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FINAL PROJECT REPORT

**DESIGN AND OPTIMIZATION OF AN
AIRCRAFT WING AIRFOIL**

DAVID CHAPARRO RODRÍGUEZ

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TITLE: DESIGN AND OPTIMIZATION OF AN AIRCRAFT WING AIRFOIL

AUTHOR: DAVID CHAPARRO RODRÍGUEZ

SUPERVISOR: SERGIO DE LUCAS BODAS

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RESUMEN

La industria aeroespacial actual ofrece oportunidades para el continuo desarrollo e implementación de nuevos diseños. Actualmente existe un amplio horizonte de posibilidades para continuar con esta evolución en el diseño y en la perfección de las aeronaves.

El diseño y la optimización de las aeronaves ofrece una gran versatilidad e importantes avances en el desarrollo aeroespacial. Por ello a través de este proyecto se ha llevado a cabo el diseño y la optimización de un perfil alar, debido a que los perfiles alares influyen directamente en un elemento fundamental en el diseño de las aeronaves, sus alas. Para ello se han tenido en cuenta diferentes puntos de diseño a los que se somete una aeronave durante su plan de vuelo, además, siendo más exactos se ha enfocado todo este análisis en una aeronave de transporte regional, debido a que, con el crecimiento de la industria aeroespacial, se espera un notable desarrollo dentro de este nicho de la industria.

De esta forma se pueden realizar diferentes diseños y análisis, para verificar las diferencias en el diseño de los perfiles alares y su influencia aerodinámica, valorando qué ventajas tiene un diseño sobre otro y entendiendo mejor hacia qué tendencia está evolucionando la industria aeroespacial.

Utilizando diferentes softwares de diseño para modelado 2D, gracias a métodos basados en técnicas de diseño, como la creación de las curvas de Bézier, así como para los análisis aerodinámicos realizados, a través de la teoría de la línea de sustentación y la dinámica de fluidos computacional, se definen las características y propiedades de los modelos de los diferentes perfiles alares. Las conclusiones sobre la comparación de los parámetros obtenidos en ambas direcciones facilitarán un amplio análisis para el proyecto.

Palabras clave: Aeroespacial, aeronaves, alar, alas, aerodinámica, Bézier, sustentación, Dinámica de fluidos computacional.

ABSTRACT

The current aerospace industry offers opportunities for ongoing development and implementation of new designs. Currently, there is a vast horizon of possibilities to continue with this evolution in the design and improvement of aircraft.

Design and optimization of aircraft provide great versatility and significant advancements in aerospace development. Therefore, through this project, the design and optimization of an airfoil have been carried out, since airfoil directly influence a key element in aircraft design, their wings. Different design points that an aircraft undergoes during its flight plan have been considered. Moreover, to be more precise, this entire analysis has been focused on a regional transport aircraft, because, with the growth of the aerospace industry, a notable development is expected within this industry niche.

In this way, various designs and analyses can be carried out to check the differences in the design of the airfoil and their aerodynamic influence, defining the advantages of one design over another and better understanding the trend the aerospace industry is evolving towards.

Using various 2D design software, thanks to design-based methods, such as the creation of Bézier curves, as well as for the aerodynamic analyses carried out through the lifting-line theory and computational fluid dynamics, the characteristics and properties of the models of different airfoil are defined. The conclusions about the comparison of the parameters obtained in both directions will facilitate a comprehensive analysis for the project.

Keywords: Aerospace, aircraft, airfoil, wings, aerodynamics, Bézier, lift, Computational fluid dynamics.

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Cuando inicié mi aventura universitaria, solo era un chico curioso, interesado por la Aviación y hoy en día soy un Ingeniero Aeroespacial, dispuesto a continuar creciendo profesionalmente y afrontar los retos que me esperan.

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My parents have given me all the teachings and values that complete me today, which are the backbone of my philosophy of life, both personally and professionally. My family has made me grow, believing in effort and humility, giving me an education and a life that I consider ideal for me. Without their constant motivation and faith in me, pursuing my aspirations would not have been possible. My family has helped me fulfill my dreams.

When I started my university adventure, I was just a curious boy, interested in Aviation and today I am an Aerospace Engineer, willing to continue growing professionally and face the challenges that await me.

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List of Abbreviations

AoA	Angle of Attack
CD	Drag Coefficient
CFD	Computational Fluid Dynamics
CL	Lift Coefficient
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
IDE	Integrated Development Environment
MATLAB	Matrix Laboratory
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
SD	Selig-Donovan
UK	United Kingdom
US	United States

Chapter 1. INTRODUCTION

The aerospace industry is a novel industry that is continuously developing, which is why throughout history, the aerospace industry has grown exponentially, being an example of development and technological growth.

Aviation has also been linked to the different stages that have been experienced socially, both wars and major crises or world trends have directly influenced the development of the industry and aviation.

Due to the First World War, new aircraft designs had to be developed to fulfill the different new missions, such as reconnaissance aircraft.

Another notable fact is how after World War II, the development of commercial aviation was encouraged due to all the advances that had occurred during this stage and many military resources began to be used in commercial aviation.

It is also noteworthy how from the 1950s, there was exponential growth in air travel, in the stage known as the "jet age", with the development of jet aircraft that caused a significant improvement in conditions of each flight and the characteristics of the aircraft, since these could carry a greater amount of cargo than previous aircraft, which reduced air fares, facilitating access to aviation for different social classes.

That is why the idea of carrying out this project arose, because since the beginning of aviation, the industry has been in continuous development and continues to do so today, innovating and improving the conditions of each flight, the characteristics of each aircraft. Adapting to each era and its social needs.

Currently, the aerospace industry is in a transition stage towards the development of more sustainable and economic energies, prioritizing efficiency, fuel savings and improving the characteristics of each aircraft, thus increasing their longevity and keeping operational aircraft of previous generations.

For this reason, through this project the main objective has been set to design and optimize different aerodynamic airfoils, which will be analysed in different flight regimes simulating the specific conditions that a regional transport aircraft would experience, in this way another can be undertaken the secondary objective, which is to demonstrate my technical skills acquired during training as an Aerospace Engineer, designing, optimizing and analyzing the different prototypes of wing airfoils, through different software used professionally in the aerospace industry and applying the necessary calculations for analysis.

1.1 Problem approach or statement

The essence of the project is based on the fact that the contemporary aeronautical field provides opportunities for the continuous development and implementation of new designs. Currently, there is an extensive horizon of possibilities to continue with the improvement and transformation of the conception of aircraft.

Therefore, the purpose is to face this project as a challenge that allows manifesting the skills and knowledge acquired as an Aerospace Engineer, through research, design and evaluation of the different aerodynamic analyses linked to the proposed wing airfoil prototypes.

1.2 Project objectives

The main objective is to carry out the design and optimization of an aircraft wing airfoil. For this, different design points are analysed, taking into account the different flight regimes to which the aircraft can be subjected, in order to determine what differences these models have and understand the importance of optimizing the design of the wing airfoils to improve efficiency of an aircraft thanks to advanced aerodynamics.

The design and modeling of the wing airfoils, as well as the aerodynamic analysis, are aimed at putting into practice the knowledge acquired in the subjects "ADVANCED DESIGN IN AIRCRAFT", "ADVANCED FLUID MECHANICS AND COMBUSTION" and "ADVANCED AERODYNAMICS AND AEROELASTICITY", in this way, part of the training as an Aerospace Engineer can be reflected.

1.3 Report structure

In this section the structure of the report is described, initially an introduction is made about the definition and characteristics of airfoils, to continue with the evolution of wings and the importance of materials in the aeronautical industry. In addition, after this, the introduction to the different methods that will be carried out during the project is developed, as well as the software that will be used.

Next, the methodology carried out during the project is presented, initially defining the design of the wing airfoils through the Bézier code, followed by its optimization through an optimized database with the proposed theories, continuing with the analysis corresponding to the proposed design points. Afterwards, the project continues with the analysis and discussion of the results obtained in XFLR5 and ANSYS CFD.

Finally, after explaining the methodology of the project, as well as the analyses carried out and its conclusions, the report continues with future work and with the steps that would be taken to continue investigating the project. In the annexes the information on the development of the designed prototypes is appreciated, using MATLAB and XFLR5 with all the parameters, also in this section the analyses carried out through ANSYS are explained.

Chapter 2. STATE OF THE ART

This section of the document provides an introduction to the project, as well as explaining in detail what a wing is and the different analyses that are carried out in the project.

2.1 Airfoil

An airfoil is the term used to describe the cross-sectional shape of an object that, when moving through a fluid such as air, creates an aerodynamic force. These airfoils are used in aircraft as wings to generate lift or as propeller blades to generate thrust. Both forces occur perpendicular to the airflow. Drag is a consequence of the production of lift or thrust and acts parallel to the airflow.

As confirmed through research carried out on airfoils [1], the origin of the use of this term goes back to the end of the 19th century, when improvements in aerodynamic surfaces were investigated. Although it was known that flat surfaces could create lift if positioned at an angle, there was skepticism as to whether curved shapes, resembling bird wings, could generate more lift or do so more efficiently. In that period, Otto Lilienthal, a renowned researcher, was exploring similar concepts. Together with his brother Gustave, Otto delved into the study of aeronautics from the late 1860s, focusing on how birds flew. During the 1870s, he carried out various experiments on wing morphology and collected information about air pressure using a rotating arm and natural winds. Lilienthal concluded and reaffirmed the idea that a cambered wing was more efficient than a flat one in terms of generating lift. In 1889, he presented his discoveries in a revolutionary work entitled "Der Vogelflug als Grundlage der Fliegekunst" (Birdflight as the Basis of Aviation). Lilienthal argued that the secret to efficient flight lay in the cambered shape of the wing. In addition, he experimented with different curvatures and thicknesses.

In relation to this, it is important to note that the airfoils used by the Wright brothers closely resembled the Lilienthal sections, thin and highly curved. This was possibly due to the fact that early tests of airfoil sections were performed at extremely low Reynolds number, where such sections performed more favorably than thicker ones. The mistaken belief that efficient airfoils needed to be thin and extremely curved was one reason some of the earliest aircraft were biplanes.

2.1.1 Aerodynamic characteristics

The fundamental principle governing an airfoil is described by Bernoulli's theorem [2], in essence, this states that the total pressure is equal to the static pressure (due to the weight of the air above it) plus the dynamic pressure (produced by the movement of the air).

Air flowing over the upper surface of the airfoil must move faster, resulting in increased dynamic pressure. The consequent decrease in static pressure creates a pressure difference between the upper and lower surfaces, which is known as lift and opposes the weight of the aircraft.

As the angle of attack (the angle between the chord line and the relative airflow) increases, more lift is produced. However, once the critical angle of attack is reached the airfoil stalls.

The comparison of the airfoils will be carried out using the software XFRL5 and ANSYS.

2.1.2 Geometric characteristics

As has been demonstrated after research carried out [3], airfoils have various characteristics that allow them to be differentiated from each other and describe their properties, as can be confirmed:

- Leading Edge: Forward edge of the airfoil.
- Trailing Edge: Aft edge of the airfoil.
- Chord: Line connecting the leading and trailing edge. Denotes the length of the airfoil.
- Mean Camber Line: Line drawn halfway between the upper and lower surface of the airfoil. Denotes the amount of curvature of the wing.
- Point of Maximum Thickness: Thickest part of the wing expressed as a percentage of the chord.

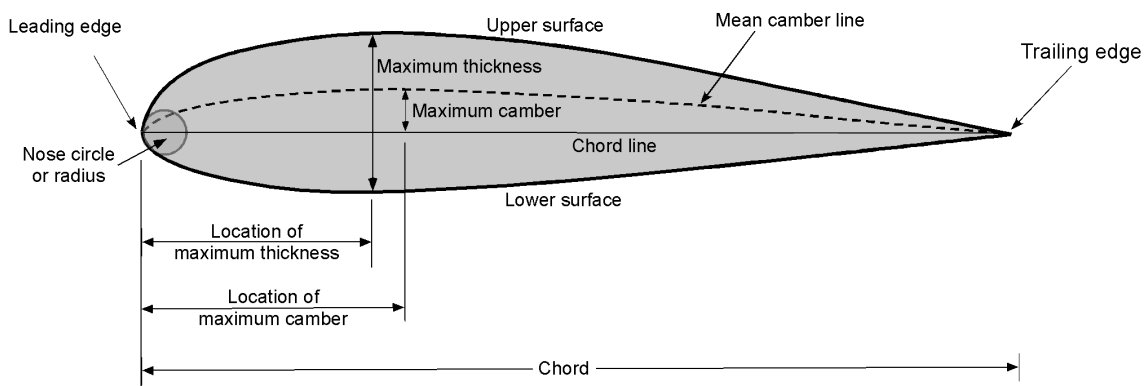


Figure 1: Airfoil geometry [3]

By altering each of the above characteristics of an airfoil, the designer can define the performance of the wing to make it suitable for its particular task. For example, a crop duster plane may have a thick, steeply raked wing that produces a large amount of lift at low speed. Alternatively, a jet would have a thin wing with minimal inclination to allow it to cruise at high speeds.

In the design of aerodynamic airfoils, the geometric characteristics are taken into account because by altering each of these characteristics, the performance of the airfoil can be varied for its specific objective.

2.1.3 Airfoil nomenclature

In this section, after carrying out an in-depth investigation on the airfoils [2], Horatio F. Phillips can be confirmed to have been responsible for the first patented aerodynamic shapes in 1884. Phillips was a British aviation pioneer who carried out early experiments using wind tunnels to study airfoils. Later, in 1902, the Wright brothers carried out similar experiments, which led them to design more efficient aerodynamic structures, developing relatively efficient shapes that contributed to their first successful flight on December 17, 1903. At the dawn of aviation, aerodynamic designs relied heavily on customization and instinct.

According to the investigations carried out [3], it can be confirmed that the most suitable airfoils in most practical engineering applications have been obtained through a process of development and evolution. In this way, theory and experimentation have been used to design the aerodynamic surfaces that meet the objectives set in each project, for each type of aircraft and conditions. To do this, starting in the 1920s, computational tools were available for the first time to produce and analyse different aerodynamic characteristics. The development of the Thin Airfoil Theory by Max Munk in the United States and Hermann Glauert in the United Kingdom, during the 1920s, further discovered how the camber of an airfoil affected its lift and momentum. pitch.

In addition, it is also remarkable how Theodorsen & Garrick in the early 1930s [3], tackled the problem of defining the pressure distribution of an airfoil having an arbitrary thickness and shape. By these advances, the design of practical airfoils was further aided, and further by methods such as the conformal mapping method, first developed by Prandtl & Tietjens.

Therefore, thanks to these advances in research and by this last approach, it was possible to calculate the pressure distributions and the resulting characteristics of the moment of lift and pitch of some special shaped "Joukowski" airfoils. Its aerodynamic properties were measured through wind tunnel tests, starting in the late 1920s in Gottingen in Germany and by NACA (National Aeronautics and Space Administration) in the United States from 1930 onwards, as confirmed through the research process carried out during the project [3].

All these experimental advances to define and measure the characteristics of the airfoils, were succeeded by the development of numerical methods, validated to predict the pressure distributions along the chords and the characteristics of the airfoils, without making so many measurements in the wind tunnels. Currently it is possible to define the aerodynamic characteristics of the airfoils accurately, through the different software available, such as XFLR5 or ANSYS. Even so, both study methodologies are complementary and measurements through wind tunnels are sometimes used, because they are more realistic, mainly when operating with higher angles of attack, higher subsonic and transonic Mach numbers or lower Reynolds numbers.

It is because of all these advances in design and research that there are different types of wing airfoils. The wing airfoils usually have codes that identify them according to certain geometric and aerodynamic characteristics. These codes may vary according to different classification systems. These systems assign specific numbers and letters to represent the geometric and aerodynamic characteristics of the airfoils. Some of the best known coding systems are:

- NACA system (National Advisory Committee for Aeronautics): This system uses a numerical code to describe the characteristics of the airfoil. The numbers in the code indicate the maximum curvature, the position of maximum curvature, and the maximum thickness of the airfoil [4].
- Selig-Donovan system: Also known as the SD system, it is similar to the NACA system but uses letters instead of numbers [5].
- Göttingen system: Developed at the Göttingen Institute for Aerodynamic Research in Germany, it uses a numerical code that represents the characteristics of the airfoil [6].
- Wortmann System: Uses a four-digit number to describe the characteristics of the airfoil. The first two digits represent the shape of the airfoil, while the last two indicate the maximum thickness [7].

2.1.4 Camber

It is defined as camber [2], to the convexity of the curve that the average line of a airfoil has with respect to the straight line that joins the points of the leading edge and the trailing edge, that is to say, it is the difference of the maximum distance between the two lines, which is a measure of the convexity of the airfoil.

The camber plays an important role in the geometry of the wing airfoils, since, in relation to the dynamics of the wing airfoil, its lift depends on the air speed, the angle of attack and its design.

Airfoils can be of two main types, symmetric, where the top and bottom contours are identical, and cambered, where the two surfaces display distinct shapes. Additionally, certain airfoils possess a specific kind of camber at the trailing edge that curves upward, termed as reflex camber. Such a design is frequently found in flying wings, helicopters, and autogiros. A supercritical airfoil will generally incorporate a negatively curved lower surface. Designers can also vary the camber along the wing to improve stall and recovery characteristics.

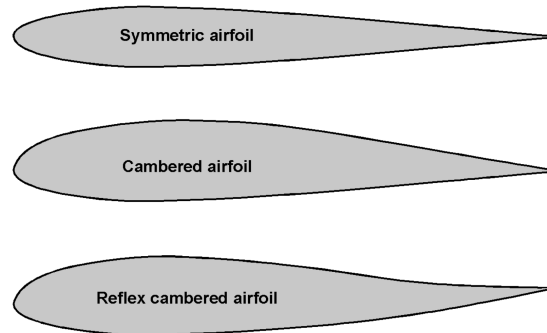


Figure 2: Airfoil Camber [3]

2.1.5 Thickness ratio

The thickness-to-chord ratio, is a concept that compares the maximum vertical thickness of a wing with its chord. The optimum Thickness ratio depends on the regime at which the aircraft is designed; its value usually decreases as the aircraft maximum speed increases.

As can be seen in Figure 1, the straight line that joins the leading edge with the trailing edge is the chord line of the airfoil, while the maximum distance between the upper and lower surfaces of the airfoil is called thickness. It is important to understand these terms as they are important features that allow differentiating airfoils.

2.2 The wings

The wings are structural surfaces that produce a lift force on aircraft, this is why they are usually known as lifting surfaces. Throughout the history of aviation and engineering, different wing designs have been developed due to continuous evolution, which has been very significant. The first designs were carried out based on engineering principles, manual analysis and experimentation with different prototypes.

As can be confirmed [8], a notable fact in the design of the wings was the introduction of wing airfoils by NASA in the 1930s, these airfoils have been essential in the development and optimization of the different models, along with the choice of materials and production methods.

Due to the continuous evolution, to the current progress in research and in aerospace technology, the detailed study and analysis of the forces that act on aircraft allow us to work on enhancing the performance and efficiency of aircraft, focusing on minimizing the impact of aerodynamic drag and reduce the weight of the different materials that make up the aircraft.

The following elements can be found in the structure of a wing [3]:

- **Skin:** Is the exterior contour of the wing and is essential for its aerodynamic properties. The skin's role is to provide shape, support tension and compression forces.
- **Spars:** Are positioned throughout the wing, offering strength and resistance against ongoing pressures and constant forces, including bending and twisting, ensuring the wing's structural stability.
- **Stringers:** These are lighter-density spars that extend lengthwise across the wing. Their purpose is to manage the varied stresses faced by the skin and distribute them to other structural components and the formers.
- **Ribs:** These are the structural supports that, in conjunction with the spars, define the wing's shape. The ribs stretch from the leading edge to the trailing edge, but their configurations can vary based on the specific wing design. Their primary role is to manage the stresses experienced by the skin.
- **Fuel tank:** Are tanks that contain the fuel and in the aircraft are frequently integrated into the wings. This is because positioning the weighty fuel directly in the wings, where the lift is generated, the stress during takeoff and flight is reduced.
- **Flight control systems:** They are primary and secondary control systems that enhance the aircraft's flight stability.

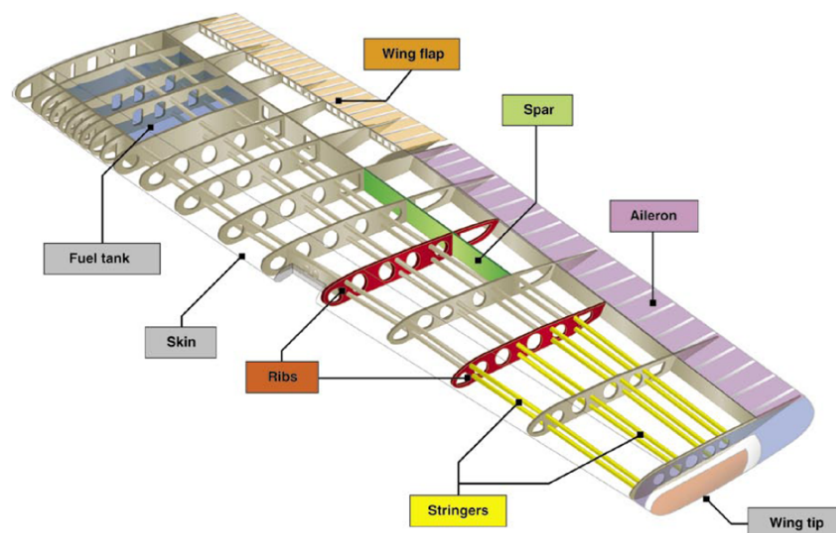


Figure 3: Wing structure [9]

The wings can also be identified based on their position:

- High wing: Situated on the top section of the fuselage, ensuring considerable stability for the plane.
- Middle wing: Positioned at the central section of the fuselage and is frequently found in commercial planes.
- Low wing: Positioned below the fuselage and is typical in aerobatic aircraft, combat aircraft and a few commercial jets.

Furthermore, it is also remarkable how thanks to advances in aviation, there is a wide variety of aircraft options, according to the investigations carried out during the project [10], this variety has led to the creation of different wings, designed to adapt to specific flight modes:

- Rectangular: These wings are designed for aircraft that fly at lower speeds and are often found on training aircrafts.
- Tapered: This type of wing refines the design of the rectangular wing. The chord changes throughout its span. It is highly efficient because of its superior aerodynamic characteristics and simplicity in production.
- Elliptical: These wings are notably efficient, with a planform shape resembling an ellipse where the leading and trailing edges come close together.
- Delta: It is a wing similar to swept wings, the delta wing takes on a triangular shape and boasts strong structural effectiveness.
- Trapezoidal Wing: The design features the trailing edge shifting forward and the leading edge moving backward. Such a wing configuration provides exceptional performance.
- Ogive: This wing is used in very high-speed aircrafts.
- Swept: These wings come in variations like swept-back, swept-forward, and variable sweep. These wing designs are optimal for mitigating the effects of Mach on fast-moving aircraft.

2.3 Materials

In the aeronautical industry, the materials used in the design and manufacture of each aircraft have been studied in depth and have been given great importance throughout history. Correctly defining materials is an essential process in aircraft design, since the materials used directly influence the performance of the aircraft.

Referring to the investigations carried out [11], it is confirmed that initially it was understood that light materials were the most suitable for the manufacture of aircraft, which is why they tried to use them in each design, these light materials were wood, struts, tension cables, and fabrics, but with the development of research and technology, the aerospace industry has evolved, which allows us to have new materials with great properties and characteristics, which favor performance and manufacturing.

The evolution of the materials used in aviation has been significant since the Wright brothers carried out their first manned flight in 1903 [12]. Since that historical milestone, there have been variations in the materials used, which has generated a wide range of possibilities with unique properties and adapted to the specific objectives of each project.

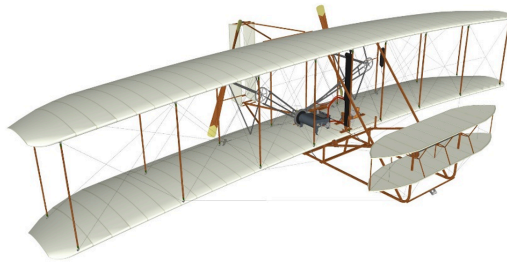


Figure 4: 1903 Wright Flyer [13]

At the dawn of the 20th century, metals gained momentum in industry thanks to their notorious strength and rigidity. In particular, aluminum alloy stood out as the predominant material in the manufacture of airframes, it is remarkable how since the beginnings of aviation safety and other considerations of flight performance directly influenced design choices in aircraft construction.

Aluminum alloys, known for their lightness, became the main structural materials in aviation, accounting for 70-80% of the weight in most civil aircraft structures throughout the 20th century, and continue to be of great importance. However, since the middle of the century, the use of composite materials in aerospace structures has been increasing due to the development of high-performance composites.

The materials predominantly used in aerospace structures include aluminum alloys, titanium alloys, high-strength steels, and composites, accounting for over 90% of the airframe weight.

This approach has driven the constant development of new composite materials and alloys, which has significantly improved our capabilities and performance in the aerospace field.

2.4 Bézier curves

After doing extensive research [14], it can be confirmed that Bézier curves are a method of representation and design of curves used in computational design, modeling and other engineering applications, since they provide an accurate representation of different shapes. These curves were developed by the French mathematician Pierre Bézier in the 1960s while he was working on automobile design for the Renault company.

A Bézier curve is defined by a set of control points (nodes) that determine its shape. Depending on the number of control points, we can have Bézier curves of different orders.

To calculate a point on the Bézier curve, a weighted combination of the control points is used. The general formula for a Bézier curve of degree n is:

$$P(t) = \sum_{i=0}^n P_i b_{i,n}(t); \quad t \in [0,1]$$

Equation 1: General formula for a Bézier curve [14]

Where:

- $P(t)$ is the point on the Bézier curve in the parameter t ($0 \leq t \leq 1$).
- P_i are the checkpoints.
- $b_{i,n}(t)$ are the binomial coefficients, which depend on the degree n and the parameter t .

These binomial coefficients are calculated using the formula:

$$b_{i,n}(t) = \binom{n}{i} t^i (1-t)^{n-i}; \quad i = 0, \dots, n$$

Equation 2: Bézier curve binomial coefficients [14]

Where:

- n is the degree of the Bézier curve ($n-1$ is the number of segments that make up the curve).
- i is the iteration index that varies from 0 to n .

The resulting curve is an interpolation of the control points, and the parameter t controls the position along the curve, where $t = 0$ represents the start point and $t = 1$ the end point.

Bézier curves have unique properties that allow the modeling and optimization of airfoils. The Bézier parameterization of order n will have control points which are the control variables to control the shape of the airfoil. By changing the position of one or more control points, the shape of the airfoil can be changed.

2.5 De Casteljau's algorithm

In this section a deep investigation has been carried out on The De Casteljau algorithm [14], which is a graphical and analytical method for evaluating Bézier curves at a specific point. One of the main advantages of this algorithm is its numerical stability compared to direct Bernstein formulas.

For a Bézier curve given by control points P_0, P_1, \dots, P_n , the purpose of the De Casteljau algorithm is to repeatedly divide line segments between control points until a single point on the Bézier curve is obtained. This point is the location of the curve at the given parameter t (where t is a value between 0 and 1). The application of the algorithm to generate a Bézier curve with n control parameters is described below in a simplified manner:

1. Subdivision of segments for a given value of t .

- Obtain the point Q_0 in the segment P_0P_n .

$$Q_0 = (1 - t) \cdot P_0 + t \cdot P_n$$

Equation 3: Q_0 point equation [14]

- Obtain the point Q_n in the segment P_nP_{n+1} .

$$Q_n = (1 - t) \cdot P_n + t \cdot P_{n+1}$$

Equation 4: Q_n point equation [14]

2. Subdivision of segments again:

- Obtain the point R_0 between Q_0 and Q_n

$$R_0 = (1 - t) \cdot Q_0 + t \cdot Q_n$$

Equation 5: R_0 point equation [14]

- Obtain the point R_n between Q_n and Q_{n+1}

$$R_n = (1 - t) \cdot Q_n + t \cdot Q_{n+1}$$

Equation 6: R_n point equation [14]

3. Obtain the point of the curve:

- The point S_0 between R_0 and R_n is a point on the Bézier curve at t :

$$S_0 = (1 - t) \cdot R_0 + t \cdot R_n$$

Equation 7: S_n point equation [14]

For Bézier curves with more control points, it is necessary to keep iterating the subdivision process according to the number of control points.

2.6 Forces

This section considers the basic forces that act on an aircraft, which facilitate its ability to perform its flight mission. The aircraft maintains stability and achieves its objectives thanks to experiencing these forces during flight:

Taking into account the investigations carried out [15], it can be confirmed that the basic forces acting on an aircraft are:

- Thrust: It's the force that causes the movement of an aircraft forward in the air, countering the resistance presented by drag.
- Drag: This force is characterized as a mechanical resistance working against the motion of a moving entity. It arises from the contact and interaction between a solid object and a fluid, be it liquid or gas. In aviation, drag is an aerodynamic resistance hindering motion and is produced by every part of the aircraft.
- Lift: This aerodynamic force counterbalances the weight of an aircraft and keeps it in the air, the wings are the primary source that generate this force but this force is generated by each element of the airplane.
- Weight: It is a force that is generated by the gravitational attraction of the earth on any element. While weight is influenced by gravitational fields, aerodynamic forces are mechanical and depend on the interplay of components.

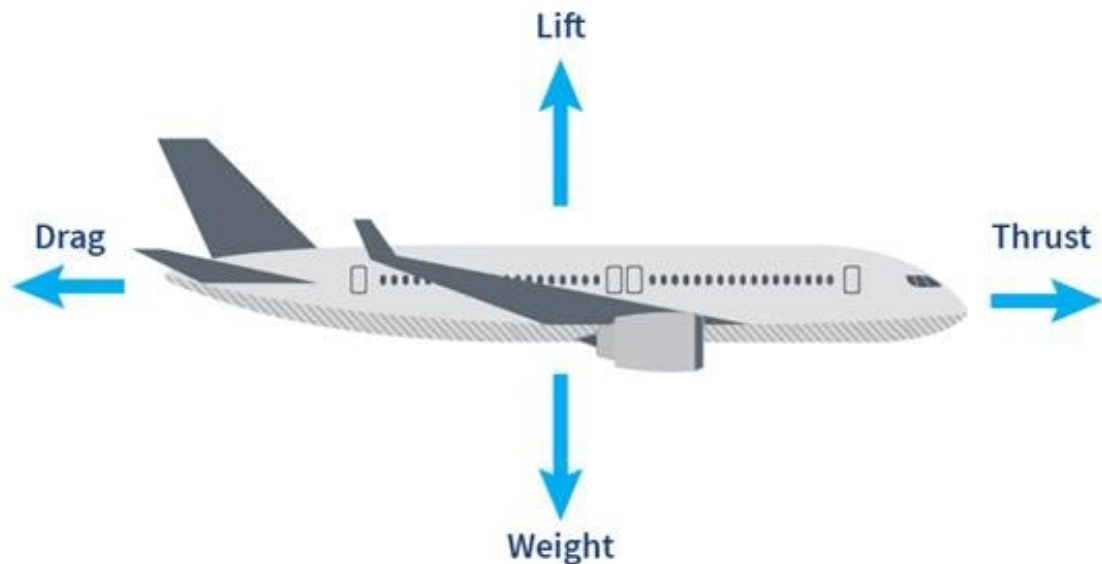


Figure 5: The four forces acting on an aircraft [15]

2.7 Lifting line theory

This section explains the lifting line theory, also known as the theory of the spiral wing, for which different investigations have been carried out on this theory [2], the lifting line theory is a fundamental concept in aerodynamics, which is used to analyse the lift distribution generated by a wing in flight, since it is especially useful for calculating the lift of high aspect ratio wings, which have a dominant coordinate leading to a quasi-bidimensional flow in most of the wing surfaces. This theory approaches lift from the point of view of the vortices produced by the wing taking into account those vortices appearing in the wing tips which reduces the lift coefficient when comparing with an infinite wing (or what is the same, an airfoil).

This theory was developed independently by Frederick W. Lanchester in 1907, and by Ludwig Prandtl in 1918–1919 after working with Albert Betz and Max Munk. The main idea behind the lift line theory is to consider that lift occurs along an imaginary "line" on the wing called the "lifting line". This line is perpendicular to the airflow relative to the wing and extends across the entire span of the wing.

The theory of the lifting line is fundamentally based on the following concepts, which are briefly explained as they are not the objective of this project:

- Lift and Circulation. The lift L of an airfoil is related to the circulation Γ around that airfoil by the following equation:

$$L = \rho \cdot V \cdot \Gamma$$

Equation 8: Lift equation [2]

Where:

- L is the lift.
 - ρ is the density of the fluid.
 - V is the velocity of the fluid around the airfoil.
 - Γ is the circulation around the airfoil.
- Kutta-Joukowski relationship. This is an extension of the previous relationship that directly connects lift with circulation:

$$L = \rho \cdot V \cdot \Gamma \cdot b$$

Equation 9: Kutta-Joukowski relationship [2]

Where:

- b is the wingspan.

- Wingtip vortices. Vortices generated at the wingtips due to the difference in pressures between the top and bottom of the wing contribute to induced drag.
- Lift distribution. The lifting line theory describes how lift is distributed along the span of the wing. For an ideal elliptical wing, the lift distribution is elliptical and can be described mathematically.

It is important to mention that the lifting line theory is a simplified approximation and does not consider some of the more complex aerodynamic phenomena that occur in real wings. However, it is a valuable tool for obtaining initial estimates of an aircraft's lift and drag, and is widely used in the design and preliminary analysis of wings and aircraft. For more accurate analysis, more advanced methods such as dashboards or CFD codes are used. However, it is quite useful in some design in order to estimate the range of bi-dimensional lift coefficient at which the wing airfoil distribution must be designed.

2.8 Computational Fluid Dynamics

The Computational Fluid Dynamics method is defined below, for which different investigations have been carried out [2], Computational Fluid Dynamics (CFD), is a method that through mathematical calculations models those physical phenomena that are associated with fluid flow problems.

To solve fluid flow problems before the Computational Fluid Dynamics method was developed, two different types of methodology were used, these methodologies were the analytical mythology that was limited to simplified cases and the experimental methodology, which implied high costs for its process. That is why the Computational Fluid Dynamics method is so important, because it is a very practical method that allows you to simulate a wide spectrum of problems and projects, at comparatively low costs.

The CFD method is a process that is included as a tool in the software that uses it. CFD processes are defined by the following sequence of steps: pre-processing, resolution and post-processing.

The Computational Fluid Dynamics (CFD) approach is established through the fundamental equations that define the physical principles of fluid dynamics. This method is supported by the use of mathematical models, as well as the governing equations known as the Navier-Stokes equations. Additionally, through the application of the second law of motion and the principles of conservation of energy, it is possible to characterize the dynamics of particles through conservation of mass, conservation of momentum, and conservation of energy.

Conservation of mass

The equation for the conservation of mass defines that mass is conserved, this equation is also known as the continuity equation [2]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0$$

Equation 10: Continuity equation [2]

Where

$$\vec{U} = [u, v, w]$$

Equation 11: U vector for continuity equation [2]

Conservation of momentum

Conservation of momentum is based on Newton's second law which defines that the force on a body is equal to the mass of a body times its acceleration, $F = ma$ where m is the mass of the fluid particle and a is its acceleration.

If this is applied to a particular particle in a flow, which is under pressure, the viscous and body forces constitute the following momentum equations, which define conservation of momentum [2].

On the x axis,

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u u}{\partial x} + \frac{\partial \rho u v}{\partial y} + \frac{\partial \rho u w}{\partial z} = -\frac{\partial p}{\partial x} + \mu \frac{\partial}{\partial x} \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} \right) + \rho f_x$$

Equation 12: Conservation of momentum in X

On the y axis,

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v u}{\partial x} + \frac{\partial \rho v v}{\partial y} + \frac{\partial \rho v w}{\partial z} = -\frac{\partial p}{\partial y} + \mu \frac{\partial}{\partial y} \left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z} \right) + \rho f_y$$

Equation 13: Conservation of momentum in Y

On the z axis,

$$\frac{\partial \rho w}{\partial t} + \frac{\partial \rho w u}{\partial x} + \frac{\partial \rho w v}{\partial y} + \frac{\partial \rho w w}{\partial z} = -\frac{\partial p}{\partial z} + \mu \frac{\partial}{\partial z} \left(\frac{\partial w}{\partial x} + \frac{\partial w}{\partial y} + \frac{\partial w}{\partial z} \right) + \rho f_z$$

Equation 14: Conservation of momentum in Z

Conservation of energy

The energy equation is based on the principle that energy is conserved. It is also called the First Law of Thermodynamics [2]. Its general form is given in:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho E \vec{U}) = \rho \dot{q} + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - p \nabla \cdot \vec{U} + \lambda (\nabla \cdot \vec{U})^2 + \mu \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + 2 \left(\frac{\partial w}{\partial z} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right]$$

Equation 15: Energy conservation

These formulas are crucial for CFD development. They are discretized and solved, taking into account the points to be examined in the contour, to then algebraically address the proposed problems.

These equations can be solved using different techniques, such as the finite volume method (FVM), the finite difference method (FDM) or through the finite element method (FEM).

2.9 Softwares

2.9.1 MATLAB

This section defines what the MATLAB software is, after the research work carried out [16], MATLAB is a software used mainly for numerical analysis, matrix calculation, simulation, modeling, and data visualization. The name MATLAB is an abbreviation of "MATrix LABoratory" (Matrix Laboratory), developed by MathWorks, MATLAB provides a wide range of functions and tools that allow users to perform a variety of mathematical and scientific tasks efficiently.

Furthermore, as has been proven [17], It is important to note that MATLAB is proprietary software and although there is a free version called "GNU Octave" that offers similar functionality and is compatible with many MATLAB programs, the main version of MATLAB requires a license to use.

Finally, being a programming language, MATLAB also has an integrated development environment (IDE) that makes it easy to write, run, and debug code. MATLAB uses a syntax similar to other programming languages, but its primary focus is matrix and vector manipulation, making it especially well-suited for scientific and engineering applications.

2.9.2 XFLR5

In this section, as has been verified [18], XFLR5 is a design and simulation software, intended for the design and aerodynamic analysis of airfoils, wings and aircraft. XFLR5 comes from "X-FOIL Revisited" as it is an updated version of the original XFOIL software.

This software is based on numerical methods and perturbation theory analysis to calculate aerodynamic characteristics, thanks to which it has forward and inverse Xfoil analysis capabilities, wing design and analysis capabilities based on Lifting Line Theory, in the Vortex Lattice method and in the 3D panel method.

XFLR5 is an important software within the aerospace industry since it allows design and simulation, it is also an accessible software that allows its use to a wide community of users.

2.9.3 ANSYS

ANSYS, as can be confirmed [19], is an engineering design and simulation software that is widely used within the aerospace industry. The word "ANSYS" is an acronym of "Analysis Systems", which reflects its fundamental purpose, to provide numerical analysis tools to solve complex problems in engineering and design.

ANSYS is based on the finite element method (FEM). It is used to simulate computer models of structures, electronic components or machines, to analyse the different attributes of interest in each analysis, which allows determining how a product with different specifications will work, in this way simulations can be carried out to determine some conclusions prior to the manufacture of the product.

ANSYS software is widespread within different industries, since through its use a wide variety of engineering problems can be addressed, thus allowing the design and development of new systems.

Chapter 3. METHODOLOGY

In this chapter the design of the airfoils is carried out through the Bézier parameterization, analysis, Lifting line Theory and optimization. Then, after performing the optimization and selection of the optimal airfoil, the selected airfoil will be aerodynamically analysed at the proposed design points, in XFLR5 and ANSYS.

3.1 Bézier Curves

In the design of airfoils, shape parameterization is very important for the optimization process. The parameterization method must be a precise and flexible method to be able to correctly model the different shapes that are required within the design characteristics.

Bézier curves are a mathematical method for defining smooth curves using control points. In the context of airfoil design, Bézier curves can be used to create a parametric representation of the airfoil shape. An airfoil can be defined by specifying the position of control points along its upper and lower surfaces. By manipulating the positions of these control points, it is possible to generate different airfoil shapes.

To define a family of airfoils using Bézier curves, it is necessary to vary the positions of these control points systematically. Here's a theoretical approach:

1. **Number of Control Points:** Define the number of control points to use for each airfoil. A common choice is seven control points for each surface (upper and lower), but this can vary depending on the complexity of the desired airfoils.
2. **Control Point Coordinates:** For each airfoil in the family, it is necessary to define the coordinates (x, y) of these control points. These coordinates determine the shape of the Bézier curve.
3. **Parametric Variation:** To create a family of airfoils, systematically vary the control point coordinates within a certain range. The rules or mathematical functions must be defined to change the positions of control points while ensuring the resulting curves remain smooth.
4. **Interpolation:** Interpolate between the control points to generate the airfoil shape. Bézier curves smoothly connect these control points, creating a continuous curve. It is possible to use various interpolation methods, such as De Casteljau's algorithm, to compute the coordinates of points along the curve.

By varying the Bézier parameters within predefined bounds, it is possible to create a range of airfoil shapes that share a common parametric representation. This approach allows for efficient exploration of different airfoil designs and can be particularly useful in the iterative process of optimizing airfoil performance for specific applications.

3.1.1 MATLAB's Bézier Function

This section describes the development of airfoils using MATLAB, for this MATLAB's Bézier Function is used to generate dot airfoils as accepted by XFLR5. In the Bézier function it is necessary to define the parameters that act as control points for the airfoil design. The 5 Aerodynamic Parameters taken into consideration:

1. Max thickness of the chord: 16%
2. Position of Max thickness: 25%
3. Continuity if curvature of leading edge
4. Position of Trailing edge: (1,0)
5. Position of Leading edge: (0,0)

These aerodynamic parameters were basically defined as control points for the Bézier function. Taking 5 control points, three fixed and combining them provided us with $3^5=243$ airfoils. The MATLAB's Bézier Function is described in detail in Appendix 1. MATLAB – Bézier curves.

The code provided us with dot airfoils of 243 airfoils in .txt format, the files format was changed to .dat so it can be viewed by XFLR5. The airfoils were visualized in XFLR5 as shown below:

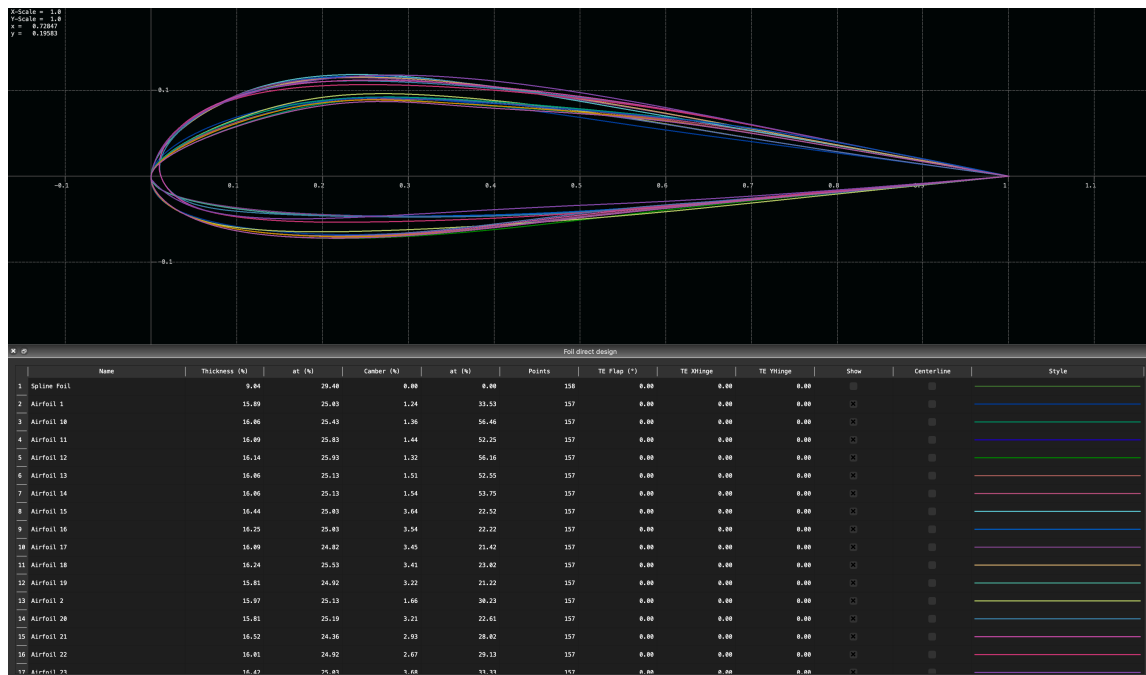


Figure 6: Airfoils designed by MATLAB's Bézier Function

3.2 Boundary Conditions

To carry out the analysis, the boundary conditions had to be previously defined. For this, it has been defined that the purpose of the analysis is to analyse aerodynamically the airfoil designed under the conditions of take off and cruise flight, based on the sources investigated [20] and on the requirements proposed by the project tutor, the following data is defined:

- On take off
 - At a height of sea level
 - Velocity of 68m/s = 0.2 MACH
 - With air density of 1.22501 kg/m³
 - A kinematic viscosity of 1.7894e-5 N sec/m²
 - Temperature of 288 K
 - Reynolds number of 4655239
 - Alpha: -5°; 0°; 5°; 10°; 15°; 20°

- On cruise
 - At a height of 20000ft
 - Velocity of 130m/s = 0.42 MACH
 - With air density of 0.65270 kg/m³
 - A kinematic viscosity of 1.5915e-5 N sec/m²
 - Temperature of 248.5 K
 - Reynolds number of 5331410
 - Alpha: -5°; 0°; 5°; 10°; 15°; 20°

With these boundary conditions, it has been determined in what type of regime the simulations are developed through the Reynolds number. Taking into account the Reynolds numbers of the two design points of the Project, it can be confirmed that the simulations will be carried out in turbulent regimes.

3.3 Database interpolation

In this section, after having designed the airfoils with the proposed control points, the 243 airfoils are analysed and a database is created to interpolate the parameters of all designed airfoils.

3.3.1 XFLR5 Database

Taking into account the boundary conditions defined in the 3.2 section, the aerodynamic analysis is developed for each airfoil in XFLR5 Direct Foil Analysis, to provide the results over a range of the angles of attack from -10 to 20 degrees. This range is studied to provide a wide spectrum of data that allows to focus the analyses on the proposed design points.

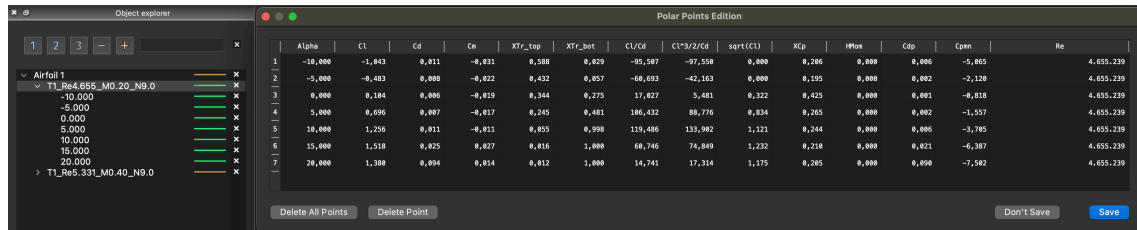


Figure 7: Airfoils XFLR5 Direct Foil Analysis

3.3.2 EXCEL Database

In this way it is possible to create a database, which will be used through MATLAB for:

- Interpolates between the points and provides the values of CL and CD for any set of parameters.
- This data could be used for feeding a lifting line theory or directly in a bi-dimensional optimization.
- Select with the optimization the optimal Airfoil for the project.

The results were stored in the EXCEL document attached below “Database.xlsx”:



	A	B	C	D	E	F
1	Airfoil Name	Altitude	Mach number	AoA	Cl	Cd
2	Airfoil 1	Sea level	0,2	-10	-1,0489	0,01057
3	Airfoil 1	20000ft	0,42	-10	-1,1101	0,01133
4	Airfoil 1	Sea level	0,2	-5	-0,4837	0,00775
5	Airfoil 1	20000ft	0,42	-5	-0,5035	0,00781
6	Airfoil 5	Sea level	0,2	0	0,104	0,00599
7	Airfoil 1	20000ft	0,42	0	0,1474	0,0065
8	Airfoil 1	Sea level	0,2	5	0,6967	0,00643
9	Airfoil 1	20000ft	0,42	5	0,757	0,00845
10	Airfoil 1	Sea level	0,2	10	1,2453	0,01017
11	Airfoil 1	20000ft	0,42	10	1,1525	0,01387
12	Airfoil 1	Sea level	0,2	15	1,5352	0,0236

Figure 8: Airfoils Database

3.3.3 MATLAB Database interpolation

Now a code in MATLAB is designed to interpolate among the datapoints in database, so is possible to get the results for any required set of parameters. The code designed for interpolation is explained in Appendix 1. MATLAB – Database interpolation.

The code loads the data from excel file “Database.xlsx” and interpolates between the points and provides the values of CL and CD for any set of parameters.

Through this code it is possible to interpolate the CL and CD values for any airfoil, selecting any angle of attack value between -10 degrees and 20 degrees. To carry out this interpolation, the following conditions must be taken into account, which must be defined in the code, in this way the values for each flight regime will be interpolated:

- Take off: sea level and 0.2 Mach
- Cruise: 20000ft and 0.42 Mach

The database has been made in Excel and is imported into MATLAB, in this way, through the designed code, the interpolated values of CL and CD can be obtained. It is important to note that because the database has been made with the data obtained from the XFLR5 analysis, it may have some airfoils that for certain alpha values do not have CL and CD values (since XFLR5 has not been able to analyse it in those conditions), then the interpolation for only a few airfoils might be in a lesser range than others, that is, for some airfoils, depending on the range of analysis of each airfoil, only the parameters between -5 degrees and 15 degrees can be interpolated.

3.4 Lifting Line Theory application

This section defines the application of the lifting line theory that drinks from the polar (Alpha, CL and CD) during the project. In this case, through the MATLAB code for the lifting line Theory detailed in Appendix 1. MATLAB – Lifting line Theory, it is possible to read the database and generate the Lift coefficient and Drag coefficient for the different angles of attack, as well as the lift distribution along the span of the wing. The total lift and drag on the wing is also calculated through the code.

To apply the lifting line theory, the following wing parameters have been taken into account, which have been defined by taking as a reference the characteristics of a regional transport aircraft and its flight regimes:

- Span = 27m
- Wing area = 50m²
- Wing loading = 400kg/m²
- Taper ratio = 0.4
- Chord = 2.65m

Lifting line theory required all the wing parameters to calculate the total lift and drag acting on the wing. Previous data is used for defining the Wing lift coefficient required to perform the Aircraft mission: cruise and take-off.

Then, the lifting line allows determining the range of bi-dimensional lift coefficient at which the aircraft should be optimized, which are used in the optimization.

Thanks to running the code designed for Lifting Line Theory application, it is possible to develop the coefficients corresponding to take off and cruise, which will be used in the optimization function.

3.5 MATLAB's Optimization Function

In this section, the development of optimization is explained as well as the way in which it has been applied through the design of MATLAB code and its execution. The MATLAB code is available in Appendix 1. MATLAB – Optimization.

Optimization is multi-objective, one objective is to reduce the drag in cruise and the other objective is to reduce the drag in take-off, so the following objective function is defined:

$$\emptyset = k \cdot CD_{Cruise} + (1 - k)CD_{Take-off}$$

Equation 16: Objective Function

The k combines both drags and it is necessary to vary k between 0 and 1 with an increment of 0.1. Through the optimization function it is possible to reduce the drag in the design point.

In the Optimization function it is necessary to previously execute the code designed for Lifting Line Theory application and use the following Excel file “CL and CD of Wing.xlsx”, generated with the lifting line theory.



This Excel file provides the aerodynamic drag coefficients corresponding to takeoff and cruise, which will be used in the optimization function.

Through this process, it is possible to optimize and analyse the 243 designed airfoils, in order to choose the airfoil that has the best characteristics for the proposed design points.

The following tables, whose data has been extracted from the excel file “CL and CD of Wing.xlsx” show the 10 airfoils with the most optimal Drag coefficients according to the optimization requirements for Take off and Cruise through the lifting line theory application.

TAKE OFF			
Airfoil Name	AoA	Lift Coefficient	Drag Coefficient
Airfoil 118	5 degrees	1.618	0.01184
Airfoil 2	5 degrees	1.416	0.01208
Airfoil 15	5 degrees	1.707	0.01236
Airfoil 188	5 degrees	2.373	0.01236
Airfoil 54	5 degrees	1.530	0.01244
Airfoil 187	5 degrees	1.623	0.01280
Airfoil 53	5 degrees	1.510	0.01286
Airfoil 189	5 degrees	2.460	0.01290
Airfoil 48	5 degrees	1.438	0.01296
Airfoil 18	5 degrees	1.726	0.01302

Table 1: Optimization for TAKE OFF

CRUISE			
Airfoil Name	AoA	Lift Coefficient	Drag Coefficient
Airfoil 118	4 degrees	1.553	0.01323
Airfoil 2	4 degrees	1.308	0.01341
Airfoil 3	4 degrees	1.321	0.01345
Airfoil 54	4 degrees	1.445	0.01351
Airfoil 188	5 degrees	2.653	0.01360
Airfoil 145	0 degrees	1.410	0.01364
Airfoil 15	3 degrees	1.381	0.01366
Airfoil 48	4 degrees	1.331	0.01367
Airfoil 12	4 degrees	1.328	0.01368
Airfoil 8	4 degrees	1.331	0.01368

Table 2: Optimization for CRUISE

With these table, is possible to check which airfoils meet the optimization criteria, since through the optimization based on lifting line Theory, the Airfoil that has lowest drag coefficient with maximum lift coefficient is defined.

Finally, after applying the optimization, the optimal airfoil for the proposed design points is the Airfoil 118, as indicated by MATLAB through the commands defined in the “Command Window”. In the next section, this airfoil is analysed through XFLR5 and ANSYS CFD, to determine its aerodynamic characteristics.

3.6 Airfoil 118 analysis

Taking into account the previously defined boundary conditions, in this section the analysis of Airfoil 118 is carried out, since as it has been determined, it is the optimal airfoil designed in this project. The XFLR5 analysis and the ANSYS CFD analysis for the Airfoil 118 are defined below.

3.6.1 XFLR5 analysis

To perform the XFLR5 analysis the Airfoil 118 is taken for simulation. This section shows the different parameter studied for airfoil for the different angles of attack:

- Lift Coefficient
- Drag Coefficient
- Momentum Coefficient

Through this analysis, the purpose is to aerodynamically analyse the Airfoil 118 in two different flight regimes:

- On take off
 - At a height of sea level
 - Velocity of 68m/s = 0.2 MACH
 - Reynolds number of 4655239
- On cruise
 - At a height of 20000ft
 - Velocity of 130m/s = 0.42 MACH
 - Reynolds number of 5331410

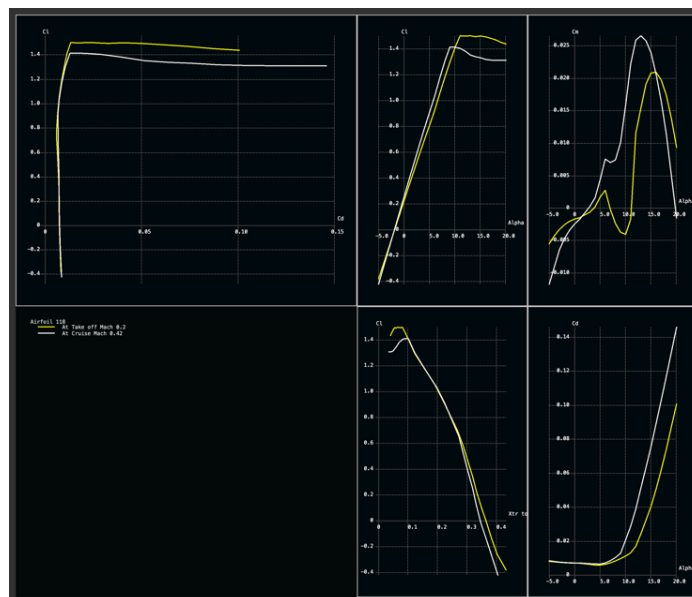


Figure 9: Airfoil 118 XFLR5 analysis

The tables that show the values obtained in the analysis are shown below, reflecting the values that can be seen in the previous graphs:

TAKE OFF, At Sea Level, Mach 0.2				
	Lift coefficient	Drag coefficient	Moment coefficient	CL/CD
Angle of attack -5 degrees	-0.380	0.00809	-0.005	-47.878
Angle of attack 0 degrees	0.222	0.00711	-0.002	32.099
Angle of attack 5 degrees	0.809	0.00596	0.001	136.721
Angle of attack 10 degrees	1.397	0.01124	-0.002	123.906
Angle of attack 15 degrees	1.509	0.04059	0.021	38.092
Angle of attack 20 degrees	1.441	0.10058	0.009	14.415

Table 3: XFLR5 Take off analysis

CRUISE, At 20000ft, Mach 0.42				
	Lift coefficient	Drag coefficient	Moment coefficient	CL/CD
Angle of attack -5 degrees	-0.420	0.00842	-0.012	-49.931
Angle of attack 0 degrees	0.254	0.00712	-0.002	35.671
Angle of attack 5 degrees	0.907	0.00649	0.004	139.888
Angle of attack 10 degrees	1.413	0.02143	0.016	68.688
Angle of attack 15 degrees	1.332	0.07546	0.024	17.648
Angle of attack 20 degrees	1.310	0.14647	-0.001	9.002

Table 4: XFLR5 Cruise analysis

As can be seen, the results obtained in both simulations are similar, although the boundary conditions are different.

It is appreciable how in both cases the Airfoil from 15 degrees of inclination in the angle of attack, stalls, generating less Lift coefficient and more drag coefficient than at angles less than 15 degrees, since it has exceeded the stall angle.

As expected, the lift coefficient at zero angle of attack and the lift coefficient derivative with the angle of attack increases with the Mach number due to the compressibility effects.

3.6.2 ANSYS CFD analysis

To perform the CFD analysis the Airfoil 118 is taken for simulation. This section shows the different contours studied for the wing CFD for the different angles of attack. The contours studied are:

- Contours of Static pressure
- Contours of Velocity magnitude

Through CFD analysis, the purpose is to aerodynamically analyse the Airfoil 118 in the two flight regimes proposed during the project.

- Take off

At angle of Attack of -5 degrees:

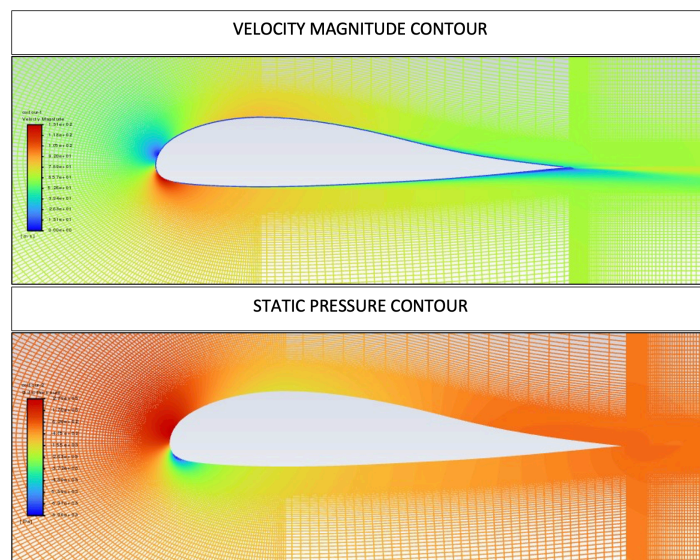


Figure 10: TAKE OFF - Contours at angle of attack of -5 degrees

For this angle, it is appreciable how in the contour of "VELOCITY MAGNITUDE" the highest values are in the lower part of the leading edge, this is because in the upper part of it, there is more air pressure and therefore in that area the velocity is lower.

In the contour of "STATIC PRESSURE" it is appreciable how the pressure is higher at the top of the leading edge, this is due to the inclination of the airfoil.

At this angle of attack the coefficients obtained are -0.270 and 0.00916 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack -5 degrees	
Lift coefficient	-0.270
Drag coefficient	0.00916

Table 5: TAKE OFF - Coefficients at angle of attack of -5 degrees

At angle of Attack of 0 degrees:

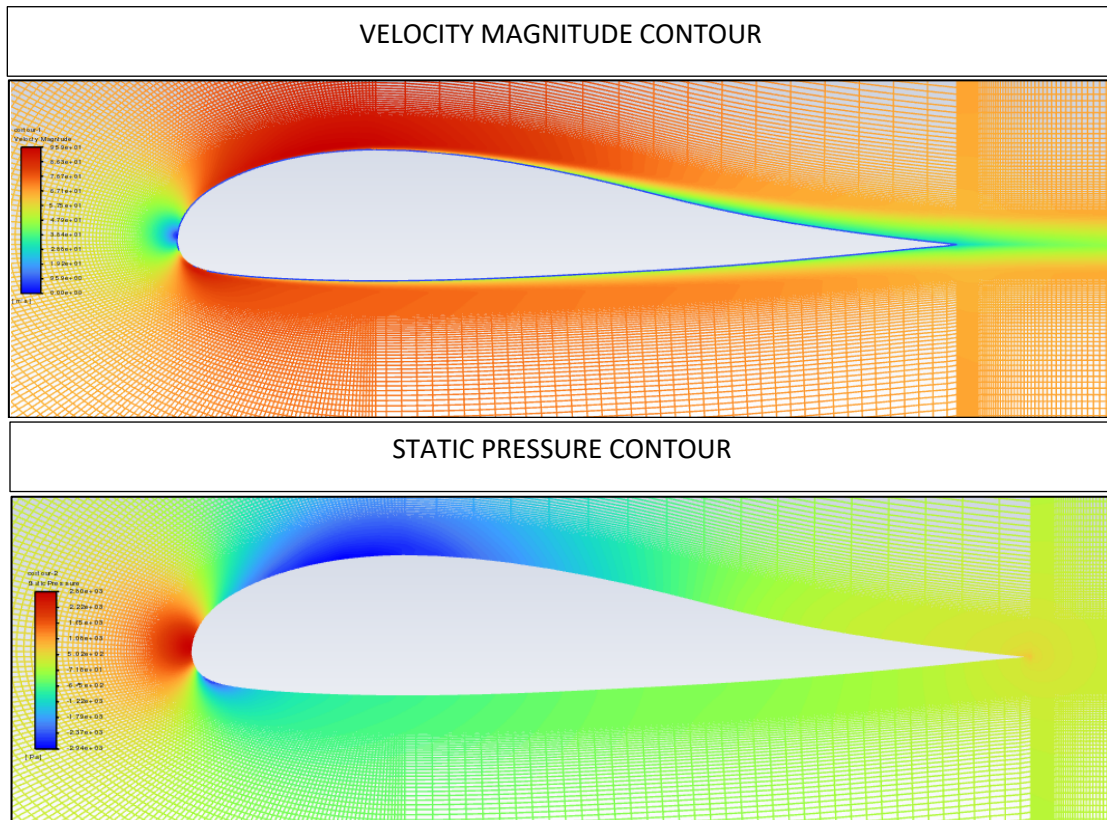


Figure 11: TAKE OFF - Contours at angle of attack of 0 degrees

For this angle of attack, it seems that the pressure on the upper surface of the airfoil decreases, which causes the velocity on the upper face to increase.

In fact, in the contour of "VELOCITY MAGNITUDE" it can be seen how the highest values are found on the upper face, after the stagnation point.

The coefficients obtained for this angle of attack are 0.198 and 0.00835 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 0 degrees	
Lift coefficient	0.198
Drag coefficient	0.00835

Table 6: TAKE OFF - Coefficients at angle of attack of 0 degrees

At angle of Attack of 5 degrees:

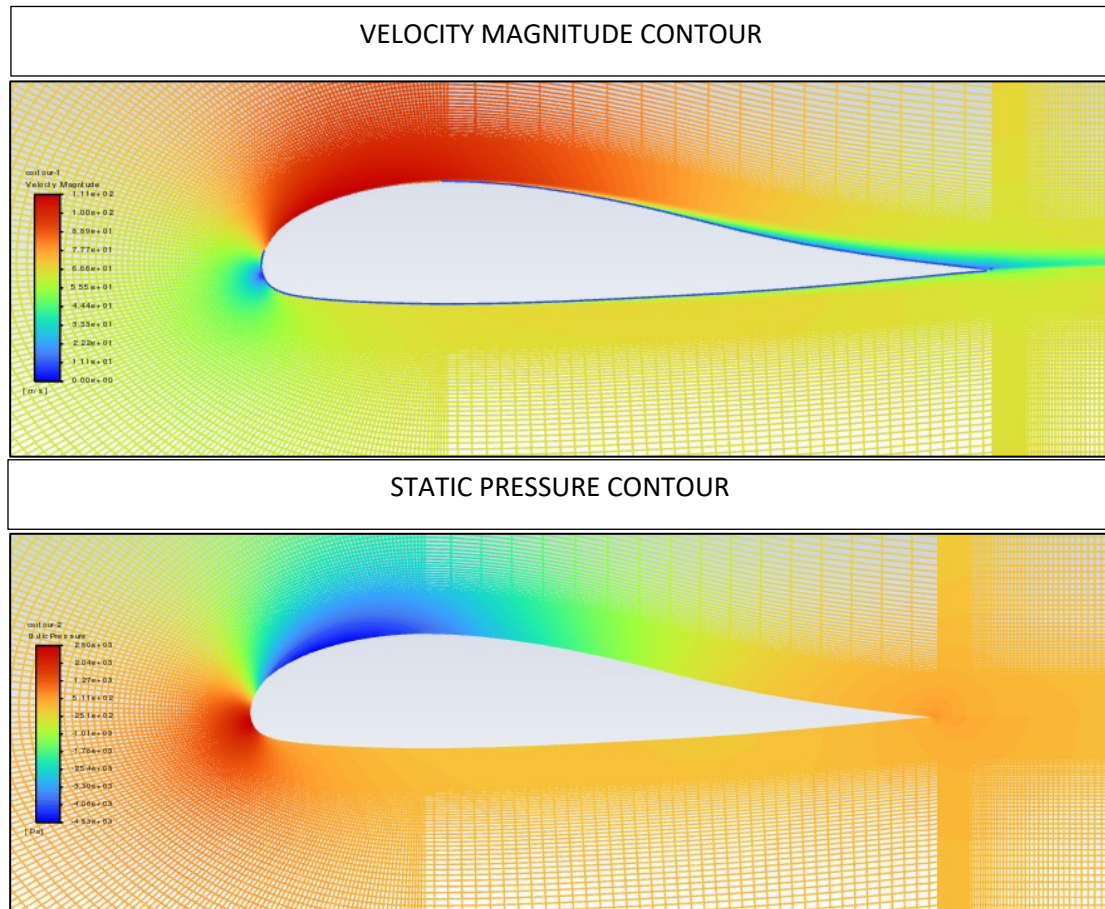


Figure 12: TAKE OFF - Contours at angle of attack of 5 degrees

As the angle of attack is progressively increasing during the analysis, it can be seen how the velocity at the top of the airfoil increases. In this case also, the stagnation point has moved towards the lower part of the leading edge. It can also be seen that the pressure distribution on the lower surface of the wing is homogeneous.

The coefficients obtained for this angle of attack are 0.697 and 0.01054 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 5 degrees	
Lift coefficient	0.697
Drag coefficient	0.01054

Table 7: TAKE OFF - Coefficients at angle of attack of 5 degrees

At angle of Attack of 10 degrees:

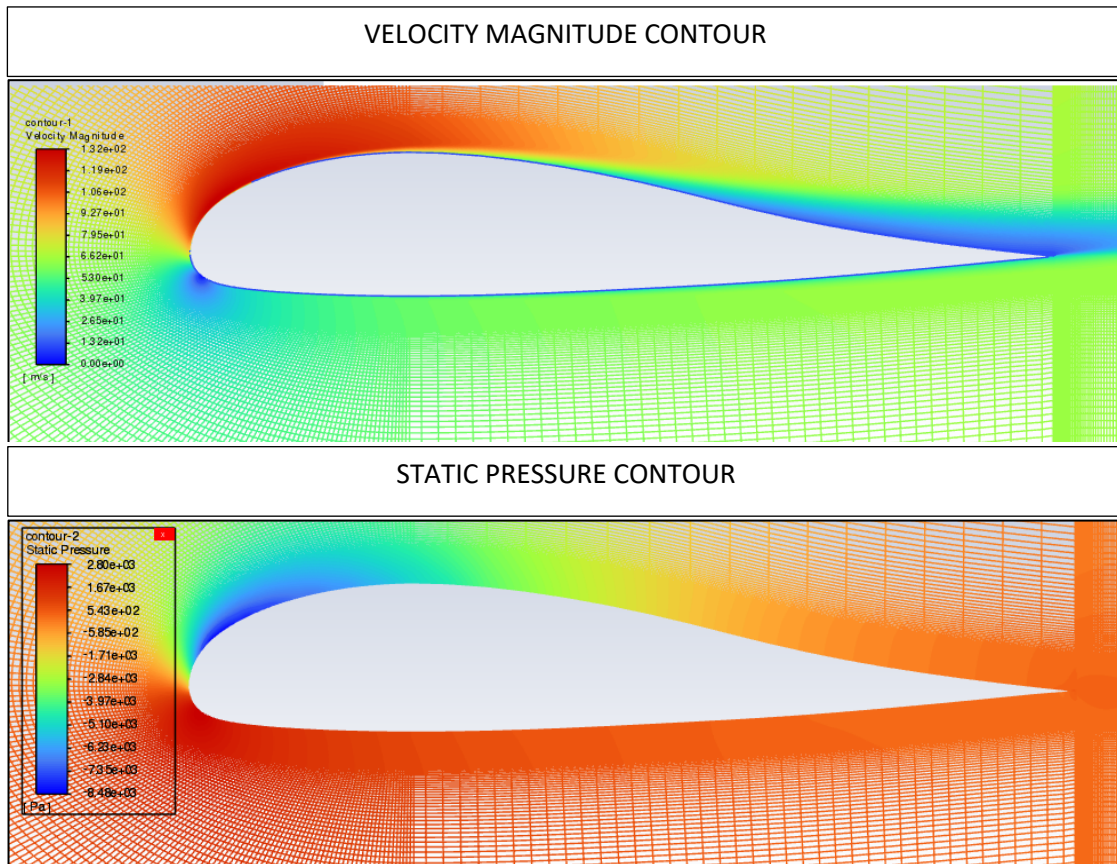


Figure 13: TAKE OFF - Contours at angle of attack of 10 degrees

At 10 degrees of angle of attack it is appreciable how the boundary layer of the wing is detached. It is also remarkable how the contour of "VELOCITY MAGNITUDE" values increase and in the highlighted area on the upper surface of the airfoil.

Also, can be seen how the speed at the upper of the wing increases due to the angle of attack is progressively increasing during the analysis and the pressure is distributed along the lower surface of the airfoil.

The coefficients obtained for this angle of attack are 1.173 and 0.01667 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 10 degrees	
Lift coefficient	1.173
Drag coefficient	0.01667

Table 8: TAKE OFF - Coefficients at angle of attack of 10 degrees

At angle of Attack of 15 degrees:

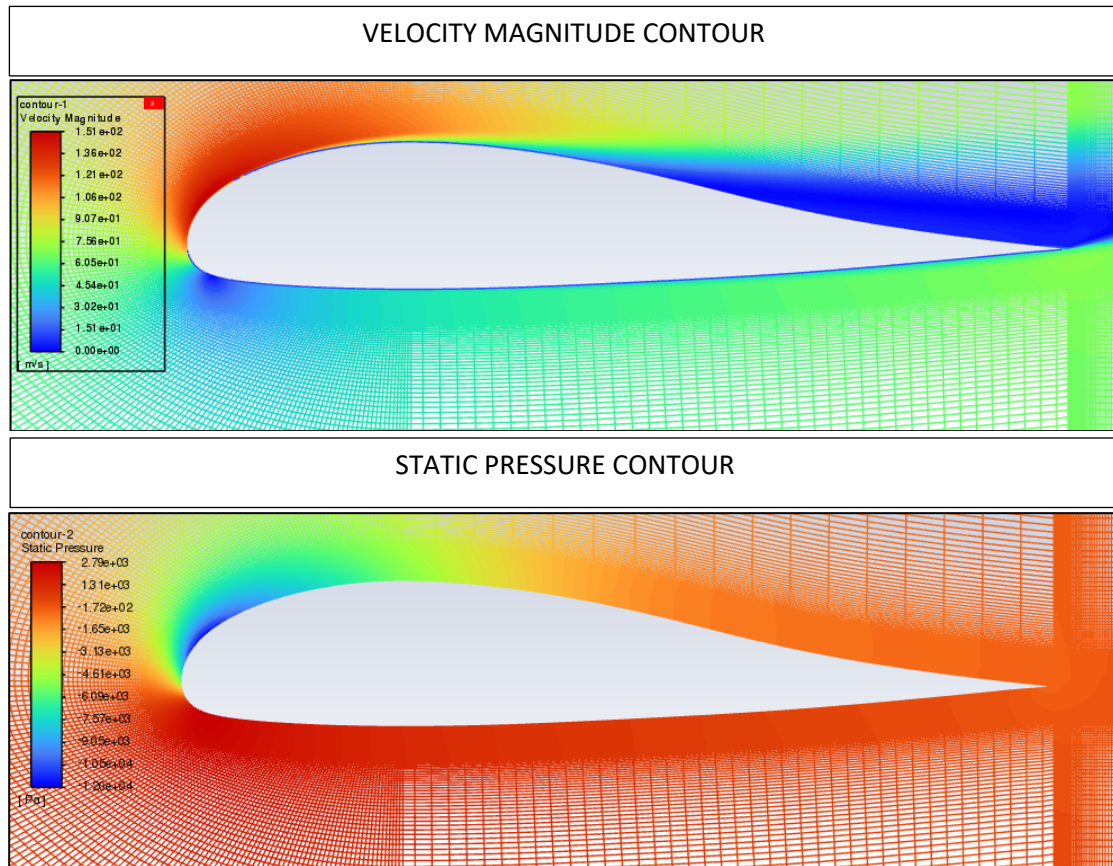


Figure 14: TAKE OFF - Contours at angle of attack of 15 degrees

At 15 degrees of angle of attack, is appreciable how the boundary layer of the wing is detaching as it increases his wake. The pressure on the lower surface increases. The airfoil approaches its staling angle. That is why the detachment of the boundary layer occurs.

The coefficients obtained for this angle of attack are 1.422 and 0.06233 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 15 degrees	
Lift coefficient	1.422
Drag coefficient	0.06233

Table 9: TAKE OFF - Coefficients at angle of attack of 15 degrees

At angle of Attack of 20 degrees:

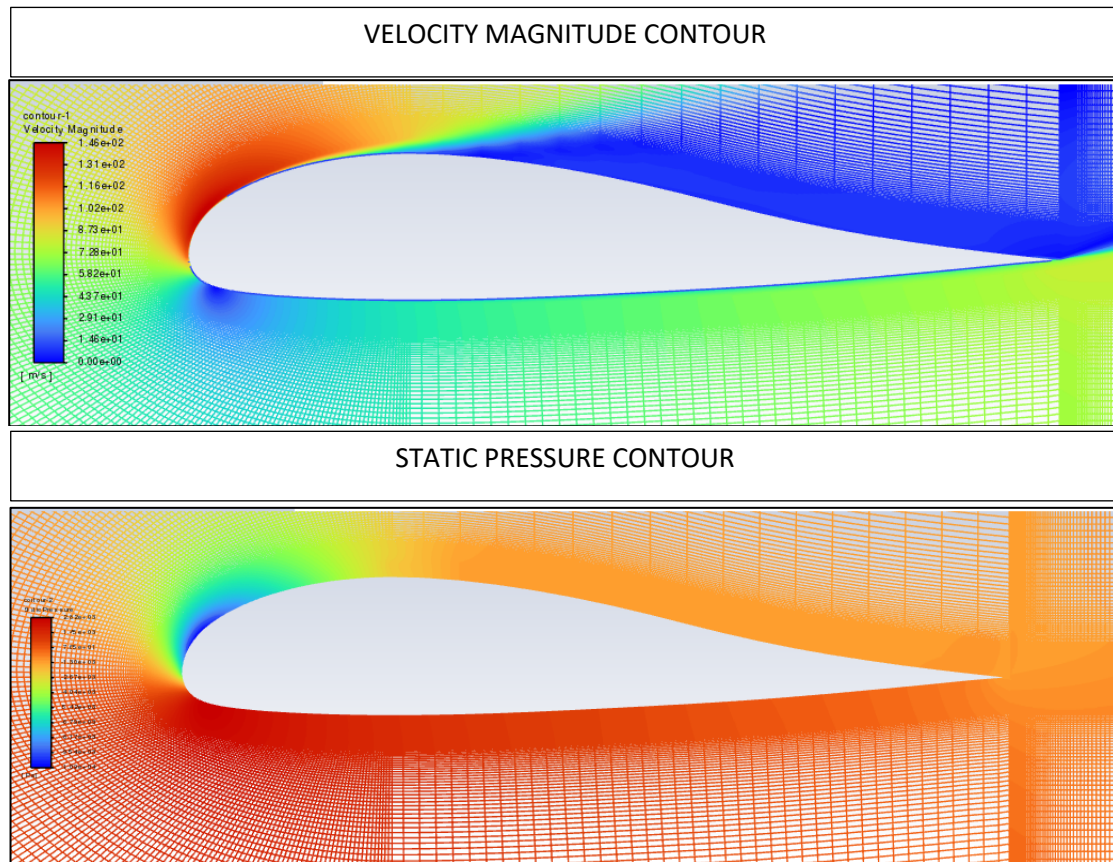


Figure 15: TAKE OFF - Contours at angle of attack of 20 degrees

For this angle of attack, at 20 degrees of angle of attack, the pressure on the lower surface increases. Furthermore, the airfoil has exceeded its staling angle due to the increase in the detachment of the boundary layer, it is appreciable how increases its wake.

The coefficients obtained for this angle of attack are 1.388 and 0.11753 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 20 degrees	
Lift coefficient	1.388
Drag coefficient	0.11753

Table 10: TAKE OFF - Coefficients at angle of attack of 20 degrees

- Cruise

At angle of Attack of -5 degrees:

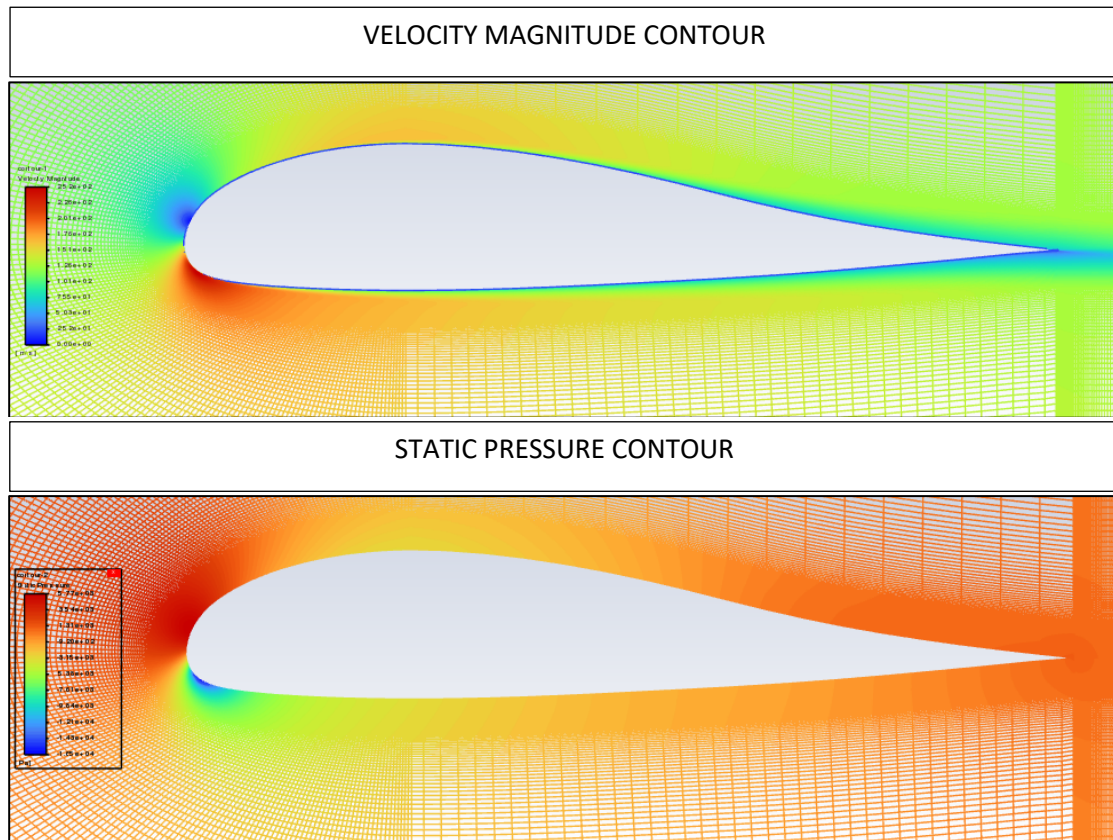


Figure 16: CRUISE - Contours at angle of attack of -5 degrees

For -5 degrees of angle of attack, it is noted that the pressure and velocity distribution is similar for the upper surface and for the lower surface of the airfoil.

Also, the coefficients obtained for this angle of attack are -0.372 and 0.00902 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack -5 degrees	
Lift coefficient	-0.372
Drag coefficient	0.00902

Table 11: CRUISE - Coefficients at angle of attack of -5 degrees

At angle of Attack of 0 degrees:

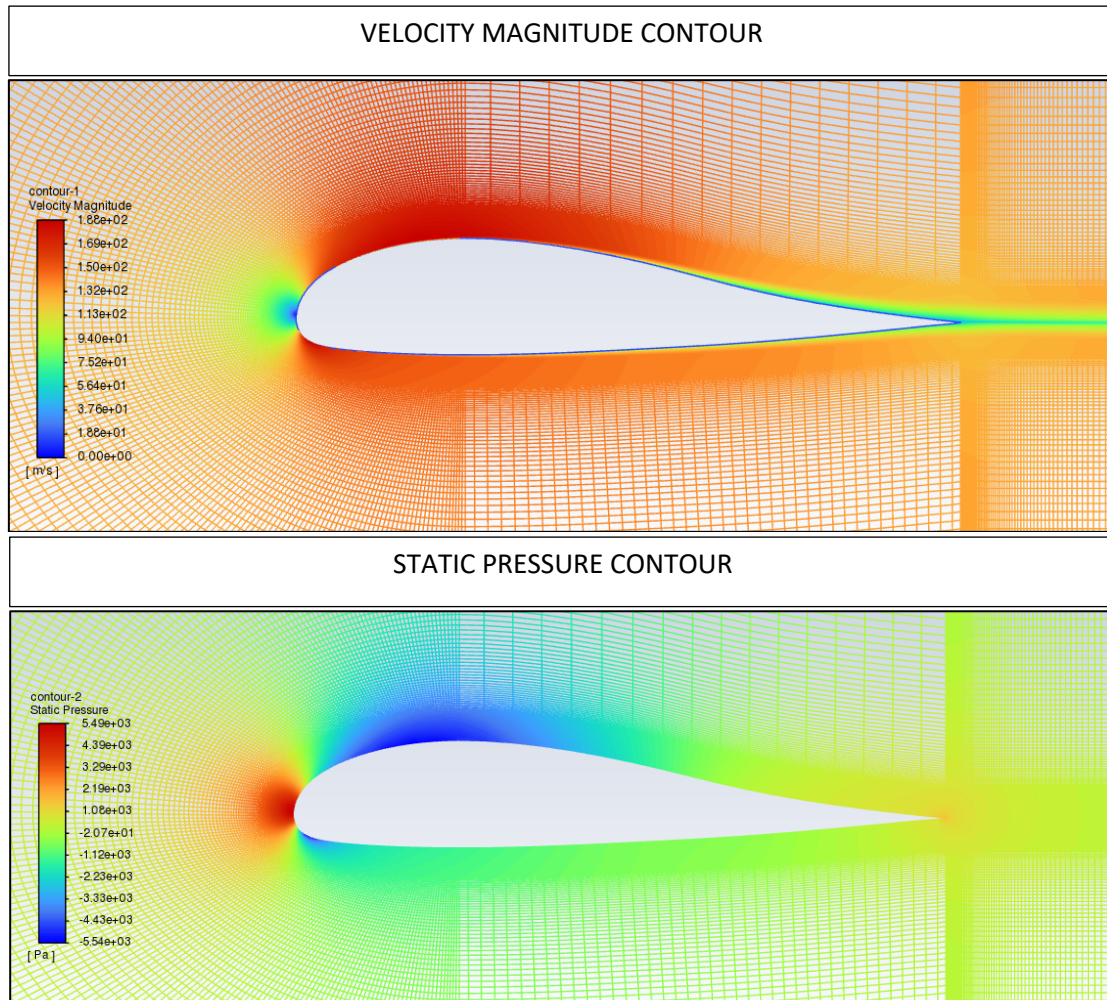


Figure 17: CRUISE - Contours at angle of attack of 0 degrees

For this angle of attack, 0 degrees, it can be verified that the distribution of pressures and velocity is different for the upper surface and the lower surface of the airfoil, that is why the air circulates at a higher speed in the upper surface, producing the downwash effect.

The coefficients obtained for this angle of attack are 0.199 and 0.00813 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 0 degrees	
Lift coefficient	0.199
Drag coefficient	0.00813

Table 12: CRUISE - Coefficients at angle of attack of 0 degrees

At angle of Attack of 5 degrees:

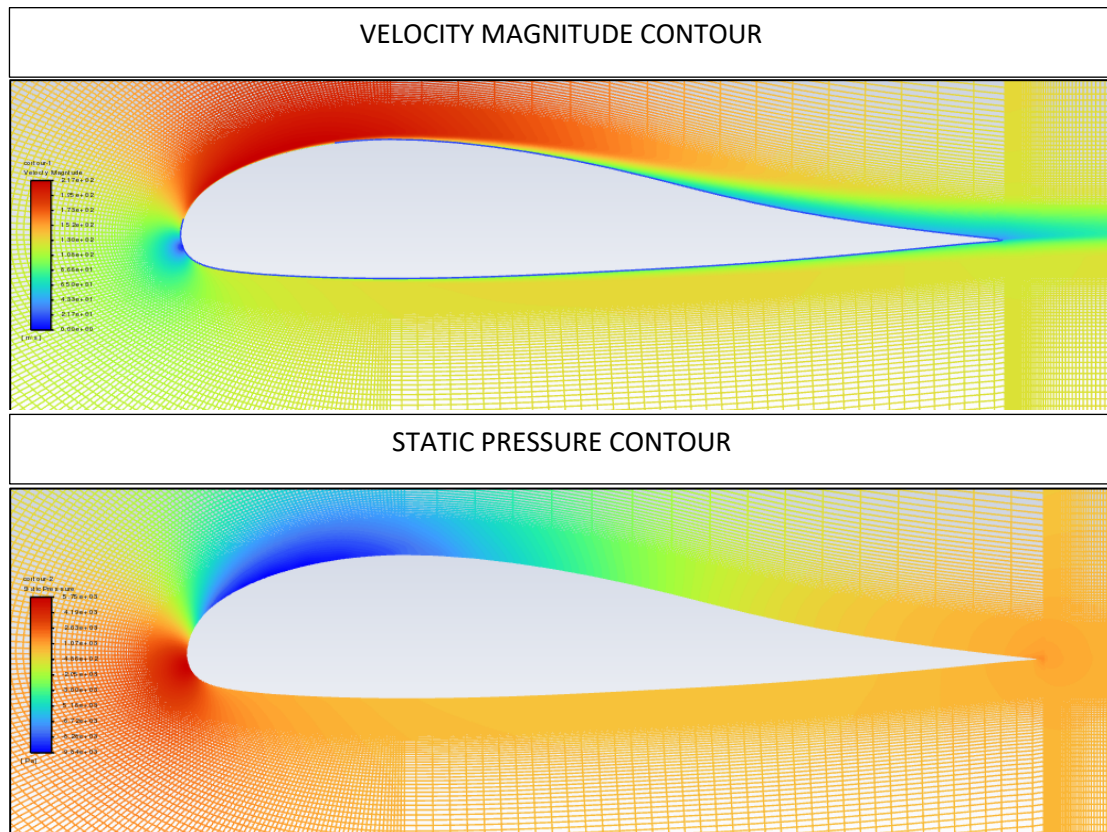


Figure 18: CRUISE - Contours at angle of attack of 5 degrees

It can be seen how the velocity of the air at the upper surface of the wing increases, this is because the inclination of the angle of attack has increased and causes the air to circulate at a higher speed in the upper surface because the air pressure is less. It is also appreciable how the contour of "VELOCITY MAGNITUDE" values increase.

The coefficients obtained for this angle of attack are 0.756 and 0.01140 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 5 degrees	
Lift coefficient	0.756
Drag coefficient	0.01140

Table 13: CRUISE - Coefficients at angle of attack of 5 degrees

At angle of Attack of 10 degrees:

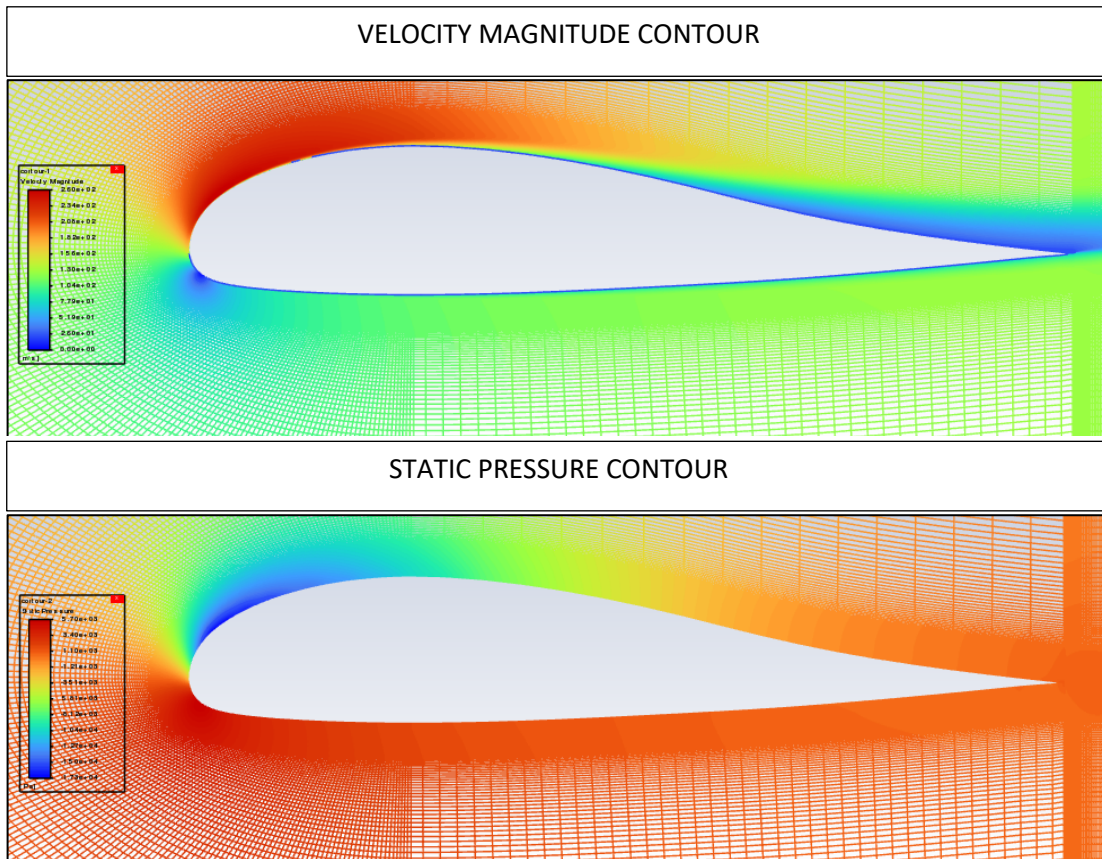


Figure 19: CRUISE - Contours at angle of attack of 10 degrees

For angle of attack of 10 degrees it is appreciable how the boundary layer of the airfoil is detached.

The coefficients obtained for this angle of attack are 1.272 and 0.02245 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 10 degrees	
Lift coefficient	1.272
Drag coefficient	0.02245

Table 14: CRUISE - Coefficients at angle of attack of 10 degrees

At angle of Attack of 15 degrees:

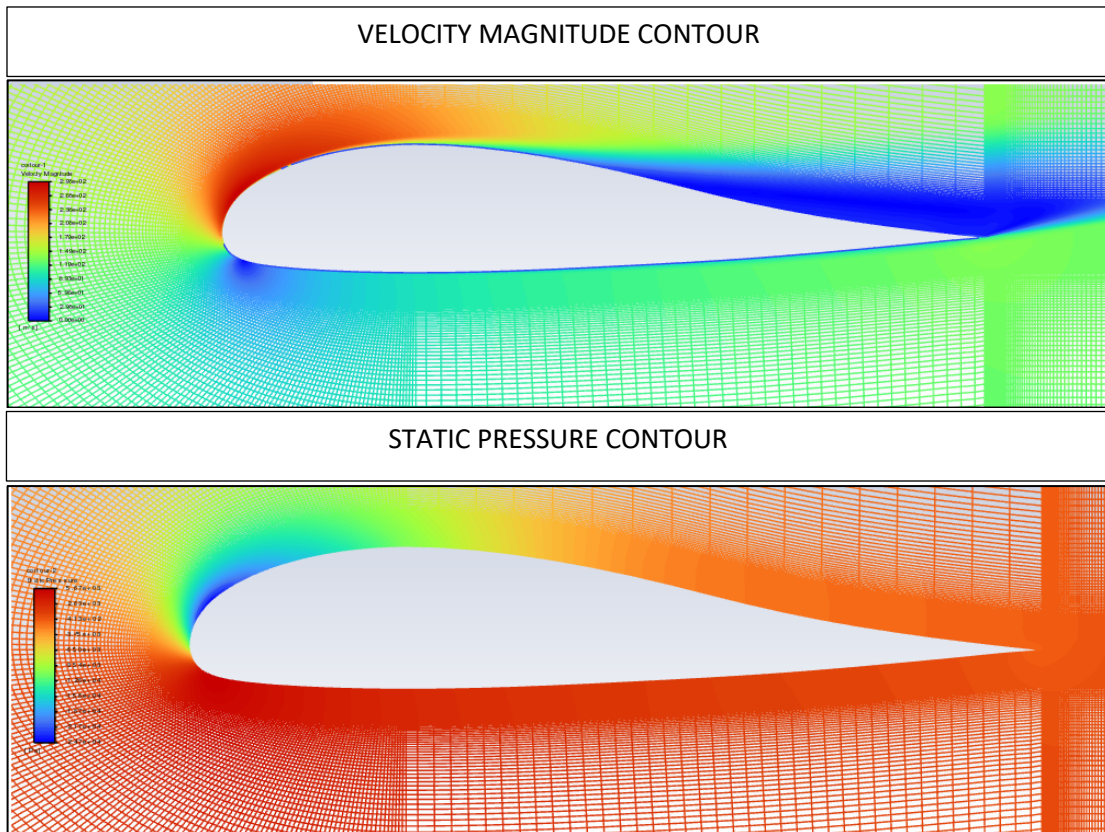


Figure 20: CRUISE - Contours at angle of attack of 15 degrees

At 15 degrees of angle of attack is appreciable how the boundary layer of the airfoil is detaching as the wake increases. The pressure on the lower surface increases.

The coefficients obtained for this angle of attack are 1.128 and 0.07613 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 15 degrees	
Lift coefficient	1.128
Drag coefficient	0.07613

Table 15: CRUISE - Coefficients at angle of attack of 15 degrees

At angle of Attack of 20 degrees:

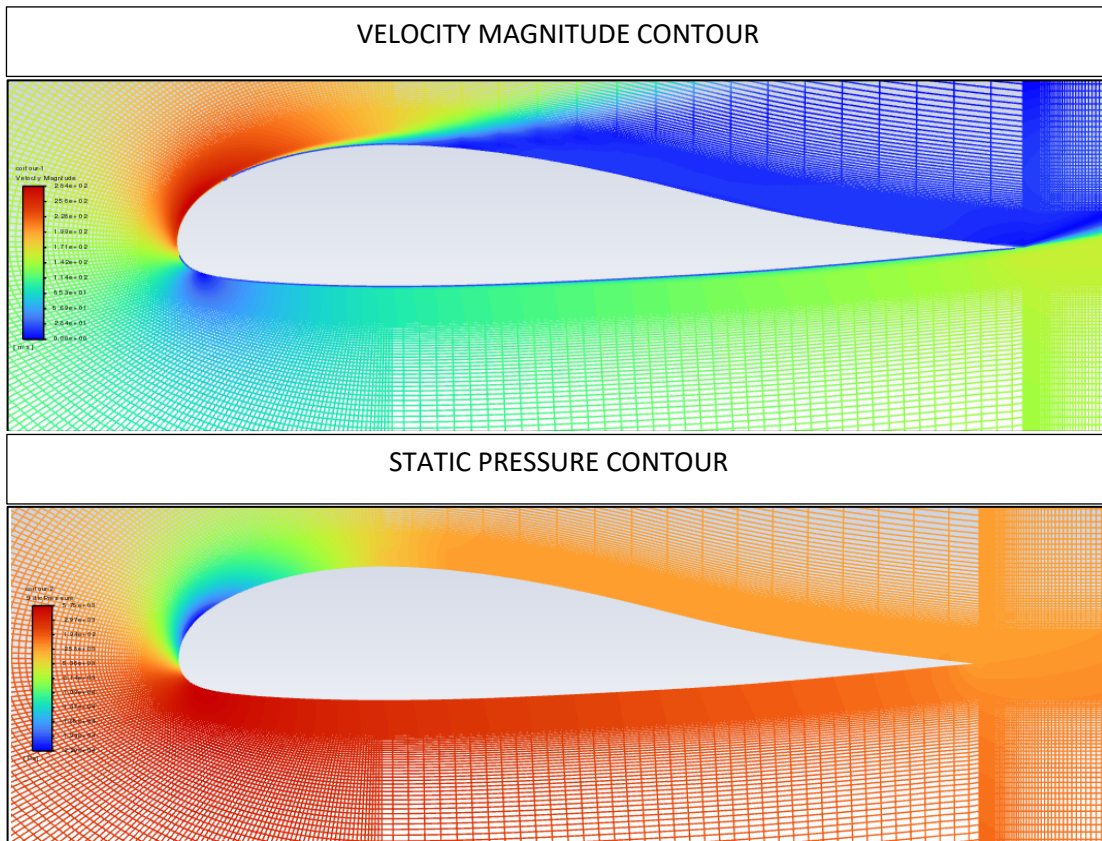


Figure 21: CRUISE - Contours at angle of attack of 20 degrees

In this case, at 20 degrees of angle of attack, the pressure on the lower surface increases and the airfoil has exceeded its staling angle due to the increase in the detachment of the boundary layer.

The coefficients obtained for this angle of attack are 1.115 and 0.14925 for the Lift coefficient and for the Drag coefficient, respectively.

Angle of attack 20 degrees	
Lift coefficient	1.115
Drag coefficient	0.14925

Table 16: CRUISE - Coefficients at angle of attack of 20 degrees

Chapter 4. RESULTS

In this section the results obtained for the aerodynamic analyses of the designed models are analysed.

4.1 Comparison of XFLR5 and ANSYS CFD

To analyse the results obtained through the XFLR5 and ANSYS CFD for the two flight regimes defined for the airfoil 118, the lift and drag forces will be calculated for each angle of attack, in this way the results for each model will be compared and their aerodynamic differences can be determined.

To begin with, we compute the lift force. As defined in section 2.6, Lift is an aerodynamic force arising from the airplane's movement through the atmosphere.

Factors influencing Lift include air density, the square of the velocity, the characteristics of the air such as viscosity and compressibility, the surface area over which the air flows, the shape of the body, and its angle relative to the airflow. The formula to determine lift is:

$$L = C_L \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot A$$

Equation 17: Lift equation [21]

Where

L : Lift force C_L : Lift coefficient ρ : Density of fluid (kg/m³)
 v : Velocity (m/s) A : Surface area

Then the drag force is defined. As mentioned in section 2.6, the drag is the force that counteracts an aircraft's movement in the atmosphere. The formula to compute drag is:

$$D = C_D \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot A$$

Equation 18: Drag equation [22]

Where

D : Drag force C_D : Drag coefficient ρ : Density of fluid (kg/m³)
 v : Velocity (m/s) A : Surface area

Then, after understanding the concepts of Lift and Drag, their determined values are calculated for the simulations and then once the corresponding calculations have been made, below in the next page is possible to see the tables with the results obtained for each flight regime proposed.

TAKE OFF, At Sea Level, Mach 0.2								
	XFLR5				ANSYS CFD			
	Lift coefficient	Lift force	Drag coefficient	Drag force	Lift coefficient	Lift force	Drag coefficient	Drag force
Angle of attack -5 degrees	-0.380	-1071.84 N	0.00809	22.81 N	-0.270	-761.57 N	0.00916	25.83 N
Angle of attack 0 degrees	0.222	626.18 N	0.00711	20.05 N	0.198	558.48 N	0.00835	23.55 N
Angle of attack 5 degrees	0.809	2281.89 N	0.00596	16.81 N	0.697	1965.98 N	0.01054	29.73 N
Angle of attack 10 degrees	1.397	3940.43 N	0.01124	31.7 N	1.173	3308.61 N	0.01667	47.02 N
Angle of attack 15 degrees	1.509	4256.34 N	0.04059	114.48 N	1.422	4010.95 N	0.06233	175.81 N
Angle of attack 20 degrees	1.441	4064.54 N	0.10058	283.69 N	1.388	3915.04 N	0.11753	331.5 N

Table 17: Airfoil analysis at TAKE OFF

CRUISE, At 20000ft, Mach 0.42								
	XFLR5				ANSYS CFD			
	Lift coefficient	Lift force	Drag coefficient	Drag force	Lift coefficient	Lift force	Drag coefficient	Drag force
Angle of attack -5 degrees	-0.420	-2316.43 N	0.00842	46.43 N	-0.372	-2051.69 N	0.00902	49.74 N
Angle of attack 0 degrees	0.254	1400.89 N	0.00712	39.26 N	0.199	1097.54 N	0.00813	44.83 N
Angle of attack 5 degrees	0.907	5002.39 N	0.00649	35.79 N	0.756	4169.57 N	0.01140	62.87 N
Angle of attack 10 degrees	1.413	7793.14 N	0.02143	118.19 N	1.272	7015.48 N	0.02245	123.81 N
Angle of attack 15 degrees	1.332	7346.39 N	0.07546	416.18 N	1.128	6221.27 N	0.07613	419.88 N
Angle of attack 20 degrees	1.310	7225.06 N	0.14647	807.82 N	1.115	6149.57 N	0.14925	823.16 N

Table 18: Airfoil analysis at CRUISE

Once the corresponding calculations have been made, below it is appreciable the tables with the results obtained for each flight regime, taking into account the tables Table 17 and Table 18:

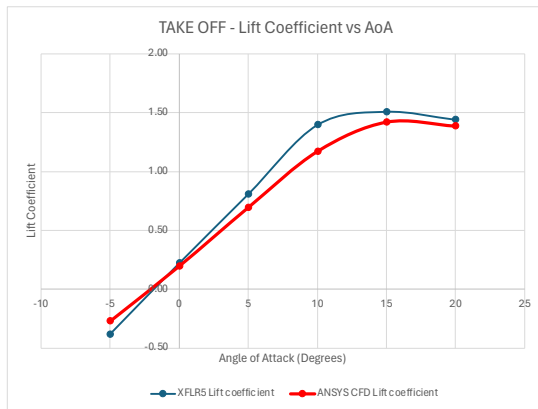


Figure 22: TAKE OFF – Lift Coefficient

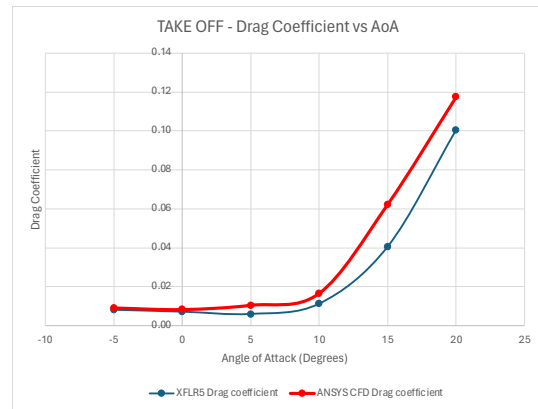


Figure 23: TAKE OFF – Drag Coefficient

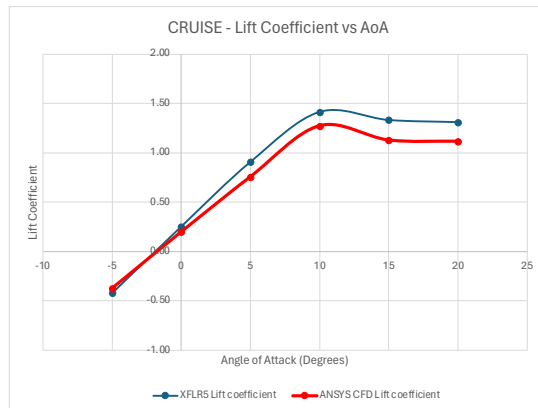


Figure 24: CRUISE – Lift Coefficient

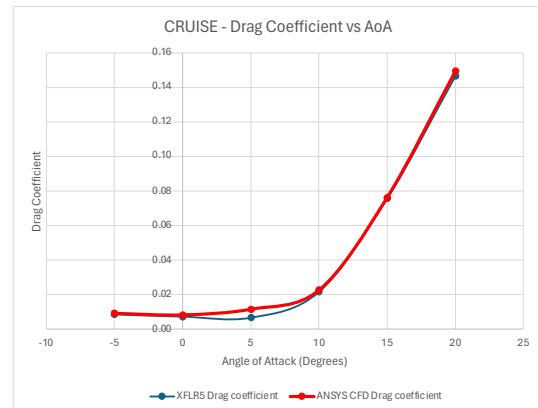


Figure 25: CRUISE – Drag Coefficient

As can be seen, despite the aerodynamics differences of the two models, the values obtained for the coefficients in general terms are similar, it can be seen that this airfoil maintains its remarkable aerodynamic properties in both point design.

It can be noted that the values obtained for the Lift coefficient are higher for the take off conditions, which provides greater lift. In addition, it can also be observed, in the Cruise model, the airfoil stalls earlier as expected. However, the drag coefficient is lower at Cruise conditions.

To analyze the forces, when an Airfoil is being analysed, 1 square meter has been taken as a reference value of area. Below are the graphs corresponding to the Lift and Drag forces that have been obtained for the airfoil analysis.

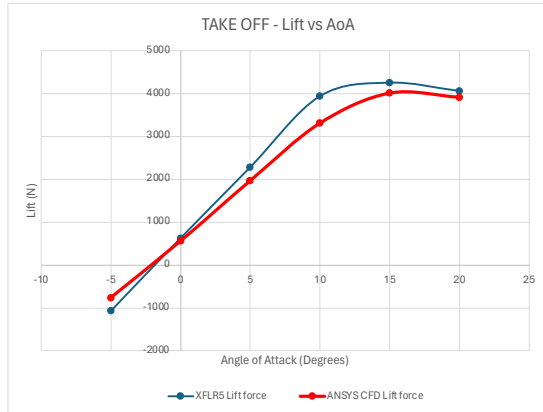


Figure 26: TAKE OFF – Lift

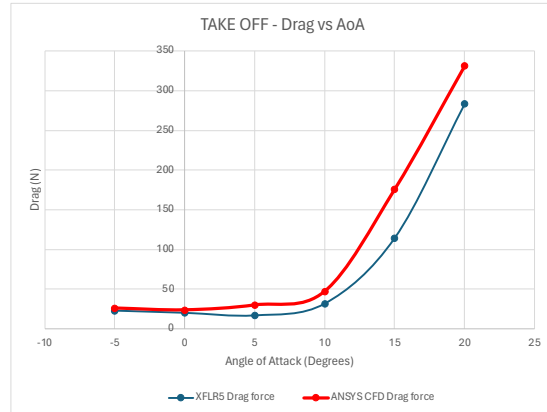


Figure 27: TAKE OFF – Drag

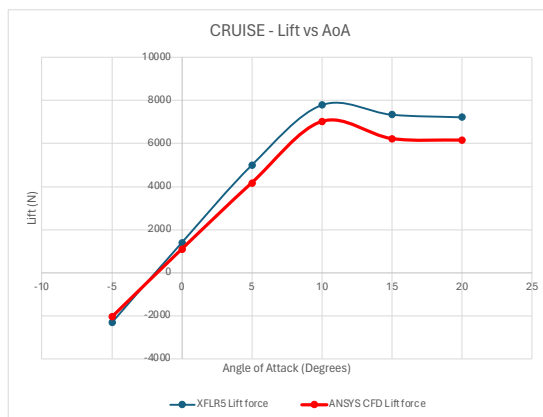


Figure 28: CRUISE – Lift

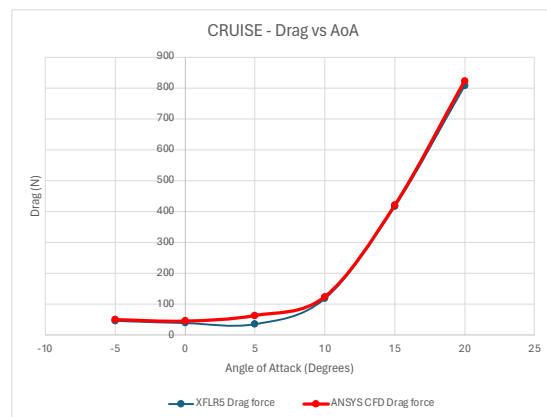


Figure 29: CRUISE – Drag

For the forces it can be seen, as with the coefficients, that the values are similar despite using different analysis software.

In the comparison of the forces generated, the difference in the absolute values of the forces between different flight regimes is more appreciated, since they have different boundary conditions.

Finally, as has been seen, when comparing the results between the two different softwares, these results are similar, therefore, they verify each other, but in general, the Drag values are lower for XFLR5, this is because it is a potential software, so the slopes of the derivative increase with respect to ANSYS.

It is also interesting to analyze the relationship of the Lift Coefficient and Drag Coefficient parameters with each other, below is an analysis of the CL/CD for the proposed alpha. In this way, the performance and aerodynamic behavior of the airfoil can be studied at each design point:

	CL/CD			
	TAKE OFF		CRUISE	
	XFLR5	ANSYS CFD	XFLR5	ANSYS CFD
Angle of attack -5 degrees	-46.97	-29.48	-49.88	-41.24
Angle of attack 0 degrees	31.22	23.71	35.67	24.48
Angle of attack 5 degrees	135.74	66.13	139.75	66.32
Angle of attack 10 degrees	124.29	70.37	65.94	56.66
Angle of attack 15 degrees	37.18	22.81	17.65	14.82
Angle of attack 20 degrees	14.33	11.81	8.94	7.47

Table 19: Airfoil CL/CD analysis

As can be seen through CL/CD, the take off flight regime has better aerodynamic performance as the angle of attack increases, which is a consistent result because the angle of attack to which it is exposed during this flight regime, while the cruise regime has better performance for low angles of attack.

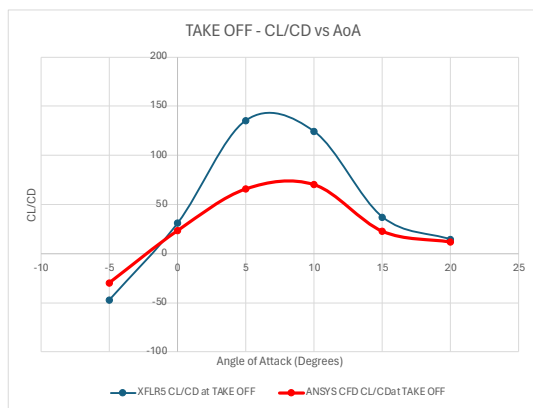


Figure 30: TAKE OFF – CL/CD

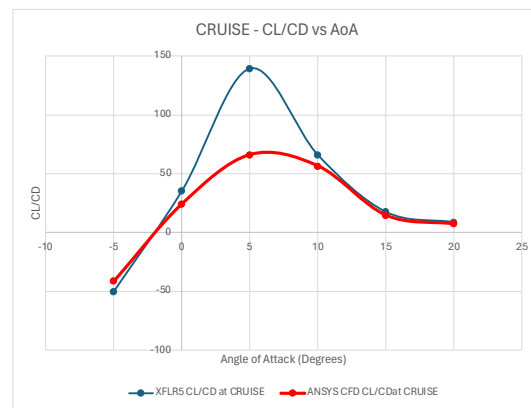


Figure 31: CRUISE – CL/CD

Chapter 5. CONCLUSIONS

In the design and optimization of an aircraft wing airfoil the following conclusions have been obtained:

- Initially, through Bézier Curves and MATLAB, it has been possible to design different airfoils to be studied, in this way it has been possible to obtain a wide variety of airfoils to analyse, depending on the design points.
- An aerodynamic analysis has been designed through XFLR5 software to study the aerodynamic properties of all airfoils and create a database. All this process has been carried out under aeronautical quality standards.
- Through the use of different software, it has been possible to create an initial database, to later carry out the selection of the optimal airfoil designed for the project, according to the proposed requirements through interpolation and optimization.
- The designed and optimal airfoil is analysed aerodynamically to determine its properties and verify them. For this, the XFLR5 software, ANSYS CFD have been taken into account.
- It is important to highlight the application of Lifting line Theory, which has allowed selecting the range of bi-dimensional lift coefficient at which the airfoil has been designed, furthermore it is possible to define the coefficients corresponding to take off and cruise, which are used in the optimization function and this lifting line theory could be used for including additional parameters such as wing torsion, taper ratio and aspect ratio in the optimization.
- Finally, it can be concluded that an airfoil has been designed and optimized for the takeoff and cruise design points, meeting the proposed requirements for a regional transport aircraft.

Chapter 6. FUTURE WORKS

The objective of this project has been the design and optimization of an aircraft wing airfoil, to analyse it aerodynamically. The aerodynamic analysis has been carried out by submitting the wing airfoil to different design points, taking into account the different flight regimes to which the aircraft can be subjected, the take off and cruise regime. This project is a great opportunity to continue studying different cases for the design of a wing since there are many reasons to continue:

- In this project, the designs that have been carried out have been simplified designs, since the 3D development of the wings has not been taken into account and the flight control surfaces have not been taken into account either. So creating a more complete design is a possibility to continue with this project in the future.
- An interesting option to continue with the project is the possibility of carrying out research on composite materials in the aerospace industry and creating different prototypes, in this way one could study which material is the most recommendable.
- In this project, the performance of structural analyses has not been considered, accepting the project as an aerodynamic design and optimization project, therefore a point that is interesting to analyse in the future is to design a wing structure and carry out its structural analysis. In addition to subjecting the wing to other types of loads that are not only found at the proposed points.
- In addition, it would also be interesting to aerodynamically analyse the different prototypes in a flight regime that is not at take off or cruise speed, as well as to recreate a dimensioned model and analyse it in more detail through the wind tunnel.

APPENDICES

Appendix 1. MATLAB

Bézier curves

The MATLAB code that has been designed to design the airfoils through the Bézier curves is defined:

```
addpath('C:\Users\davidchapparorodriguez\desktop\bezier');

% Define the fixed control points
fixedControlPoints = [
    0.0 0.0;
    0.25 0.0;
    0.16 0.0;
    0.5 0.0;
    1.0 0.0;
];

% Define the additional control points
additionalControlPointsSet = [
    % Define additional control points as [x y; ...]
    0.25 0.0;
    0.16 0.0;
    0.5 0.0;
];

% Number of points to generate on the curve
numPoints = 100;

% Specify the file path
fileSavePath = 'C:\Users\davidchapparorodriguez\Desktop\dotairfoilsnew';

% Create the directory if it doesn't exist
if ~exist(fileSavePath, 'dir')
    mkdir(fileSavePath);
end

% Counter for filenames
fileCounter = 1;

% Iterate over all combinations of additional control points
for i = 1:size(additionalControlPointsSet, 1)
    for j = 1:size(additionalControlPointsSet, 1)
        for k = 1:size(additionalControlPointsSet, 1)
            for m = 1:size(additionalControlPointsSet, 1)
                for n = 1:size(additionalControlPointsSet, 1)

                    % Check if any control points are the same
                    %if i ~= j && i ~= k && i ~= m && i ~= n && j ~= k && j ~= m && j ~= n && k ~= m
                    && k ~= n && m ~= n

                        additionalControlPoints = [
                            additionalControlPointsSet(i, :);
                            additionalControlPointsSet(j, :);
                            additionalControlPointsSet(k, :);
                            additionalControlPointsSet(m, :);
                            additionalControlPointsSet(n, :);
                        ];
                        % Combine fixed and additional control points
                        allControlPoints = [fixedControlPoints;
                            additionalControlPoints];
```

```

library                                     % Evaluate the Bézier curve at many points using the
                                             curvePoints = bezier.eval(allControlPoints, numPoints);

                                             % Generate the filename
fileCounter);                             filename = sprintf('%s\\airfoil_%03d.txt', fileSavePath,

                                             % Display the filename
disp(['Saving file: ' filename]);

                                             % Save the curve points to the specified file
save(filename, 'curvePoints', '-ascii');

                                             % Increment the file counter
fileCounter = fileCounter + 1;
end
end
end
end
end
%end

```

Database interpolation

The MATLAB code that has been designed to develop the database is defined, in relation to the polar results that have been obtained from XFLR5:

```

% Define the Excel file path
excelFilePath = 'C:\Users\davidchapparorodriguez\Desktop\Database.xlsx';

% Load data from the Excel file into a table
dataTable = readtable(excelFilePath);
% Define the desired airfoil, altitude, Mach number, and AoA
desired_airfoil = 'Airfoil 30';
desired_altitude = 'Sea level'; % Change to '20000ft' if needed
desired_mach = 0.2; % Change to 0.42 if needed
desired_aoa = 4.5;

% Use logical indexing to extract data for the desired combination
matching_rows = strcmp(dataTable.AirfoilName, desired_airfoil) &
strcmp(dataTable.Altitude, desired_altitude) & (dataTable.MachNumber ==
desired_mach);

% Extract the data for the desired combination
desired_data = dataTable(matching_rows, :);

% Check if there are at least two data points for interpolation
if sum(abs(diff(desired_data.AoA)) >= eps) >= 2
    % Perform interpolation only if there are enough data points
    interpolated_cl = interp1(desired_data.AoA, desired_data.Cl, desired_aoa);
    interpolated_cd = interp1(desired_data.AoA, desired_data.Cd, desired_aoa);

    % Display the results
    fprintf('For Airfoil: %s, Altitude: %s, Mach: %.2f, AoA: %.2f\n',
desired_airfoil, desired_altitude, desired_mach, desired_aoa);
    fprintf('Interpolated Cl: %.4f\n', interpolated_cl);
    fprintf('Interpolated Cd: %.5f\n', interpolated_cd);
else
    % If there are not enough data points for interpolation, set to NaN or any
other appropriate value
    fprintf('Insufficient data points for interpolation.\n');
end

```

Lifting line theory

The MATLAB code that has been designed to develop the Lifting line Theory and apply it to any airfoil designed through interpolation is defined. This Code allows to expand the database with the CL and CD corresponding to each airfoil:

```
clc; close all;
clear all;
% Define the Excel file path
excelFilePath = 'C:\Users\davidchaparrorodriguez\Desktop\Database.xlsx';

% Load data from the Excel file into a table
dataTable = readtable(excelFilePath);

% Define the desired altitude, Mach number, and AoA
desired_altitude = 'Sea level'; % Change to '20000ft' if needed
desired_mach = 0.2; % Change to 0.42 if needed

% Define the range of AoA values for interpolation (from -10 to 20 degrees)
aoaRange = -10:20;

% Loop through each airfoil from 6 to 100
for airfoilIndex = 1:118

    % Define the desired airfoil name
    desired_airfoil = ['Airfoil ' num2str(airfoilIndex)];

    % Initialize variables to store interpolated Cl and Cd values
    interpolatedCl = NaN(size(aoaRange));
    interpolatedCd = NaN(size(aoaRange));

    % Loop through each AoA value for interpolation
    for aoaIndex = 1:length(aoaRange)
        desired_aoa = aoaRange(aoaIndex);

        % Use logical indexing to extract data for the desired combination
        matchingRows = strcmp(dataTable.AirfoilName, desired_airfoil) &
            strcmp(dataTable.Altitude, desired_altitude) & (dataTable.MachNumber ==
            desired_mach);

        % Extract the data for the desired combination
        desiredData = dataTable(matchingRows, :);

        % Check if there are at least two data points for interpolation
        if sum(abs(diff(desiredData.AoA)) >= eps) >= 2
            % Perform interpolation only if there are enough data points
            interpolatedCl(aoaIndex) = interp1(desiredData.AoA, desiredData.Cl,
            desired_aoa);
            interpolatedCd(aoaIndex) = interp1(desiredData.AoA, desiredData.Cd,
            desired_aoa);
        else
            % If there are not enough data points for interpolation, set to NaN
            interpolatedCl(aoaIndex) = NaN;
            interpolatedCd(aoaIndex) = NaN;
        end
    end

    % Display the results for each airfoil
    fprintf('Airfoil: %s, Altitude: %s, Mach: %.2f\n', desired_airfoil,
    desired_altitude, desired_mach);
    fprintf('Interpolated Cl: %.4f\n', interpolatedCl);
    fprintf('Interpolated Cd: %.5f\n', interpolatedCd);
    fprintf('-----\n');
```

```
% Plot interpolated Cl and Cd against AoA for this airfoil
figure;
subplot(2,1,1)
% hold on;
plot(aoaRange, interpolatedCl, 'r.-', 'DisplayName', 'Interpolated Cl');
xlabel('Angle of Attack (AoA)');
ylabel('Coefficient of Lift C_{L}');
title(['Coefficient of Lift vs. AoA for ' desired_airfoil]);
xlim([-10,20])
grid on;
hold on;
subplot(2,1,2)
plot(aoaRange,interpolatedCd, 'r.-', 'DisplayName', 'Interpolated Cd');
xlabel('Angle of Attack (AoA)');
ylabel('Coefficient of Drag C_{D}');
title(['Coefficient of Drag vs. AoA for ' desired_airfoil]);
% legend('Location', 'Best');
% xlim([-10,20])
grid on;
hold off;
end
V_cruise = 130;
V_takeoff = 68.059
density_sea_level = 1.225;
density_cruise = 0.65;
span = linspace(0,27,length(aoaRange))
c = 2.65

for i=1:length(aoaRange)
    Total_lift = 0
    Total_Drag = 0
    for j=1:length(span)
        q_takeoff = 0.5*density_sea_level*(V_takeoff^2);
%         q_takeoff = 0.5*density_cruise*(V_cruise^2)
        Lift_takeoff(j) = q_takeoff*span(j)*c*interpolatedCl(i);
        Drag_takeoff(j) = q_takeoff*span(j)*c*interpolatedCd(i);
        Total_lift=Total_lift+Lift_takeoff(j);
        Total_Drag=Total_Drag+Drag_takeoff(j) ;
    end
    Lift(i)= Total_lift;
    Drag(i) = Total_Drag;
end
vpa(Lift',6)
```


Optimization

The code that has been developed from MATLAB to apply the optimization function that has been defined unfolds below:

```
% Load data from the Excel file
excelFilePath = 'C:\Users\davidchaparrorodriguez\Desktop\CL and CD of
Wing.xlsx';
[num, txt, raw] = xlsread(excelFilePath);

% Extract data from the loaded Excel file based on column headings
% Assuming the Excel columns are in the same order as described
CL_cruise = num(:, 1);      % CL at cruise
CD_cruise = num(:, 2);      % CD at cruise
CL_takeoff = num(:, 3);     % CL at takeoff
CD_takeoff = num(:, 4);     % CD at takeoff
phi_values = num(:, 5:end); % Phi values at k=0.1 to k=1

% Define the number of wings (based on the number of rows in the Excel file)
numWings = size(phi_values, 1);

% Define constraints (e.g., CL and CD constraints)
CL_cruise_constraint = 1.3; % Example: Minimum CL for cruise
CD_cruise_constraint = 0.02; % Example: Maximum CD for cruise
CL_takeoff_constraint = 1.5; % Example: Minimum CL for takeoff
CD_takeoff_constraint = 0.05; % Example: Maximum CD for takeoff

% Define optimization options
options = optimoptions('fmincon', 'Algorithm', 'interior-point', 'Display',
'iter', 'MaxIterations', 100);

% Define the optimization objective function for drag
fitnessFunction = @(x) optimizeDrag(x, CD_cruise, CD_takeoff);

% Define the initial guess for optimization
x0 = rand(numWings, 1); % Random initial guess (can be customized)

% Set upper and lower bounds for optimization variables (k values)
lb = zeros(numWings, 1); % Lower bounds (k values between 0 and 1)
ub = ones(numWings, 1); % Upper bounds (k values between 0 and 1)

% Perform constrained optimization
[x_optimized, fval] = fmincon(fitnessFunction, x0, [], [], [], [], lb, ub, [],
options);

% Display the optimized k values
disp('Optimized k values:');
disp(x_optimized);

% Display the corresponding fitness (objective) value
disp(['Optimized fitness (objective) value: ', num2str(fval)]);

% It is possible to use the optimized k values to select the best airfoils
% based on the fitness function.
% Define the optimization objective function for drag
function fitness = optimizeDrag(x, CD_cruise, CD_takeoff)

% Calculate estimated CD during cruise and take off using the given x values
    CD_cruise_calculated = CD_cruise + (1 - x) .* (CD_takeoff - CD_cruise);
    CD_takeoff_calculated = CD_takeoff;
    % Define weight factors
    weight_cruise = 0.5; % Weight for CD during cruise
    weight_takeoff = 1 - weight_cruise; % Weight for CD during takeoff

    % Calculate the weighted drag
    fitness = weight_cruise * CD_cruise_calculated + weight_takeoff *
CD_takeoff_calculated;
end
```

Appendix 2. XFLR5 Analysis

This section explains the process that has been followed to carry out the XFLR5 analysis for the Airfoil 118.

1. Initially, after having chosen the airfoil to analyse, this airfoil is imported into XFLR5, in a .dat format.

AIRFOIL 118							
X - axis	Y - axis	X - axis	Y - axis	X - axis	Y - axis	X - axis	Y - axis
1	0	0.227	0.1205	0.0018	-0.0056	0.3372	-0.0456
0.9608	0.0041	0.2126	0.1196	0.0031	-0.0092	0.3512	-0.0453
0.9244	0.0083	0.1986	0.1183	0.0047	-0.0126	0.3653	-0.0448
0.8906	0.0124	0.185	0.1168	0.0065	-0.0156	0.3793	-0.0444
0.8592	0.0166	0.1719	0.1149	0.0087	-0.0185	0.3935	-0.0439
0.8301	0.0207	0.1591	0.1127	0.0112	-0.021	0.4076	-0.0433
0.8031	0.0248	0.1468	0.1103	0.014	-0.0234	0.4218	-0.0428
0.7779	0.0289	0.1349	0.1076	0.0171	-0.0256	0.4359	-0.0422
0.7546	0.0329	0.1235	0.1046	0.0206	-0.0275	0.4501	-0.0415
0.7328	0.037	0.1126	0.1015	0.0244	-0.0293	0.4642	-0.0409
0.7125	0.041	0.1021	0.0982	0.0287	-0.0309	0.4783	-0.0402
0.6934	0.0451	0.0921	0.0947	0.0333	-0.0324	0.4923	-0.0395
0.6754	0.0491	0.0827	0.091	0.0384	-0.0337	0.5063	-0.0388
0.6583	0.053	0.0737	0.0872	0.0438	-0.0349	0.5202	-0.0381
0.642	0.057	0.0653	0.0833	0.0498	-0.036	0.5341	-0.0374
0.6262	0.0609	0.0575	0.0792	0.0561	-0.037	0.5478	-0.0367
0.6109	0.0647	0.0502	0.0751	0.0629	-0.0379	0.5614	-0.036
0.5959	0.0686	0.0434	0.0709	0.0702	-0.0388	0.575	-0.0353
0.5809	0.0724	0.0373	0.0667	0.078	-0.0396	0.5884	-0.0345
0.5658	0.0761	0.0317	0.0624	0.0863	-0.0404	0.602	-0.0338
0.5506	0.0798	0.0267	0.0582	0.095	-0.0412	0.6159	-0.0331
0.535	0.0835	0.0223	0.0539	0.1042	-0.0419	0.6301	-0.0322
0.5191	0.0871	0.0184	0.0497	0.1139	-0.0425	0.645	-0.0313
0.503	0.0906	0.015	0.0455	0.1239	-0.0431	0.6606	-0.0303
0.4867	0.094	0.012	0.0414	0.1343	-0.0437	0.677	-0.0292
0.4702	0.0973	0.0094	0.0373	0.1451	-0.0442	0.6945	-0.028
0.4536	0.1004	0.0073	0.0334	0.1562	-0.0447	0.7132	-0.0266
0.4369	0.1034	0.0055	0.0296	0.1677	-0.0451	0.7333	-0.025
0.4201	0.1063	0.004	0.026	0.1794	-0.0455	0.7548	-0.0232
0.4034	0.1089	0.0028	0.0225	0.1915	-0.0458	0.778	-0.0213
0.3866	0.1113	0.0019	0.0193	0.2038	-0.0461	0.8031	-0.0191
0.3698	0.1135	0.0012	0.0162	0.2163	-0.0463	0.8301	-0.0166
0.3532	0.1155	0.0007	0.0134	0.2291	-0.0465	0.8592	-0.0139
0.3366	0.1172	0.0003	0.0109	0.2421	-0.0466	0.8906	-0.0109
0.3202	0.1186	0.0001	0.0086	0.2553	-0.0466	0.9244	-0.0076
0.304	0.1198	0	0.0066	0.2687	-0.0466	0.9608	-0.004
0.288	0.1206	0	0.0049	0.2822	-0.0465	1	0
0.2723	0.1211	0	0.0036	0.2958	-0.0464		
0.2569	0.1213	0	0.0026	0.3095	-0.0462		
0.2418	0.1211	0.0008	-0.0016	0.3233	-0.0459		

Table 20: Airfoil 118 POINTS

2. Once the airfoil to be analysed has been defined, the development of the analysis to be carried out continues.

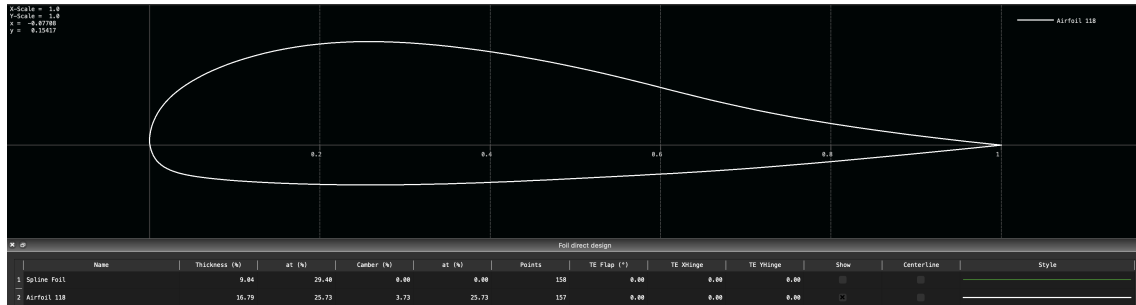


Figure 32: Airfoil 118

In this case, two different analyses have been defined, based on the boundary conditions. To do this, it is necessary to access the "Define Analysis" module on the "Analysis" page. Once in the module, the boundary conditions are defined:

- On take off
 - At a height of sea level
 - Velocity of 68m/s = 0.2 MACH
 - Reynolds number of 4655239

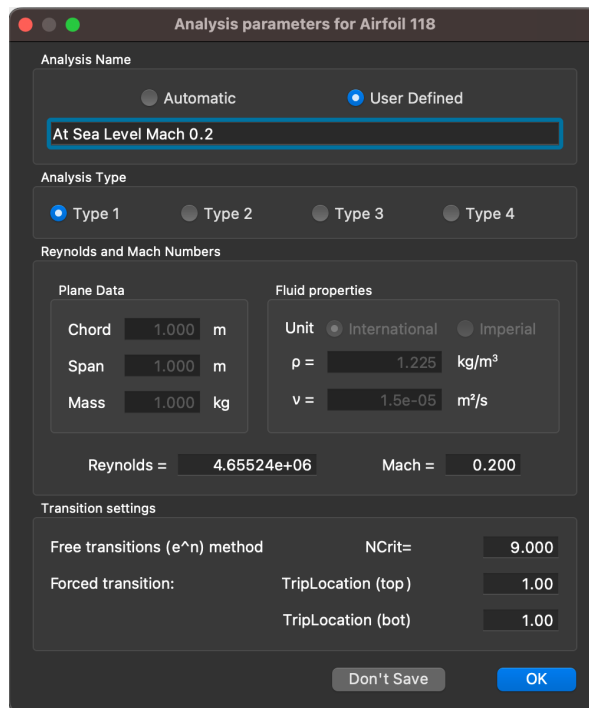


Figure 33: TAKE OFF - Analysis parameters for Airfoil 118

- On cruise
 - At a height of 20000ft
 - Velocity of 130m/s = 0.42 MACH
 - Reynolds number of 5331410

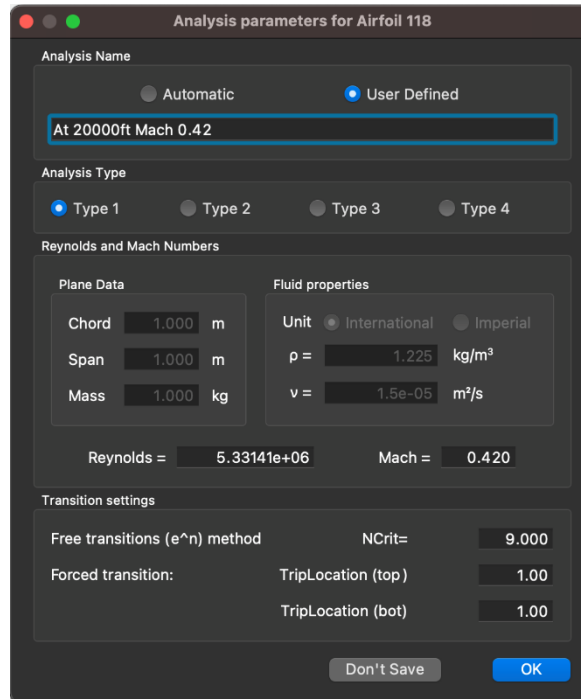


Figure 34: CRUISE - Analysis parameters for Airfoil 118

3. Finally, the analysis settings of the simulation are defined, in this case it is necessary to define the following, to represent the proposed alphas.

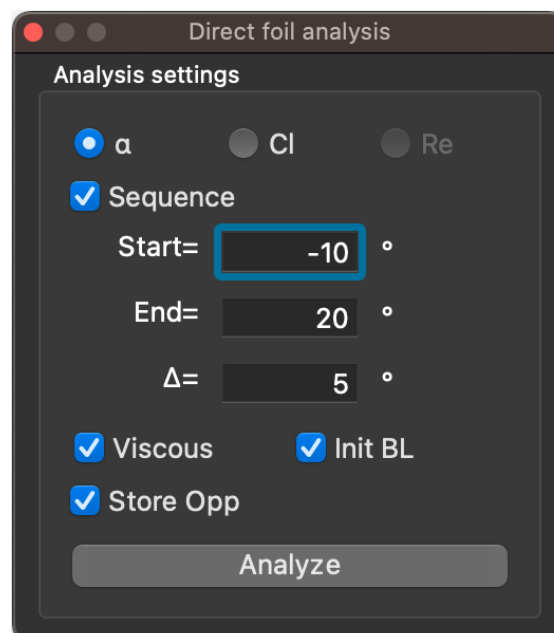


Figure 35: XFLR5 Analysis settings

Appendix 3. ANSYS Computational Fluid Dynamics Analysis

This section explains the process that has been followed to carry out the CFD analysis through the ANSYS software for the Airfoil 118.

In this section, the design points defined in the project taken into account, the take off flight regime and the cruise.

The CFD simulation has been carried out in ANSYS, specifically through the ANSYS FLUENT module, which is divided into the following processes:

1. Geometry

In this part, we have proceeded to introduce the geometry of the airfoil and then generate the geometry of their surroundings.

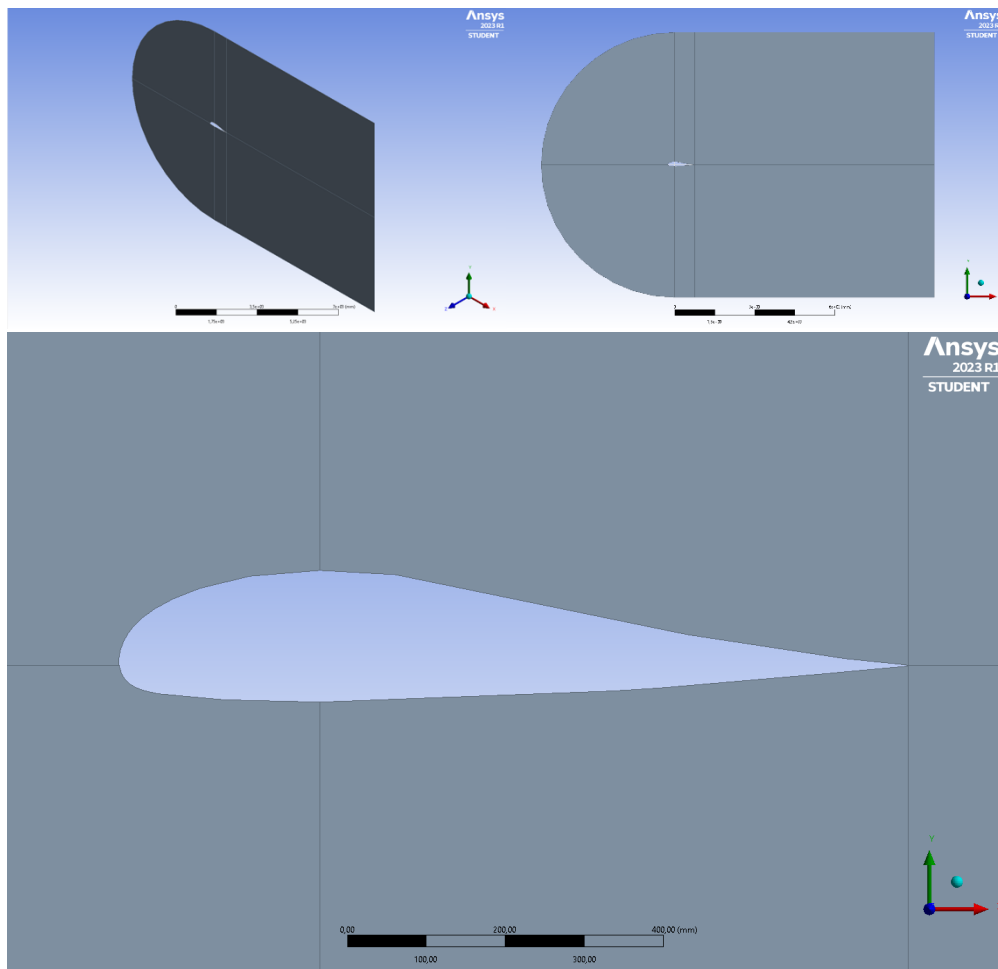


Figure 36: Airfoil 118 geometries in ANSYS Computational Fluid Dynamics

2. Meshing

The procedure of geometry meshing is a crucial step in the analysis. The accuracy of the results largely hinges on the quality of the mesh. After shaping the geometry, various meshing techniques were employed. These variations aimed to enhance the analysis's efficiency. Notably, refined meshing was applied in areas where the flow has a significant impact on the airfoil.

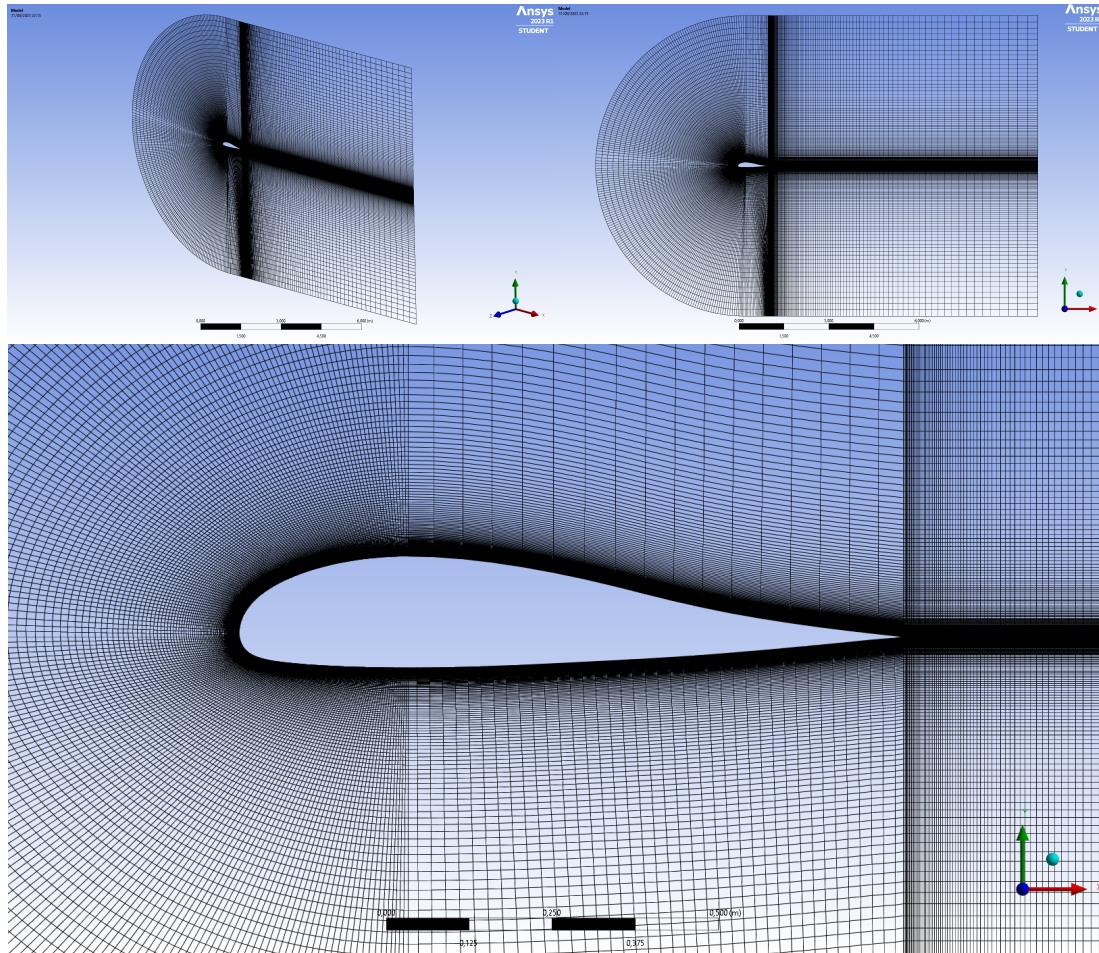


Figure 37: Meshing airfoil 118 in ANSYS Computational Fluid Dynamics

Finally, after trying to optimize the meshing, the mesh has been achieved with the following parameters:

AIRFOIL 118 MESH	
Elements	Nodes
139250	139907

Table 21: Airfoil 118 meshing parameters in ANSYS Computational Fluid Dynamics

3. Setup (it includes the defining of boundary conditions and physics of simulation)

The CFD of aerodynamic modules uses a k-epsilon. In this simulation the k-epsilon turbulence mode is used and also the Energy equation is turned on due to involvement of heat transfer. Air is selected as the fluid within the computational fluid domain. This simulation is maintained in a consistent state. The input boundary condition is set as pressure far field, necessitating the definition of both Mach number and angle of attack values, for this the Mach number value is 0.2 for take off and 0.42 for cruise, the values for angle of attack depend on the situation in which it is required to do simulation.

The angles in which the CFD analysis has been done are for -10° , -5° , 0° , 5° , 10° , 15° and 20° . These angles have been chosen because through them it is possible to have an extensive aerodynamic study of the airfoil in the two models and compare the results.

In the setup section, the reports that have been considered important for the CFD analysis have also been defined. These reports that have been considered necessary for the analysis are:

- Obtaining Lift Coefficient
- Obtaining Drag Coefficient
- Contours of Static pressure
- Contours of Velocity magnitude

4. Solutions and Results

Finally, after defining the boundary conditions and the reports, the analysis for each simulation begins.

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