DESIGN OF A WING SECTION AND STRUCTURAL ANALYSIS

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Abstract: *This study presents the process of a wing section design and analysis of structural behavior to evaluate its aerodynamic and structural performance under real flight conditions. The conclusive design of the wing section is determined using the Trefftz plane method. This method provides essential data about critical areas of the structure, and it is used to improve structural and aerodynamic performance.*

Key words: CFD, wing section, airfoil, NACA, Trefftz plane method, ANSYS

1. INTRODUCTION

This scientific paper intends to study the aerodynamic phenomena that occur on the surface of a wing section during flight conditions by making use of ANSYS. To have an accurate evaluation of the structure, the specific flight conditions of an aircraft (altitude and speed) will serve as input data. Computed information can be used further on as input for finite element analysis.

2. WING STRUCTUREAL CHARACTERISTICS

An aircraft's wing is a complex structural component, essential in achieving the most favorable aerodynamic efficiency. The wing structure must be designed to withstand the forces exerted on its surface during flight without failure. Generally, aluminum is often used in designing this type of structure, but recently there have been numerous studies evaluating the characteristics of structures made of composite materials.

A wing section refers to a part of an aircraft wing that includes specific structural components.

The main components of an aircraft wing: skin, spars and stringers that are positioned perpendicular to the airfoil chord, and ribs that run parallel to the airfoil chord. These structural components play a key role in resisting high force loads. These components are represented in Figure 2.

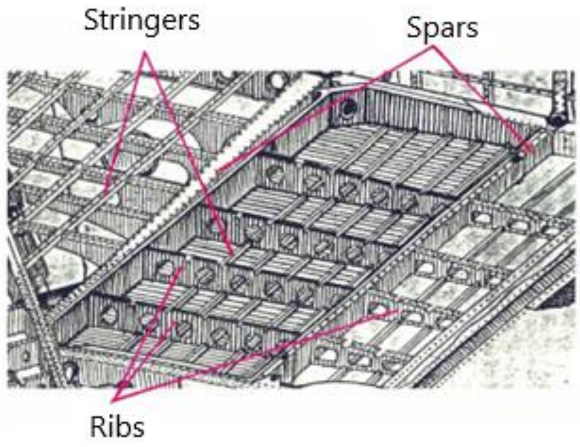

Figure 2. Aircraft wing components[1]

There are several types of configuration and shapes that can be considered when designing an aircraft. However, the choice of which type to use varies based on the aircraft mission. It is important to highlight that the wing design impacts multiple factors such as: control at different flight speeds, lift, maneuverability and stability of the aircraft.

An aircraft wing can be classified according to its location on the fuselage: high wing, midwing and low wing. These configurations are illustrated in Figure 3.

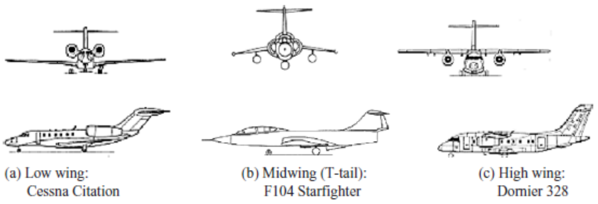

Figure 3. Different wing configuration based on fuselage positioning [2]

At the same time the wing can be classified according to its shape: elliptic, rectangular, trapezoidal, swept, delta and ogival. Figure 4 provides an overview of the different wing shapes.

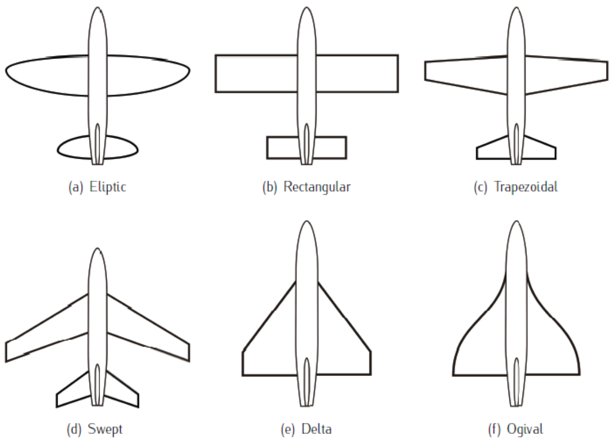

Figure 4. Different wing shapes[3]

The elliptical shape is difficult to manufacture but it has the best results in terms of aerodynamic efficiency.

Suitable for military aircraft, the delta wing is primarily used in supersonic flights. An evolved version of delta wing is the ogival shaped wing adopted by famous Concorde.

The majority commercial aircrafts feature swept wings, while the trapezoidal wing is mainly used by charter aircraft.

3. FUNDAMENTALS OF AERODYNAMICS

A The wing is an aerodynamic structure designed to generate lift while moving through a fluid. The three-dimensional surface is defined by the following elements: span, chord line and thickness.

An airfoil is the cross-sectional shape of a wing, the key characteristics of an airfoil such as chord line and thickness are shown in Figure 5. Aircraft designed to perform subsonic flights feature airfoils characterized by a round appearance at the leading edge and a sharp appearance at the trailing edge, often with a symmetrical curvature of the upper and lower surfaces.

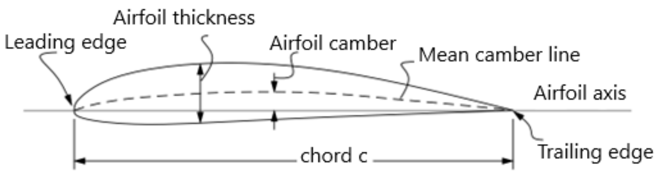

Figure 5 Airfoil characteristics[4]

While an aerodynamic structure is moving through a fluid it produces a total aerodynamic force. The component of this force that is perpendicular to the wing’s direction of motion is referred to as the lift force. The component of the total aerodynamic force that is parallel to the wing’s direction of motion is referred as drag force. A key factor in generating the lift force is represented by the angle of attack, which can be simply defined as angle formed between the relative airflow and the chord line. The forces exerted on an airfoil are illustrated in Figure 6.

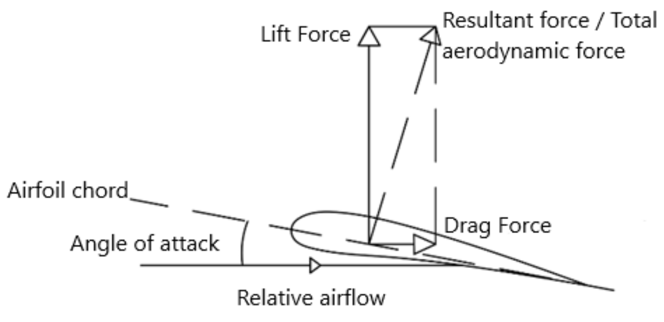

Figure 6 Forces exerted on an airfoil[5]

The aerodynamic efficiency of a wing is expressed by the lift to drag ratio. Achieving a high ratio value means that a significantly lower thrust force is required to move the body through fluid.

Concepts from the field of fluid mechanics are applied in the design and structural analysis of a wing. In theory, the characteristics of fluid flow around a moving body can be determined by solving the Navier-Stokes equations. However, except for the bodies with a simple geometry, these equations are difficult to solve, therefore equations with a lower level of complexity are adopted.

For generating lift, the wing must be positioned at a certain angle of attack, different configurations are presented in Figure 7. When this condition is met, the fluid will be redirected towards the lower surface of the wing. As the wing changes the direction of the fluid by exerting a force on it, the fluid will exert an opposite force on the structure according to the principle of action and reaction. On the upper surface of the wing there will be a low-pressure area, while on the lower side of the wing there will be a high-pressure area. These pressure differences can be determined directly using specific instruments (wind tunnel) or can be calculated by using Bernoulli's principle.

The lift can be determined by making use of the pressure differences, the different velocities of the fluid on the lower and upper surface of the wing, or the total change in momentum of deflected air[6]. This discussion is the starting point in choosing the appropriate mathematical approach.

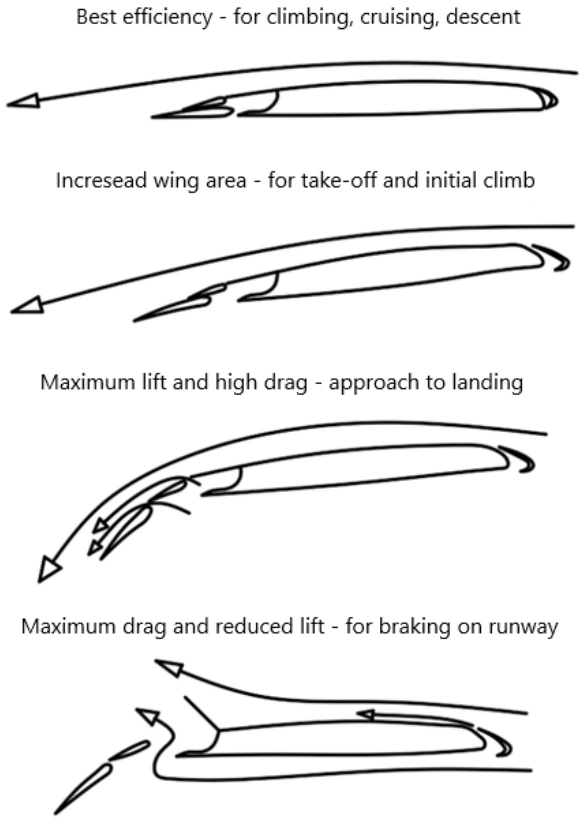

Figura 7. Wing configurations[6]

The flow of a fluid over a three-dimensional wing is different from the flow of a fluid over a two-dimensional airfoil section of a wing[7]. Comparing the two scenarios, the main difference noticed at first glance is an additional component of the fluid acting from the wing tip towards the wing root. Figure 4 provides an overview of this aerodynamic aspect.

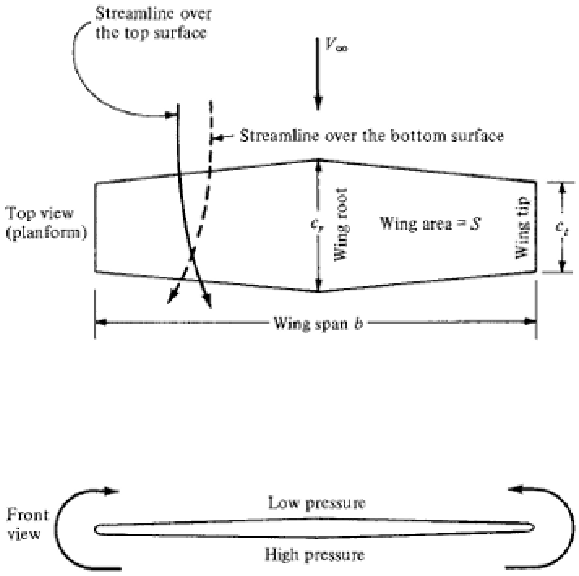

Figure 8 Curvature of streamline in the spanwise direction[7]

As defined earlier, the lift force is generated by the pressure difference between the upper and lower surface of the wing. This non-uniform pressure distribution creates lift, however as a side effect the fluid flow tends to curve around the wing tip area, being able to pass from the high-pressure area (lower area of the wing) to the low-pressure area (upper area of the wing). For this reason, a new component acting on the upper surface of the wing will occur, certainly the component is exerted from the wing tip towards the wing root and influences the streamlines on both lower and upper surface of the wing.

This occurrence has a major importance in aerodynamic studies because the fluid flow at the wing tip creates a circular motion that propagates downstream, resulting in a vortex. The phenomenon is shown in Figure 9, these vortices impact aerodynamic efficiency by increasing the drag force.

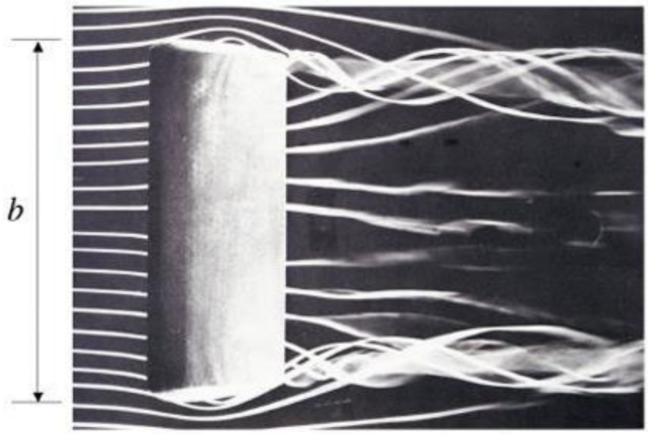

Figure 9 Formation of wing tip vortices on a rectangular wing[7]

4. DESIGN OF THE WING SECTION

Computer-aided design (CAD) is an indispensable tool today, making it easier to design new products and test their capabilities.

The first step in designing the win was choosing the NACA 23012 airfoil. The length of the airfoil at the wing root is 1900 mm, while the length of the airfoil at the wing tip is 625 mm. These dimensions were chosen to replicate the actual wing geometry used on Cessna 550 Citation II[8] for better simulation results.

The fundamental idea from which the design has been initiated is the multi-spar structure, without a doubt in the wing design are integrated two spars with a semi-elliptical cross section. At the same time conventional components such as ribs and stringers have been integrated in the structure design. The completed design of the wing is shown in Figure 10.

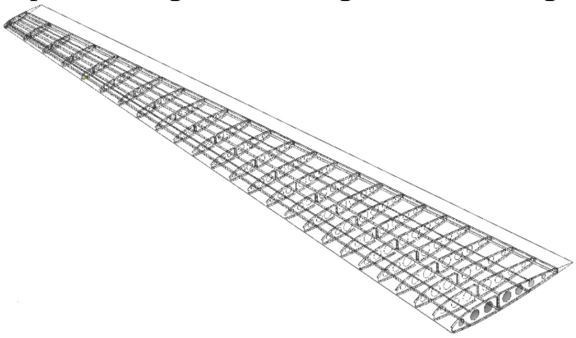

Figure 10. Design of wing structure

Note that the control surfaces (spoiler, flap and aileron) and the systems contained within the structure (fuel tank and landing gear) are not considered in the design of the wing because the final purpose of this study is to analyze the structural behavior of a wing section. A wing section is a segment of an aircraft wing that is defined by the characteristics of each component. Figure 11 presents the conclusive design of the wing section. Most of the time for accurate results the wing is divided into several sections to facilitate structural analysis.

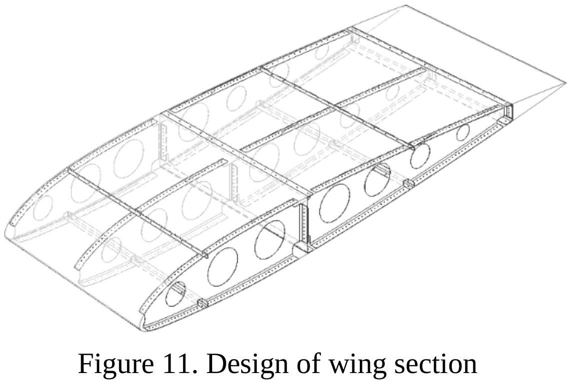

Figure 11. Design of wing section

5. APPROACH TO STRUCTURAL CALCULATION

There are two methods that can be adopted to calculate the fluid flow over the wing surface: the surface integration method and the Trefftz plane method. In this paper we will proceed with the second method. The Trefftz plane method also know as the wake integration method is usually used to calculate the forces and moments exerted on the body under study. Instead of directly evaluating the pressure and forces on the wing surface, the method extracts data from a plane positioned downstream to the wing and perpendicular to the streamline. Figure 12 presents the placement of Trefftz plane based on the information above.

The method is related to an integral form of momentum equation applicable in fluid mechanics. As a result, forces exerted on a wing can be determined by applying this method.

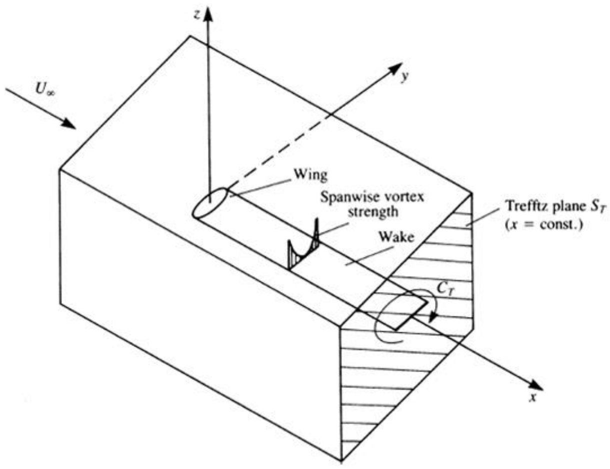

Figure 12. Position of Trefftz plane [7]

Assuming steady and ideal flow with no external forces acting on the wing, the momentum equation can be written in the following form:

$$\int_S \rho q(q.n)dS = F - \int_S pndS \tag{1}$$

The integral form of pressure is expressed by the second term. In this domain of interest, a cartesian coordinate system is applied, oriented parallel to free fluid flow velocity U_∞ and the velocity vector q.

$$q = (U_\infty + u, v, w) \tag{2}$$

Calculating the x component of the force (drag), the equation takes the following form:

$$D = -\int_S \rho(U_\infty + u)[(U_\infty + u)dydz + vdxdz + wdxdy] \\ -\int_S pdydz \tag{3}$$

Next the pressure is determined through the application of Bernoulli's equation:

$$p - p_\infty = \frac{\rho}{2}U_\infty^2 - \frac{\rho}{2}[(U_\infty + u)^2 + v^2 + w^2] \\ = -\rho u U_\infty - \frac{\rho}{2}(u^2 + v^2 + w^2) \tag{4}$$

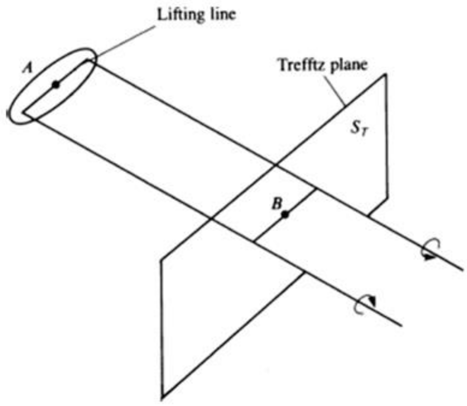

Figure 13. Trefftz plane adopted for the calculation of induced drag [7]

The next step is to insert this equation into the drag equation:

$$\begin{aligned} D = &-\rho\int_S U_\infty (U_\infty + u)dydz \\ &-\rho\int_S (U_\infty + u)(udydz + vdxdz + wdxdy) \\ &+\rho\int_S uU_\infty dydz + \frac{\rho}{2}\int_S (u^2 + v^2 + w^2)dydz \end{aligned} \tag{5}$$

By using the continuity equation for perturbations, the terms in the first and third part of the previous equation will simplify. Furthermore, if the domain of interest is sufficiently large, the velocity components disappear everywhere but, on the wake as illustrated in Figure 12.

Velocity components will be produced only on the y and z directions because of the parallel position of the wake to the local free stream as presented in Figure 13 and ideal flow assumption. We will determine the drag by integrating the v and w components on the Trefftz plane.

$$D = \frac{\rho}{2}\int_{S_T} (v^2 + w^2)dydz \tag{6}$$

Equation (6) can be rewritten in terms of vorticity in the following form:

$$D = \frac{\rho}{2}\int_{S_T} \left[\left(\frac{\partial\phi}{\partial y}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2\right]dydz \tag{7}$$

6. CFD RESULTS AND CONCLUSIONS

After creating the wing section 3D model, the CAD file was exported to Ansys. By utilizing Design Modeler, the wing section model was prepared, and we defined the domains of interest for CFD simulation.

The mesh network is a crucial step in achieving accurate results. The Ansys Meshing module is used to create a fine mesh on the critical areas.

Next step is to choose the computational conditions according to the real flight parameters and the particularities of the Trefftz plane method.

The simulation was iterated 500 times and the results generated are illustrated from Figure 14 to Figure 20. Ansys provides these visual representations to understand how the fluid flow over the wing section influences parameters such as speed and pressure.

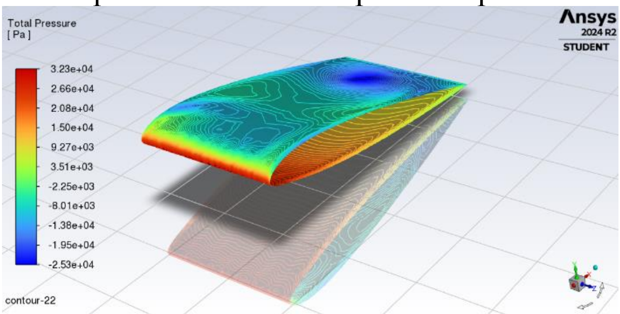

Figure 14 . Total pressure

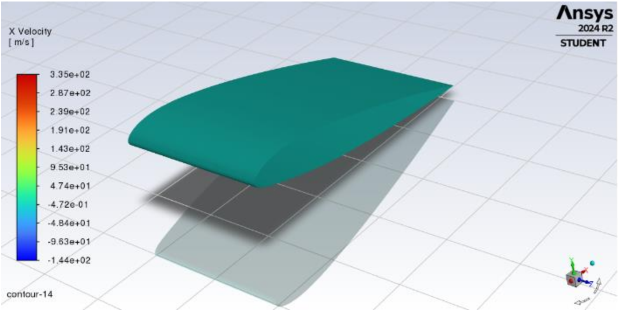

Figure 15. X velocity

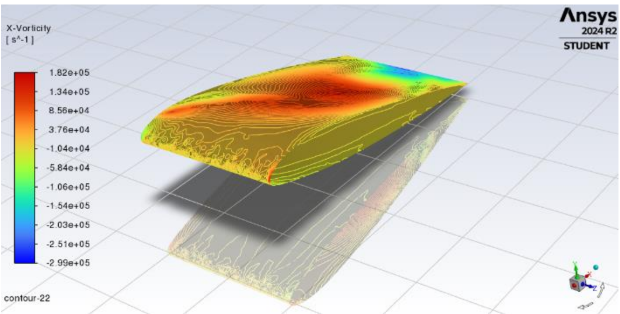

Figure 16. X vorticity

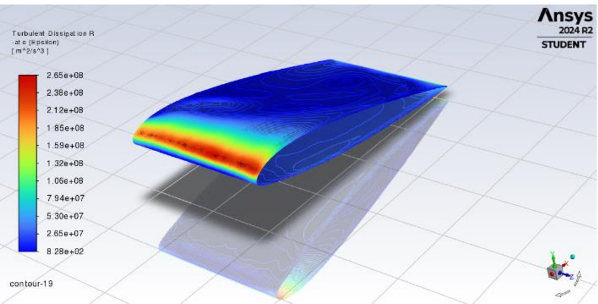

Figure 17. Turbulent dissipation rate

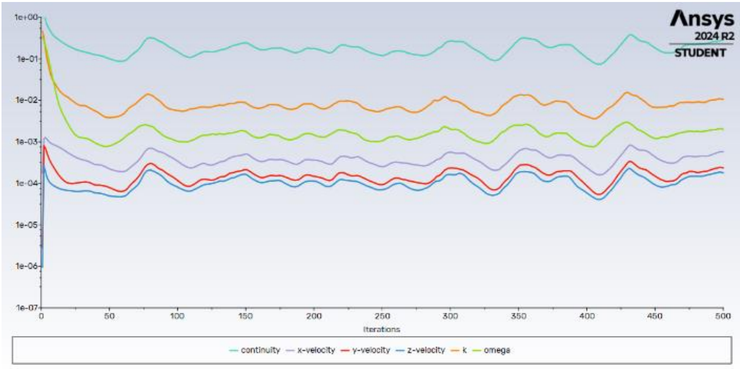

Figure 18. Residuals scaling after 500 iterations

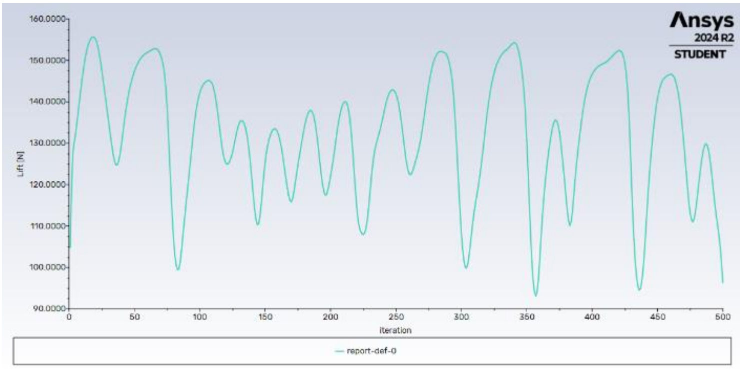

Figure 19. Lift evolution after 500 iterations

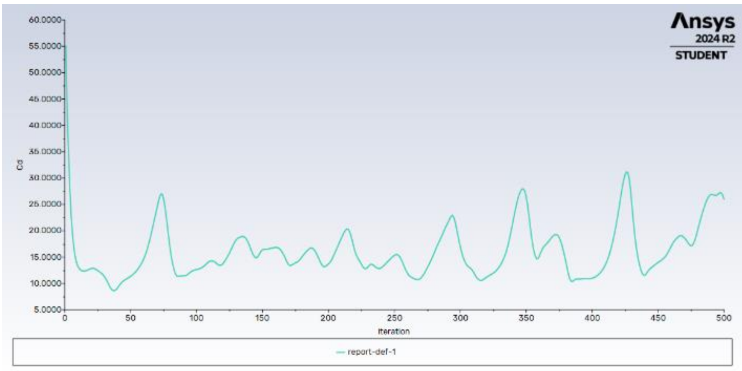

Figure 20. Evolution of drag coefficient after 500 iterations

Focusing on pressure distribution on the wing section, it can be concluded that there is a zone of high pressure on the lower surface of the wing section, which indicates the generation of lift force. However, in certain areas exposed to long term loading, there is a risk of structural deformation [9]. On the upper surface of the wing section, a low-pressure area is visible, which reflects the efficiency of airfoil in generating lift.

Vortices plots indicate losses in aerodynamic efficiency. The areas affected by turbulence are particularly important, as they highlight the regions that require measures to reduce drag force and optimize the overall performance [10].

The values obtained for the aerodynamic coefficients characterize the overall performance of the wing, and their ratio is essential for evaluating and improving the aerodynamic efficiency.

Based on the results, improvements can be implemented for the model, such as optimizing the aerodynamic profile to reduce drag. Also, structural performance can pe improved in critical areas of the model by validating experimental test.

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