

Airfoil Analysis

Ryan Howell

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1 Introduction

Through reading the textbook and Xfoil.jl documentation as a part of this assignment I learned about the panel method. By experimenting with Xfoil.jl functions I observed the aerodynamic effects of airfoils. In this report I will discuss some key takeaways from the reading and will explore the effects of manipulating the airfoil shape and environmental conditions using the panel method. These results will be verified through comparison with published experimental, CFD and Xfoil data.

2 Background Readings

The textbook covers the basic aerodynamics of airfoils, the NACA airfoil, and the panel method's underlying approach and assumptions. These are central to understanding how the Xfoil functions work and how to interpret its results. This section highlights key takeaways from the readings.

2.1 Airfoils

The forces acting on an airfoil include a lift force perpendicular to the free stream velocity and a drag force acting in line with the free stream velocity. The chord of the airfoil, drawn directly between the leading and trailing edges, serves as a reference point. The angle of attack, the angle between the chord line and the free-stream flow, along with other properties such as Reynolds number and airfoil shape, affect the behavior and performance of the airfoil.

2.2 NACA Standardization

The NACA airfoil consists of numbers relating to the maximum camber, distance of the maximum camber from the leading edge, and the maximum thickness of the airfoil. The first number relates to the maximum camber, referring to the maximum distance between the chord and the camber line. The camber line is equidistant from the upper and lower surfaces of the airfoil. The second number indicates the location of that maximum camber from the leading edge. The last two digits refer to the maximum thickness of the airfoil. These three numbers are relative percentages of those distances as a percentage of the chord line length. With this 4 digit system basic airfoil shapes can be standardized for use across experiments.

2.3 Panel Method Approach

The panel method divides the airfoil into various linear panels. The vorticities at the center of each panel are then used to calculate and sum the forces experienced by the airfoil, characterizing its behavior with lift, drag and moment coefficients. To perform these calculations boundary conditions and overall air flow behavior must be assumed and controlled. The induced velocity is assumed to go to zero as you move away from the object being analyzed. It also must be assumed that the flow is perfectly tangent to the air foil. To ensure continuous flow off the sharp trailing edge, the Kutta condition is enforced. These assumptions allow the equations used in the panel method functions to be derived.

3 Effect of the Angle of Attack on a Airfoil

This section presents graphics produced through Xfoil that demonstrate the effect of the angle of attack on airfoil behavior. These figures will include plots of lift, drag, and moment coefficients as functions of the angle of attack.

3.1 Lift Coefficient

As shown in Figure 19 the lift coefficient increases with angle of attack. However, in this case as the Angle of Attack surpasses ten degrees, it drops, indicating the stall angle of the airfoil. To achieve lift the angle of attack must stay below the stall angle of the airfoil. Similarly, there is a negative stall angle. The lift produced by the airfoil is maximized just before this stall angle.

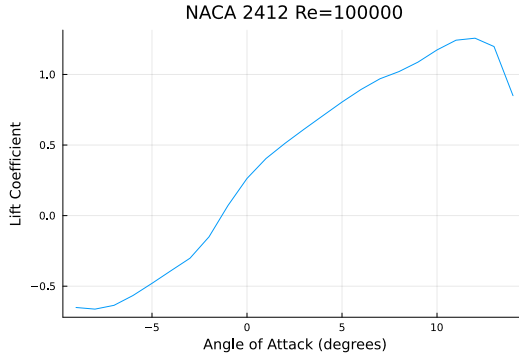


Figure 1: Lift of a NACA 2412 airfoil in flow with a Reynolds number of 100 thousand

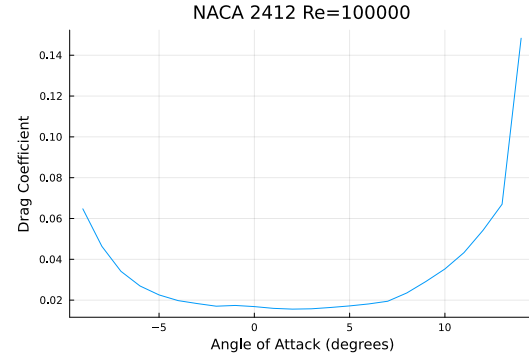


Figure 2: Drag of a NACA 2412 airfoil in flow with a Reynolds number of 100 thousand

3.2 Drag Coefficient

As shown in Figure 2 the Drag coefficient increases with angle of attack, this change however is relatively gradual. However, once the Angle of Attack surpasses ten degrees it shoots up. This is likewise related the stall angle of the airfoil, when the lift plummets the drag increases sharply. These forces together cause the plane to stall. To avoid insurmountable drag, the angle of attack must stay below the stall angle. Optimizing the angle of attack must consider both the total lift of the airfoil and the effect of drag and potential stalling.

3.3 Moment Coefficient

As shown in Figure 3 the Moment coefficient stays relatively constant in the negative hundredths but fluctuates as lift and drag change. It increases as you move away from zero in either direction, with the minimum value near zero. Noticeably, as drag begins to sharply increase, the moment coefficient starts decreasing.

4 Published Data Comparison

Exploring how the panel method results from Xfoil compare to CFD, published Xfoil data, and experimental data for the same airfoil, we see a relatively close match. By comparing it to published data from Xfoil programs we can verify the functions are working as expected, while other comparisons help us evaluate the effectiveness of the panel method in general. In the CFD and experimental plots, there are slight differences from the Xfoil data, but the overall trends are the same.

4.1 Xfoil Comparisons

Looking at Xfoil data generated by others for 6412 and 0012 NACA airfoils using a Reynolds number of 1 million, we can verify if our Xfoil code is providing realistic results [Aer24]. As shown by comparing

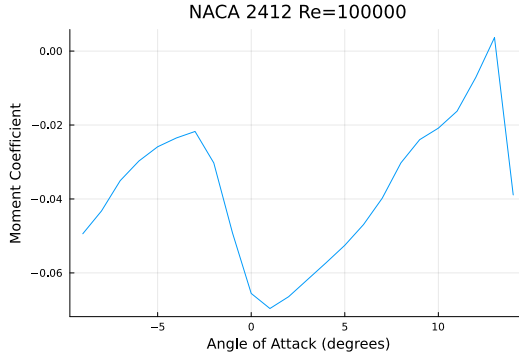


Figure 3: Moment of a NACA 2412 Airfoil in Flow with a Reynolds Number of 100000

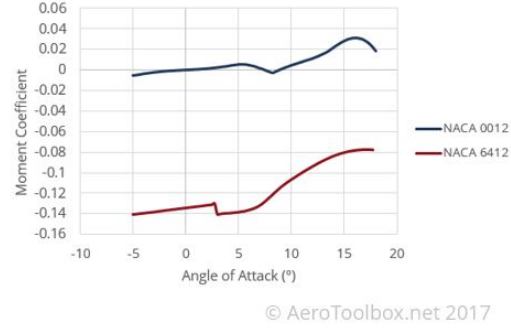


Figure 4: Moment Coefficients found using Xfoil, third party

Figures 5 and 7 with Figure 4, Figure 5. However, Figure 7 shows good approximate values but doesn't match the data as closely. These comparisons indicate that these Xfoil functions use similar methodology to the one used by the authors of the article, yet there are potential differences in the particular NACA airfoil datasets used. This is confirmed by comparing Figure 7 to a published plot from the source of the airfoil data points, showing an exact match (see Figure 6) [Too24]. Comparing the drag and lift coefficients for each airfoil, we see exact matches (Comparing Figure 8 to Figures 9, 10, 11, and 12). Confirming that this panel method code functions as expected.

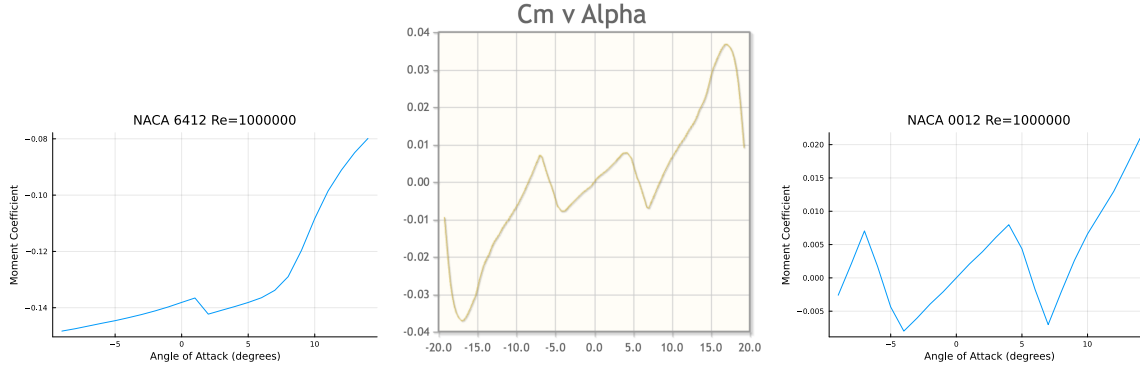


Figure 5: Moment Coefficient of a NACA 6412 Airfoil with a Reynolds number of 1 Million

Figure 6: Moment Coefficient of a NACA 0012 Airfoil third party

Figure 7: Moment Coefficient of a NACA 0012 Airfoil with a Reynolds number of 1 Million

4.2 CFD Comparisons

Looking at an article published that used CFD on a NACA 2412, we see an additional match [KGS20]. Comparing Figure 2 to Figure 14 you can see the similar trend of sharp uptakes in drag as the stall angle is approached and passed. Similarly, there is a similar linear portion up to a stall angle in Figure 1 and Figure 13. However the exact values in these differ slightly, likely mostly due to a difference in Reynolds number since the one used in the CFD calculations wasn't readily available.

4.3 Experimental Data Comparisons

To compare with experimental data, I used a study conducted by NASA [AB94] in the 90's testing airfoils in a wind tunnel to verify the Xfoil data. Comparing Figures 17 and 18 to Figures 15 and 14 we see extremely similar patterns and stall angles. The values of the coefficients for those angle of attacks are also close, showing a good match between the experimental data and the Xfoil-generated plots.

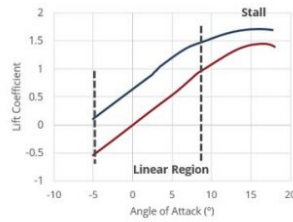


Figure 8: Lift Coefficients found using Xfoil, third party

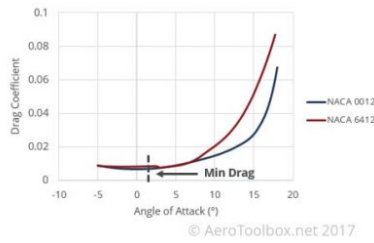


Figure 9: Lift Coefficient of a NACA 6412 Airfoil with a Reynolds number of 1 Million

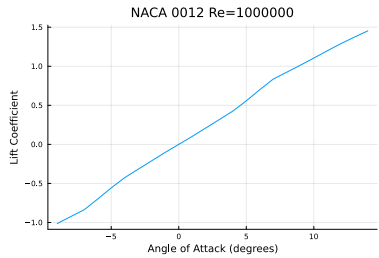


Figure 10: Lift Coefficient of a NACA 0012 Airfoil with a Reynolds number of 1 Million

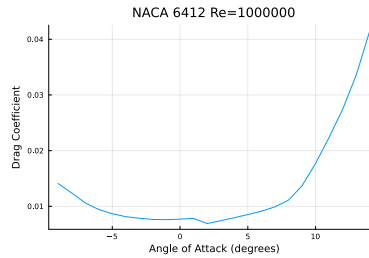


Figure 11: Drag Coefficient of a NACA 6412 Airfoil with a Reynolds number of 1 Million

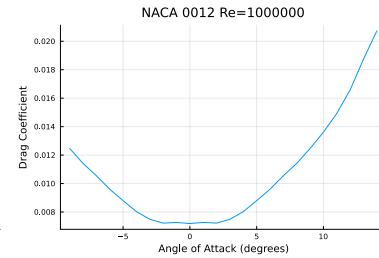


Figure 12: Drag Coefficient of a NACA 0012 Airfoil with a Reynolds number of 1 Million

4.4 Comparison Conclusion

The Xfoil method aligns well with real data, CFD simulations, and other Xfoil programs. Overall, the panel method is accurate in estimating the lift, drag, and moment coefficients of a NACA airfoil for a given angle of attack and Reynolds number.

5 Reynolds Number Effect

The Reynolds number is a dimensionless value that represents the ratio of inertial to viscous forces. It characterizes the behavior of a fluid as it flows over a plate and determines if the flow is turbulent or laminar, affecting the lift, drag, and moment of the plane.

5.1 Lift Coefficient

As the Reynolds number increases the flow becomes more turbulent. Turbulent flow can follow sharper curves for longer, allowing the airfoil to handle more extreme angles of attack before stalling, as seen by comparing Figures 19 and 17.

5.2 Drag Coefficient

At low angles of attack, the drag coefficient is similar, but it increases much quicker with higher Reynolds numbers due to more eddies and vortices. This increases boundary layer thickness which increases skin friction drag, and causes larger pressure differences increasing the pressure drag. This effect on the drag coefficient can be seen by comparing Figures 20 and 21.

5.3 Moment Coefficient

As observed in Figures 22 and 23 in Appendix A, the moment coefficient becomes more level and less responsive to changes in the angle of attack. This could be due to increased mixing, delayed separation of more turbulent flow, or perhaps the increased turbulence causes a more even pressure distribution.

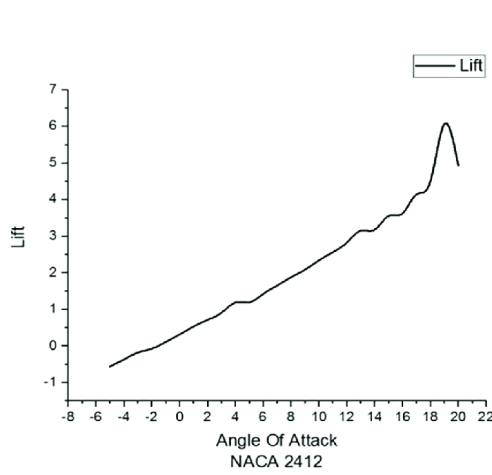


Figure 13: Lift Coefficient of a NACA 2412 Airfoil Calculated with Computational Fluid Dynamics

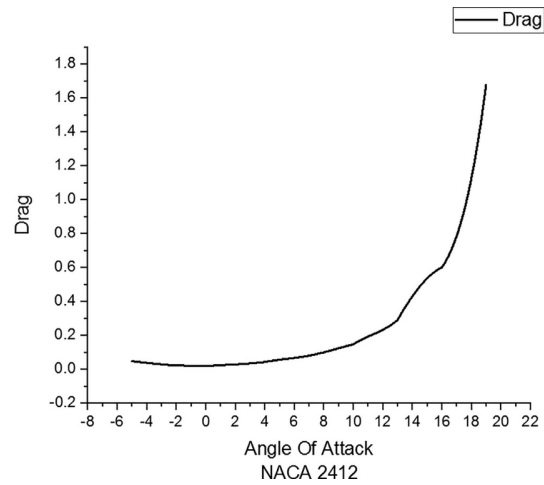


Figure 14: Drag Coefficient of a NACA 2412 Airfoil Calculated with Computational Fluid Dynamics

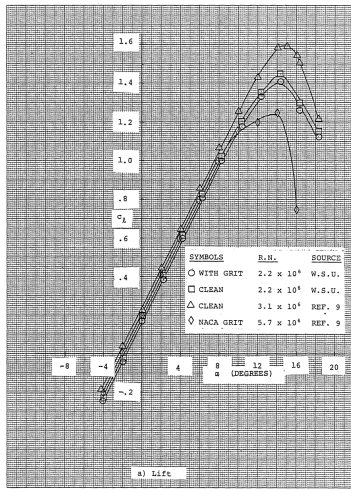


Figure 15: Lift Coefficient of a NACA 2412 Airfoil Determined Experimentally

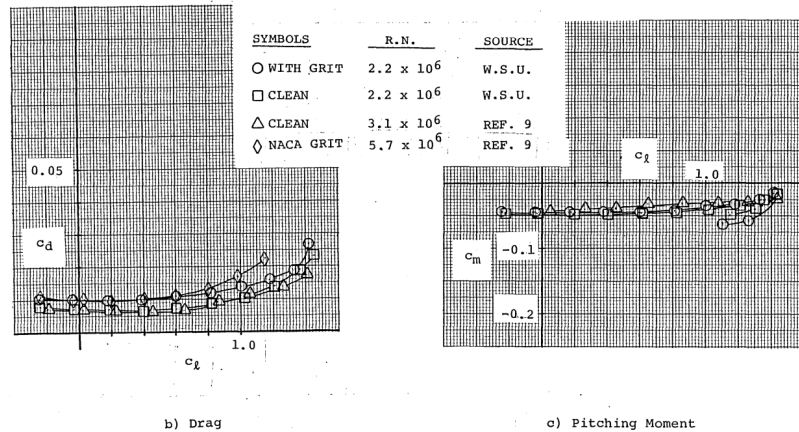


Figure 16: Drag Coefficient of a NACA 2412 Airfoil Determined Experimentally

6 Effect of Airfoil Shape

The shape of the airfoil significantly affects fluid flow impacting the lift, drag, and moment coefficients.

6.1 Camber

Camber, the curve or asymmetry of the wing, is one way to manipulate airfoil shape. It is the maximum distance between the chord line and a line equidistant between the upper and lower surfaces. For a symmetrical airfoil the camber is 0.

6.1.1 Lift to Drag Ratio

Increased camber results in a positive shift in the lift to drag ratio, with greater periods of low drag and more rapid increases to higher drag coefficients. This can be seen by comparing Figures 24, 25 and 26 in Appendix B.

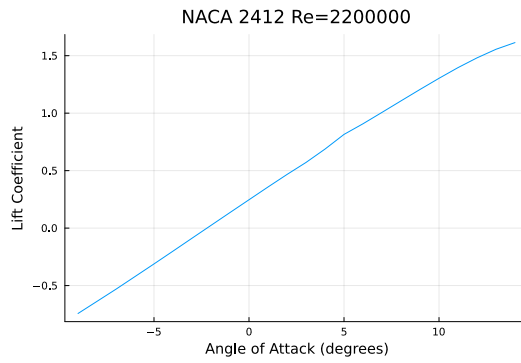


Figure 17: Lift Coefficient of a NACA 2412 Airfoil with a Reynolds Number of 2.2 Million

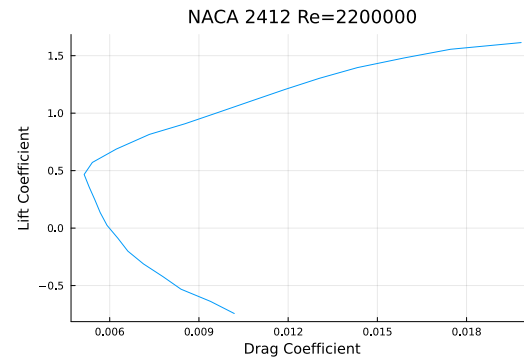


Figure 18: Drag vs Lift Coefficients of a NACA 2412 Airfoil with a Reynolds Number of 2.2 Million

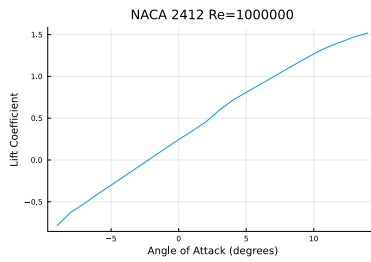


Figure 19: Lift of a NACA 2412 Airfoil in Flow with a Reynolds Number of 1 Million

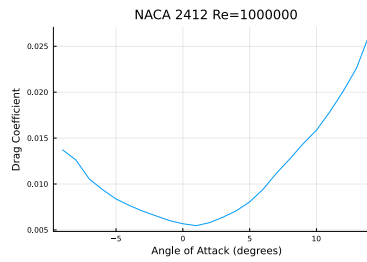


Figure 20: Drag of a NACA 2412 Airfoil in Flow with a Reynolds Number of 1 Million

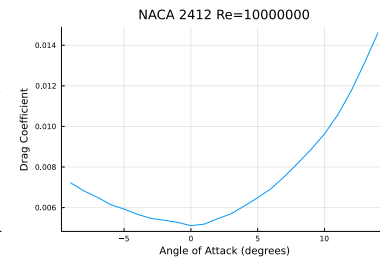


Figure 21: Drag Coefficient of a NACA 2412 Airfoil with a Reynolds Number of 10 Million

6.1.2 Lift Curve Slop

The slope of the lift coefficient versus the angle of attack increases with increased camber, as shown by comparing Figures 19, 9 and 10.

6.2 Thickness

Thickness, the maximum distance between the upper and lower surfaces of the airfoil perpendicular to the chord line, is another way we can manipulate the shape of the airfoil.

6.2.1 Lift to Drag Ratio

For thinner airfoils the lift coefficient plateaus or maxes out sooner when compared to the drag. This can be seen by comparing Figures 27, 28, 25 and 29 in Appendix C.

6.2.2 Lift Curve Slope

Thickness has little effect on the slope of the lift curve. However, it does seem to postpone the stall angle, shown by comparing Figures 30, 31, 19 and 32 in Appendix D.

References

- [AB94] David N. Anderson and Daryl L. Bonhaus. Simplified aerodynamic analysis of slender delta wings with leading-edge vortex flows. Technical report, NASA Technical Memorandum 110419, 1994. Accessed: 2024-09-10.
- [Aer24] AeroToolbox. Lift, drag, and moment coefficient. 2024. Accessed: 2024-09-10.

- [KGS20] Arnav Kulshreshtha, Sanjeev Kumar Gupta, and Piyush Singhal. Fem/cfd analysis of wings at different angle of attack. *Materials Today: Proceedings*, 26:1638–1643, 2020. 10th International Conference of Materials Processing and Characterization.
- [Too24] Airfoil Tools. Naca 0012h airfoil details, 2024. Accessed: 2024-09-11.

A Camber Lift to Drag Ratio Plots

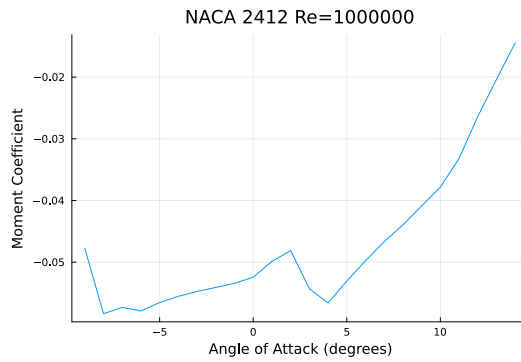


Figure 22: Moment Coefficient of a NACA 2412 Airfoil with a Reynolds Number of 1 Million

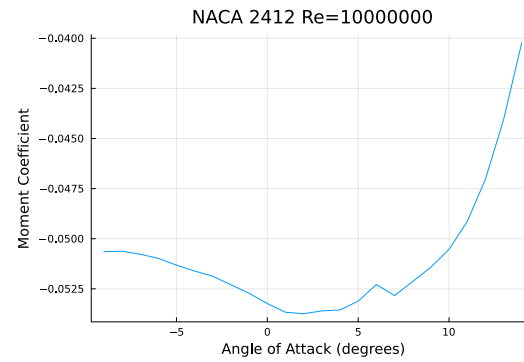


Figure 23: Moment Coefficient of a NACA 2412 Airfoil with a Reynolds Number of 10 Million

B Camber Lift to Drag Ratio Plots

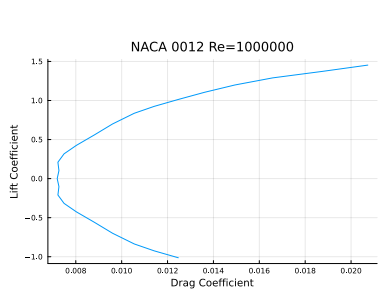


Figure 24: Drag vs Lift Profile NACA 0012

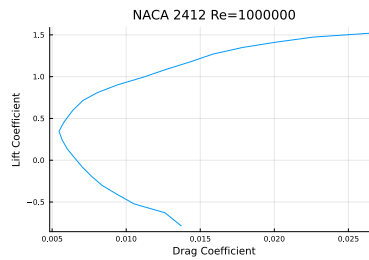


Figure 25: Drag vs Lift Profile NACA 2412 with a Reynolds number of 1 Million

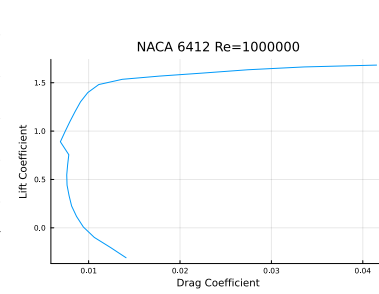


Figure 26: Drag vs Lift Profile NACA 6412

C Thickness Lift to Drag Ratio Plots

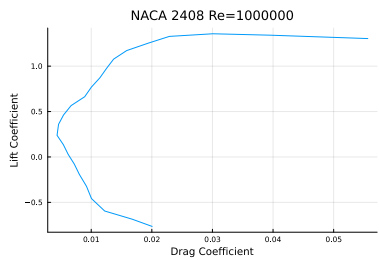


Figure 27: Drag vs Lift Profile NACA 2408

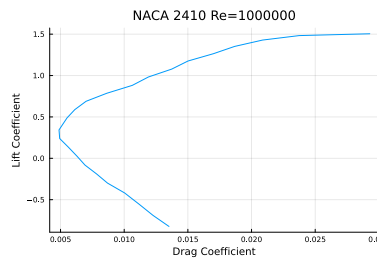


Figure 28: Drag vs Lift Profile NACA 2410

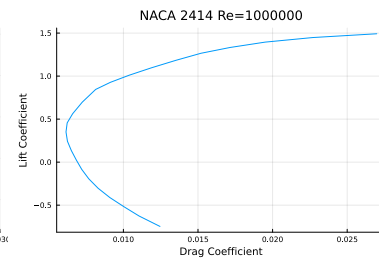


Figure 29: Drag vs Lift Profile NACA 2414

D Thickness Lift Curve Slope Plots

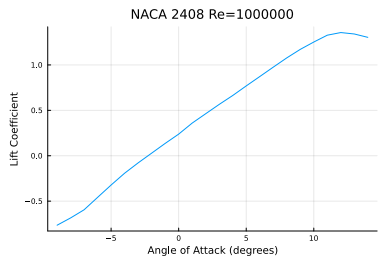


Figure 30: Drag vs Lift Profile
NACA 2408

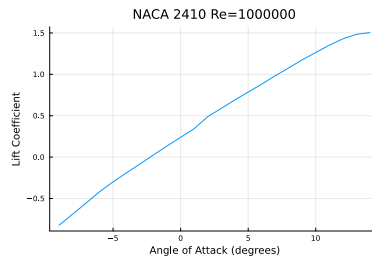


Figure 31: Drag vs Lift Profile
NACA 2410

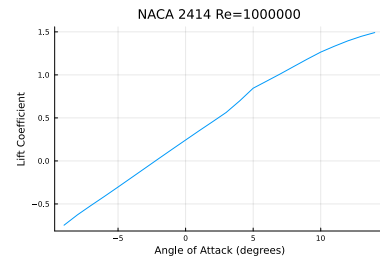


Figure 32: Drag vs Lift Profile
NACA 2414