Investigating the Tubercle Effect on the NACA 24xx airfoil series: Investigation Using Ansys Fluent

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Nature is a remarkable source of inspiration for engineering designs, and certain organisms are meticulously studied to gain knowledge from them. One of these organisms, the humpback whale, has a unique characteristic on their fins. Tubercles on the leading edge of their fins help them maneuver more efficiently through water. Inspired by these tubercles, this research paper analyzes the aerodynamic changes due to tubercles on the leading edge of airfoils. While adequate progress has been made in the study of symmetrical airfoils, the exploration of cambered airfoils has been comparatively limited. This research paper aims to perform a comparative analysis of the performance of the NACA 24xx airfoil series. This cambered airfoil series is studied using Ansys CFD software. NACA 2408 (thin airfoil), NACA 2410 (Not thin nor thick airfoil), and NACA 2412 (Thick airfoil) airfoils are studied. In the search of potential applications for the aviation industry, this paper aims to simulate flight conditions of lighter aircrafts; because of this, a flow speed of 65 m/s was set. Independent variables include airfoil shape, thickness, angle of attack, tubercle size, and tubercle frequency, while the dependent variables studied are lift and drag. The airfoils tested had minimal improvements to lift and many iterations had increases in drag, resulting in insignificant changes to the lift to drag ratio. However, NACA 2410 did have noticeable improvements at angles of attack of 5 and lower.

I. Nomenclature

AOA = angle of attack
C_l = lift coefficient
C_d = drag coefficient
Re = Reynolds number
v = fluid velocity
A = amplitude
c = chord length of original airfoil
c' = chord length of airfoil at the point where the lower part of the tubercle is located
NP = number of planes
SF = scale factor
W = wavelength
S = wingspan

II. Introduction

Humpback whales are some of the most impressive organisms found in nature, being one of the heaviest animals on the planet they possess an incredible aquatic maneuverability for their size and weight. The tubercles, illustrated in Figure 1, (golf-sized bumps on the leading edge of their fins) on their fins have been proven to be a major responsible for this ability [1].

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Figure 1. Image of a humpback whale fin and its tubercles.

Over the past years many researchers have investigated the potential applications of adding tubercles to wing-like structures reaching to the conclusion that for small Reynolds numbers they can have a better performance when the optimal configuration is found [2].

In 2001, Dr P. Watts and Dr. F. E. Fish conducted the first ever CFD study of an airfoil modified with leading edge tubercles. Inspired by the increased maneuverability that tubercles gave to humpback whales, the two scientists to analyze how leading edge tubercles would affect the NACA 634-021 aerodynamic performance (this airfoil was chosen as it closely resembled the geometry of a humpback whale fin). Interestingly, not only did they confirm that the moment coefficient would increase (as expected by observing humpback whale behavior), but they also found an increase of 4.8% in lift, a 10.9% induced drag reduction, and a 17.6% increase in lift to drag ratio [3]. This paper analyzed the NACA 634-021 airfoil at a flow velocity of 1 m/s, a 10 degree AOA, and an unknown tubercle size. Over time, more researchers have investigated this effect reaching the same conclusion: for a small Reynolds number, tubercles lead to an increased Cl/Cd ratio. Papers like 'Influence of Leading-Edge Tubercle with Amplitude Modulation on NACA 0015 Airfoil'[4], or "Reynolds Number Effect of Leading Edge Tubercles on Airfoil Aerodynamics," [5] show similar results and an improved behavior in the post stall regime. They were performed with different airfoils and conditions (only a small Reynolds number was mimicked).

This report analyzes the experimental results obtained from the ANSYS CFD simulations of the airfoils NACA 2408, NACA 2410, and NACA 2412. The goal is to analyze if the tubercle effect (with sinusoidal tubercle) is affected by the size of the airfoil's camber (thus different airfoils with the same location for the maximum camber were analyzed). Additionally, it will also be seen whether tubercle wavelength has an effect on the aerodynamic performance of the airfoils; amplitude is constant with a value of 0.025 meters. The airfoils had a chord length and wingspan of 1 meter, with varying tubercle wavelengths of 0.5, 0.25, 0.2, and 0.1 meters.

III. Methodology

A. Airfoil Geometry and Creation

The airfoils were developed using the ANSYS Workbench tool [6]. The coordinates of the airfoils NACA 2408, NACA 2410, and NACA 2412 were exported from the website 'Airfoil Tools'. The non-tubercled wings were created by simply extruding the airfoil obtained from the coordinates. In order to replicate the tubercles, the lower part of each tubercle had to be sized to have an amplitude of 0.025 m. To do so, the following equation was used:

$$SF = 1 - \frac{A}{c} = 1 - \frac{2*25}{1000} = 0.95$$

Equation 1. Chord scale factor formula and calculation.

Knowing the scale factor, it was easy to calculate the chord of the new airfoil (lowest part of the tubercle) by using the following equation:

$$c' = c \cdot SF = 1 \cdot 0.95 = 0.95\,m$$

Equation 2. Scaled chord formula and calculation.

Once the max chord length and the minimum chord lengths were known it was a matter of knowing the number of planes required in order to reach the 1 m desired wingspan. To do so, the following equation was used:

$$NP = 1 + \frac{2*S}{W}$$

Equation 3. Number of planes formula.

The distance between planes was computed using the following equation:

$$DP = \frac{W}{2}$$

Equation 4. Distance between planes formula.

With desired wavelengths equal to 0.5 m, 0.25 m, 0.2 m, and 0.1 m, and a known wingspan of 1 m, the following table summarizes the number of planes needed to replicate each tubercled wing, and the spacing between them:

Wingspan (m)	Wavelength (m)	NP	DP (m)
1	0.5	5	0.25
1	0.25	9	0.125
1	0.2	11	0.1
1	0.1	21	0.05

Figure 2. Table showing variables Wavelength, NP, and DP which are used to design the tubercled wings.

Below, the top view of the NACA 2410 wing with tubercles of wavelength equal to 0.2 is shown. The number of planes NP is highlighted in the form of lines (11 for this case):

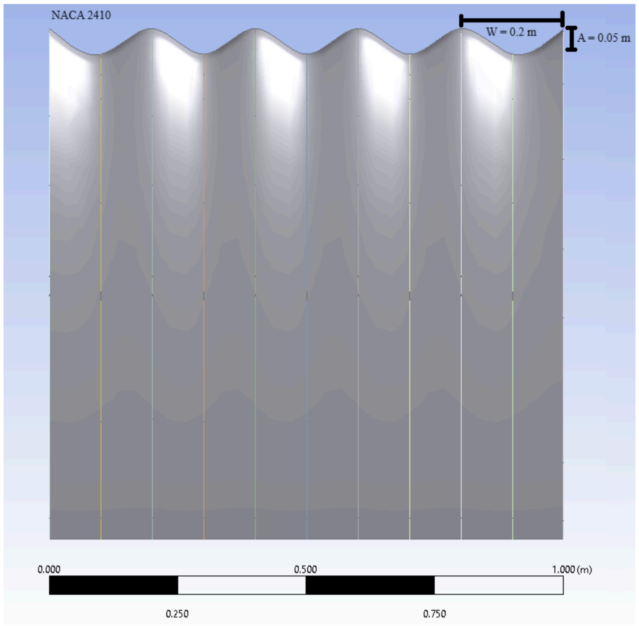

Figure 3. Image of the NACA 2410 airfoil with tubercles of 0.2 m wavelength and 0.025 m amplitude.

B. Experimental Setup and Procedure

All analyses were conducted using the Ansys suite of computational fluid dynamics software, specifically using Ansys Design Modeler for the geometry and Ansys Fluent for the meshing and flow solutions. Excel spreadsheets containing the relative coordinates of the airfoil geometries (full scale and 95% scale) were converted into text files that can be used by Design Modeler to create sketches that replicate the airfoil shape. Using the previously stated formulas, the required planes were created in separate models for NACA 2408, NACA 2410, and NACA 2412, and then subsequently all the tubercle variations for each airfoil. Creating the complete body required the “Skin/Loft” tool, which creates smooth curves over the planes created.

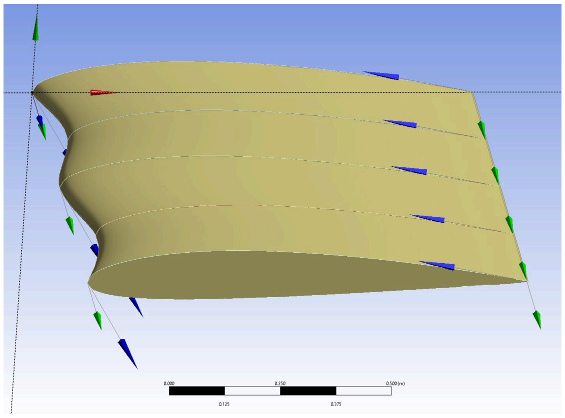

Figure 4. Image of the NACA 2410 airfoil with tubercles of 0.5 m wavelength and 0.025 m amplitude after use of the “Skin/Loft” function.

Ansys Fluent relies on the fluid area being analyzed, so a wind tunnel test section was created around the airfoil, with a half circle of 7.5 meters centered on the airfoil leading edge and a 15 meter long rectangle trailing behind it. The large size compared to the airfoil minimizes edge and compression effects. After extruding and subtracting the airfoil body from the test section body, each face was named for meshing and property assignment. One significant issue encountered was the meshing limitations with the student edition of Ansys, which has a mesh cell limit. This reduced the ideal fidelity of the solution, but the results obtained are still representative of high-fidelity simulations due to a large cell density around the airfoil. Even though accuracy is sacrificed in areas farther away from the airfoil, conclusions about tubercles’ effect on lift and drag solutions are achievable [7]. Down the wingspan, the body is split into 80 divisions, while down the chord the body is split into 50 divisions. Radially around the airfoil within 0.1 meters, the body is split into 20 divisions. The entire wind tunnel section was limited to mesh cell sizes that are 0.15 meters in width or lower to increase overall accuracy.

Importing the meshes into Fluent allows for automated improvements of low quality cells. These tests specified that the 1% worst quality cells would get improvements. Inlet parameters were specified to be at 65 meters per second with a dynamic viscosity of 1.789×10^{-5} Pascal seconds, and the reference values for the drag and lift coefficient computations were set to the same values. For angles of attack other than 0 degrees, the velocity was split into y and x components. Lift and drag coefficients were set to be reported to the corresponding unit vector determined by the current angle of attack. Lift is perpendicular to the angle of attack while drag is parallel. The maximum residuals for computation accuracy were assigned to 1×10^{-5}. While the maximum iterations allowed was 1200, all simulations converged within 200 [1].

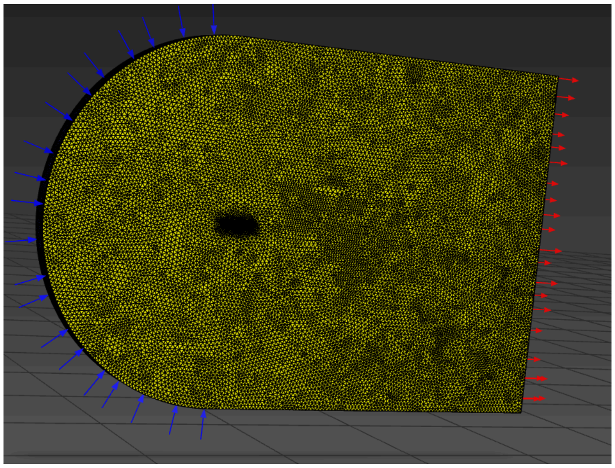

Figure 5. Side view of NACA 2410 tubercled wing test section after meshing.

IV. Results

The following plots display the summary of the experimental results obtained from the CFD analysis. All the graphs were made using the data from the Appendix:

NACA 2408

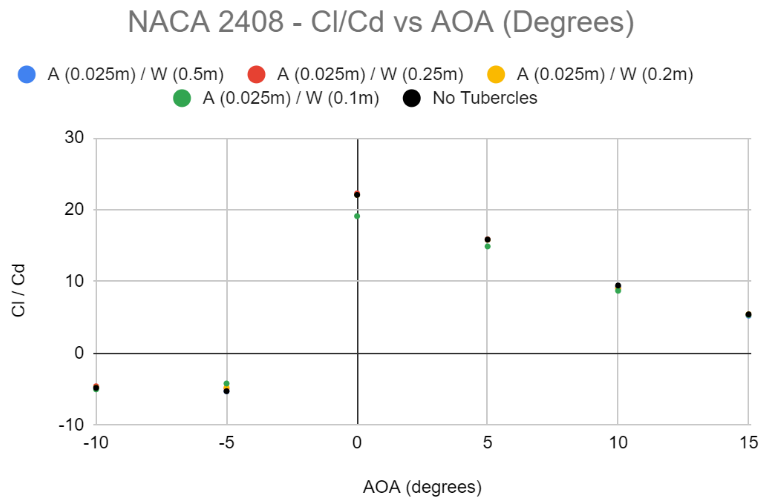

Figure 6. NACA 2408 graph showing Cl/Cd vs AOA (degrees) for all wing designs.

For the NACA 2408 wings, it is seen that the maximum Cl/Cd is obtained at AOA = 0 degrees by the tubercles sized with W = 0.25 m. In comparison to the non-tubercled wing, this wing has a Cl/Cd 0.89%. All the other tubercled wings provided an inferior Cl/Cd value at AOA = 0 degrees. For all positive AOA the non-tubercled airfoil provided larger Cl/Cd values except for AOA = 5 degrees where the tubercled designs with wavelength = 0. 5 m and 0.25 m provided a slightly larger value. The wing with the worst performance was the one with the smallest tubercles, while the two best were the ones in the middle which had a very similar behavior (W = 0.2 m, and then W = 0.25 m).

NACA 2410

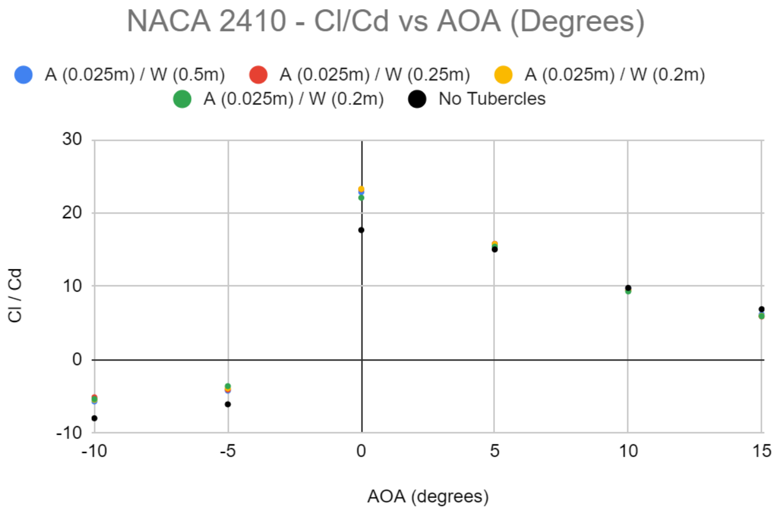

Figure 7. NACA 2410 graph showing Cl/Cd vs AOA (degrees) for all wing designs.

For the NACA 2410 wings, it is seen that the maximum Cl/Cd is obtained at AOA = 0 degrees by the tubercles sized with W = 0.25 m. In comparison to the non-tubercled wing, this wing has a Cl/Cd 24.09% larger showing a significant improvement. All the other tubercled wings provided a superior Cl/Cd value at AOA = 0 degrees, and in comparison to the non-tubercled wing, all of them had Cl/Cd value 20% larger at minimum. As the positive AOA increases, the difference between the tubercled and non =-tubercled wings diminishes. At AOA = 5 degrees, the largest difference of Cl/Cd values between a tubercled wing and a non-tubercled wing comes from the wing with tubercles of W = 0.25 m (approximately 5% larger); all the other tubercled designs have a slightly larger Cl/Cd values. After AOA = 10 degrees, the non-tubercled airfoil shows a superior performance with slightly higher Cl/Cd values. The wing with the worst performance was the one with the smallest tubercles, while the two best were the ones in the middle which had a very similar behavior (W = 0.2 m, and then W = 0.25 m).

NACA 2412

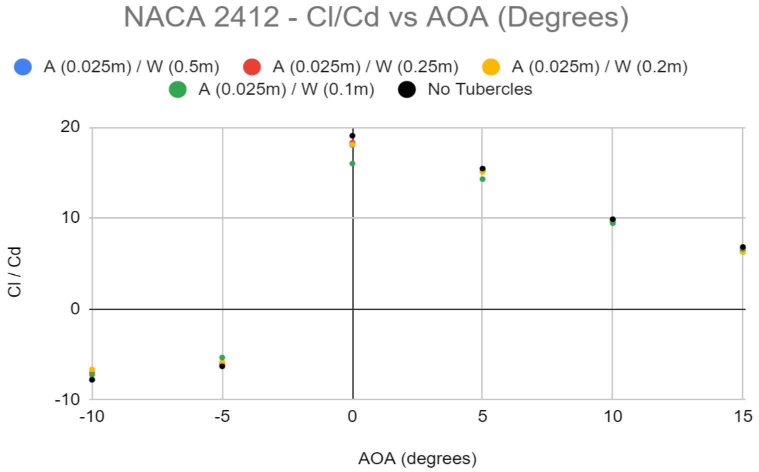

Figure 8. NACA 2412 graph showing Cl/Cd vs AOA (degrees) for all wing designs.

For the NACA 2412 wings, again, it is seen that the maximum Cl/Cd is obtained at AOA = 0 degrees. In this case, unlike in the previous ones, the non-tubercled wing provides an improved Cl/Cd for all AOA. In comparison to the best tubercled wing (W = 0.25 m), the non-tubercled wing provides a Cl/Cd 4.18 % higher which is significantly better. All other airfoils have an even larger difference at AOA = 0 degrees with the maximum difference being 19.17% worst. As AOA increases the differences diminish but the non-tubercled airfoil proves to be superior for all AOA. Again, the wing with the worst performance was the one with the smallest tubercles, while the two best were the ones in the middle which had a very similar behavior (W = 0.2 m, and then W = 0.25 m).

V. Discussion

The first thing that stands out is the superior performance of the NACA 2410 tubercled wings in comparison to NACA 2408 and NACA 2412. Not only are the Cl/Cd values higher but the difference between the highest Cl/Cd tubercled values and non-tubercled values is significantly better than that of the NACA 2408 and NACA 2412 (24.09% larger for NACA 2410 in comparison to 0.89% larger for NACA 2408, and 4.18 smaller for NACA 2412). Additionally this trend follows as the AOA increases; performance is still better for NACA 2410. Further study would involve understanding why this phenomenon occurs.

With the data obtained, no relationship exists between camber size, tubercles, and wing performance. The tubercled wing with the largest camber (NACA 2412) showed the worst performance however, the thinnest airfoil (NACA 2408) did not show a superior behavior to that of the wing which was neither thin nor thick (NACA 2410).

With tubercle size significant conclusions are obtained. When the tubercles are very small (W = 0.1 m), the performance decreases. This behavior agrees with the one obtained in the paper "Reynolds Number Effect of Leading Edge Tubercles on Airfoil Aerodynamics," [5]. However, it is important to notice that in this paper, the wing with the largest wavelength does not show the best performance. The previous paper analyzed wings with maximum wavelength equal to 21% of the chord. This paper analyzes similar tubercle sizes and adds a significantly larger one (50% of the chord). A possible explanation for why the behavior of the tubercled wing with W = 0.5 m is not better than W = 0.2 m and W = 0.25 m is that these two are closer to the optimal configuration. Further analysis should be performed to find the actual optimal configuration.

Although accuracy has been sacrificed due to only having available the ANSYS Workbench Student version, trend identification is achievable as mentioned in the Experimental Setup and Procedure section. Because of this, it is possible to identify what has a greater effect on the Cl/Cd values of the wings. The figures 9 through 23 in the Appendix illustrate tables of the Cl and Cd vs AOA (degrees) for all the wings and tubercles analyzed. As the data is discussed it can be seen if the reason why in many occasions the Cl/Cd value is greater for the non-tubercled airfoil is a smaller Cl, a larger Cd, or both for the tubercled airfoils. For the NACA 2408 case, it is interesting to see that for the positive AOA (except 15 degrees) the Cd is smaller for the tubercled wings than for the non-tubercled wings; this means that the reason why the Cl/Cd is smaller or slightly bigger for tubercled wings than regular the regular NACA 2408 wing is that the Cl values are smaller. In other words, tubercles for NACA 2408 produce less drag but also significantly less lift. For the NACA 2410, the Cd trend continues and expands to AOA = -5 degrees. From AOA = -5 degrees onwards, the Cd of the tubercled wings is significantly smaller. Additionally, on this occasion, up to AOA = 10 degrees, they are also producing more lift giving a higher Cl for the tubercled wings than the non-tubercled. Both conditions lead to the significant improvement in Cl/Cd mentioned in the results section for the wing NACA 2410. The NACA 2412 tubercled wings are simply not good enough in comparison to the previous two. On this occasion, a lower Cl and a higher Cd from the tubercled wings lead to a significant decrease in the Cl/Cd with respect to the non-tubercled wing. Overall, and as a trend, it can be said that Cd tends to be smaller for tubercled airfoils at lower AOA than its non-tubercled counterparts. NACA 2412 escapes this trend but even then the Cl has a more negative effect on the Cl/Cd value than the Cd.

VI. Conclusion

With most cambered airfoils tested in this series of simulations, no major increases in lift or lift over drag can be found, but small variances in Cl/Cd were discovered at the lowest and highest angles of attack simulated. The exception to this statement is the NACA 2410, which had a noticeable improvement at angles of attack of 0 or lower. This increase was mitigated at any higher AOAs. However, the drag difference between the basic and tubercled airfoils increased universally as the AOA was changed away from 0, only becoming higher as the AOA was further modified. Due to minor increases in lift, this increased drag had very little effect on Cl/Cd.

If more research is done on tubercled airfoils, improving the fidelity of the simulations would be a great increase in accuracy along with allowing for more structured conclusions about the tubercles' effect on the local pressure and velocity around the subject airfoil. As for the airfoil itself, larger ranges of AOA are suggested to investigate stall effects at common flight speeds. Tests on airfoils with more extreme cambers also can assist in making more general conclusions about the tubercles' effect on cambered wings, in addition to varying the distribution of tubercles on the leading edge, such as decreasing their amplitude as the distance from the fuselage increases.

Acknowledgements

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Appendix

NACA 2408:

NACA 2408 - A (0.025m) / W (0.5m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.28105	0.058586	-4.797221179
-5	-0.068638	0.012947	-5.301459798
0	0.18474	0.0083705	22.07036617
5	0.43951	0.027685	15.87538378
10	0.65358	0.070438	9.278798376
15	0.79419	0.15155	5.240448697

Figure 9. Table for NACA 2408 - A (0.025m) / W (0.5m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2408 - A (0.025m) / W (0.25m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.29626	0.064293	-4.607966653
-5	-0.068864	0.013968	-4.930126002
0	0.18523	0.0083164	22.27285845
5	0.44002	0.027712	15.87831986
10	0.65328	0.071945	9.08026965
15	0.7954	0.14852	5.355507676

Figure 10. Table for NACA 2408 - A (0.025m) / W (0.25m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2408 - A (0.025m) / W (0.2m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.29438	0.061543	-4.78332223
-5	-0.068935	0.014456	-4.76860819
0	0.1853	0.0083982	22.06425186
5	0.43925	0.027774	15.81515086
10	0.64927	0.072169	8.996522052
15	0.79578	0.14625	5.441230769

Figure 11. Table for NACA 2408 - A (0.025m) / W (0.2m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2408 - A (0.025m) / W (0.1m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.27581	0.054835	-5.029816723
-5	-0.064504	0.015286	-4.219808976
0	0.18371	0.009614	19.10859164
5	0.43445	0.029175	14.89117395
10	0.64304	0.073819	8.711036454
15	0.78856	0.14769	5.33929176

Figure 12. Table for NACA 2408 - A (0.025m) / W (0.1m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2408 - No tubercles			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.2856	0.059192	-4.824976348
-5	-0.069263	0.013101	-5.286848332
0	0.19221	0.0087071	22.07508815
5	0.45459	0.028703	15.83771731
10	0.68195	0.072233	9.440975731
15	0.75864	0.13994	5.421180506

Figure 13. Table for NACA 2408 - No tubercles showing Cl, Cd, and Cl/Cd and AOA.

NACA 2410:

NACA 2410 - A (0.025m) / W (0.5m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.25886	0.04552	-5.68636
-5	-0.04813	0.01140	-4.22093
0	0.20681	0.00905	22.84840
5	0.46116	0.02923	15.77478
10	0.68912	0.07098	9.70865
15	0.84922	0.13724	6.18785

Figure 14. Table for NACA 2410 - A (0.025m) / W (0.5m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2410 - A (0.025m) / W (0.25m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.25806	0.05030	-5.13042
-5	-0.04746	0.01165	-4.07374
0	0.20769	0.00894	23.24012
5	0.46115	0.02919	15.79930
10	0.67842	0.07129	9.51634
15	0.82948	0.14075	5.89329

Figure 15. Table for NACA 2410 - A (0.025m) / W (0.25m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2410 - A (0.025m) / W (0.2m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.25120	0.04590	-5.47265
-5	-0.04629	0.01187	-3.90099
0	0.20891	0.00897	23.29843
5	0.46275	0.02935	15.76446
10	0.68246	0.07207	9.46888
15	0.83944	0.14033	5.98190

Figure 16. Table for NACA 2410 - A (0.025m) / W (0.2m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2410 - A (0.025m) / W (0.1m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.24631	0.04590	-5.36670
-5	-0.04445	0.01233	-3.60492
0	0.20663	0.00935	22.08836
5	0.45770	0.02969	15.41648
10	0.67174	0.07212	9.31484
15	0.81410	0.13721	5.93324

Figure 17. Table for NACA 2410 - A (0.025m) / W (0.1m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2410 - No tubercles			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.32184	0.04032	-7.98274
-5	-0.08279	0.01361	-6.08213
0	0.17737	0.01003	17.68395
5	0.43846	0.02915	15.04099
10	0.68160	0.06957	9.79676
15	0.87081	0.12639	6.88986

Figure 18. Table for NACA 2410 - No tubercles showing Cl, Cd, and Cl/Cd and AOA.

NACA 2412:

NACA 2412 - A (0.025m) / W (0.5m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.31080	0.03982	-7.80532
-5	-0.08091	0.01305	-6.19952
0	0.17207	0.00954	18.03347
5	0.42604	0.02805	15.18805
10	0.66104	0.06750	9.79260
15	0.79555	0.12351	6.44118

Figure 19. Table for NACA 2412 - A (0.025m) / W (0.5m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2412 - A (0.025m) / W (0.25m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.30798	0.04378	-7.03472
-5	-0.07919	0.01317	-6.01489
0	0.17375	0.00949	18.30489
5	0.42569	0.02804	15.18369
10	0.64712	0.06708	9.64742
15	0.79592	0.12596	6.31883

Figure 20. Table for NACA 2412 - A (0.025m) / W (0.25m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2412 - A (0.025m) / W (0.2m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.29150	0.04370	-6.67048
-5	-0.07890	0.01345	-5.86573
0	0.17379	0.00960	18.10181
5	0.42409	0.02810	15.09002
10	0.64210	0.06696	9.59002
15	0.77039	0.12323	6.25164

Figure 21. Table for NACA 2412 - A (0.025m) / W (0.2m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2412 - A (0.025m) / W (0.1m)			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.30411	0.04190	-7.25748
-5	-0.07701	0.01439	-5.35252
0	0.17056	0.01066	16.00300
5	0.41660	0.02916	14.28669
10	0.64443	0.06832	9.43239
15	0.81885	0.12372	6.61857

Figure 22. Table for NACA 2412 - A (0.025m) / W (0.1m) showing Cl, Cd, and Cl/Cd and AOA.

NACA 2412 - No tubercles			
AOA (degrees)	Cl	Cd	Cl/Cd
-10	-0.31135	0.03994	-7.79505
-5	-0.08118	0.01284	-6.32448
0	0.17303	0.00907	19.07129
5	0.43193	0.02795	15.45533
10	0.67373	0.06821	9.87715
15	0.86433	0.12665	6.82456

Figure 23. Table for NACA 2412 - No tubercles showing Cl, Cd, and Cl/Cd and AOA.

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