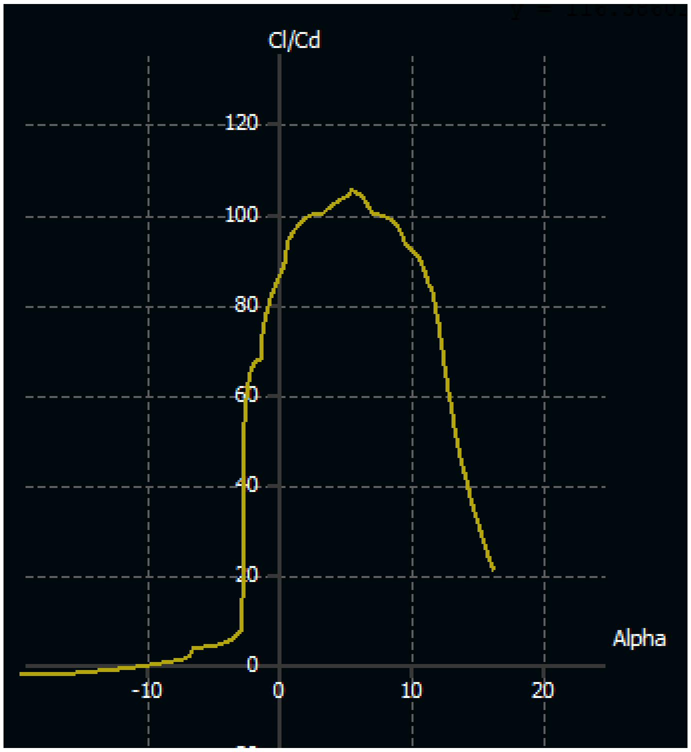

Figure 3.3 (Selig S1223 “Cl/Cd vs AoA”)

Key findings:

The Selig S1223 airfoil demonstrates peak aerodynamic efficiency at an angle of attack (AoA) of approximately 5.4°, where the lift-to-drag ratio (Cl/Cd) reaches a value of 105. This makes it the most aerodynamically efficient airfoil among the three analyzed in this report.

It maintains high Cl/Cd values across a wide AoA range from 0° to about 10°which aligns well with the AoA range expected during the mission’s cruise and takeoff phases. Although its efficiency curve is less smooth compared to the NACA airfoils, the S1223 consistently shows superior efficiency throughout most of the AoA range.

At the calculated AoA for takeoff and landing, the Cl/Cd values are approximately 86.8 and 86, respectively indicating excellent performance in these flight phases. However, it's important to note that the maximum aerodynamic efficiency (Cl/Cd = 105) occurs at an AoA that is not directly exploited in this mission profile, meaning the airfoil’s full efficiency potential may not be utilized during normal operations.

Cl vs. Xtr top (laminar flux on wing upper surface 0-1)(*figure 3.4*)

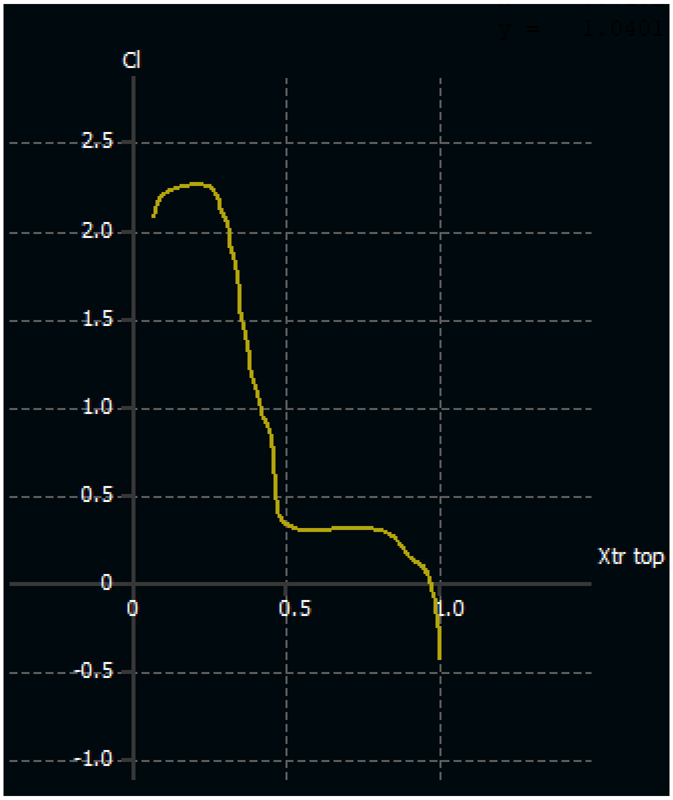

Figure 3.4 (Selig S1223 "Cl vs Xtr top")

Key findings :

At first glance, the Selig S1223 airfoil appears to exhibit excellent laminar flow characteristics, as it maintains an Xtr (transition point) close to 1.0 at low lift coefficients indicating an extended laminar region on the upper surface. At Cl ≈ 1.3 (takeoff condition), the Xtr_top reaches approximately 0.38, and at cruise conditions (Cl = 1.1), it extends to around 0.4, values comparable to or better than those of the NACA 4418.

While this might suggest good aerodynamic efficiency at low Cl, the Cl vs Cd graph reveals otherwise: the drag coefficient is relatively high in this region. This apparent contradiction is explained by the airfoil's geometry its high curvature induces significant pressure (form) drag, which outweighs the frictional benefits of extended laminar flow.

This means that despite the promising laminar flow characteristics seen in the Xtr graph, the airfoil is not efficient at low Cl. The S1223 is designed to operate at higher lift coefficients and very low angles of attack. Therefore, attempting to take advantage of its laminar behavior at low Cl would not be aerodynamically efficient due to the elevated pressure drag in that regime.

Cm vs. Alpha (plane tendency to pitch) (*figure 3.5*)

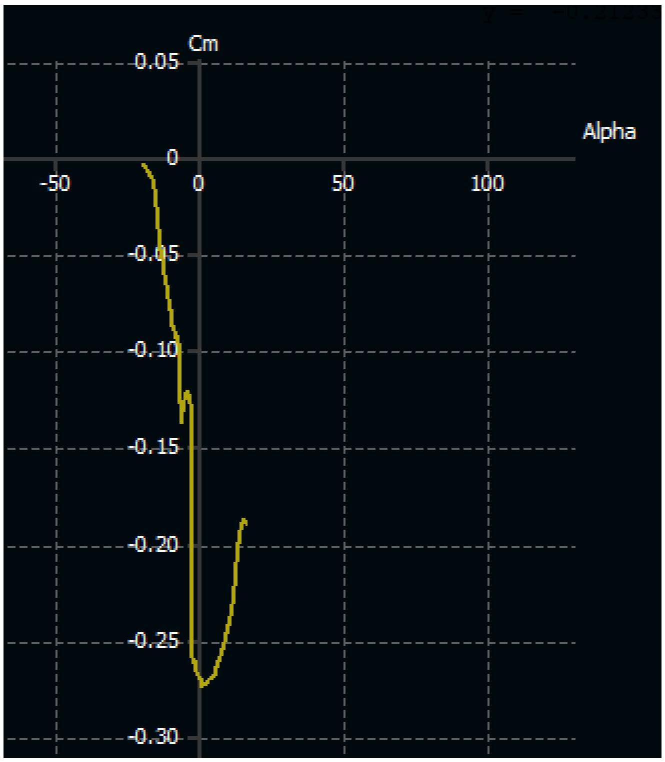

Figure 3.5 (Selig S1223 "Cm vs AoA")

Key findings:

At an angle of attack (AoA) of 0° corresponding to cruise conditions the moment coefficient (Cm) of the Selig S1223 is approximately -0.268, which is the most negative among all the airfoils analyzed. This indicates a strong nose-down pitching moment, requiring significant counteraction from the horizontal stabilizer. Such compensation can increase the trim drag and reduce overall cruise efficiency.

During takeoff, the Cm remains highly negative at around -0.27, again the highest (most negative) among the airfoils considered. This persistent nose-down tendency implies greater instability in pitch and may result in a more challenging flight behavior, especially in manual or scaled applications where control surfaces are limited.

Overall, although the S1223 performs well in terms of lift and aerodynamic efficiency, its high negative Cm values suggest increased control effort and trim drag, potentially compromising stability and making it less ideal for applications that prioritize smooth handling and efficient cruise performance.

Tabulated Results

	NACA 4418	NACA 2412	Selig S1223
AoA Cruise (Cl 1.1)	6.2	8.3	-0.62
AoA Take off (Cl 1.3)	8.6	11.1	0.92
Stall AoA (°)	15.5	15.5	12
Aerodynamic efficiency peak Cl/Cd / AoA	99.9/7	88/5.1	105.25/5.4
Aerodynamic efficiency at Cruise Cl/Cd	98.9	74.3	81.9
Aerodynamic efficiency at Take Off Cl/Cd	95.8	61.2	95.4
Cm at Cruise AoA	-0.087	-0.041	-0.27
Cm at Take Off AoA	-0.076	-0.025	-0.27

Laminar Flux Cruise	0.4	0.06	0.4
Laminar Flux Take Off	0.34	0.027	0.38

Analysis and Interpretation

Based on the results:

- The **NACA 4418** offers a good compromise between high lift and acceptable drag, especially at low Reynolds numbers. It shows the highest values of aerodynamic efficiency among the three airfoils. However, it is important to note that this does not necessarily make it the most overall efficient airfoil, since it operates at a higher angle of attack (AoA) compared to the **Selig S1223**, which results in increased pressure drag. Even so, the NACA 4418 remains the most efficient and stable profile among those analyzed in this report.

- Structurally, the most challenging airfoil to integrate would be the **NACA 2412**, as it requires a relatively high minimum AoA of 8.3° under normal operation. This implies a significant angular discrepancy between the airfoil and the fuselage, complicating the wing-fuselage integration. Next in structural complexity is the **NACA 4418**, which requires a minimum AoA of 6.2°. In contrast, the **Selig S1223** performs efficiently at an AoA near zero, making structural integration easier. However, this comes with trade-offs: its lift coefficient (Cl) varies significantly with small changes in AoA, making it more sensitive, less predictable, and harder to maneuver.

- The **Cm** values for both NACA airfoils are relatively close to zero and negative, indicating that they would not require excessive compensation from the tailplane to counteract pitching tendencies. In contrast, the **Selig S1223** shows a significantly more negative Cm value of -0.27 at both cruise and takeoff conditions. This makes it inherently less stable and less efficient overall, as it would require greater stabilizer deflection, increasing both pressure and friction drag.

Design trade-offs considered:

- Stall margin for takeoff vs. L/D for cruise

- Simplicity of manufacturing

Conclusions

The preliminary airfoil analysis supports the selection of NACA 4418 for the main wing design of the Standard Class aircraft. This airfoil provides a strong balance of aerodynamic efficiency, predictable stall behavior, and structural feasibility at cruise and takeoff conditions.

Compared to the Selig S1223, which shows high efficiency at narrow AoA ranges but suffers from poor pitch stability and sensitivity, the NACA 4418 offers stable Cl/Cd ratios across a broader range, with moderate pitching moments and better control characteristics. While the S1223 excels in low AoA operation, the compensation required by the tailplane for its negative Cm reduces its overall aerodynamic performance.

In terms of manufacturability, the NACA 4418 also presents a simpler integration with the fuselage than the NACA 2412, which demands higher incidence angles.

Therefore, based on aerodynamic performance, stability, and design simplicity, the NACA 4418 is the most suitable airfoil for this aircraft's mission profile.

Attachments and References

- **References:**

***Lift Equation | Glenn Research Center | NASA*. (2023, November 20). Glenn Research Center | NASA. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/lift-equation-2/**