Investigation and Analysis of NACA Airfoils in Viscous, Incompressible Flow Conditions using XFOIL

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Introduction

The report of interest focuses on the aerodynamic analyses of three specific NACA (National Advisory Committee for Aeronautics) airfoils – NACA 23012, NACA 2412, and NACA 64A012 under viscous, incompressible flow conditions. Using an open-source airfoil analysis tool known as XFOIL[1], data was collected for the performance of the three designated airfoils at a flow Reynolds number $Re = 3 * 10^6$ and across the angle of attack range $0 < \alpha° < 10$ at increments of 2 degrees. The recorded and plotted parameters were lift coefficient C_l, pitching moment coefficient C_m, and drag coefficient C_d, while lift-to-drag ratio $\frac{L}{D}$ was recorded from XFOIL but not plotted. Of particular interest were the following plots: $C_l\ vs.\ \alpha$ (the lift-curve slope), $C_m\ vs.\ C_l$ (pitching moment coefficient vs. lift coefficient), and $C_d\ vs.\ C_l$, the drag polar.

The results of this analysis were then compared against results under the same flow conditions found in a notable NACA report[2] written by Ira H. Abbott and Albert E. von Doenhoff in 1945 (henceforth referred to shorthand as 'A&D') for validation and distinction purposes. Also of particular interest in the initial problem statement was an evaluation of the performance of each airfoil against each other – particularly, the study determined the best performing airfoil at a designated $C_l = 0.5$.

X-Foil Background Information

As previously stated, the data collection process depends on the open-source command-line software XFOIL, which was designed as a design and analysis tool for individual subsonic airfoils. While the design element is irrelevant in the context of this study, the program's ability to perform analysis of an airfoil's performance across varying Reynolds numbers and sequential angles of attack is particularly useful. Written in 1986 by Professor Mark Drela at the Massachusetts Institute of Technology (MIT), the software has since become a cornerstone of open-source aerospace engineering.

The software contains the airfoil coordinates of the NACA 23012 and NACA 2412 airfoils, but the program is also able to read in and write airfoil coordinate files, such as the NACA 64A012 coordinate file[3] used in the study. The software is also capable of generating geometric profiles for each airfoil imported. Similarly, analysis of the airfoil under flow conditions produces a plot of the pressure profile across the airfoil (Figure 2), and the program's ability to analyze the same airfoil at the same Reynolds number across several angles of attack at once produced interesting results (Figure 3).

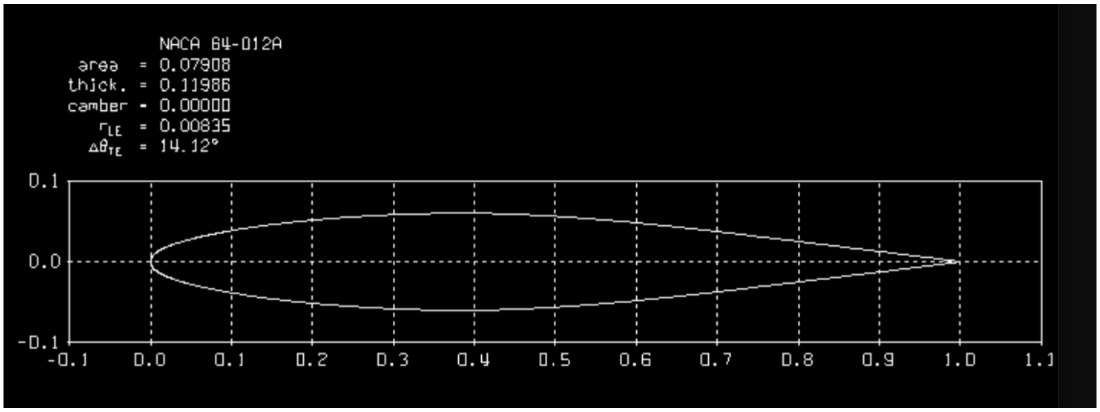


Figure 1: A geometric representation of the NACA 64012A airfoil in XFOIL

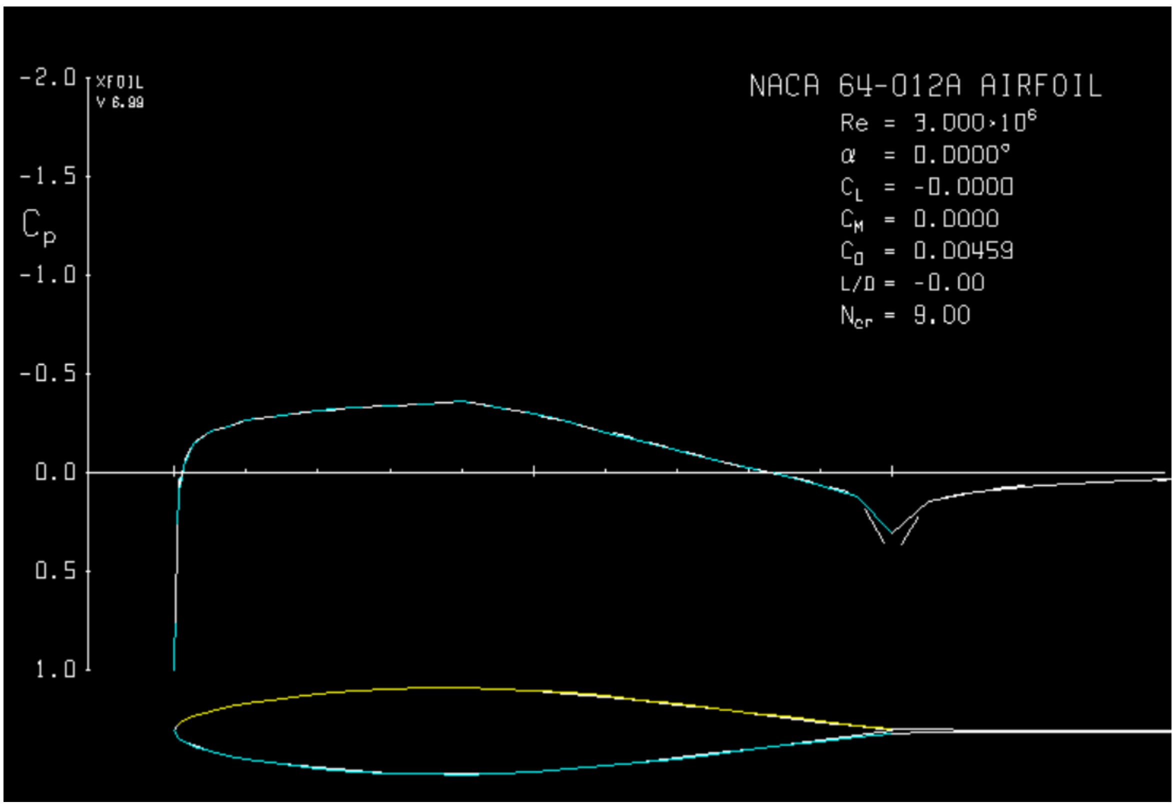


Figure 2: A sample analysis performed on NACA 64012 at the designated Re and $\alpha = 0°$ in XFOIL

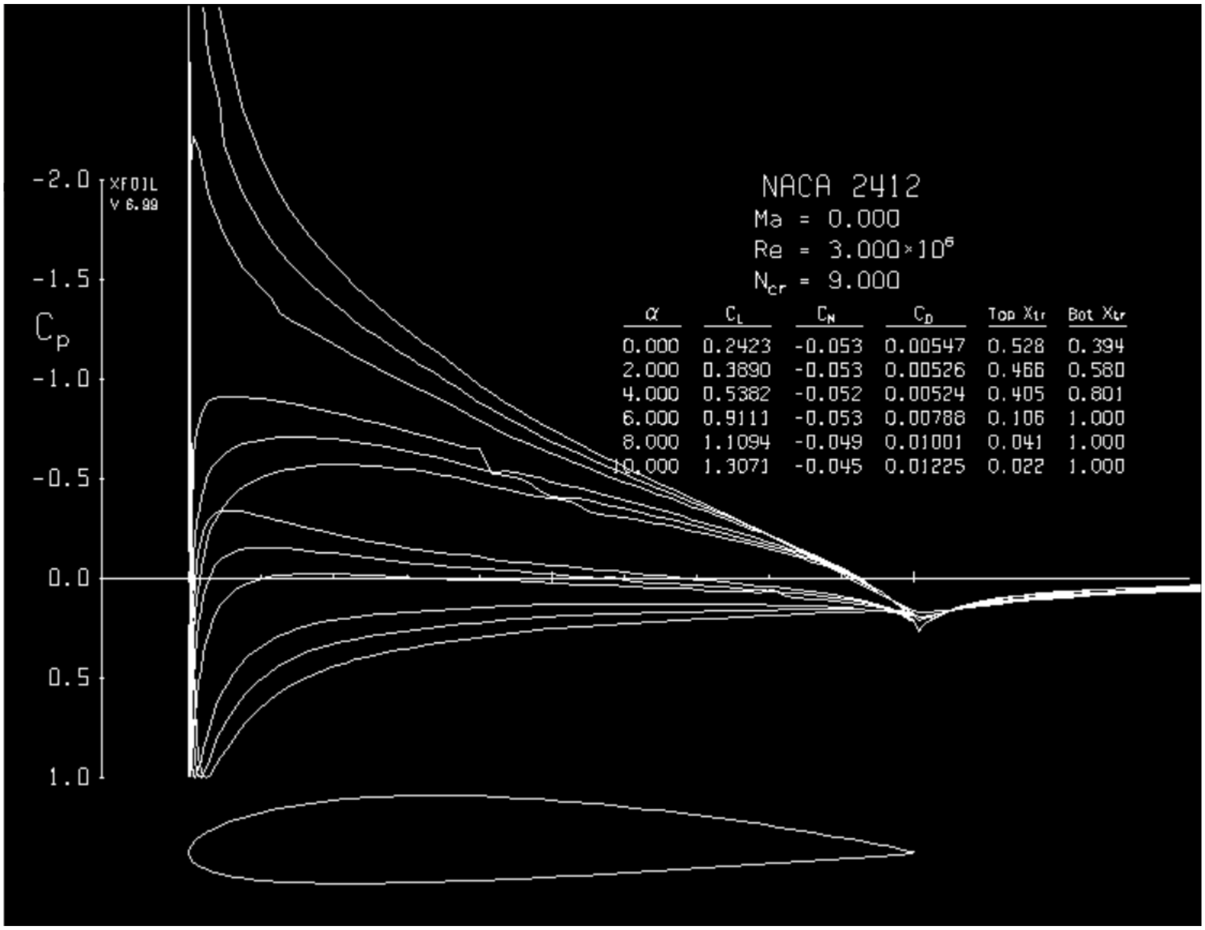


Figure 3: Analysis of NACA 2412 performed across the full range of designated angles of attack in XFOIL

As implied, the XFOIL is the exclusive source of all 'theoretical' data in the context of this study that will be used to compare against the experimental data from the A&D publication. XFOIL formulates viscous analyses by solving the resulting nonlinear system of viscous equations with a full-Newton method. It is also worth noting that the Karman-Tsien correction is incorporated. Further information can be found at the XFOIL source website[1], however the details are unnecessary for the following discussion.

Data Presentation and Discussion

As the A&D report was published in 1945, it is worth noting that the 3rd airfoil NACA 64A012 was not yet developed, as it was part of the 6-series. NACA 2412 (4-series) and NACA 23012 (5-series) were subjects of the study, however, so the comparison between current XFOIL results and the experimental data obtained in the A&D report is valid.

There were minute differences between the lift curve slope plots between data obtained from XFOIL and the A&D data for NACA 2412 (Figure 3). However, these differences were magnified in the pitching moment coefficient vs. lift coefficient (Figure 4) and drag polar (Figure 5) plots, where the A&D experimental data was less and less accurate as angle of attack increased. Interestingly, the A&D experiment consistently overestimated the corresponding drag coefficient with the obtained lift coefficients (Figure 5), while there was both overestimation and underestimation for the pitching moment coefficient, which changed directions of error as angle of attack increased (Figure 4).

It is worth noting that, because of the non-tabular nature of the A&D report, the entire experimental dataset across all three airfoils was estimated up to the given degrees of freedom in Tables 2 and 3. Naturally, these values were always less significant than the theoretical counterparts obtained from XFOIL (Table 1).

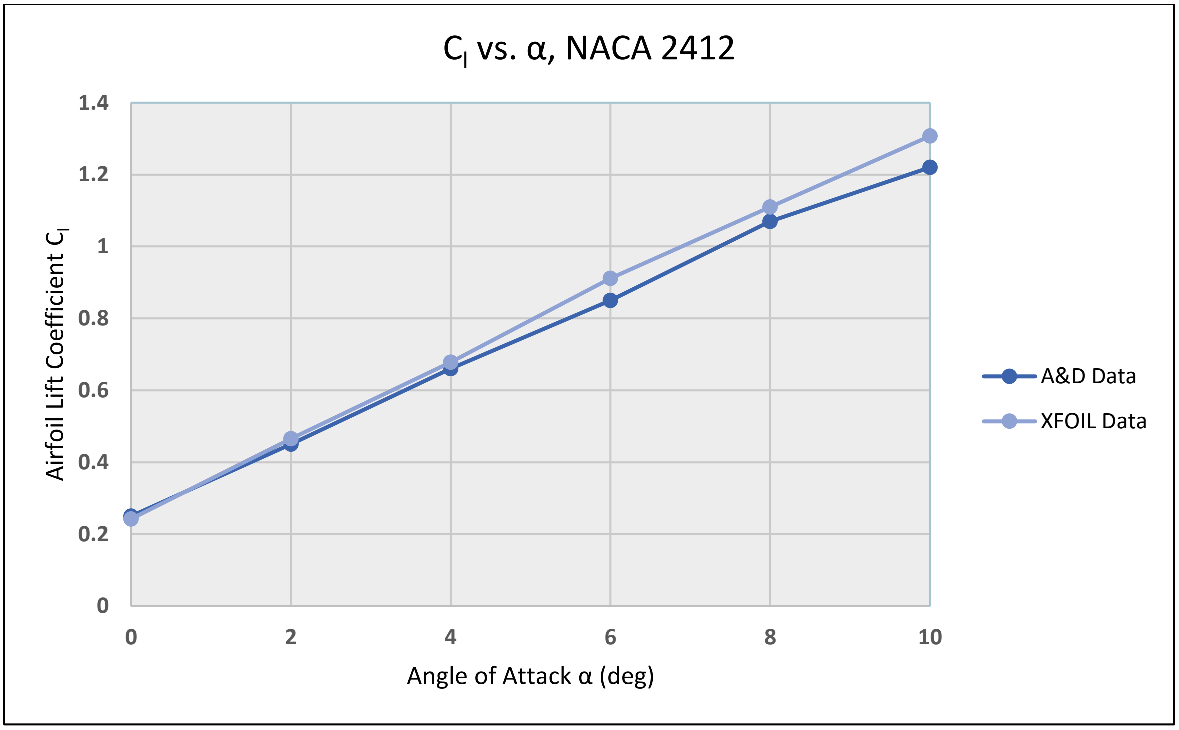


Figure 4: Experimental and theoretical lift coefficient vs. angle of attack values for NACA 2412, plotted

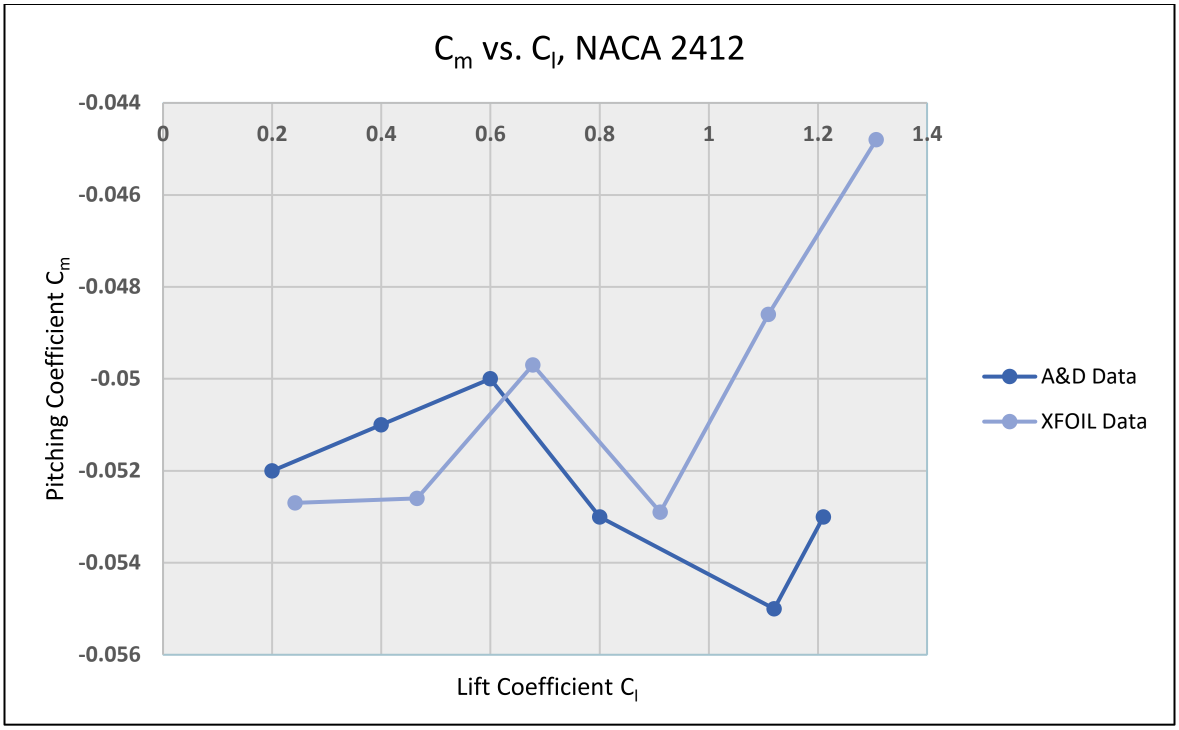


Figure 5: Experimental and theoretical pitching moment coefficient vs. lift coefficient values for NACA 2412, plotted

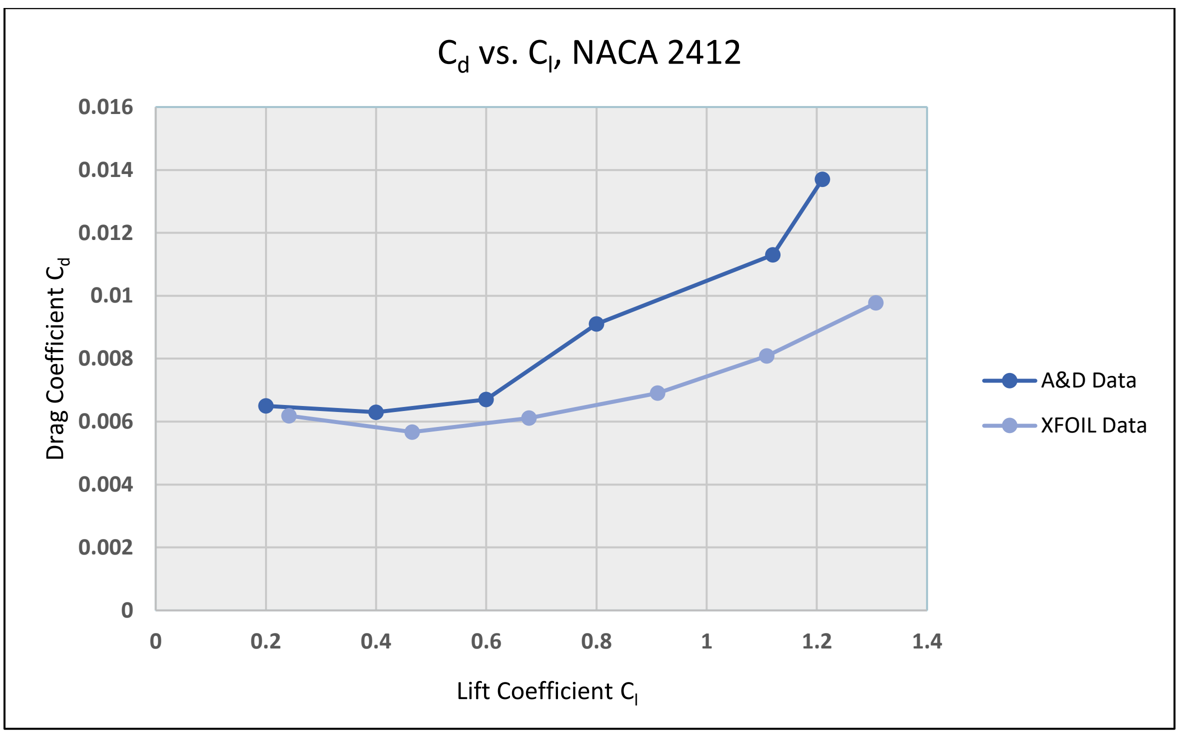


Figure 6: Experimental and theoretical drag coefficient vs. lift coefficient values for NACA 2412, plotted

$\alpha°$	C_l	C_m	C_d
0	0.2423	-0.0527	0.00547
2	0.4655	-0.0526	0.00508

4	0.6779	-0.0497	0.00571
6	0.9111	-0.0529	0.00789
8	1.1094	-0.0486	0.01001
10	1.3071	-0.0448	0.01225

Table 1: Theoretical (XFOIL) data for NACA 2412 across designated angles of attack

$\alpha°$	$C_l\ (est).$
0	0.25
2	0.45
4	0.66
6	0.85
8	1.07
10	1.22

Table 2: Experimental (A&D) estimated lift coefficients for NACA 2412 across designated angles of attack

$C_l\ (est).$	$C_m\ (est).$	$C_d\ (est).$
0.2	-0.052	0.0065
0.4	-0.051	0.0063
0.6	-0.05	0.0067
0.8	-0.053	0.0091
1.12	-0.055	0.0113
1.21	-0.053	0.0137

Table 3: Experimental (A&D) estimated pitching moment and drag coefficients with corresponding lift coefficients, NACA 2412

Similar trends held for NACA 23012 (Figures 7-9), with the specific values assigned to Tables 4-6 in a similar manner as with NACA 2412.

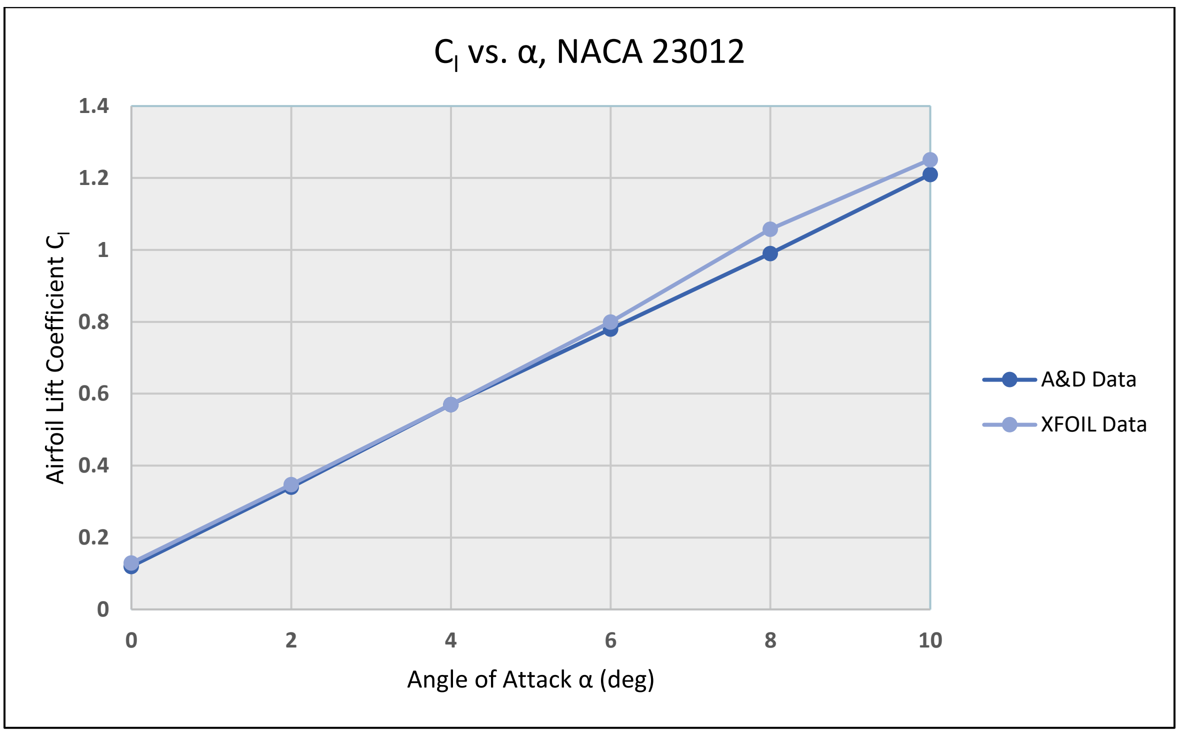


Figure 7: Experimental and theoretical lift coefficient vs. angle of attack values for NACA 23012, plotted

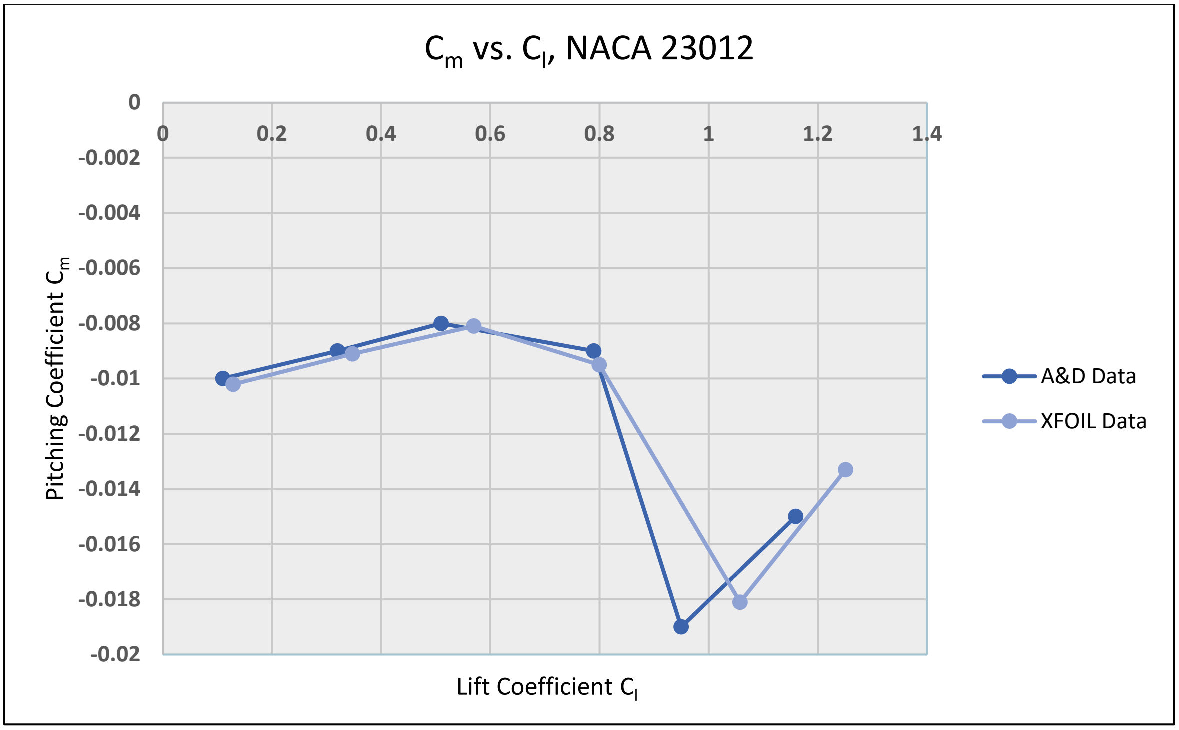


Figure 8: Experimental and theoretical pitching moment coefficient vs. lift coefficient values for NACA 23012, plotted

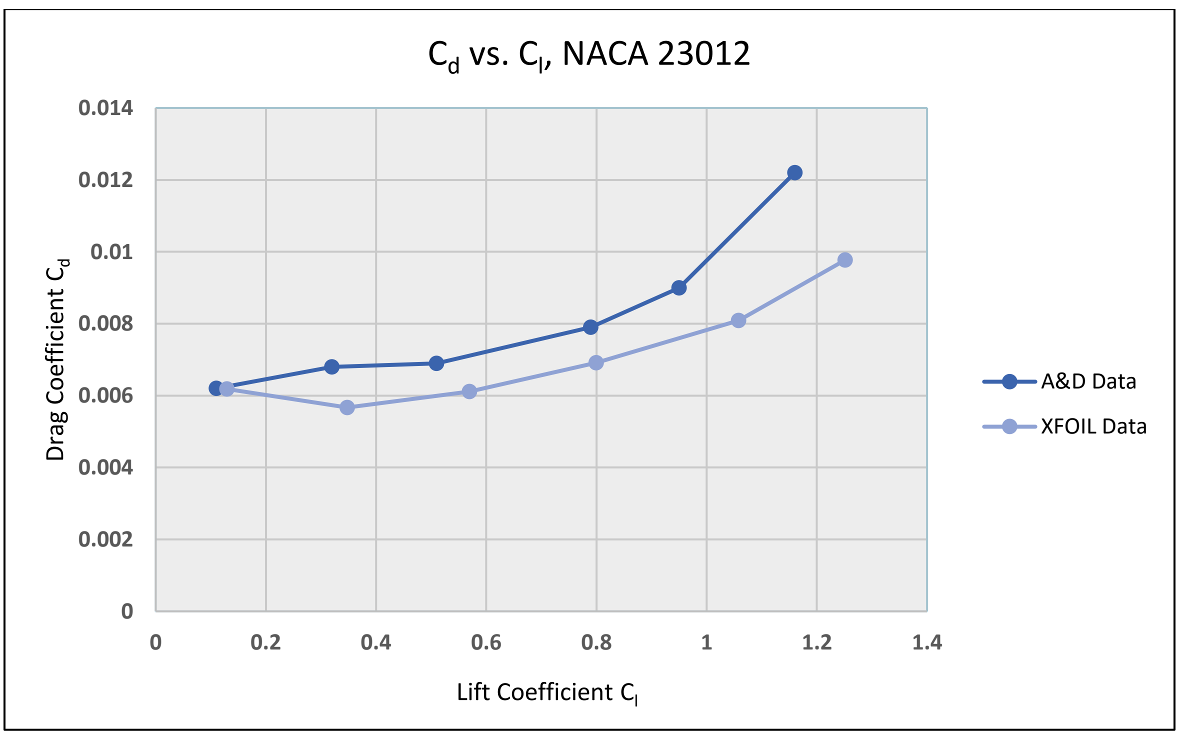


Figure 9: Experimental and theoretical drag coefficient vs. lift coefficient values for NACA 23012, plotted

$\alpha°$	C_l	C_m	C_d
0	0.1291	-0.0102	0.00618
2	0.3476	-0.0091	0.00567
4	0.5696	-0.0081	0.00611
6	0.7997	-0.0095	0.00691
8	1.0579	-0.0181	0.00809
10	1.2512	-0.0133	0.00977

Table 4: Theoretical (XFOIL) data for NACA 23012 across designated angles of attack

$\alpha°$	$C_l\ (est).$
0	0.12
2	0.34
4	0.57
6	0.78
8	0.99
10	1.21

Table 5: Experimental (A&D) estimated lift coefficients for NACA 23012 across designated angles of attack

$C_l\ (est).$	$C_m\ (est).$	$C_d\ (est).$
0.11	-0.01	0.0062
0.32	-0.009	0.0068
0.51	-0.008	0.0069
0.79	-0.009	0.0079
0.95	-0.019	0.009
1.16	-0.015	0.0122

Table 6: Experimental (A&D) estimated pitching moment and drag coefficients with corresponding lift coefficients, NACA 23012

Finally, as mentioned, there was no experimental data for the airfoil NACA 64A012, so the XFOIL data is displayed below (Figures 10-12). The specific values are shown in Table 7.

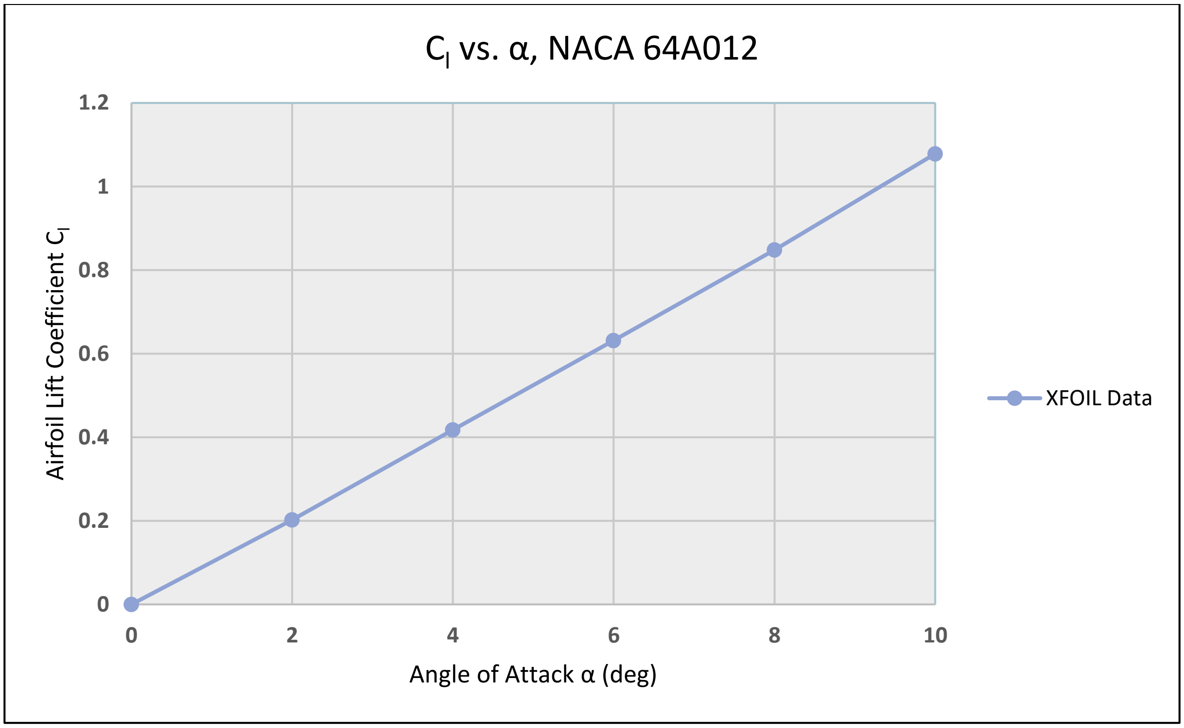


Figure 10: Theoretical lift coefficient vs. angle of attack values for NACA 64A012, plotted

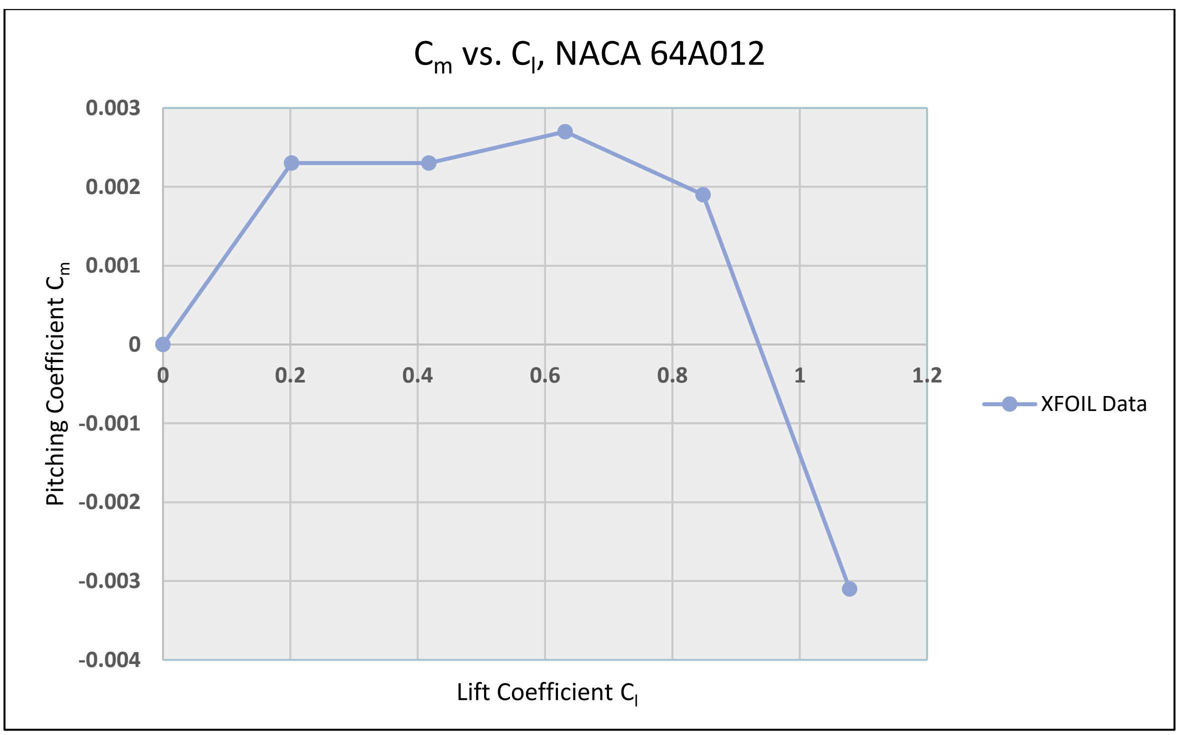


Figure 11: Theoretical pitching moment coefficient vs. lift coefficient for NACA 64A012, plotted

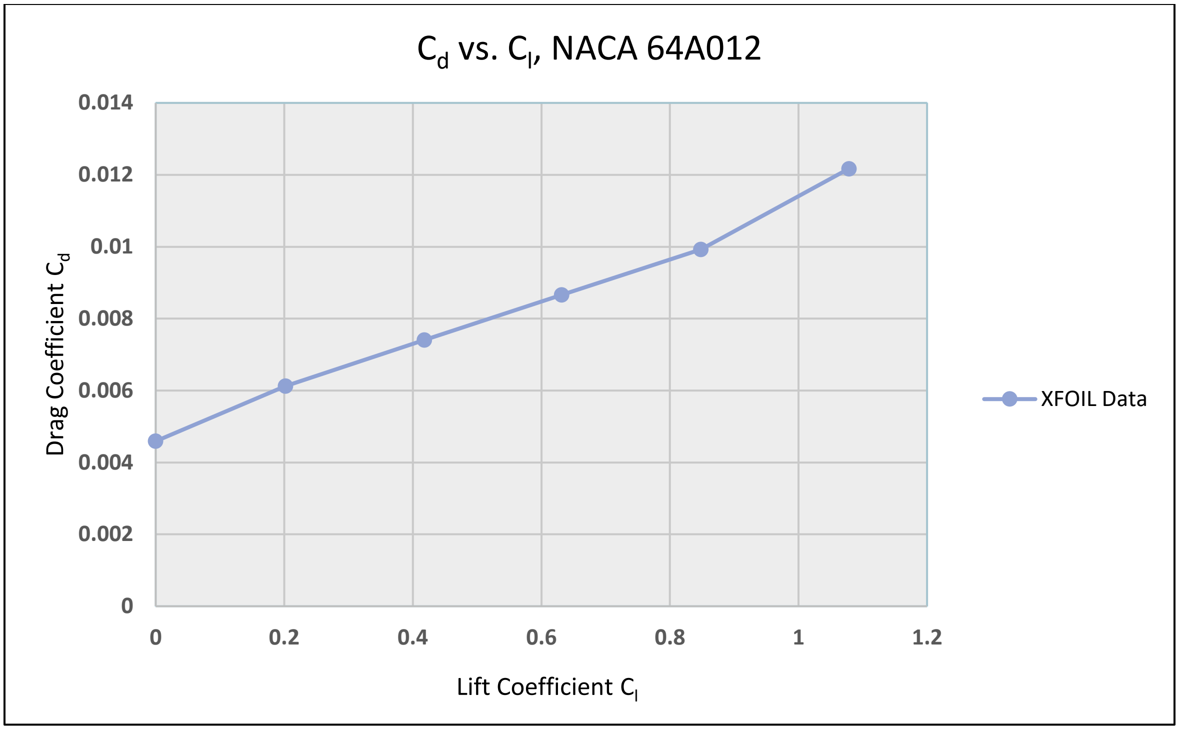


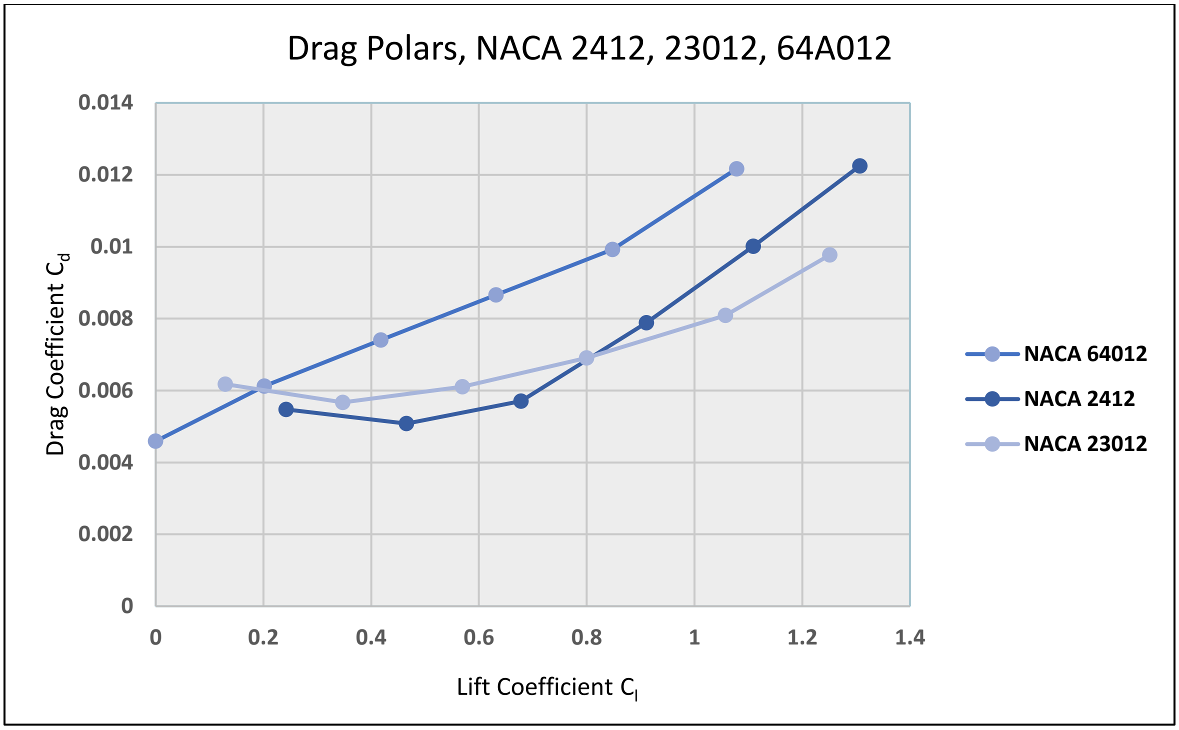
Figure 12: Theoretical drag coefficient vs. lift coefficient values for NACA 64A012, plotted

$\alpha°$	C_l	C_m	C_d
0	0.1291	-0.0102	0.00618
2	0.3476	-0.0091	0.00567
4	0.5696	-0.0081	0.00611
6	0.7997	-0.0095	0.00691
8	1.0579	-0.0181	0.00809
10	1.2512	-0.0133	0.00977

Table 7: Theoretical (XFOIL) data for NACA 64A012 across designated angles of attack

Notably, the A&D experimental data was obtained in 1945 in the Langley Two-Dimensional Low Turbulence Tunnel, where the experimental airfoil was placed inside the narrow test region such that it spanned the entire width of the region (hence, two dimensions). The approach was subject to possible sources of error, such as inaccurately constructed airfoils that either did not span the width of the test region or were not precisely the correct shape. However, given the predictability of the errors on each of the figures above, it is likely that any discrepancies are owed primarily to advancements in flow theory or fundamental assumptions in XFOIL that could not have been accurately simulated with the technology available to Abbott and Doenhoff at the time.

To evaluate the performance of each airfoil against one another, the drag polars of each airfoil were plotted in a separate plot (Figure 13). The drag polar embodies the lift-to-drag ratio of the airfoil – an airfoil can be said to perform better when it produces more drag with less lift, thus a high lift-to-drag ratio is preferable. Among the airfoils, for example, NACA 2412 has the lowest corresponding drag coefficient value at around 0.005 when C_l is approximately 0.5 – hence, NACA 2412 is said to be the best suited for operating at those conditions.



Conclusion

While the experimental (A&D) and theoretical (XFOIL) values did not always exactly agree, they produced nearly identical lift-curve slopes, and the values were similar at low angles of attack. However, as angle of attack increased, the experimental data diverged further and further away from the theoretical values, implying a systematic error concerning either the experimental setup itself or the technology involved in the 1945 A&D study.

Comparison of the theoretical drag polars of the three NACA airfoils produces results that point towards NACA 2412 as clearly the most desirable at a designated $C_l = 0.5$, which corresponds to about an angle of attack $\alpha = 4°$ for that airfoil. Using the drag polar it is possible to determine which airfoils have the highest lift-to-drag ratio, and are therefore best suited to flight, given a certain angle of attack.

References

1. Drela, Mark (1986). XFOIL Subsonic Airfoil Development System [Computer software]. Retrieved January 31, 2022, from https://web.mit.edu/drela/Public/web/xfoil/
2. Abbott, Ira, & von Doenhoff, Albert E. (1945). Summary of Airfoil Data. *National Advisory Committee for Aeronautics. Issue 824.*
3. Airfoil Tools. (n.d.). NACA 64-012A Airfoil. NACA 64-012A airfoil (N64012A-il). Retrieved January 31, 2022, from http://airfoiltools.com/airfoil/details?airfoil=n64012a-il