Aerodynamic Evaluation of NACA 6-Series Airfoils for High-Altitude Glider Applications

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Abstract

High-altitude gliders face the problems of low Reynolds numbers and reduced air density, resulting in efficient airfoil design being critical. This study compared the NACA 63-618 and 64-618 airfoil at a Re = $2 x 10^{6}$ through the use of XFOIL, while turbulence is modeled by adjusting the Ncrit values from 3-16. While both airfoils displayed similar lift results, the drag and efficiency were affected by the surface smoothness. The 63-618 had higher lift-to-drag ratios in smoother conditions, while the 64-618 was more stable in moderate turbulence. For both, maximum efficiency occurred at an angle of attack between 2 and 4 degrees. The results also suggested that an Ncrit of 7-8 is best representative for high-altitude performance for glider applications.

1. Introduction

Previous work has investigated the performance of airfoils under high altitude conditions characterised by low-Reynolds numbers. High altitude gliders are extremely useful, for applications such as atmospheric research, monitoring weather, and conducting long fuel-less flights where efficient aerodynamic performance is crucial.

For example, the *NASA APEX* flight experiment had measured the lift, drag, and boundary layer performance at altitudes above the 70,000 ft range [1], while the *Perlan-2* glider glider was made to be optimal at heights of around 60,000 feet, displaying an equilibrium between wing design while also meeting the requirement for sustainable lift in low-density air [2]. The studies highlight the obstacles engineers face when designing airfoils for high altitude flight.

Airfoil efficiency strongly influences the range and endurance of high-altitude gliders, where even small reductions in drag can have significant performance impacts. High-altitude gliders operate in environments with lower air density along with lower Reynolds numbers, making it difficult to generate abundant lift while also minimizing drag. Airfoil efficiency, which is measured by the lift-drag ratio (Cl/Cd), is a key factor in an airfoil's performance.

The NACA 6-series airfoils are well known for their ability to maintain an extended laminar flow while also attaining a lower drag, making them very suitable for high-altitude applications. However, their performance is also reliant on the surface smoothness and turbulence, which can be modeled through the critical amplification factor (Ncrit).

This study will evaluate the performance of the NACA 63-618 and 64-618 airfoils under atmospheric conditions characteristic of high-altitude flight. Using computational analysis through the use of XFOIL, the effects of varying Ncrit on drag, lift, and efficiency are all compared. This is for the objective of recognizing the ideal conditions for glider design and operation.

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2. Methodology

2.1 Airfoil Selection

- Two airfoils from the NACA 6-series were selected to be analyzed: NACA 63-618 and NACA 64-618. Both of these airfoils are known for their use in lower drag application due to its ability to have extended laminar flow over a chord length, making them appropriate candidates for high-altitude glider testing where efficiency is crucial.

2.2 Software Tool: XFOIL

All experimentation was done using XFOIL v6.99, a software developed for subsonic airfoil performance testing. XFOIL was chosen for this project due to its ability to both test for inviscid flow along with creating a boundary layer plot, allowing results to be seen for values such as the following:

- Lift coefficient (*Cl*)
- Drag coefficient (*Cd*)
- Lift-to-drag ratio (*Cl/Cd*)
- Pressure coefficient distributions (*Cp*)

The software also allows the user to change the value for *Ncrit*, which is representative of the critical amplification factor for the transition of laminar to turbulent flow.

2.3 Analysis Conditions

All airfoil testing was performed at a Reynolds number (Re) of

$$Re = 2 \times 10^6$$

This Reynolds number is accurate for gliders specifically at high-altitude where air density is reduced relative to sea-level conditions.

The critical amplification factor (*Ncrit*) was tested across 5 different values:

- *Ncrit* = 3 → Higher turbulence / rough surfaces
- *Ncrit* = 7 → Moderate turbulence
- *Ncrit* = 8 → Transitional case
- *Ncrit* = 9 → Smooth surface conditions
- *Ncrit* = 15 → Extremely smooth / theoretical best

This range helps to show the performance of a high altitude glider across both realistic atmospheric conditions and very abstract scenarios.

2.4 Computational Procedure

For each airfoil and *Ncrit* value:

1. Airfoil coordinates were loaded using the load function into XFOIL using standard `.dat` format files.
   a. Sourced from airfoiltools.com

2. The Reynolds number was set to $Re=2\times10^6$ after using the OPER function and changing it to viscous airflow, allowing Reynols number to be adjusted.

3. The *Ncrit* parameter was varied using the VPAR function and then typing and entering "n," allowing different *Ncritl* values to be tested.

4. Angle of attack was tested for when using the ASEQ function.
   a. Values that were used and were consistent throughout testing were 0.6, and 0.5.

5. A boundary layer plot was formulated, in which the values were recorded:
   a. *Cl*, *Cd*, *Cl/Cd*, and *Cp* distributions (Look below for more information)

2.5 Output Parameters

The following quantities were extracted for analysis:

- **Lift coefficient (*Cl*)** vs. angle of attack
- **Drag coefficient (*Cd*)** vs. angle of attack
- **Lift-to-drag ratio (*Cl/Cd*)** for efficiency assessment
- **Pressure coefficient (*Cp*)** distributions along the chord for flow visualization

Results were plotted and compared across *Ncrit* values to evaluate performance trends and identify optimal operating conditions for high-altitude gliders.

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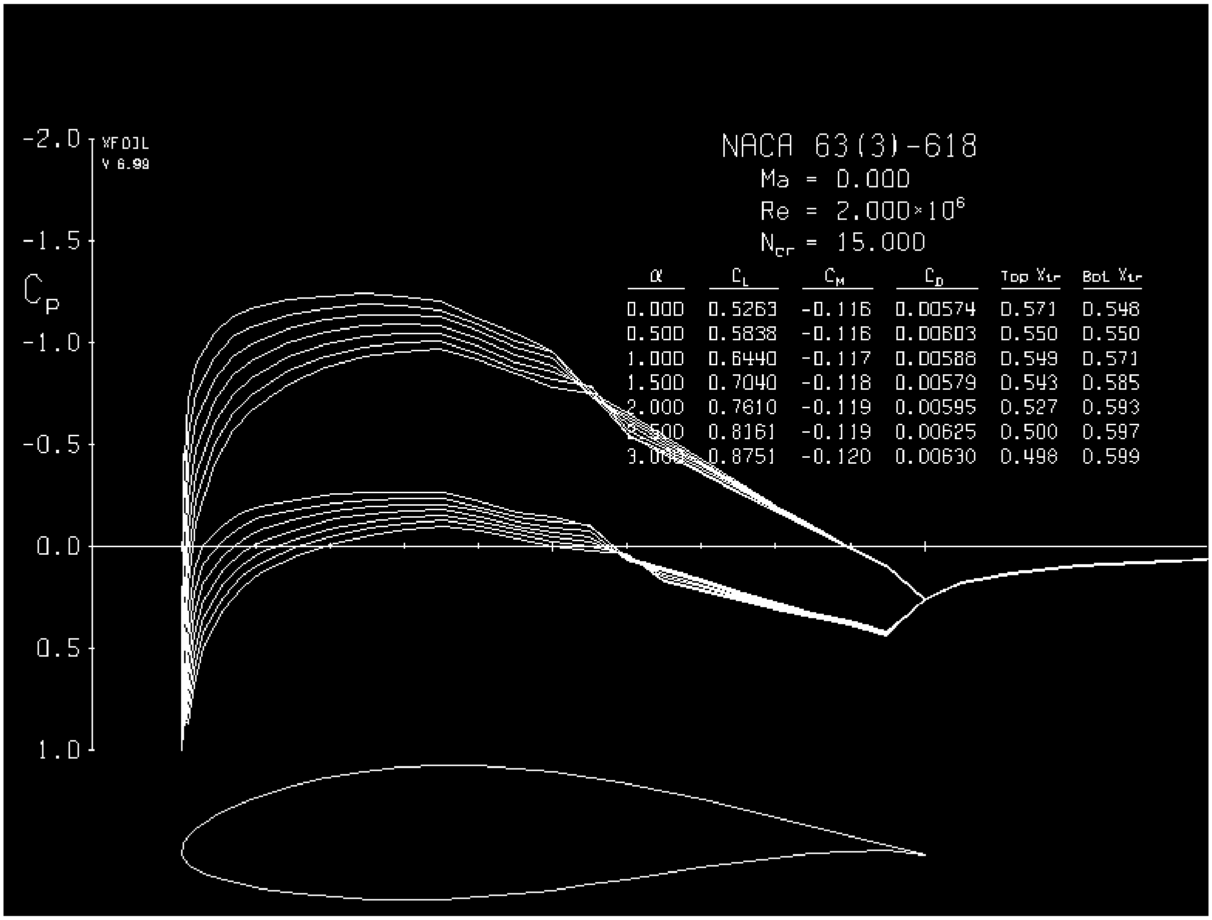
3. Results

This section shows the analysis of the two NACA 6-series airfoils: NACA 63-618 and NACA 64-618, at a constant Reynolds number of 2×10^6 and differentiating *Ncrit* values, which represent turbulence along with surface viscosity conditions.

3.1 NACA 63-618

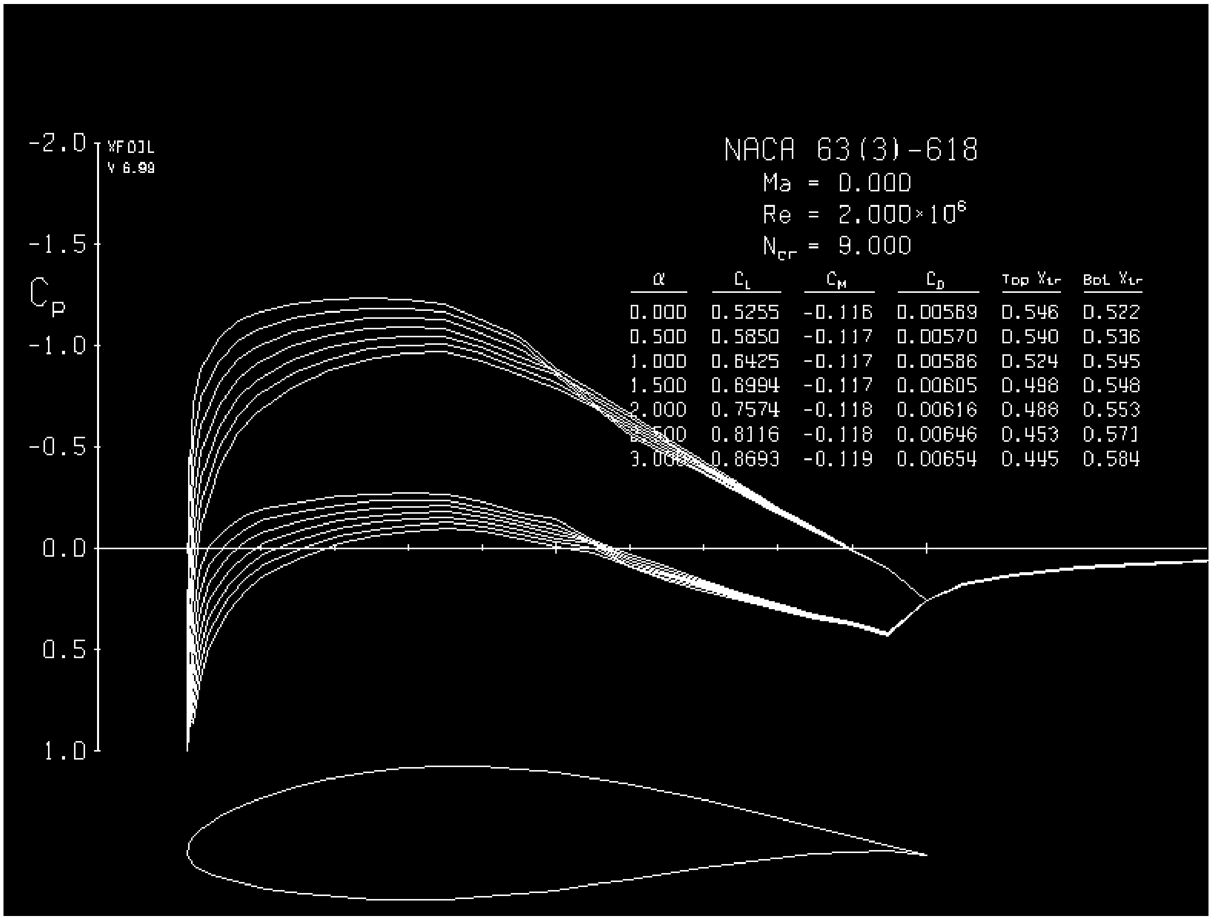
3.1.1 Ncrit = 15 (Exceptionally Smooth Conditions)



XFOIL-generated boundary layer plot for the NACA 63-618 airfoil (Re = 2×10⁶, Ncrit = 15), showing pressure distribution and transition behavior.

- **Lift (Cl):** Predictable increase, reaching ≈1.1 at α = 5°.
- **Drag (Cd):** Extremely low, ≈0.005 or less at moderate α.
- **Efficiency (Cl/Cd):** Highest between all *Ncrit* values, peaking between α = 2°–4°.
- **Pressure Distribution (Cp):** Sharper suction peak with extended laminar flow region.
- **Summary:** Shows unrealistic maximum efficiency; not representative of real-world conditions.

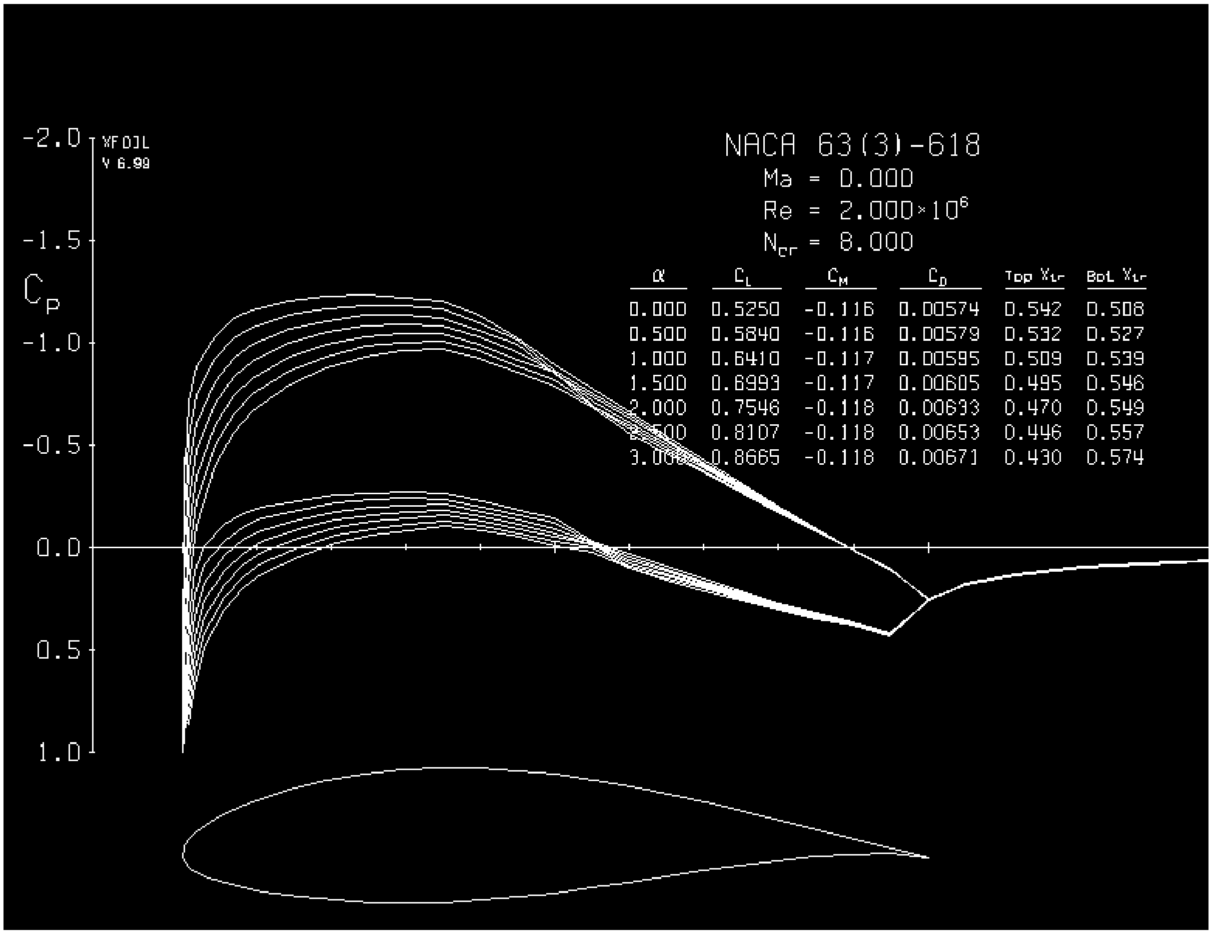
3.1.2 Ncrit = 9 (Smooth Surface, Low Turbulence [Expected Conditions])



XFOIL-generated boundary layer plot for the NACA 63-618 airfoil (Re = 2×10⁶, Ncrit = 9), showing pressure distribution and transition behavior.

- **Lift (Cl):** Increases almost evenly up to α ≈ 4°, reaching Cl ≈ 1.17 at α = 5° (stall begins).
- **Drag (Cd):** Very low, Cd ≈ 0.0059 at α = 0°.
- **Efficiency (Cl/Cd):** Peaks between α = 3°–4°.
- **Pressure Distribution (Cp):** Strong suction peak, extended laminar flow region.
- **Summary:** High efficiency with low drag; representative of smooth, controlled conditions.

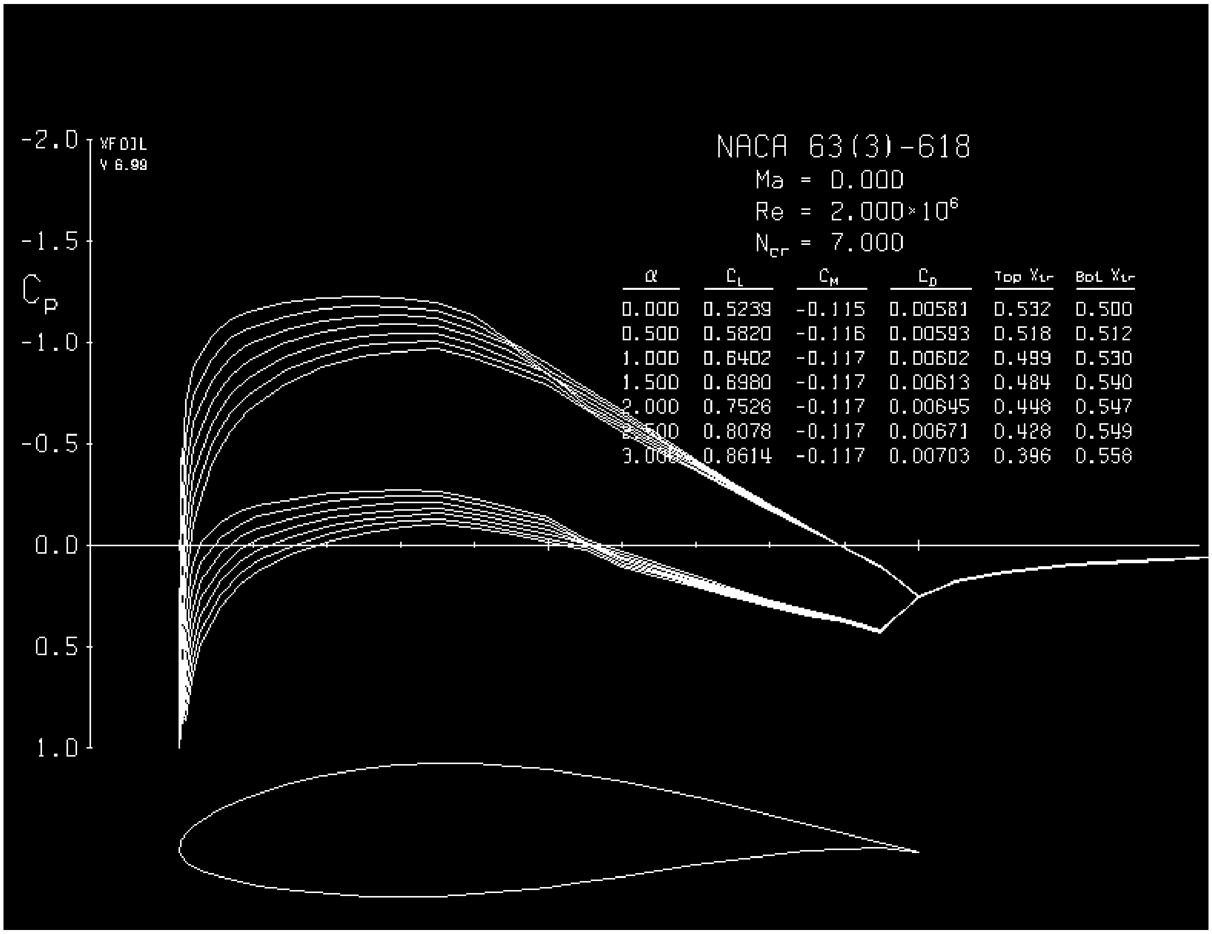
3.1.3 Ncrit = 8 (Moderately Smooth Conditions)



XFOIL-generated boundary layer plot for the NACA 63-618 airfoil (Re = 2×10⁶, Ncrit = 8), showing pressure distribution and transition behavior.

- **Lift (Cl):** Smooth increase, reaching ≈0.86 at α = 3°.
- **Drag (Cd):** Low, ≈0.0056 at α = 1°.
- **Efficiency (Cl/Cd):** Peaks between α = 2°–3° with minimal drag penalty.
- **Pressure Distribution (Cp):** Pronounced suction peak; slightly reduced laminar extent compared to Ncrit = 9.
- **Summary:** Practical balance between low drag and real-world turbulence effects.

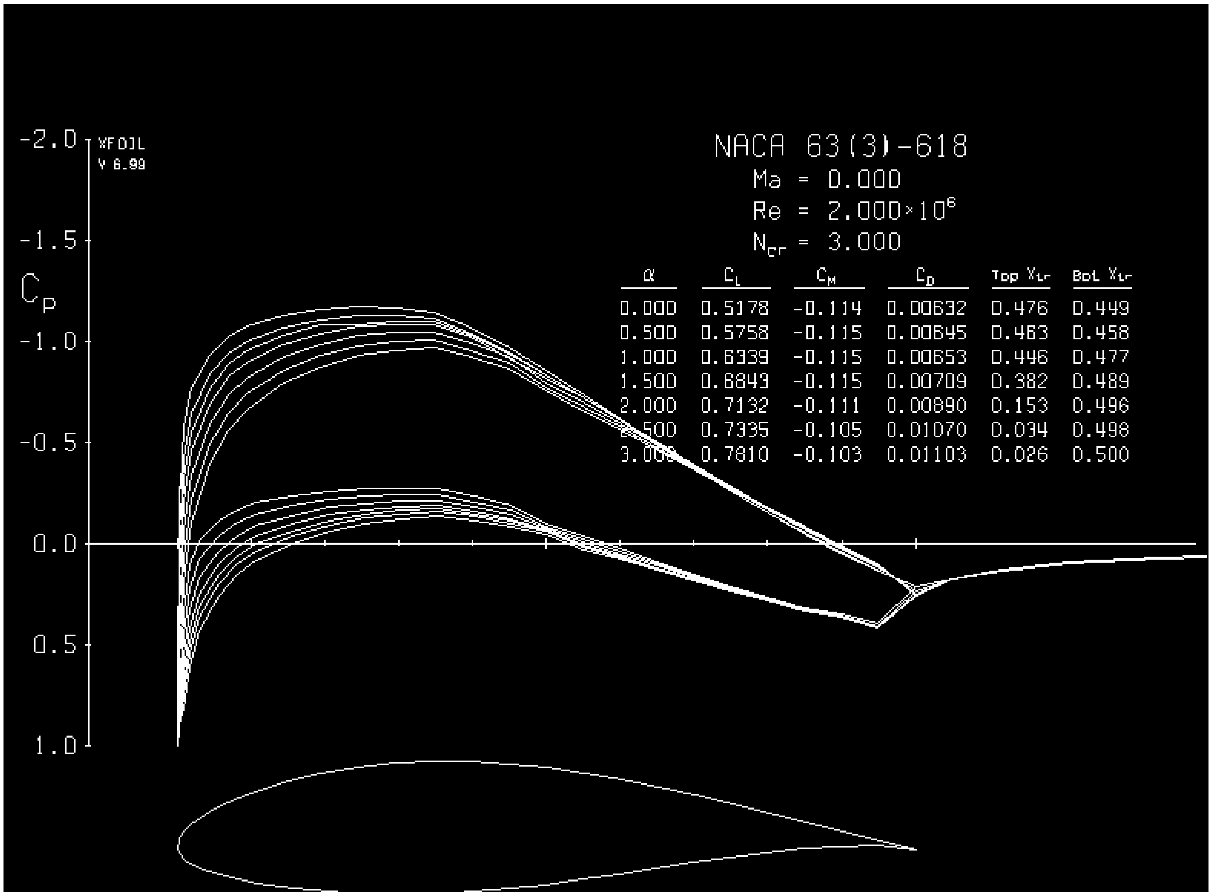
3.1.4 Ncrit = 7 (Moderate Turbulence)



XFOIL-generated boundary layer plot for the NACA 63-618 airfoil (Re = 2×10⁶, Ncrit = 7), showing pressure distribution and transition behavior.

- **Lift (Cl):** Rises from Cl = 0.523 at α = 0° to ≈0.86 at α = 3°.
- **Drag (Cd):** Slightly higher, ≈0.0058 at α = 1°.
- **Efficiency (Cl/Cd):** Peaks at α = 2°–3°, lower than smoother cases.
- **Pressure Distribution (Cp):** Clear suction peak with sharper recovery indicating earlier transition.
- **Summary:** Representative of moderate turbulence in real-world operations.

3.1.5 Ncrit = 3 (Rough Surface / High Turbulence)

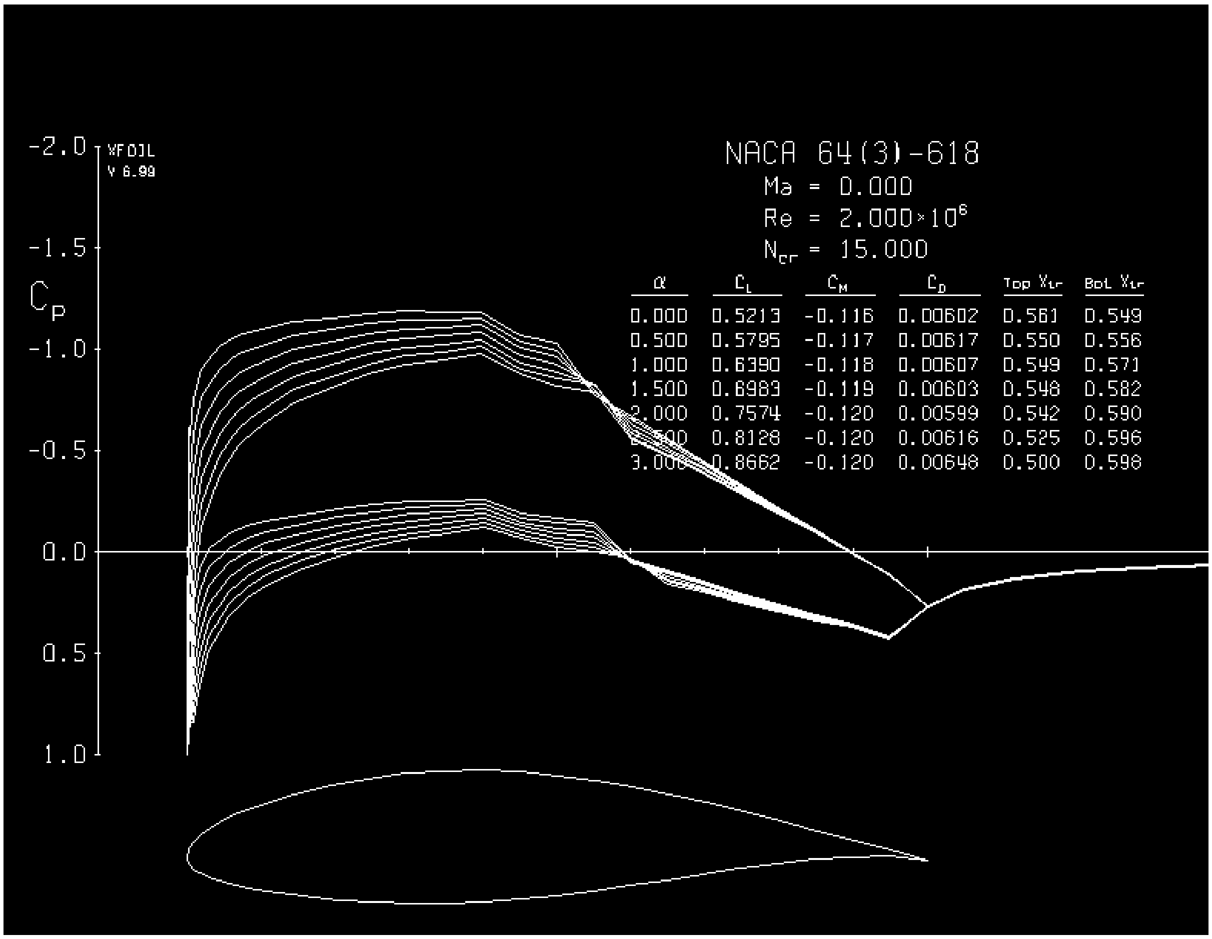


XFOIL-generated boundary layer plot for the NACA 63-618 airfoil (Re = 2×10⁶, Ncrit = 3), showing pressure distribution and transition behavior.

- **Lift (Cl):** Steady increase, reaching ≈1.0 at α = 5°.
- **Drag (Cd):** Higher, ≈0.006–0.007 at moderate α.
- **Efficiency (Cl/Cd):** Drops notably beyond α = 3° due to earlier transition and higher friction drag.
- **Pressure Distribution (Cp):** Weaker suction peak, reduced laminar flow extent.
- **Summary:** Conditions that aren't expected of a high-altitude glider to perform well in.

3.2 NACA 64-618

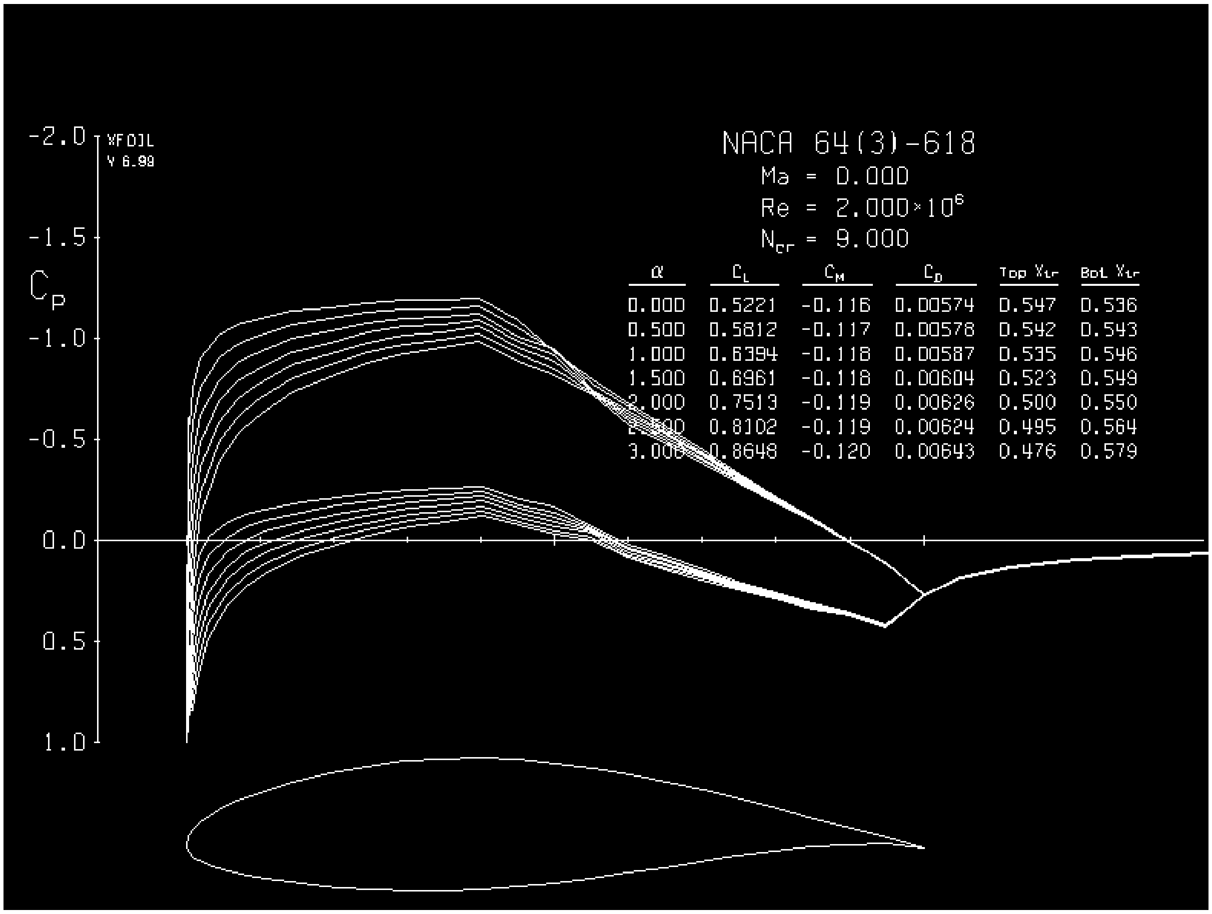
3.2.1 Ncrit = 15 (Exceptionally Smooth Conditions)



XFOIL-generated boundary layer plot for the NACA 64-618 airfoil (Re = 2×10⁶, Ncrit = 15), showing pressure distribution and transition behavior.

- **Lift (Cl):** Baseline Cl ≈ 0.52 at α = 0°, rising steadily with α.
- **Drag (Cd):** Very low, ≈0.0056 at low α.
- **Efficiency (Cl/Cd):** High, peaking between α = 2°–4°.
- **Pressure Distribution (Cp):** Pronounced suction peak, long laminar run.
- **Summary:** Theoretical smooth-surface performance; highest efficiency among Ncrit cases.

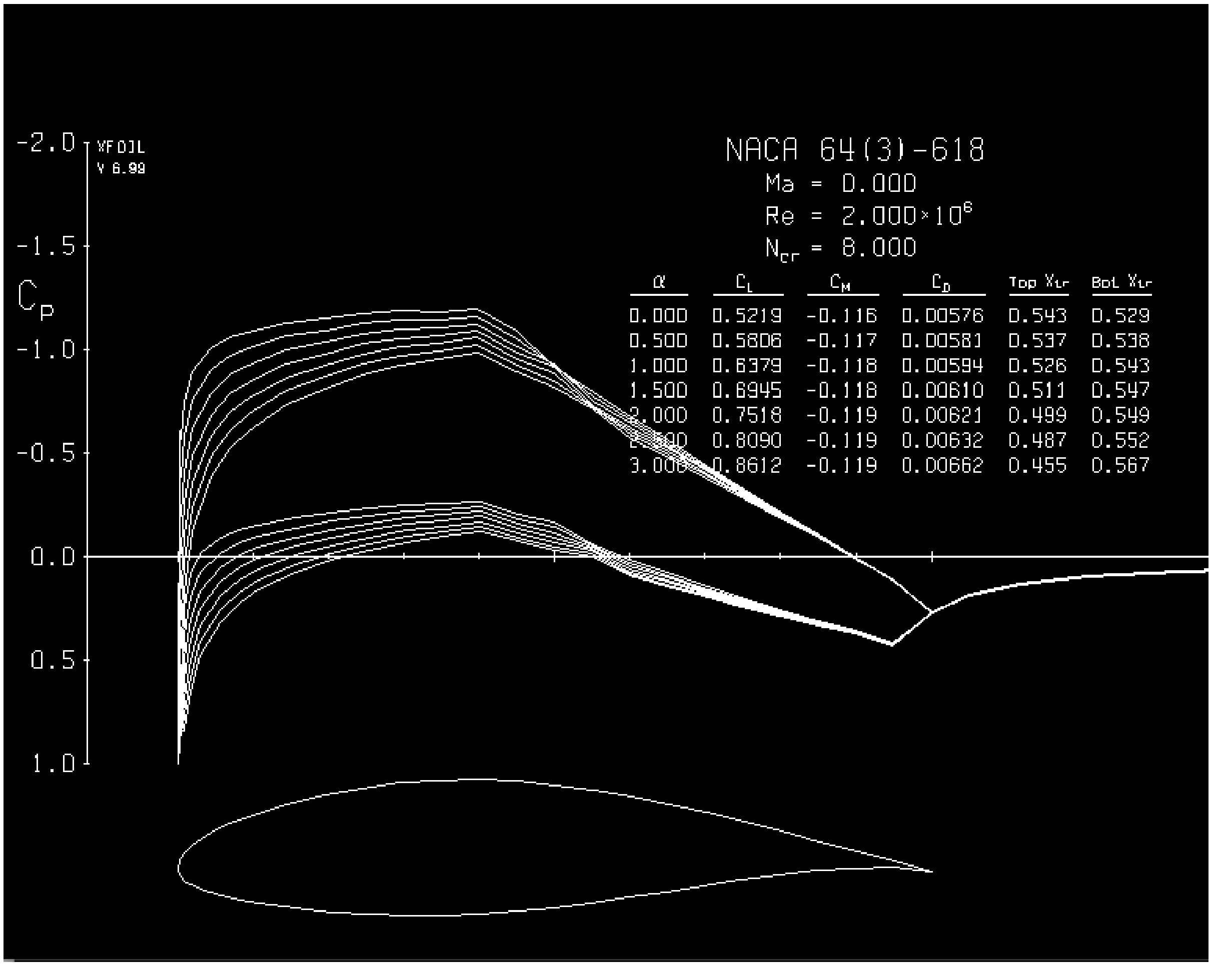
3.2.2 Ncrit = 9 (Smooth Surface, Low Turbulence)



XFOIL-generated boundary layer plot for the NACA 64-618 airfoil (Re = 2×10⁶, Ncrit = 9), showing pressure distribution and transition behavior.

- **Lift (Cl):** Cl ≈ 0.52 at α = 0°, increasing to ≈0.63–0.76 by α = 1°–3°.
- **Drag (Cd):** Low, ≈ 0.0057–0.0059 at low α.
- **Efficiency (Cl/Cd):** Peaks near α = 2°–3°.
- **Pressure Distribution (Cp):** Clear laminar suction peak with long transition length.
- **Summary:** Low drag, reliable performance under smooth conditions.

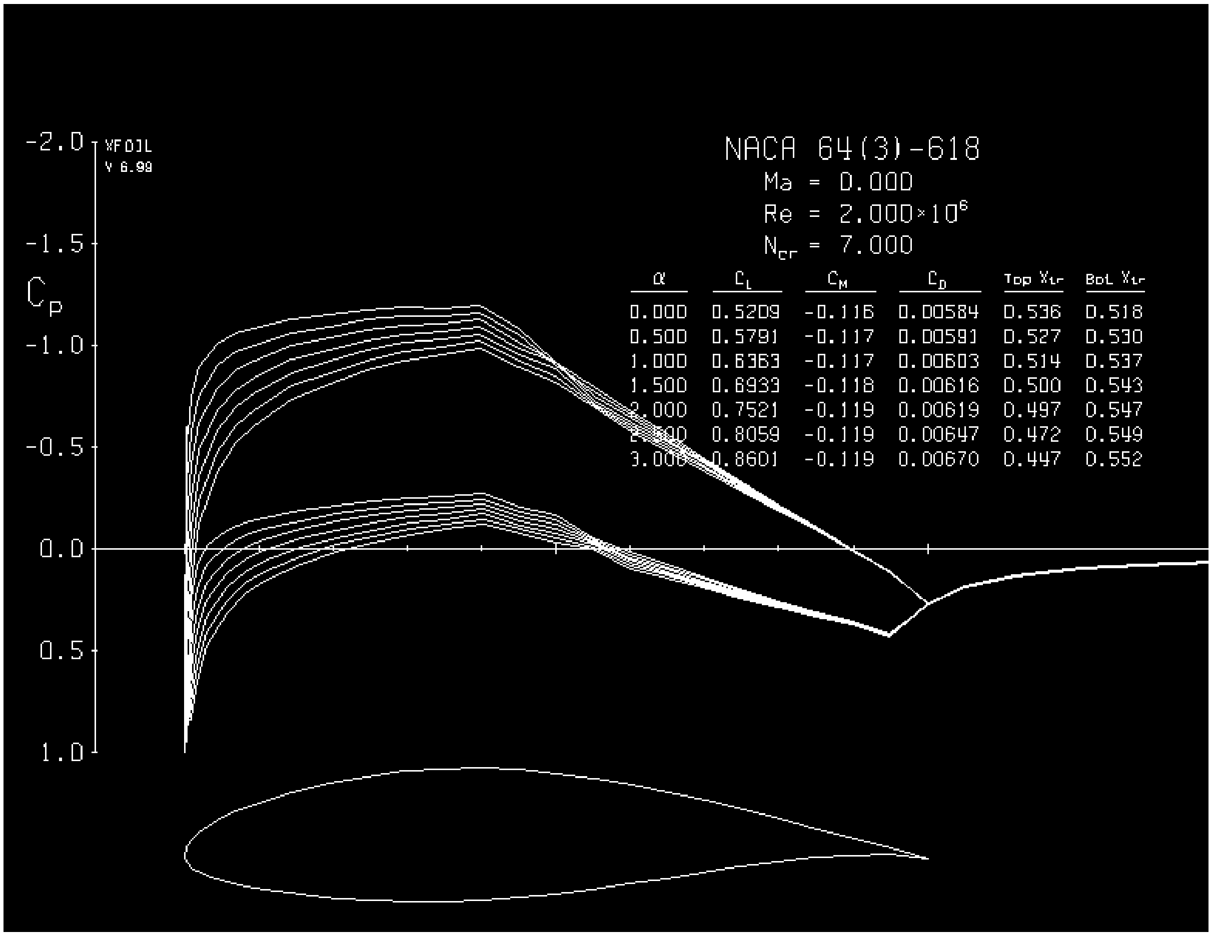
3.2.3 Ncrit = 8 (Moderately Smooth Conditions)



XFOIL-generated boundary layer plot for the NACA 64-618 airfoil (Re = 2×10⁶, Ncrit = 8), showing pressure distribution and transition behavior.

- **Lift (Cl):** Cl ≈ 0.75–0.86 at α = 3°.
- **Drag (Cd):** ≈ 0.0056–0.0061 at low α.
- **Efficiency (Cl/Cd):** Peaks between α = 2°–3°.
- **Pressure Distribution (Cp):** Pronounced suction peak, slightly moderated compared to Ncrit = 9.
- **Summary:** Balanced performance with moderate laminar flow retention.

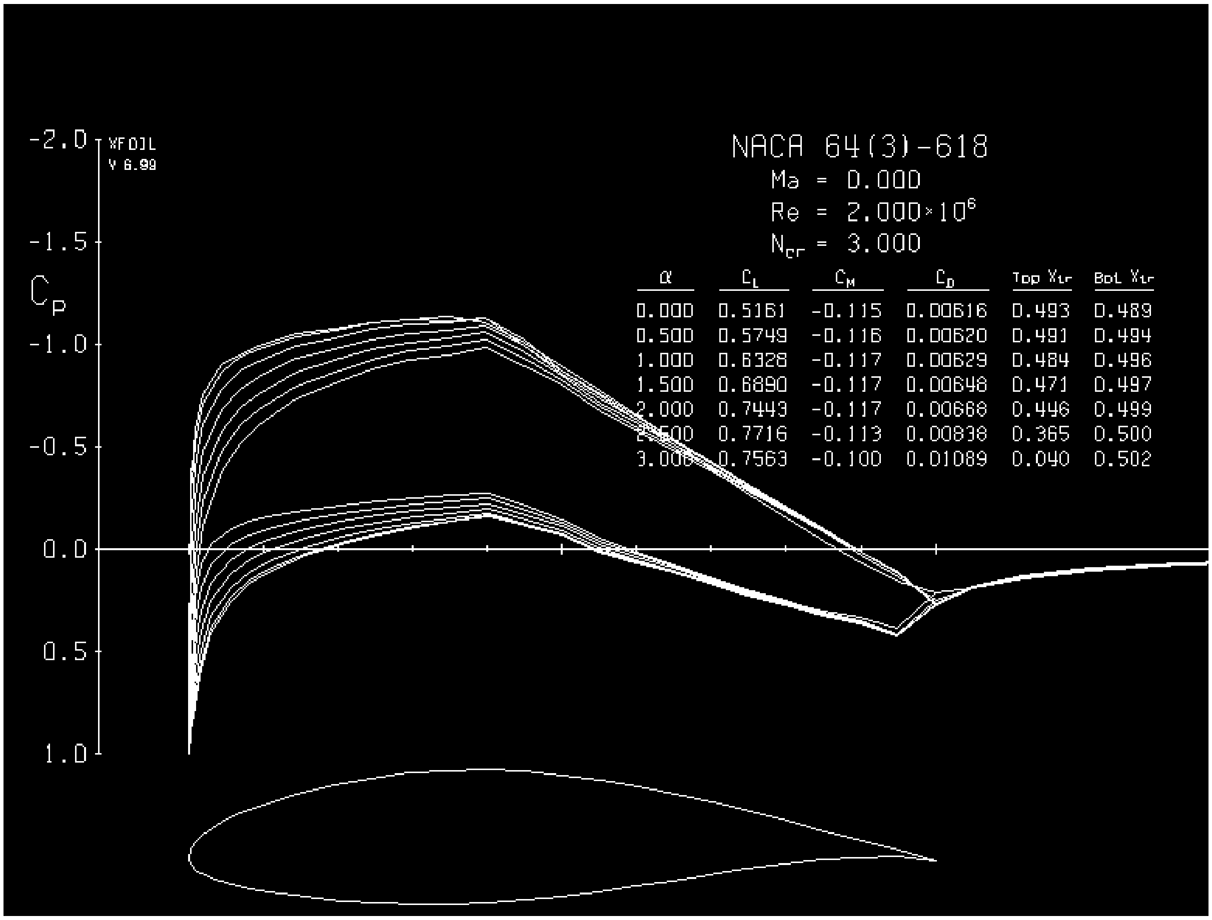
3.2.4 Ncrit = 7 (Moderate Turbulence)



XFOIL-generated boundary layer plot for the NACA 64-618 airfoil (Re = 2×10^6, Ncrit = 7), showing pressure distribution and transition behavior.

- **Lift (Cl):** Cl rises from ≈0.52 at α = 0° to ≈0.70–0.86 at α = 3°.
- **Drag (Cd):** ≈0.0058–0.0063 at low-to-moderate α.
- **Efficiency (Cl/Cd):** Best near α = 2°–3°, reduced relative to smoother cases.
- **Pressure Distribution (Cp):** Laminar suction peak present, earlier recovery than smoother cases.
- **Summary:** Representative of realistic turbulence conditions; efficiency slightly reduced.

3.2.5 Ncrit = 3 (Rough Surface / High Turbulence)



XFOIL-generated boundary layer plot for the NACA 64-618 airfoil (Re = 2×10⁶, Ncrit = 3), showing pressure distribution and transition behavior.

- **Lift (Cl):** Steady increase, Cl ≈ 1.0 at α = 5°.
- **Drag (Cd):** ≈0.006–0.008 at moderate α.
- **Efficiency (Cl/Cd):** Reduced beyond α ≈ 3° due to early transition and higher drag.
- **Pressure Distribution (Cp):** Weaker suction peak, reduced laminar extent.
- **Summary:** Conservative, real-world scenario; lowest efficiency observed.

3.3 Comparative Trends (63-618 vs 64-618)

- **Lift:** Both airfoils showcased similar Cl data with α, achieving lift at ≈ 1.0–1.17 before stall at low Ncrit

- **Drag:** Drag rises significantly as *Ncrit* decreases; smooth cases show Cd ≈ 0.005–0.0059, rough cases ≈ 0.006–0.008.

- **Efficiency:** Optimum Cl/Cd consistently occurs between α = 2°–4°, worsening with higher turbulence.

- **Design implication:** Ncrit = 7–8 represents realistic high-altitude conditions; Ncrit = 9–15 shows upper performance limits in near-perfect conditions.

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4. Discussion

- **Airfoil Comparison:** The comparison between the NACA 63-618 and 64-618 is that both airfoils flaunt similar lift performance across each *Ncrit* value, which means they both achieve comparable Cl values before stalling. Despite this, the 63-618 is slightly better in terms of maximizing lift-to-drag ratio (Cl/Cd) under smoother conditions (*Ncrit* > 8), hinting at a design more efficient for laminar flow retention over the chord. This can be traced back to the 63-series design, where it is optimized for laminar flow over a higher chord length. The 64-618, which is less efficient at maximum Cl/Cd, showcases a better stability in moderately turbulent conditions (*Ncrit* = 7-8). It also has a smoother transition from laminar to turbulent transition.

- Aside from the comparison, the results also show the tradeoffs in high-altitude glider design. The 63-618 performs at a higher efficiency compared to the 64-618 under smoother conditions characterized by Ncrits over or equal to 9. This means it can enhance range flights in low-turbulence conditions. However, expecting these conditions in the real world isn't suitable, as events such as atmospheric disturbances and surface imperfections could affect the Ncrit. In cases such as these, where the Ncrit can effectively be reduced to 7-8, the 64-618 more stable transition behavior will help to display greater consistency and stability in such conditions. These tradeoffs suggest that while maximizing overall efficiency may be helpful, it is also just as important to keep in mind the stability and reliability of the airfoil itself. Moreover, the highest efficiency occurring at an angle of attack of 2-4 degrees also shows that this is the most optimal angle for gliders to fly at.

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5. Conclusion

High-altitude gliders play a massive role when it comes to atmospheric research, weather tracking, and long fuel-free flight, making understanding their performance in these conditions to be absolutely vital.

This study assesses the performance of the NACA 63-618 and NACA 64-618 under high altitude scenarios using XFOIL, while adjusting the turbulence by varying the Ncrit values from 3 to 15. Both airfoils display a similar life performance, with maximum coefficients near the 1.0 - 1.17 range before stalling. However, efficiency along with drag varies notably with surface smoothness. Smoother conditions, which is an Ncrit greater or equal to 9, creates lower drag (Cd around 0.005-0.0059) along with high lift-drag ratios. In more turbulent conditions, which is an Ncrit less than or equal to 7), increases drag (Cd around 0.006-0.008), while also decreasing efficiency. Regardless of conditions, maximum efficiency always occurs at an angle of attack between 2-4 degrees.

Comparatively, the analysis showed that the 63-618 marginally outperformed the 64-618 when it came to maximum efficiency in smoother, more laminar conditions, likely due to its design allowing for a stronger laminar flow control. Despite this, the 63-618 displayed a better stability in moderately turbulent conditions, specifically an Ncrit of 7-8. This makes it a good candidate for real-world applications where surface defects and atmospheric disrupts are unavoidable.

Overall, Ncrit values of 7-8 are best representative for what a high-altitude glider would experience as noted by the results, while higher Ncrit values are more theoretical and can show performance limits. For high-altitude glider designs, engineering should try to combine the efficiency of the 63-618 in relevant conditions while also trying to gain the resiliency in more moderate conditions from the 64-618. This can help to create gliders that can maximise performance while also being sustainable for active high-altitude use.

References

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