ME 4030-01

Airfoil Term Project

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I. Abstract

This report is focused on the design of an airfoil that is to maximize the lift generated by a Boeing 787 aircraft at maximum altitude of 6000 feet and maximum speed of 561 miles per hour. The airfoil was selected from a curated group with experimental data accompanying each by a provided source. By using the attached information and comparing them, the optimal airfoil design chosen was the NACA4415 due to its superior aerodynamic efficiency and larger angle of attack. The NACA4415 was then compared to the conventional Boeing 737 Midspan Airfoil for Aerodynamic Efficiency, Lift Force as well as modeled for Computational Fluid Dynamics using SolidWorks. In turn, the NACA4415 had a higher Aerodynamic Efficiency at 12.41 compared to the Boeing 737's 8.75 and had a larger Lift Force capability at 8,168,179.35 lb of force compared to the Boeing 737's 5,758,515.11 lb of force. Thus, showing that the NACA4415 is indeed a better Airfoil design.

II. Introduction & Objectives

In the study of flight, airfoils are used to design a capable lift capacity for airplanes and other flying objects to gain lift. This study is used to garner the amount of lift capable of flight. It can be discerned even further by analyzing and describing the different forces acting on the airfoil at any given moment through a typical free body diagram. These airfoils are therefore typically used as the wing section on airplanes or any object that needs to gain lift to move in airspace. The general shape of an airfoil can take up many different looks and shapes, however the most common shape is the tear drop looking shape seen in Figure 1.

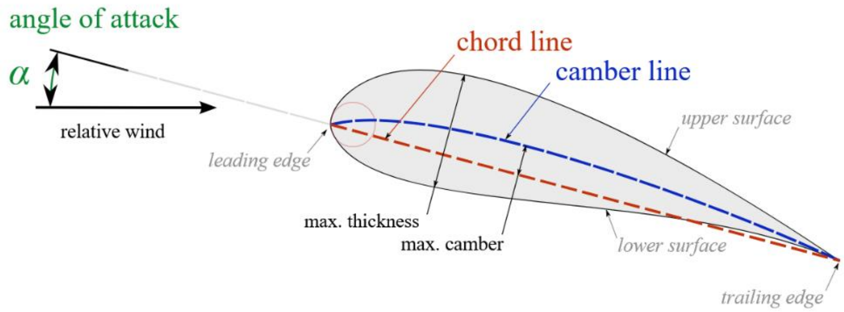

Figure 1. Airfoil General System [1]

This design can be used as the basis for several other designs and improvements upon for the study of airfoils. In turn the following variables from Figure 1.

Table 1. Airfoil General System [1]

Chord Line: Line directly in between leading edge and trailing edge **Camber Line:** Line directly in between the upper surface and lower surface **Angle of Attack:** Angle formed on the Airfoil that will correlate how much lift the airfoil can generate.

These characteristics and shapes can be modified to develop a new airfoil system to suffice and work for any given purpose. With this in mind, we can use our knowledge of Airfoils and the general body of knowledge already available to us to determine a suitable replacement for any typical plane airfoil design.

III. Experimental Methods

Given a Boeing 787 Aircraft, we are tasked to design an airfoil for the aircraft to garner lift.

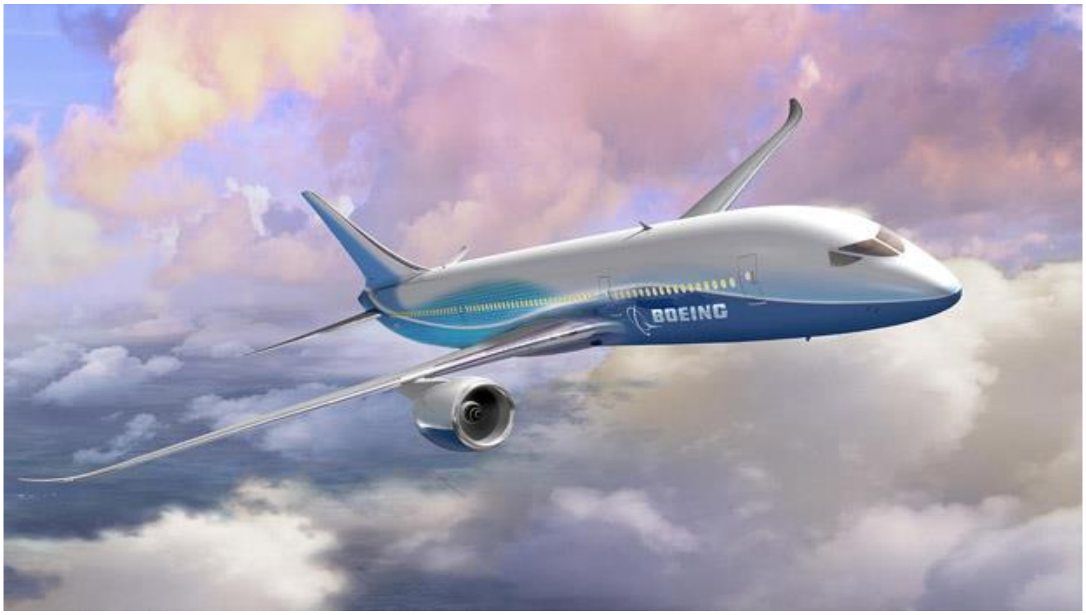

Figure 2. Boeing 787 Aircraft Artist Rendition [2]

This given variant of the aircraft will in turn have to reach an altitude of 6000ft and fly at a velocity of 561miles/hour. With these parameters we can then research other aspects regarding this plane to showcase the aspects of this simulation to have the best decision on airfoil for this plane to create max lift.

Given:

$Maximum\ Take\ Off\ Weight: 502{,}100\ lb$

$Maximum\ Landing\ Weight: 380{,}000\ lb$

Want:

$Maximum\ Lift$

With the velocity component system being placed on the bottom of the airfoil the air in turn allows for a resultant force to be exerted onto the airfoil which in turn allows the entire aircraft to exert lift and fly. A definition and diagram showing the isometric view of an airfoil can be seen in Figure 3 where the section corresponds to the definition of an airfoil section.

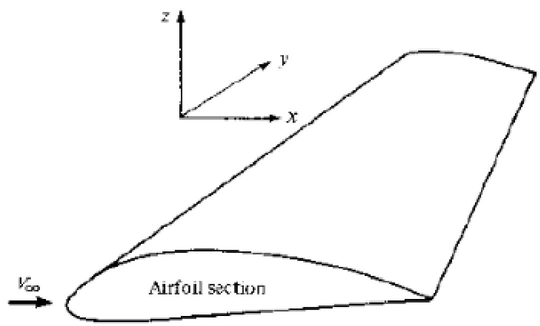

Figure 3. Airfoil Isometric View [3]

With the surrounding air creating a velocity vector in the direction of the airfoil seen as V_∞ is placed across the direction of the airfoil. The forces exerted from this are then seen in Figure 4 where the moment M on the airfoil and resultant lift force R are placed on the diagram.

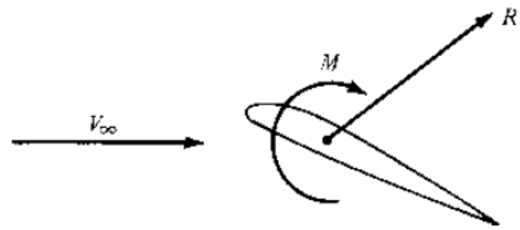

Figure 4. Forces Exerted onto Airfoil [3]

With this in mind, we can create a more detailed system design of an airfoil showcasing the forces and resultant forces on the foil system. This more detailed view of the forces and values are seen in Figure 5.

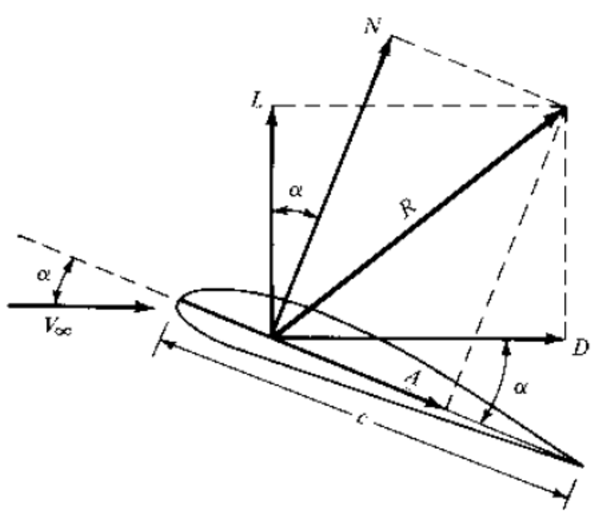

Figure 5. Resultant Forces Exerted onto Airfoil [3]

With these values denoted we can more specifically describe the values in the system which is described in Table 2.

Table 2. Airfoil General System [1]

$L = Lift = Component\ of\ R\ perpendicular\ to\ V_\infty$
$D = Drag = Component\ of\ R\ paralled\ to\ V_\infty$
$\infty = Angle\ of\ Attack$

The Lift vector denotes the force being exerted by the velocity of the air underneath the foil. The Drag vector denotes the drag experienced by the airfoil on the system. With the force being exerted on the airfoil, the direction by which the airfoil is fixed dictates the angle of attack from the respective airfoil design. This is seen in Figure 5 as α. More precisely, we can discern the differences in forces from the wing characteristics from the notion of high pressure and low-pressure parameters whereby the bottom of the airfoil uses the high pressure from the air to push the wing up into the atmosphere. This can be observed in Figure 6 where the system has the high and low pressures related to the characteristics for flight.

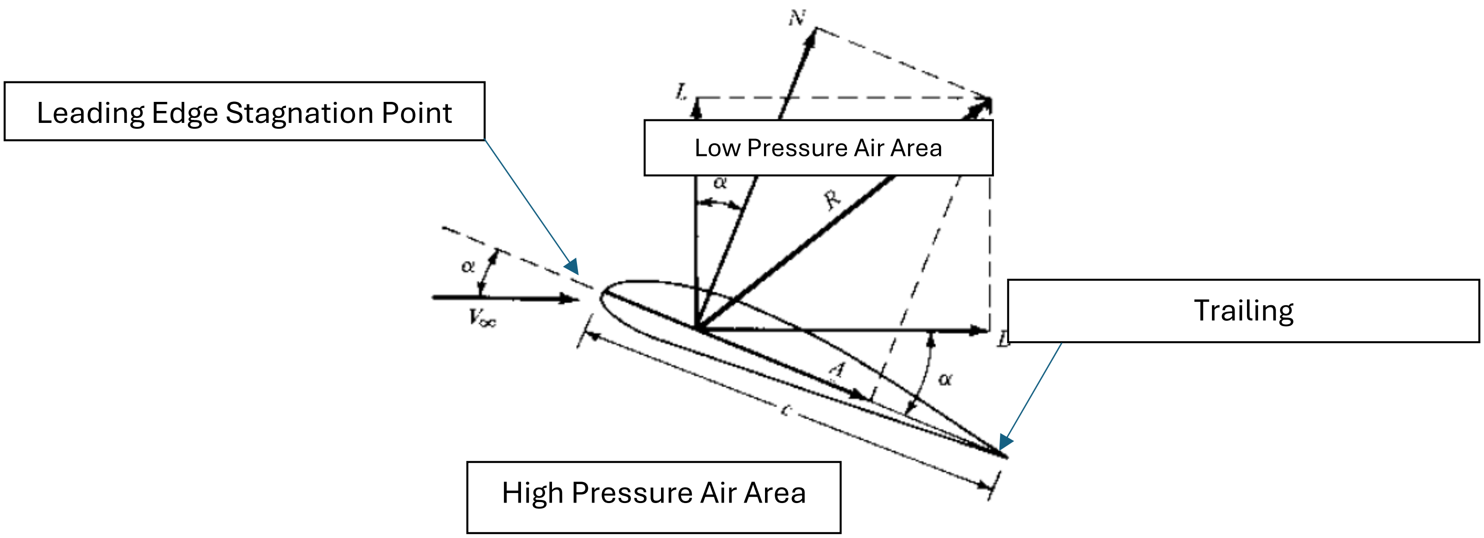

Figure 6. High Pressure Air Location [4]

In turn, we have certain already predefined types of airfoils that have been made and tested that we can test and compare for the most beneficial and applicable use for the given 737.

IV. <u>Sample Calculations</u>

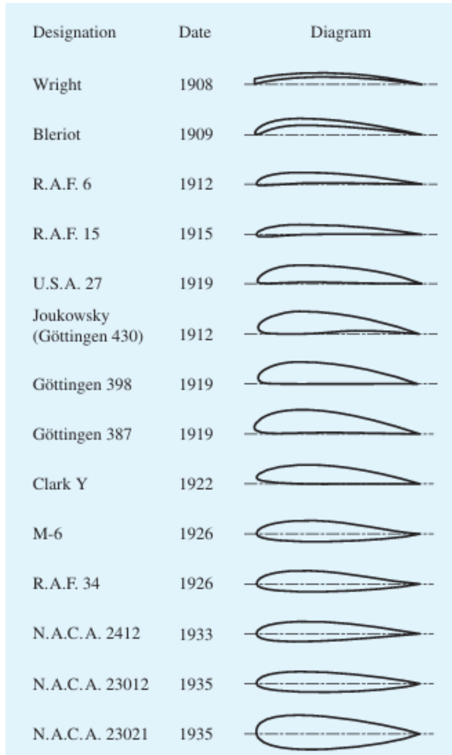

Figure 7. Pre-defined and designed airfoils [5]

Using given airfoils, as shown in figure 7, it is possible to solve and compare for the given airfoils present and compare for the given different airfoils. Using the information from the given website, we can solve for the given max lift.

$$\boldsymbol{L_{Lift\ Force} = \frac{1}{2} C_L \rho A V^2}$$

Equation 1. Lift Force Equation [1]

Table 2. Geometric Parameters/Dimensions of chosen NACA Airfoils

Airfoil	**Chord Length (m)**	**Wingspan (m)**	**Area of wing Chord Length*Wingspan**	**Velocity (m/s)**

			(m^2)	
NACA4415	13.5	55.04	743.04	230
NACA1408	9	45.3	407.7	243
NACA2411	15	39.4	591	256
NACA0012H	17.3	59.7	1032.8	185

Table 3. Comparison of NACA Airfoil [1]

$Airfoil$	Coefficient of Lift $C_{L\ Max}$	Coefficient of Drag $C_{D\ Max}$	$Alpha_{Max}$	$Aerodnynai$ $Efficiency$ $\frac{C_L}{C_d}$	$L_{Lift\ Force}$
NACA4415	**1.42**	**0.115**	**14**	**12.41**	$L_{Lift\ Force} =$ $\frac{1}{2}(1.4298)\left(1.293\ \frac{kg}{m^3}\right)(743.04\ m^2)\left(230\ \frac{m}{s}\right)^2 =$ **36,333,872 N = 8,168,179.36 lb**
NACA1408	**0.765**	**0.128**	**6.25**	**5.95**	$L_{Lift\ Force}$ $= \frac{1}{2}(0.12855)\left(1.293\ \frac{kg}{m^3}\right)(407.7\ m^2)\left(243\ \frac{m}{s}\right)$ $= 11,906,476\ N = 2,676,682.17\ lb$
NACA2411	**1.1885**	**0.1068**	**12.75**	**11.12**	$L_{Lift\ Force}$ $= \frac{1}{2}(1.1885)\left(1.293\ \frac{kg}{m^3}\right)(591\ m^2)\left(256\ \frac{m}{s}\right)^2$ $= 29,760,151\ N = 6,690,348.03\ lb$

NACA0012 H	0.7446	0.0787	8.5	9.46	$L_{Lift\ Force}$ $= \frac{1}{2}(0.7446)\left(1.293\ \frac{kg}{m^3}\right)(1032.8\ m^2)\left(185\frac{m}{s}\right)$ $= 17{,}015{,}921\ N = 3{,}825{,}331.14\ lb$

One essential key factor to determine if the plane will have lift off is to consider the magnitude of the lift force. Something to note is that the lift acts perpendicular to the directional airflow while the drag acts opposite to the directional airflow. When it comes to the concept of the lift force acting upon the airfoil, it is ideal to want the magnitude of the lift to be as high as possible. In other words, you want the lift to be greater than the weight of the plane. Now, knowing this, we can compare the results of the lift force calculated to that of the plane's weight.

If it is greater than the weight, then we'll know that the plane is sufficient for producing enough lift for the plane to lift off. In this case, however, the magnitude of the lift off weight given was 502,100 lb. Thus, this would be the threshold requirement for an airfoil that generates lift greater than this to be considered as an option. A key detail to highlight is that to obtain the most desired result for a plane, however, is to determine the most optimal airfoil that generates the same amount of lift while also at the same time being cost efficient. For example, two airfoils can generate the same magnitude of lift but realistically, the only way to determine the greatest airfoil between them is through the cost and expenses it would take to construct said airfoil. To simplify, a lower area but a high lift is the most ideal scenario.

With this in mind, the best fitted NACA airfoil from the list we've chosen was determined to be the NACA4415. Ranging around the middle of the numerical lengths between the 4 airfoils while also generating the most lift provided us all the information needed to decide on it being the most optimal airfoil design for this project.

$$\boldsymbol{q_\infty = \frac{1}{2}\rho_\infty V_\infty^2}$$

Equation 2. Dynamic Pressure Equation [1]

$$\boldsymbol{\rho_\infty = 0.0765\ \frac{lb}{ft^3}}$$

Density of Air at Standard Sea Level [1]

$$\boldsymbol{V_\infty = 561\ \frac{miles}{h}}$$

Velocity Required for Plane for Lift [1]

For a given plane to reach lift, one would use the following dynamic pressure equation to solve for the given pressure exerted onto the plane.

$$q_\infty = \frac{1}{2}\rho_\infty V_\infty^2 = \frac{1}{2}\left(0.0765\ \frac{lb}{ft^3}\right)\left(561\frac{miles}{h}\,x\,\frac{1h}{60min}\,x\,\frac{1min}{60s}\right)^2 = \boxed{0.000929\,\frac{lb}{ft^2}}$$

With these airfoils being discussed, it is possible to visualize the differences in performance in terms of lift against drag. Noticing the values in the Aerodynamic Efficiency tab, we can see that the most optimal airfoil design which will give us the best aerodynamic performance will in turn be the NACA4415. This returns with an Aerodynamic Efficiency of 12.41254. Thus, this will create the most lift in comparison to the rest of the different airfoils.

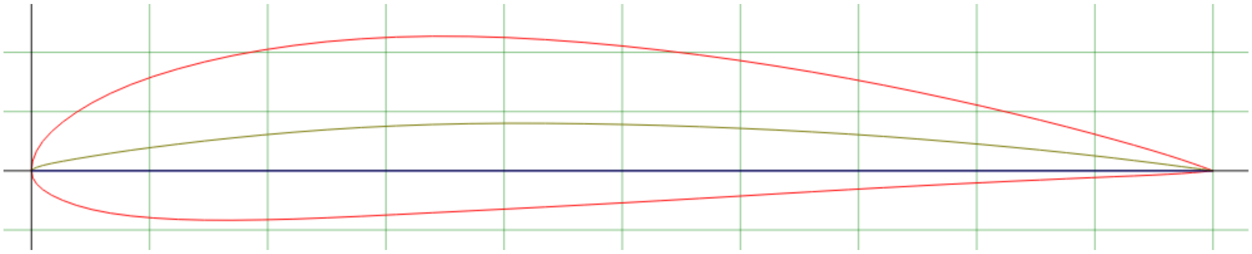

Figure 8. NACA4415 Airfoil Design [2]

With this airfoil in mind, it is then possible to create the length necessary for the plane to reach flight. This depth can be discussed as the chord length of the airfoil design. Comparing the chosen airfoil design with that of the conventional 737 Boeing Airfoil, we can see the following differences for the required values to solve the problem statement.

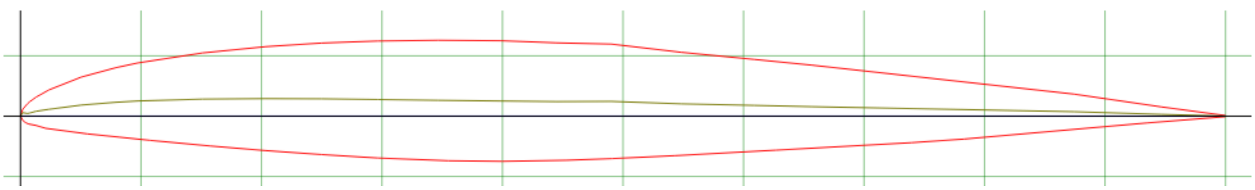

Figure 9. Boeing 737 Midspan Airfoil Design [2]

Table 4. Comparison of NACA4415 vs Boeing 737 Midspan Airfoil [1]

$\boldsymbol{Airfoil}$	**Coefficient of Lift**	**Coefficient of Drag**	$\boldsymbol{Alpha_{Max}}$	$\boldsymbol{Aerodnynamic\ Efficiency}$	$\boldsymbol{L_{Lift\ Force}}$ $\boldsymbol{L_{Lift\ Force} = \frac{1}{2} C_L \rho A V^2}$

	$C_{L\,Max}$	$C_{D\,Max}$	α	$\frac{C_L}{C_d}$	
NACA4415	1.4298	0.11519	14	12.41254	$L_{Lift\,Force} =$ $\frac{1}{2}(1.4298)\left(1.293\,\frac{kg}{m^3}\right)(743.04\,m^2)\left(230\frac{m}{s}\right)^2 =$ 36,333,872 N = 8,168,179.36 lb
BOEING 737 MIDSPAN AIRFOIL	1.008	0.11524	1.25	8.746963	$L_{Lift\,Force} =$ $\frac{1}{2}(1.008)\left(1.293\,\frac{kg}{m^3}\right)(743.04\,m^2)\left(230\frac{m}{s}\right)^2 =$ $25,615,151.40$ N = 5,758,515.11 lb

In turn, it is calculated that the NACA4415 Airfoil has better efficiency than the current Boeing 737 Airfoil given a larger angle of attack and can also in theory carry more weight due to the larger lift force compared to the convention 737 Airfoil. Expanding on this idea, we can model the given wings for this system to be the correct length necessary for the lift force to be valid for lift to occur on the given plane. Thus, for the following variant of the 747, we can model this Airfoil using SolidWorks and given the initial parameters from the project statement create a Computational Fluid Dynamics simulation on both the 737 Midspan Airfoil and NACA 4415 Airfoil to analyze the differences and similarities. While in Figure 10 we can see a mockup of a 737 with the typical chord lengths for the airfoils attached to the plane.

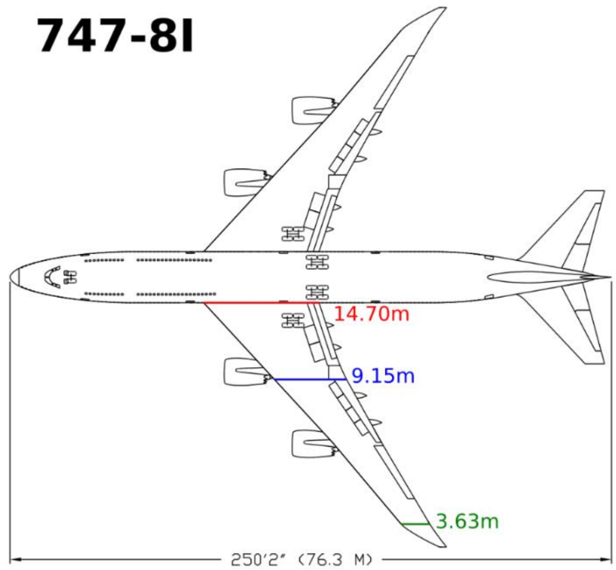

Figure 10. Boeing 737 Airfoil Lengths [3]

We can see that for the chord length for the following airfoil for the 747 we have a length of 14.70m or 48.23ft. Thus, this length can be used to help model the two airfoils later on for simulation purposes. We can also help define our settings by solving for Reynolds number for the given problem statement.

$$R_e = \frac{\rho_\infty V_\infty C}{\mu_\infty}$$

Equation 3. Reynolds Number [1]

$$R_e = \frac{\rho_\infty V_\infty C}{\mu_\infty} = \frac{(0.0765\frac{lb}{ft^3})\left(561\frac{miles}{h}x\frac{1h}{60min}x\frac{1min}{60s}\right)(48.23ft)}{(3.62x10^{-7}\frac{lb-s}{ft^2})}$$

$$R_e = 1{,}588{,}292.51 > 4000$$

$$\therefore Turbulent\ Flow$$

We can see that the fluid of air as it moves across the wings will in turn be turbulent in nature, this will help in defining the settings in our modeling software.

V. Results and Discussion

In comparison to our defined NACA4415 Airfoil, the preliminary airfoil design for the Boeing 737 was also investigated for the purposes of CAD Modeling and testing within a programmable scope.

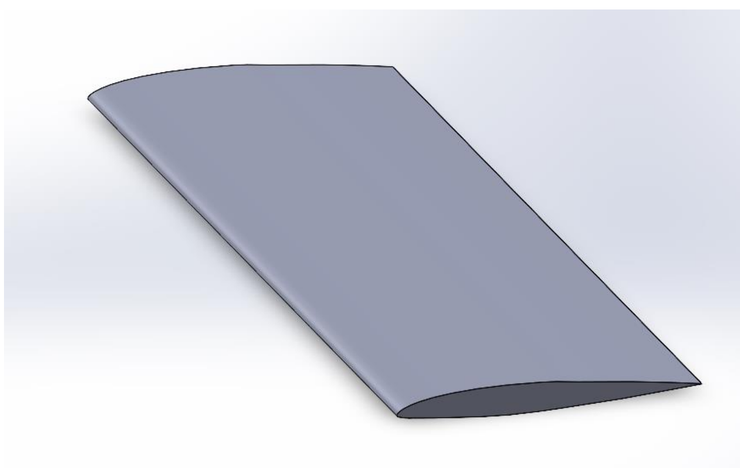

Figure 11. Boeing 737 Midspan Airfoil CAD Model

In turn, a preliminary simulation was done on this conventional airfoil using the given parameters from the problem statement at hand, with a velocity of 561 Miles/Hour, converted to S.I units to 251 Meters/Second. This can be seen in Figure 12.

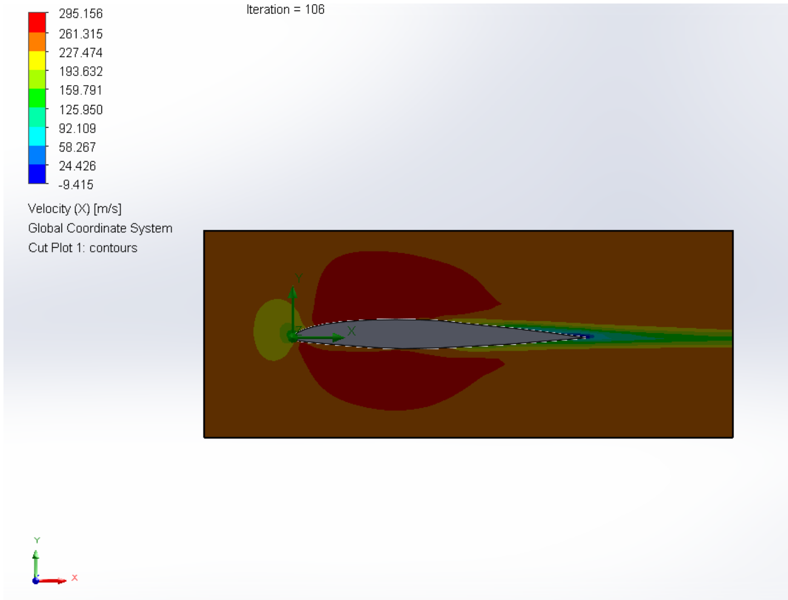

Figure 12. Boeing 737 Midspan Airfoil CFD Simulation

The simulation showed the typical forces and velocity profiles viewed on an airfoil design whereby the larger velocity values and pressure values were exerted on both the top and bottom of the airfoil as can be seen in Figure 12. The velocity profile shown in Figure 12 showcases a relatively large velocity profile. As such, it can be said that the change of directional airflow acting upon the wing affects the performance of the overall stability of the plane. More significantly, this would also indicate that the Boeing 737 itself has a low angle of attack. Having a high or low angle of attack can produce a variety of results. Having a high angle of attack, on the one hand, will cause the airflow moving across the upper surface of the airfoil to become detached which will result in a loss of lift. This process is also known as a stall. When this process occurs, the stability of the plane itself such as the Gyro will not function the most optimally. Additionally, the schematic in Figure 13 is a close zoom of the large velocity profile of the wing.

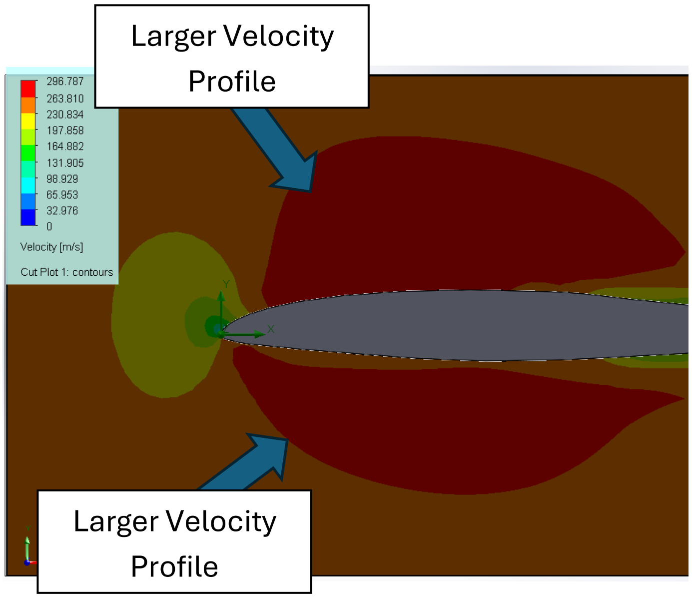

Figure 13. Boeing 737 Midspan Airfoil CFD Simulation

Other Fluid Dynamic characteristics could be observed from this simulation as well, including the Stagnation Point of the Airfoil at the very front and end of the Airfoil as seen in Figure 14 and 15.

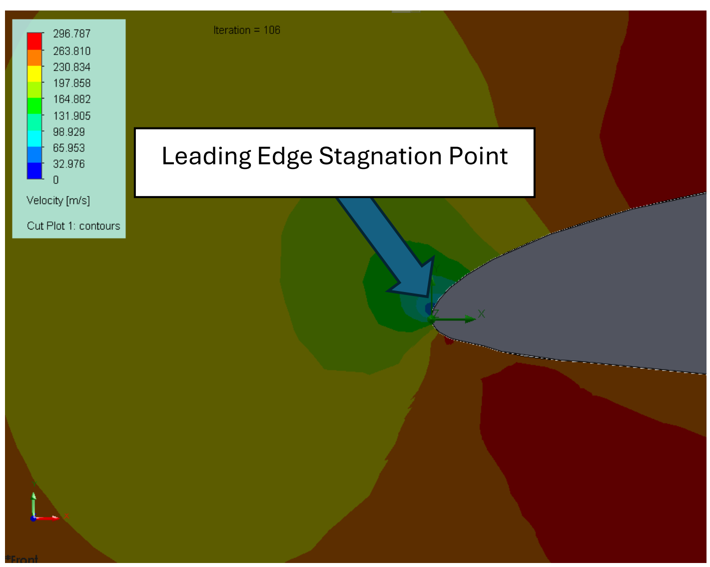

Figure 14. Boeing 737 Midspan Airfoil Leading Edge Stagnation Point

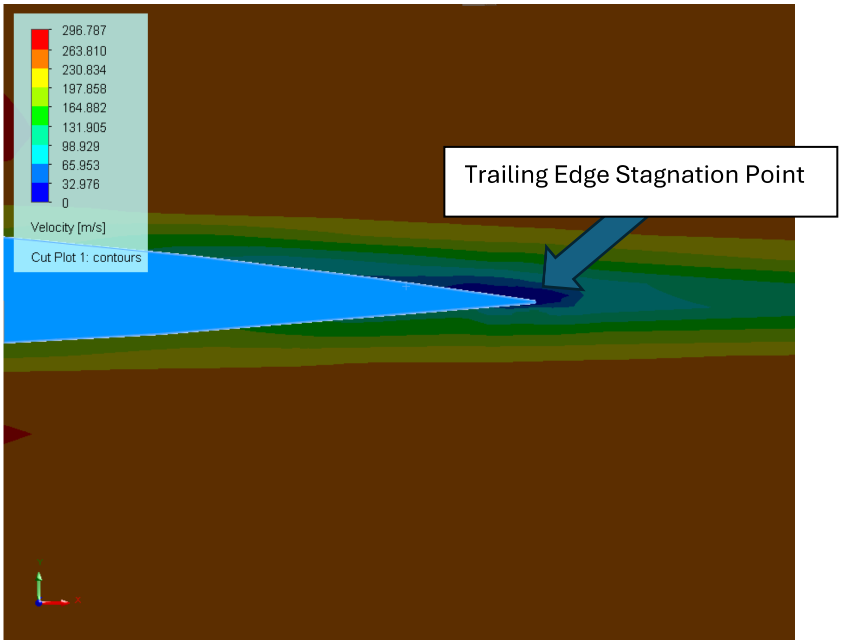

Figure 15. Boeing 737 Midspan Airfoil Leading Edge Stagnation Point

The relationship between High- and Low-pressure differences in the Airfoil shape can also be seen in Figure 16.

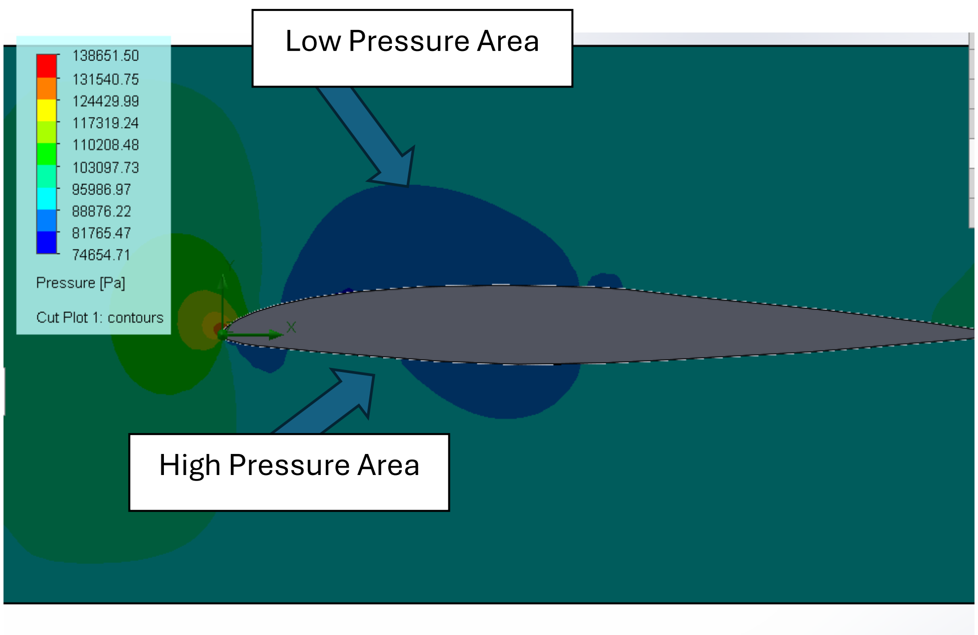

Figure 16. Boeing 737 Pressure Dissipation on Airfoil Surfaces

The pressure surface plot of the wing in a virtual wind tunnel simulation is shown in Figure 17 above. The pressure gradient of the wing is highlighted in this specific simulation result. The pressure level that the wing is operating at is indicated by the colorful spectrum labeled on the upper left portion of the picture. As can be seen in the picture, dark blue denotes the lowest pressure range with red as the maximum range. When examining the wing's upper surface, nearly every part of it has a dark blue color tint, which, in accordance with the colored scale, corresponds to the lower spectrum of pressure.

Furthermore, the same cannot be said for the entire lower surface of the wing, which has a red-colored pressure gradient. The analysis concludes that due to the top side of the wing having a smaller gradient than the bottom, the bottom of the wing experiences an absurdly large release of pressure during flight, which is what is intended for a plane to generate any form of lift. This gives the impression that the lift produced by the aircraft is more than the aircraft's weight and results in producing enough lift to become airborne.

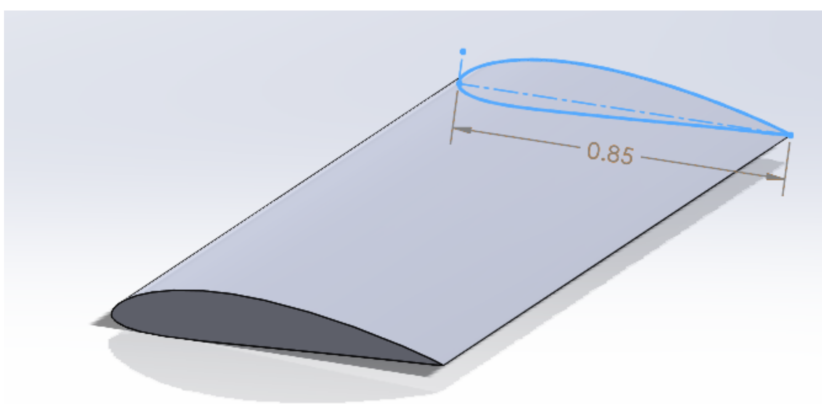

Figure 17. NACA 4415 Airfoil Solidworks CAD Model

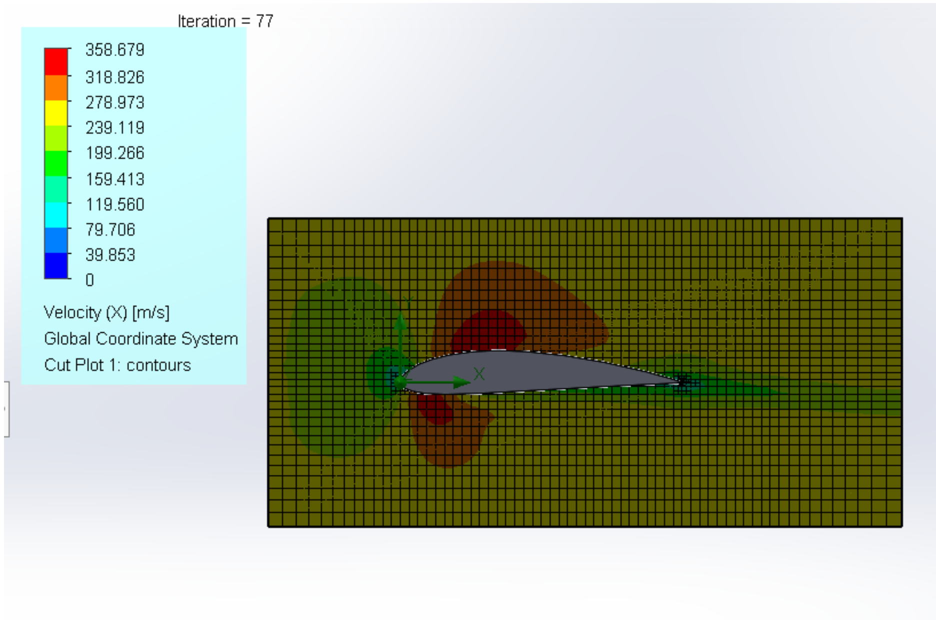

Figure 18. NACA 4415 Airfoil Velocity Gradient

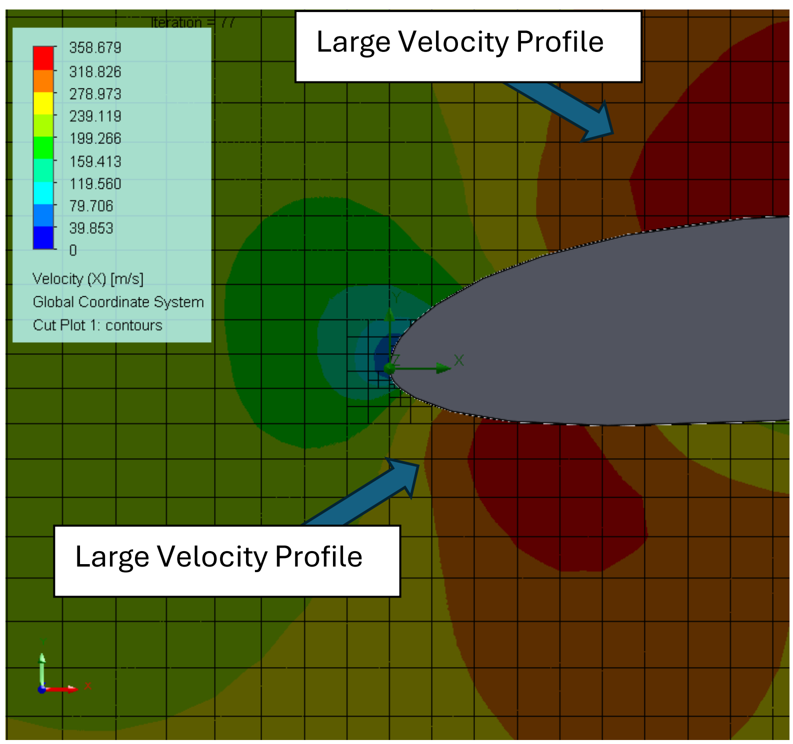

Figure 19. NACA 4415 Airfoil Stagnation Point

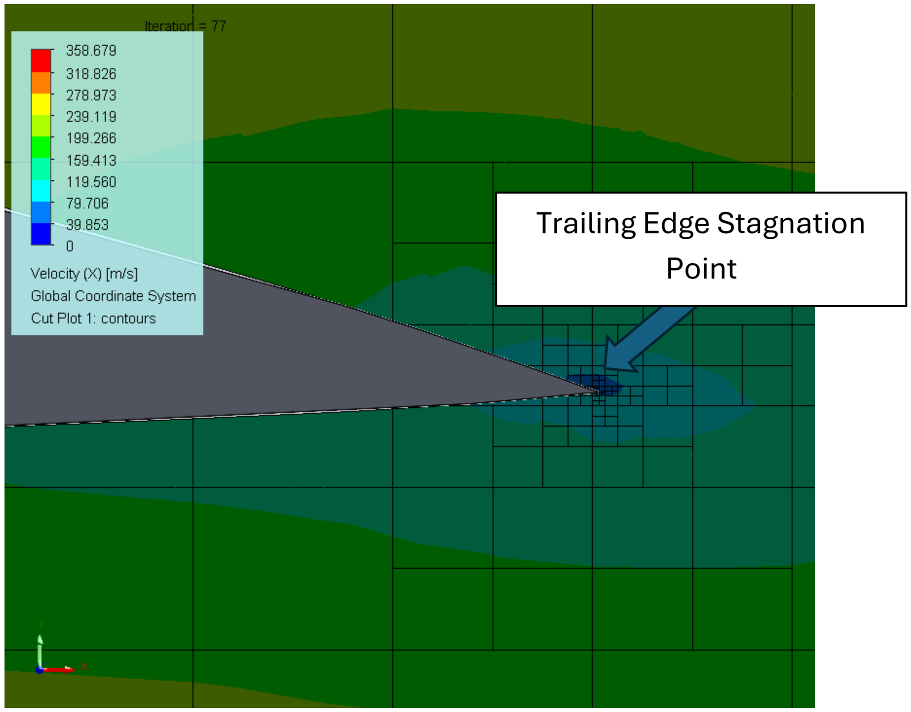

Figure 20. NACA 4415 Airfoil Trailing Stagnation Point

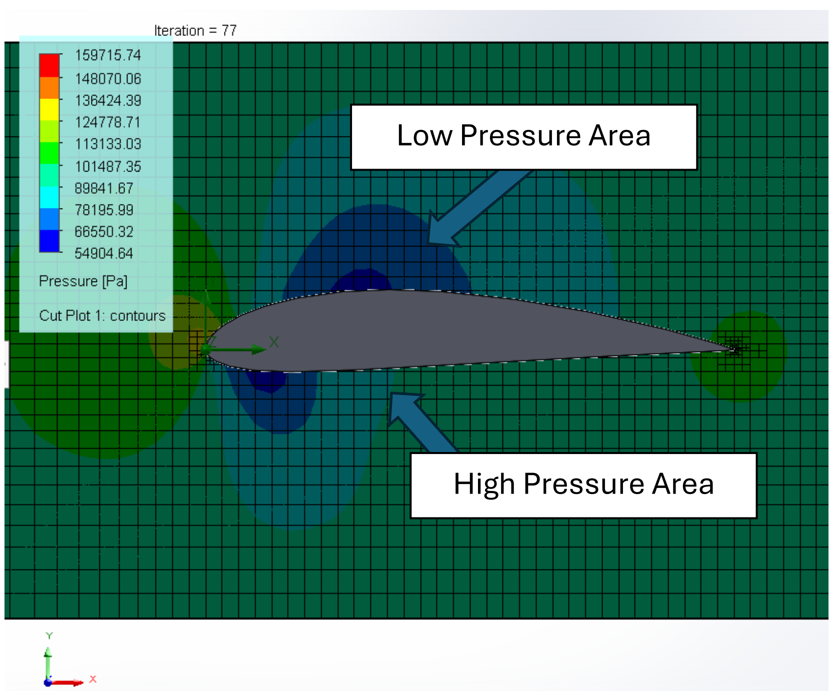

Figure 21. NACA 4415 Airfoil Pressure Surface Plot

From the flow simulation shown of the NACA4415 airfoil, the simulation show the air velocity around the upper and lower surface of the airfoil. We can see that the velocity of air in upper surface is much greater than that of lower surface. Velocity has an inverse relationship with pressure, such that as fluid velocity increases, pressure decreases and vice versa. Lift of an airplane occurs when there is a difference in pressure between the two surfaces, and the two surfaces split at the point in leading edge. Since the fluid velocity at upper surface is higher it creates a zone of low pressure and the lower surface creates a zone of high pressure. This pressure gradient creates an upward lift force that exceeds the weight of the aircraft to enable flight.

VI. Conclusion

The NACA4415 Airfoil design showed a more efficient airfoil design whereby it held a higher Aerodynamic Efficiency when compared to the conventional Boeing 737 Midspan Airfoil Design. This was in turn found by hand calculations with the given data retrieved from the Airfoil Tools website as well as from CFD through the CAD models that were derived from the data from this site. Due to this geometric consideration, the larger lift force for the NACA4415 Airfoil would also help generate the required lift for the 737 Aircraft. This beneficial use in terms of lift force and aerodynamic efficiency returned with a increase in Aerodynamic efficiency of 29.49%, an increase in lift force of 28.92%. Thus, with this increase in Lift Force and Aerodynamic Efficiency we can certainly say it would be a better option for the 737 to use this type of airfoil when moving any passengers or payload as it can only help in this regard. Other avenues that can help increase efficiency with this design can include the use of different materials for the airfoil, a larger angle of attack as well as an increase in the wingspan for the airfoil. All these attributes contribute to more feasible air travel and achieving lift.

VII. <u>References</u>

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