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Enhancing Winglet Aerodynamics for Optimum Drag Reduction through Computational Analysis

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Table of Contents

List of Figures	4
Abstract	5
Keywords:	5
1. Introduction.....	6
1.1 Aim of this study	6
1.2 Introduction to Winglets	6
1.3 History of Winglets	7
1.4 Aerodynamics of a Winglet.....	8
2. Literature Review.....	10
2.1 Types of Winglets and Wingtip Devices	10
2.1.1 Blended Winglets	10
2.1.2 Spiroid Winglet	10
2.1.3 Raked Winglet.....	11
2.1.4 Canted Winglet.....	11
2.1.5 Split Winglet	11
2.1.6 Sharklet Winglet.....	12
2.2 Advantages Claimed on Winglets and Wingtip Devices.....	12
3. Methodology	14
3.1 Fusion 360.....	14
3.2 The Winglets Used.....	14
3.3 Meshing the Designs.....	15
3.3.1 No Winglet Meshing	15
3.3.2 Sharklet Winglet Meshing.....	16
3.4 Parameters and Conditions Used	17
3.5 Boundary Conditions	18
4. Results.....	19
4.1 No Winglet	19
4.1.1 No Winglet Data	20
4.2 Canted Winglet.....	21
4.2.1 Canted Winglet Data	22
4.3 Blended Winglet.....	23

4.3.1 Blended Winglet Data	23
4.4 Sharklet Winglet.....	24
4.4.1 Sharklet Winglet Data	25
5. Conclusion	26
6. Future Goals.....	26
7. References	27

List of Figures

Figure 1. Andean Condor.....	6
Figure 2. B757 Winglet.....	7
Figure 3. Prandtl's theory for wings with finite elongation	8
Figure 4. Comparison between 2D and 3D flow about an airfoil.....	9
Figure 5. Lift distribution on a wing with finite elongation	9
Figure 6. Blended Winglet.....	10
Figure 7. Canted Winglet.....	11
Figure 8. Sharklet Winglet.....	12
Figure 9. Wing Profile on Fusion 360.....	14
Figure 10. a. No Winglet b. Canted Winglet c. Blended Winglet d. Sharklet Winglet	15
Figure 11. No Winglet Meshing.....	15
Figure 12. Sharklet Winglet Meshing	16
Figure 13. No Winglet Velocity Contours.....	19
Figure 14. Pathlines of flow on a No-Winglet Wing	19
Figure 15. a. Lift Coefficient b. Drag Coefficient	20
Figure 16. Canted Winglet Velocity Contours	21
Figure 17. Static Pressure Contours.....	21
Figure 18. Pathlines over a wing with Canted Winglet	22
Figure 19. Lift Coefficient	22
Figure 20. Drag Coefficient	22
Figure 21. Velocity Contours on a Blended Winglet	23
Figure 22. Residuals vs Iterations of the Simulation	23
Figure 23. Drag Coefficient Plot.....	23
Figure 24. Velocity Contours of Sharklet Winglet.....	24
Figure 25. Pathlines over the Wing with Sharklet Winglet.....	24
Figure 26. Velocity Vectors on the Sharklet Winglet	25
Figure 27. Residuals vs Iterations of the Sharklet Winglet Simulation	25
Figure 28. Drag Coefficient Plot.....	25

Abstract

This study investigates various winglet designs to optimize aerodynamic efficiency and reduce drag in aircraft, aiming to enhance the overall performance. Using computational analysis with models developed in Fusion 360 and ANSYS, we assessed three winglet types (canted, blended, and sharklet) under controlled boundary conditions to compare their effects on lift and drag coefficients. Findings reveal that each winglet type significantly contributes to drag reduction, with variations in performance tied to their unique geometric configurations. This research underscores the importance of tailored winglet designs for minimizing induced drag and improving lift distribution across the wingspan. Future work will focus on integrating advanced materials and adaptive shapes to further enhance winglet effectiveness under varying flight conditions.

Keywords: CFD, Winglets designs, Drag analysis, Wing Profile on Fusion 360

1. Introduction

1.1 Aim of this study

In this study we wanted to test different types of winglets and their aerodynamics to get the considerable drag reduction using computational analysis which will directly improve the aerodynamic efficiency as well as it will impact the fuel efficiency of an aircraft.

1.2 Introduction to Winglets

In aerodynamics, drag reduction is a big challenge. We use a device called winglet which is vertically placed with an angle on the end of aircraft wing which lessen induced drag resulting in improving the overall performance of an aircraft directly affecting the fuel efficiency. Winglets also play an important role in reducing the formation of vortices, which are the small rotating airflow which is created by the difference of air pressure on the wing [1].

Winglets reduce the drag that arises naturally at the wingtip. Nowadays winglets are available in different shapes and configurations, such as blended winglets, raked winglets, sharklet winglets etc. Every different design is used based on specific aircraft type and its operational needs. Computational fluid dynamics (CFD) and wind tunnel testing are essential tools in design and analysis of winglets, enabling engineers to assess performance improvements accurately. From nature we can take an example of an extraordinary bird called the Andean Condor which can fly over 100 miles without flapping because of its massive wingspan which provides a large surface area that maximizes lift. These wings are broad and gave large finger-like primary feathers at the tips which reduce drag by smoothing the airflow and giving the bird better control over its glide. In Figure 1 the wings of the Andean Condor are shown.



Figure 1. Andean Condor [17]

1.3 History of Winglets

Early Concepts (Late 1800s – Early 1900s): Sir George Cayley and other pioneers knew about wingtip vortices and their effects on lift and drag, but there were no practical solutions to deal with the issue[2]. Frederick W. Lanchester, a British aerodynamics, was one of the first to theorize the effects of wingtip vortices. His work on circulation theory helped in understanding the induced drag [3].

Modern Development (1970s): The important moment came in the development of winglet when Richard Whitcomb's revealed that wingtip vortices can be reduced by vertically extending the wingtips which later became as winglets. He showed that winglets can reduce the drag mainly at higher angle of attack, improving the lift-to-drag ratio of an aircraft. This help aircraft to fly more efficiently using less fuel and improving the range [4].

First Practical Applications (1980s): In 1980s the commercial aviation adopted the winglets with Boeing 757 and later Boeing 767 became one of the first commercial aircrafts to use winglets, eventually airlines noticed the advantages of winglets in terms of fuel efficiency and aircraft performance. Figure 2 shows the B757's blended winglet.



Figure 2. B757 Winglet [5]

Expanding Adoption (1990s – 2000s): In 1990s and 2000s the fuel prices increased all around the world and the environmental concerns grew as well, which gave boost to the winglet's adoption in all modern aircrafts.

Current Adoptions: Famous aircraft like Boeing 787 Dreamliner and Airbus A350 both objectify winglets as their standard design elements. Majority of airlines are using these aircrafts as they provide great fuel efficiency which results in low operation costs for the airlines which as well as increased fuel efficiency will allow the flights to cover longer distances which helps them to connect more destinations directly.

1.4 Aerodynamics of a Winglet

The segment perpendicular to the wingspan is called an airfoil. The flow may be described by a two-dimensional analysis in relation to the airfoil alone when considering a wing with infinite span, where the three-dimensional influence of extremities can be disregarded. When properly decomposed according to the wind axes, the resulting aerodynamic forces—which are dependent on the direction in which the air flow invests the section—represent the profile's lift (L) and drag (D). Figure 3 shows Prandtl's theory for wings with finite elongation [6].

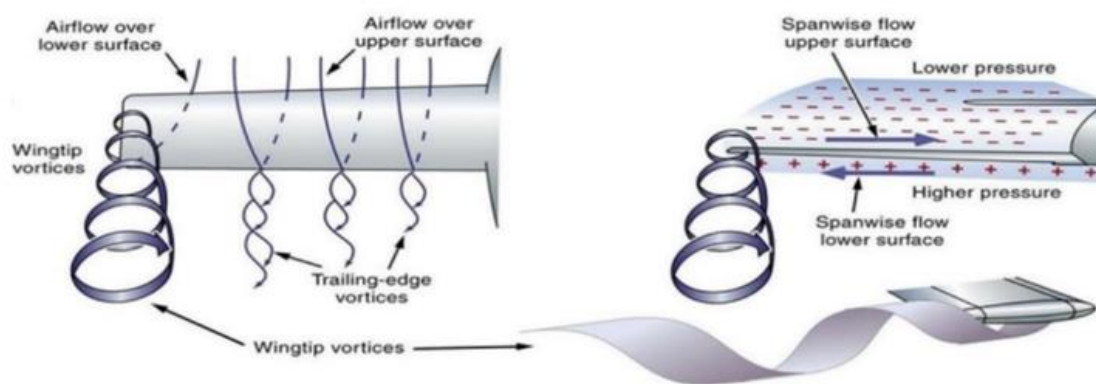


Figure 3. Prandtl's theory for wings with finite elongation [7]

A transverse component acting along the wingspan in opposite directions for the lower and upper surfaces of the wing itself is induced by the interaction of high-pressure flow on the lower surface and low-pressure flow on the upper surface at the wing tip. This phenomenon is known as cross flow. Along the wingspan, the transverse flow varies in strength, peaking at the ends of the wings (Figure 3). Since the top and bottom surfaces of the wing are in direct connection, a wake-like vortex field is created at the wing tip and spreads downstream. An extra speed component known as the downwash speed (w) is induced by this wake. This speed, combined with the angle of attack α , generates the so-called induced angle of attack. Figure 4 shows the comparison between 2D and 3D flow about an airfoil [6].

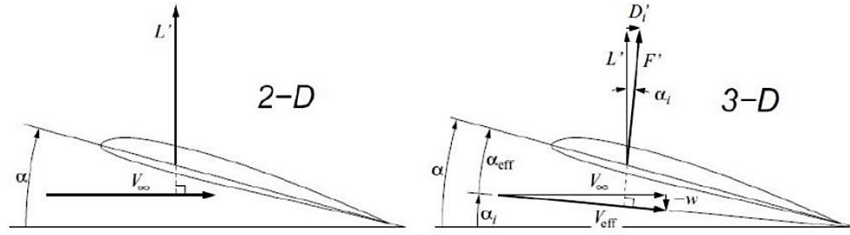


Figure 4. Comparison between 2D and 3D flow about an airfoil [8]

Induced drag is a non-null contribution of drag introduced by the induced angle of attack, even when friction and pressure drag (incompressible, non-viscous, and irrotational flow) are absent.

In fact, if the wing is narrow and has a large wingspan, the lift gradually decreases from the root to the tip, resulting in small-intensity vortices and an elliptic distribution of force (Figure 5). The induced drag coefficient is proportional to the square of the lift coefficient and decreases with increasing wing aspect ratio (AR). Figure 5 illustrates the Elliptical load distribution [9].

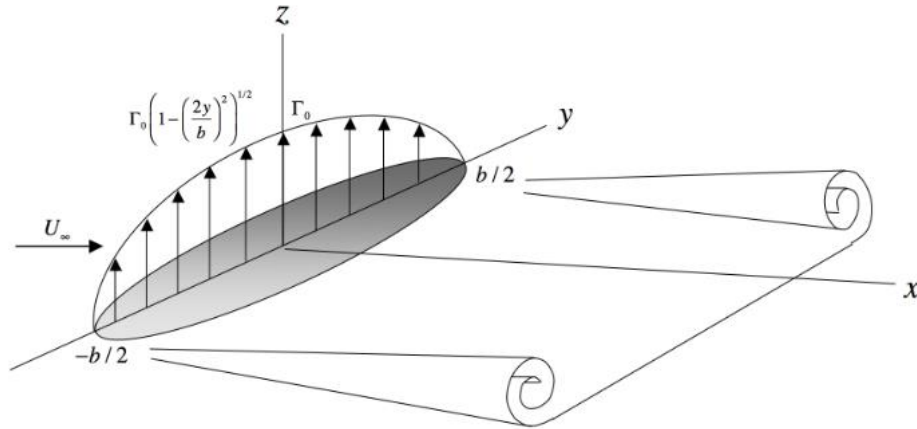


Figure 5. Lift distribution on a wing with finite elongation [9]

The total lift in this case is:

$$L = \frac{1}{2} \rho U_{\infty} \Gamma_0 b \int_{-1}^1 \left(1 - \left(\frac{2y}{b}\right)^2\right)^{1/2} d\left(\frac{2y}{b}\right) = \rho U_{\infty} \left(\frac{\pi}{4} \Gamma_0 b\right) \quad (1)$$

The equation for total lift L is derived based on the elliptical distribution of circulation along the wingspan [9].

ρ : Air Density; U_{∞} : Free stream velocity of the air speed; Γ_0 : Maximum circulation at the center of the span; b : wingspan of the wing.

2. Literature Review

2.1 Types of Winglets and Wingtip Devices

Following Whitcomb's winglet discovery, aircraft designers created a wide variety of winglets and tip devices. The following section discusses some of the winglet inventions made by the relevant aircraft manufacturer [4].

2.1.1 Blended Winglets

In 1994, Grazter from Seattle created the blended winglet. This winglet's distinctive shape consists of a smooth curve after the absence of a sharp edge at the wing/winglet intersection. In 1999, the Boeing Company and Aviation Partners Inc. (API) collaborated to design advanced blended winglets. The winglet design was created to combat the interference drag those forms at the intersection of the wing and winglet after Mike Stowell, Executive Vice President of APB, discussed the interference drag, an aerodynamic phenomenon brought on by the intersection of lifting surfaces. Both Boeing business jets and the B7371 were refitted with winglets. These flights are currently operated by both American (Southwest Airlines) and European (Ryanair) airlines [10].

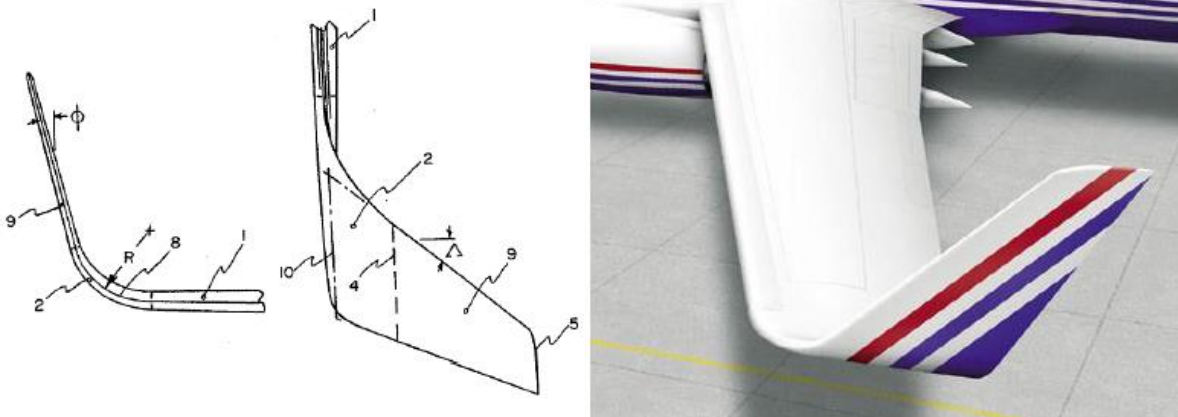


Figure 6. Blended Winglet [10]

2.1.2 Spiroid Winglet

In 1992, Gratzner received a patent for the spiroid-tipped wing technology that he had invented. Attached to the front area of the wing tip, one end of the spiroid tip forms a spiral loop that terminates at the aft portion of the wing tip. As a result, when viewed from the front, it seems oval. The purpose of the spiroid-tipped wing was to lessen the noise produced by the tip vortices as well as the generated drag. With a spiroid-tipped wing, API has conducted its flying test in a Dassault Falcon 50 [11].

2.1.3 Raked Winglet

The Raked wing tip from Boeing Company was designed by Herrick and got the patent in 2000. The raked tip is attached with the main wingtip with higher angle of sweep than the main wing. Boeing 777 long-range jets have been designed with raked wingtip [12].

2.1.4 Canted Winglet

The Winglet which is placed at some canted angle is basically known as canted winglet. They can be found on Airbus A330 and A340 aircraft and on the Boeing 747-400.



Figure 7. Canted Winglet [13]

2.1.5 Split Winglet

The Split Scimitar Winglet redefines the aerodynamics of the existing Blended Winglet on the Boeing 737NG family. The combined aerodynamic elements of the retrofit — ventral strakes, scimitar tips, and trailing edge wedges — provide a drag reduction, and corresponding range increase, of 2 percent or more for long-range missions. These winglets became standard on the final 737 NG Boeing Business Jets and are now flying on approximately 1,700 737 NG airliners.

2.1.6 Sharklet Winglet

Aircraft wingtip appendages called sharklets are made to cut drag and increase fuel efficiency. Their name comes from the fact that they resemble winglets but are usually more angular in appearance, with a sharp upward curve that mimics a shark's fin. Sharklets aid in preventing wingtip vortices—turbulent air patterns that increase drag—from forming. Sharklets help the airplane save fuel, lower CO₂ emissions, and increase payload capacity and range by reducing these vortices.

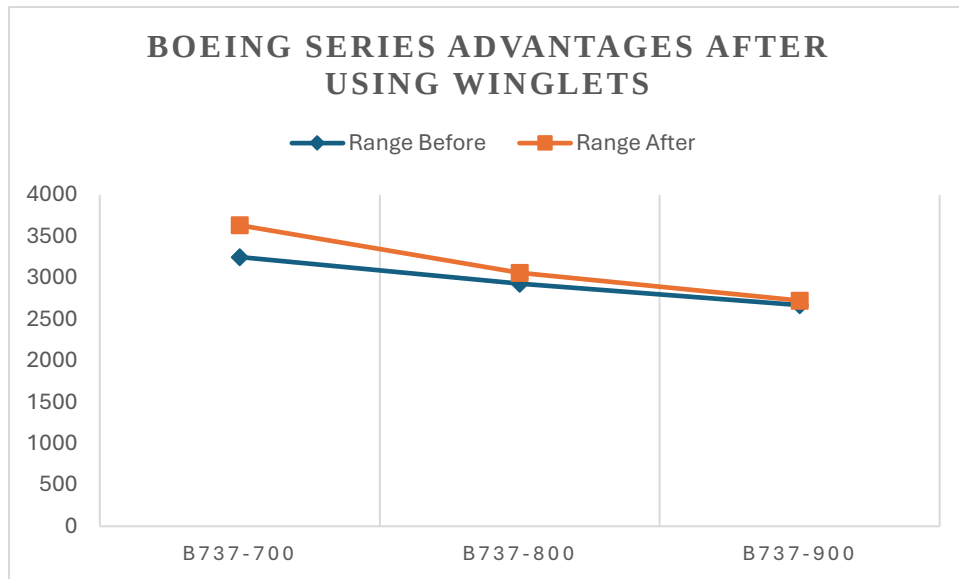


Figure 8. Sharklet Winglet [14]

2.2 Advantages Claimed on Winglets and Wingtip Devices

Ever since the winglet technology has been introduced, the advantages were being published. Dr. Whitcomb has performed an experiment with the winglet in which the winglet shows reduction in induced drag of about 20% [4]. In 1977, Heyson made an experiment to study the advantages of Whitcomb's winglet. His results indicate that winglets would reduce the induced drag more than tip extension and will be at its best when it is nearly vertical. Using Trefftz-plane theory, R.T. Jones conducted a study on winglets later in 1980 to ascertain its impact on induced drag. He concluded that, to have a gain over tip extension, the winglet's vertical length should be double that of its horizontal extension[15]. More than 2 billion gallons of fuel were saved in 2010 thanks to the APB blended winglet, according to Aviation Partners Boeing. Additionally, the APB stated that by 2014, the winglets might reduce carbon emissions overall by saving 5 billion gallons of gasoline. Because of the overall decrease in drag, the B737 saw a range gain of around 5–7%. During a 1993 flying test on Gulfstream II, API demonstrated over 10% fuel economy under cruising circumstances with spiroid-tipped wings. Reduced takeoff field length, increased fuel efficiency, and superior climb performance are all benefits of the Boeing B777 family's distinctive raked

wingtip design. A raked wing tip might reduce fuel consumption by 2%, amounting to 1.3 million fuel savings and 3.9 million carbon dioxide emissions annually³. Sharklets is the recent invention from the Airbus Company for their A320 family. They claimed that sharklets would reduce fuel burn up to 3.4% and this corresponds to 700 tons of carbon emission per aircraft in a year. Airbus also added that A320 could lift off with more weight due to the performance of sharklets⁴. The research made with spiroid tipped wing indicates that it would disperse the vortex effects within a short span of time and therefore the time for take-off and landing between the aircraft would be reduced. Graph 1 shows the increase in range after using winglets.



3. Methodology

3.1 Fusion 360

The study used the DLR-F4 wing model as it is widely used for aerodynamic investigations as well as wind tunnel testing. The wing geometry was created in Autodesk Fusion 360 for precise dimensions and visualization (Figure). DLR-F4 prototype, consisting of a fuselage in the form of a solid of revolution and a large aspect ratio swept back wing of a tapered planform, featuring a supercritical airfoil DFVLR R-4, allows the aerodynamic simulation of a typical medium-range subsonic passenger aircraft configuration [16]. Figure 9 shows the design of the wing profile.

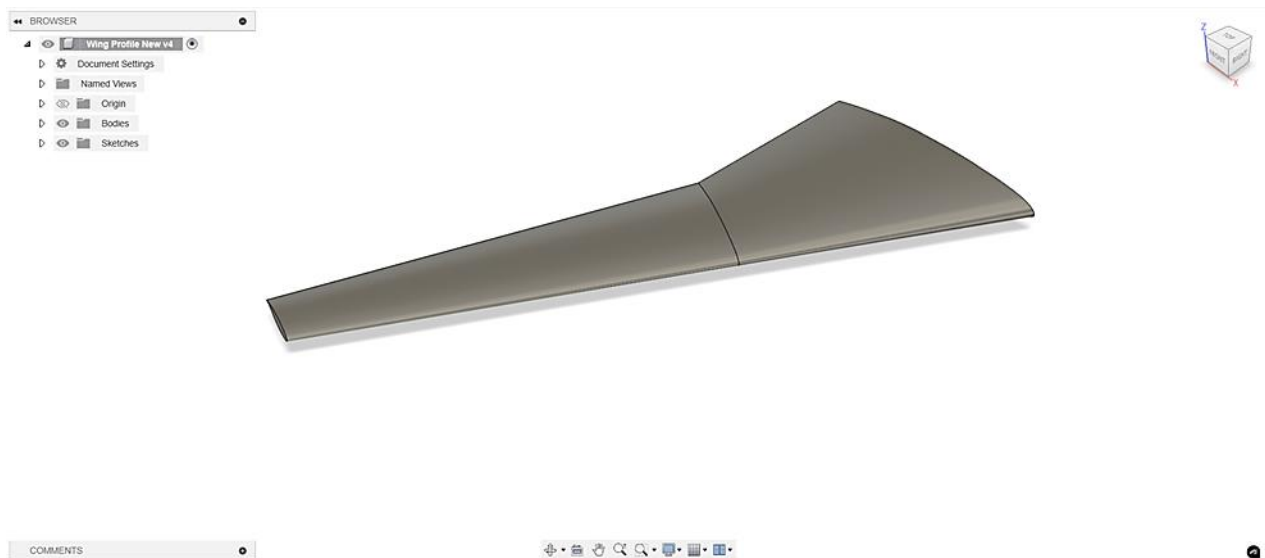


Figure 9. Wing Profile on Fusion 360

The designing of the winglets was done on Ansys because it eliminates the need to transfer files between different software platforms, which can introduce errors or compatibility issues.

3.2 The Winglets Used

Figure 10 shows the three different types of winglets used in this study, all of them were created on ANSYS and the comparison with a no-winglet effect. a. no winglet; b. canted; c. blended winglet and d. sharklet winglet.

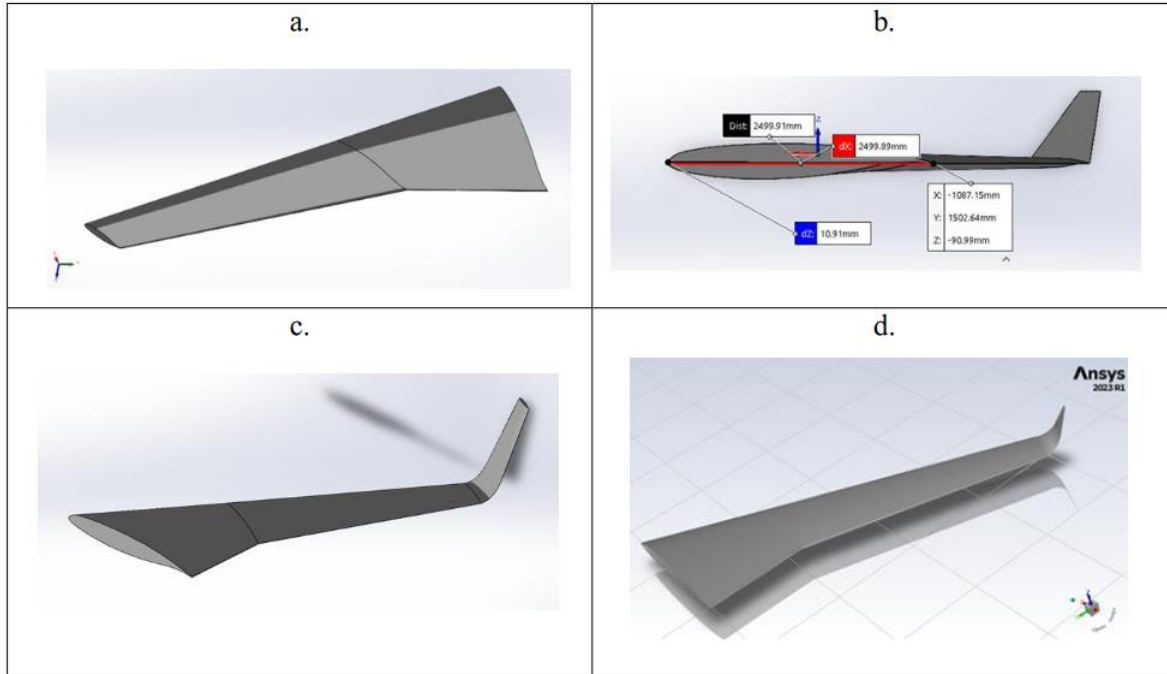


Figure 10. a. No Winglet b. Canted Winglet c. Blended Winglet d. Sharklet Winglet

3.3 Meshing the Designs

A structured mesh was generated around the wing, with particular emphasis on refining the mesh around the winglet regions. A fine mesh was used in areas with expected high flow gradients to capture details accurately and ensure numerical stability. Refer Appendix 1 for the complete meshing figures.

3.3.1 No Winglet Meshing

Figure 11 shows the structured mesh of the wing without a winglet.

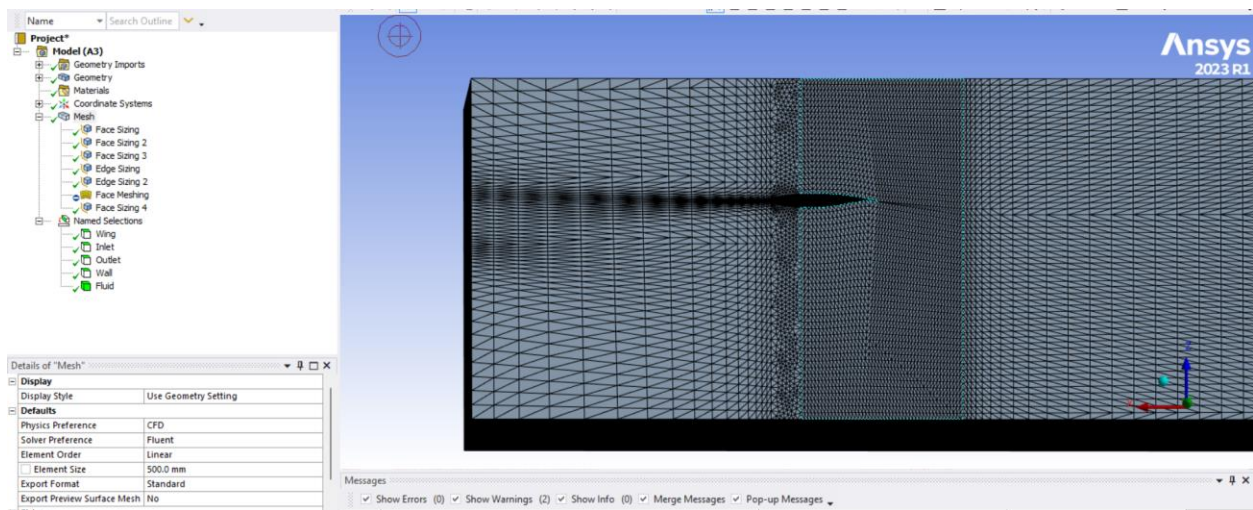


Figure 11. No Winglet Meshing

3.3.2 Sharklet Winglet Meshing

Figure 12 shows the structured mesh of the wing with a sharklet winglet.

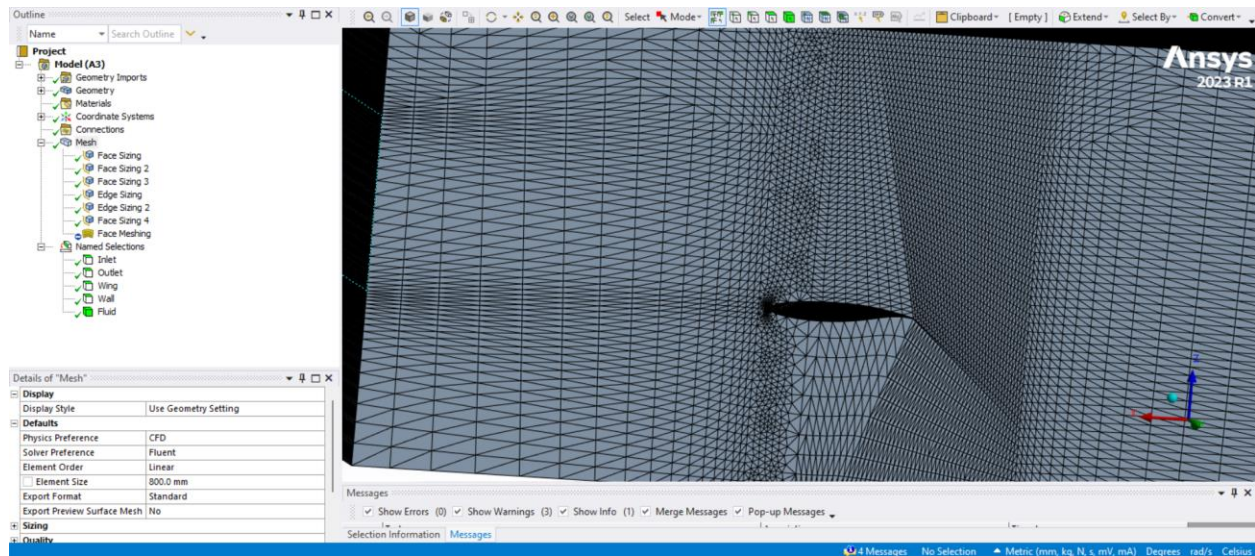


Figure 12. Sharklet Winglet Meshing

3.4 Parameters and Conditions Used

Some of the parameters, conditions and properties were fixed for the consistency in results as it will help in maintaining the repeatability and reliability of the study. Below mentioned the Material Properties and the Cell Zone Conditions, along with Reference Values.

Material Properties

— Fluid	
— air	
Density	1.225 kg/m ³
Cp (Specific Heat)	1006.43 J/(kg K)
Thermal Conductivity	0.0242 W/(m K)
Viscosity	1.7894e-05 kg/(m s)
Molecular Weight	28.966 kg/kmol
— Solid	
— aluminum	
Density	2719 kg/m ³
Cp (Specific Heat)	871 J/(kg K)
Thermal Conductivity	202.4 W/(m K)

Cell Zone Conditions

— Fluid	
— fluid	
Material Name	air
Specify source terms?	no
Specify fixed values?	no
Frame Motion?	no
Laminar zone?	no
Porous zone?	no
3D Fan Zone?	no

Reference Values

Area	1 m ²
Density	1.225 kg/m ³
Enthalpy	0 J/kg
Length	1 m
Pressure	0 Pa
Temperature	288.16 K
Velocity	60 m/s
Viscosity	1.7894e-05 kg/(m s)
Ratio of Specific Heats	1.4
Yplus for Heat Tran. Coef.	300
Reference Zone	fluid

3.5 Boundary Conditions

The boundary conditions in this study were the same for all the simulations to keep the results as accurate as possible. Below tables state all of the boundary conditions fixed in this study.

Boundary Conditions

— Inlet	
— inlet	
Velocity Specification Method	Components
Reference Frame	Absolute
Supersonic/Initial Gauge Pressure [Pa]	0
Coordinate System	Cartesian (X, Y, Z)
X-Velocity [m/s]	-60
Y-Velocity [m/s]	0
Z-Velocity [m/s]	0
Turbulent Specification Method	Intensity and Viscosity Ratio
Turbulent Intensity [%]	5
Turbulent Viscosity Ratio	10
Note: Rejected particles do not change their injection association	1187974352
— Outlet	

— outlet	
Backflow Reference Frame	Absolute
Gauge Pressure [Pa]	0
Pressure Profile Multiplier	1
Backflow Direction Specification Method	Normal to Boundary
Turbulent Specification Method	Intensity and Viscosity Ratio
Backflow Turbulent Intensity [%]	5
Backflow Turbulent Viscosity Ratio	10
Note: Rejected particles do not change their injection association	no
Backflow Pressure Specification	Total Pressure
Build artificial walls to prevent reverse flow?	no
Radial Equilibrium Pressure Distribution	no
Average Pressure Specification?	no
Specify targeted mass flow rate	no
— Wall	
— wing	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
— wall	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	0
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5

4. Results

4.1 No Winglet

In Figure 13 along the wingtip, vortices and areas of flow separation are seen in the velocity contours. Because the high-pressure air beneath the wing spills over to the low-pressure region above, the lack of a winglet permits more noticeable wingtip vortices, which enhance induced drag.

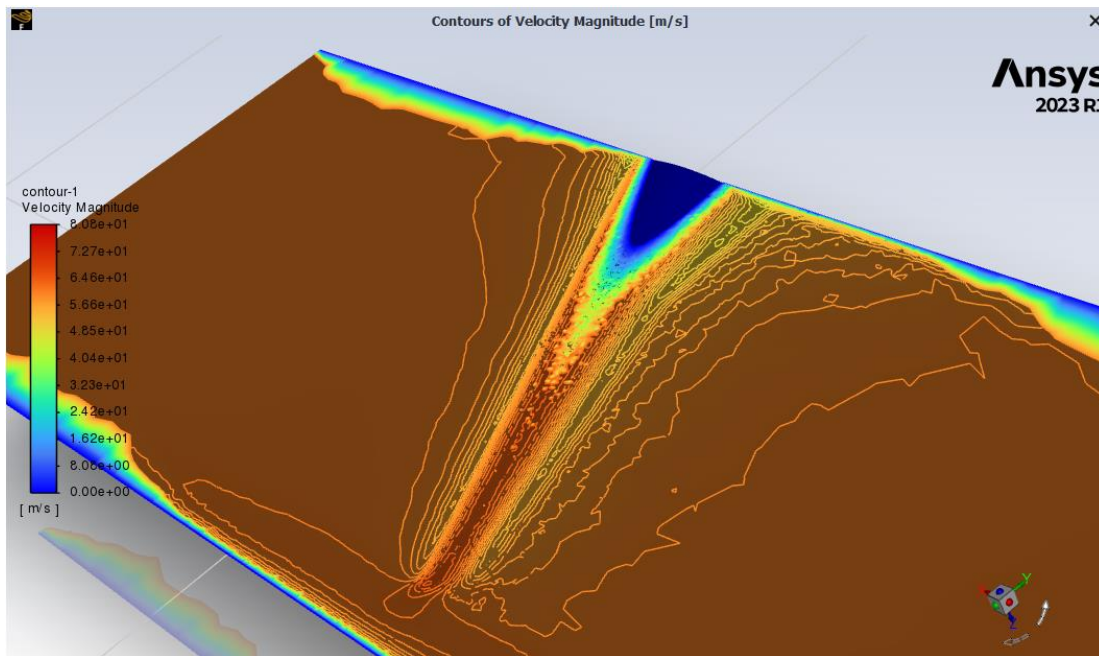


Figure 13. No Winglet Velocity Contours

Figure 14 shows the pathlines of flow of air over the wing without a winglet.

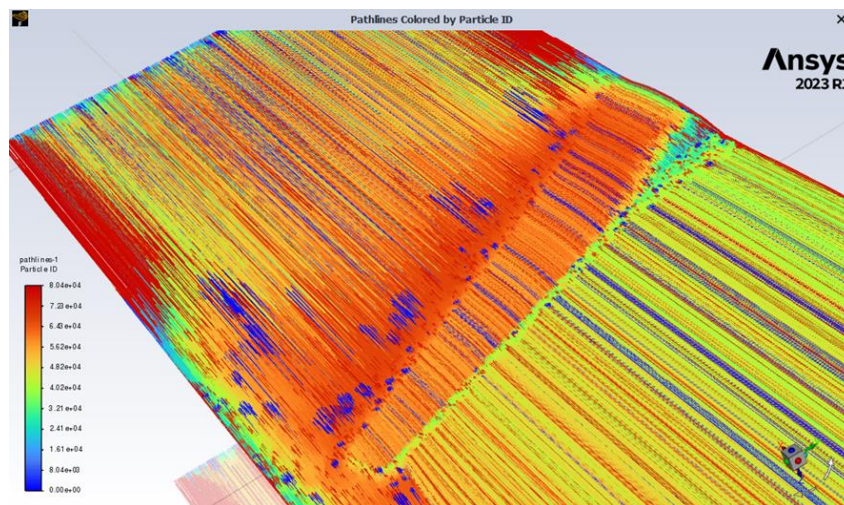


Figure 14. Pathlines of flow on a No-Winglet Wing

4.1.1 No Winglet Data

Figure 15 shows the results of Lift Coefficient and the Drag Coefficient after the simulation.

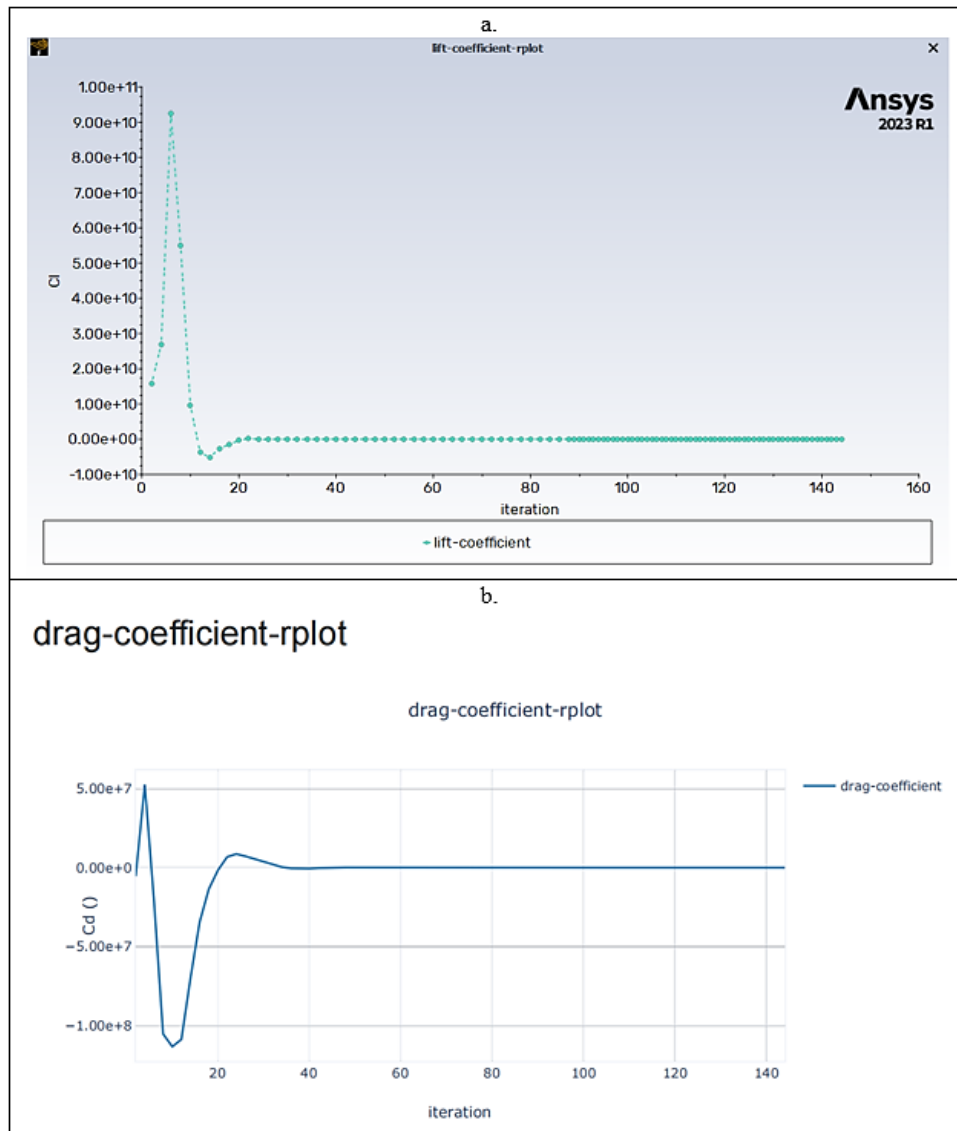


Figure 15. a. Lift Coefficient b. Drag Coefficient

4.2 Canted Winglet

It's shown in Figure 16 that the concentration of contour lines near the wingtip suggests a rapid change in velocity, indicating a strong velocity gradient. This usually corresponds to intense rotational motion in the airflow, which is a characteristic of strong vortices.

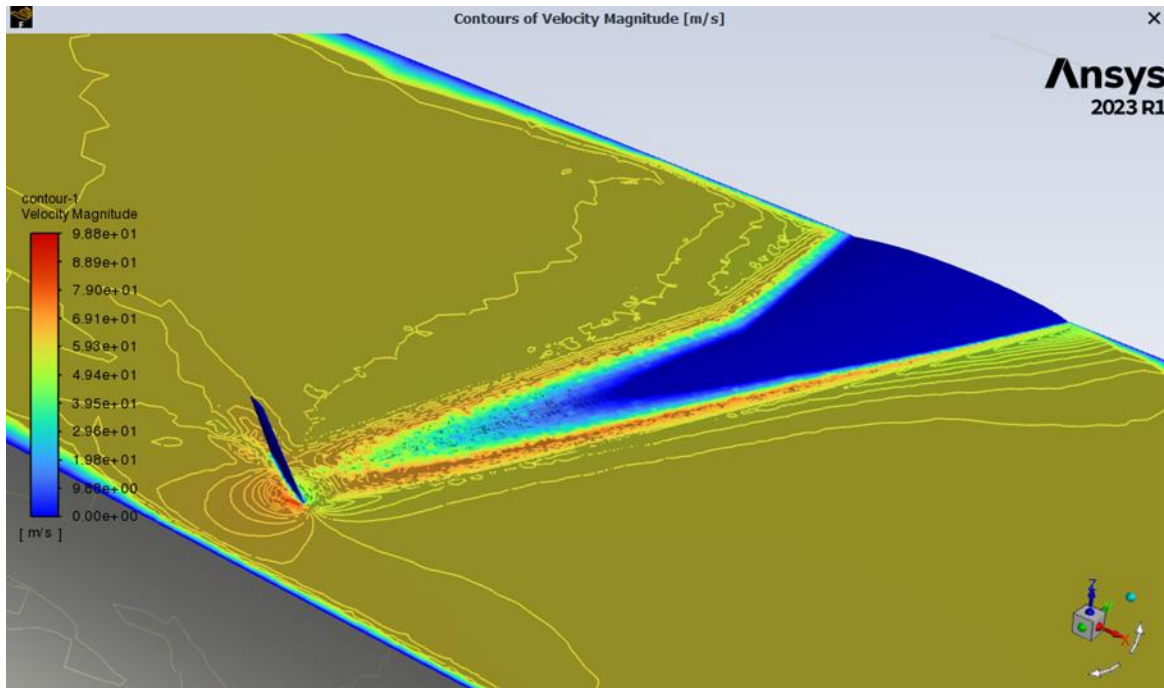


Figure 16. Canted Winglet Velocity Contours

Figure 17 shows the static pressure contours on the wing with canted winglet.

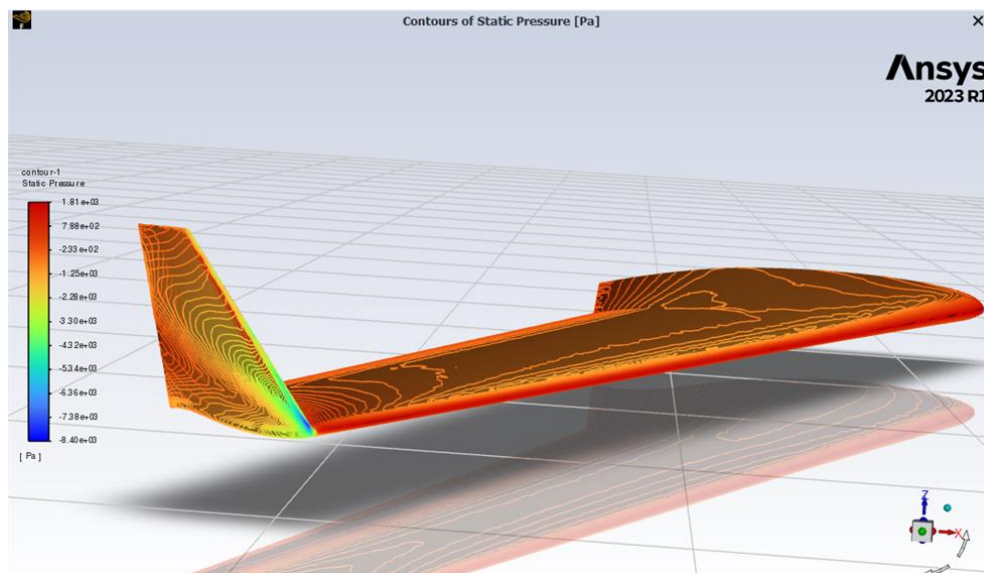


Figure 17. Static Pressure Contours

Figure18 illustrates that there are visible swirling patterns, particularly near the edge of the winglet, indicating vortex development.

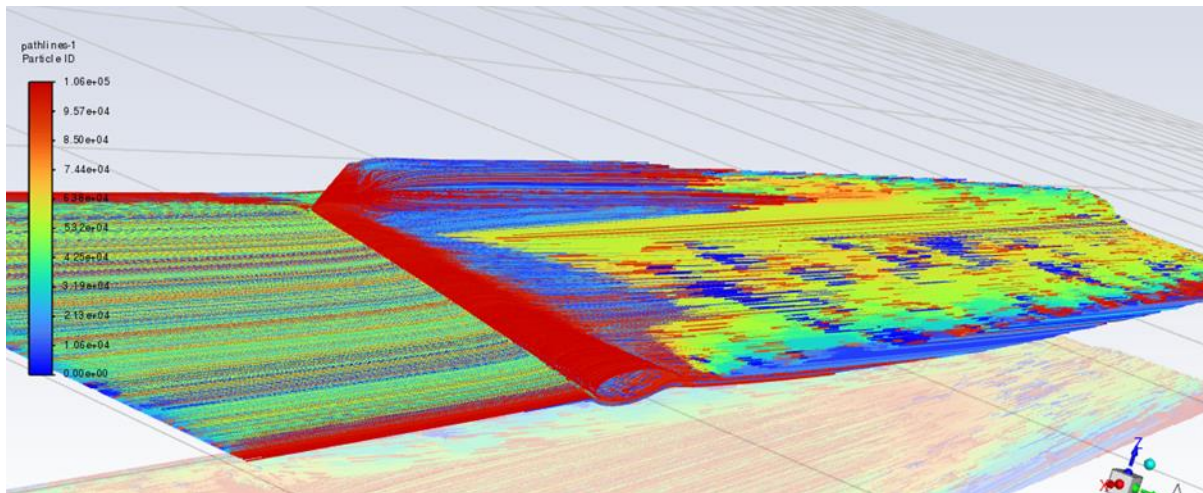


Figure 18. Pathlines over a wing with Canted Winglet

4.2.1 Canted Winglet Data

In Figures 19 and 20 the results of the Lift Coefficient and Drag Coefficient.

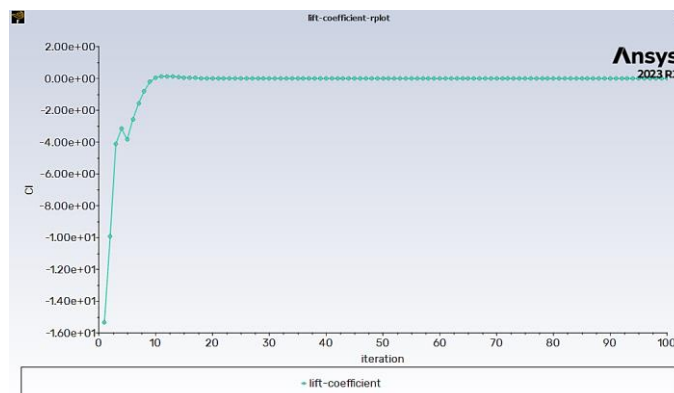


Figure 19. Lift Coefficient

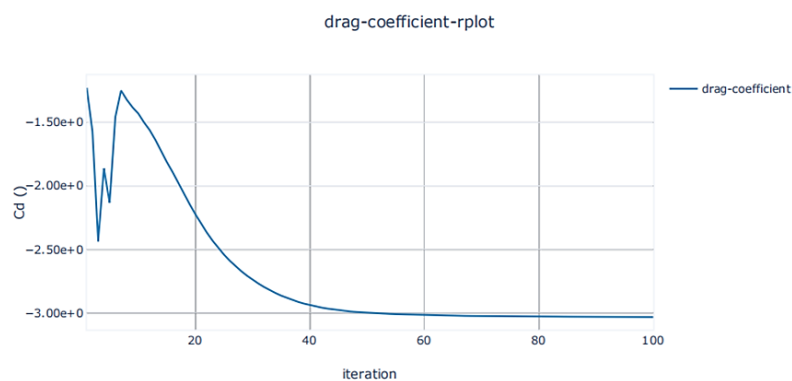


Figure 20. Drag Coefficient

4.3 Blended Winglet

In Figure 21 it shows how the air flows over and interacts with the geometry of the winglet. The flow appears to gradually smooth out as it moves toward the right, indicating stable flow after turbulence or disturbances near the object.

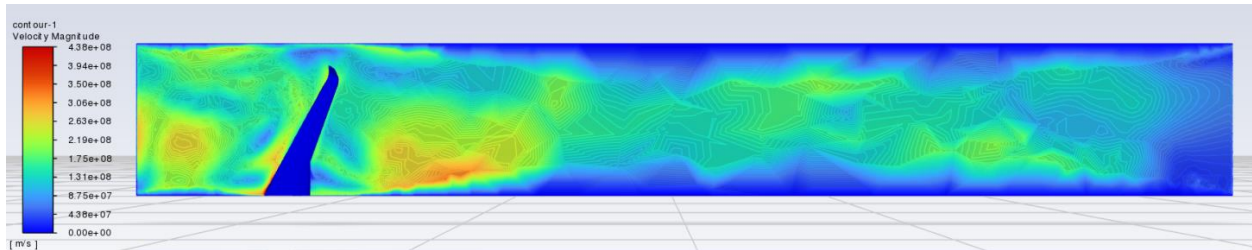


Figure 21. Velocity Contours on a Blended Winglet

4.3.1 Blended Winglet Data

Figures 22 and 23 show the Residuals vs Iterations and the Drag Coefficient plot.

Residuals

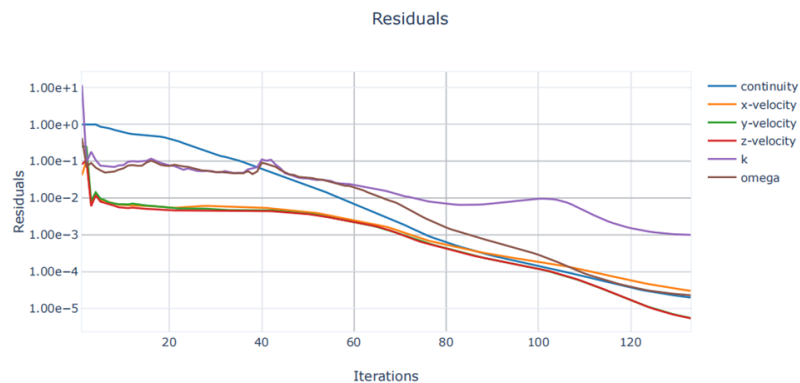


Figure 22. Residuals vs Iterations of the Simulation

drag-coefficient-rplot

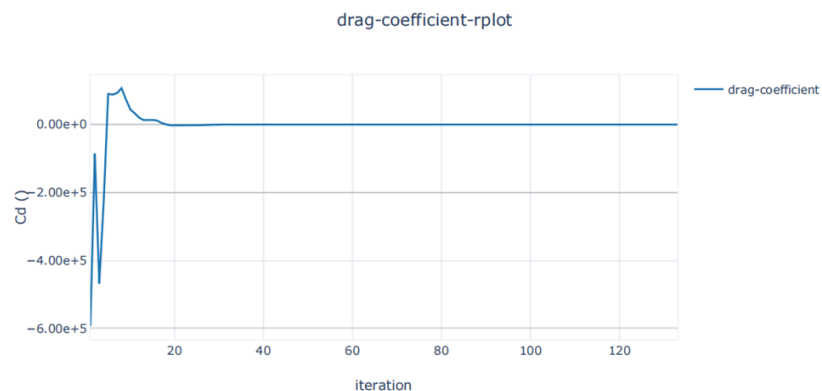


Figure 23. Drag Coefficient Plot

4.4 Sharklet Winglet

The first figure shows velocity contours highlighting smoother flow and reduced turbulence near the wingtip due to the sharklet winglet, minimizing induced drag and energy loss. The second figure uses pathlines to visualize the redirection of airflow by the sharklet, reducing vortex strength and creating a more organized wake.

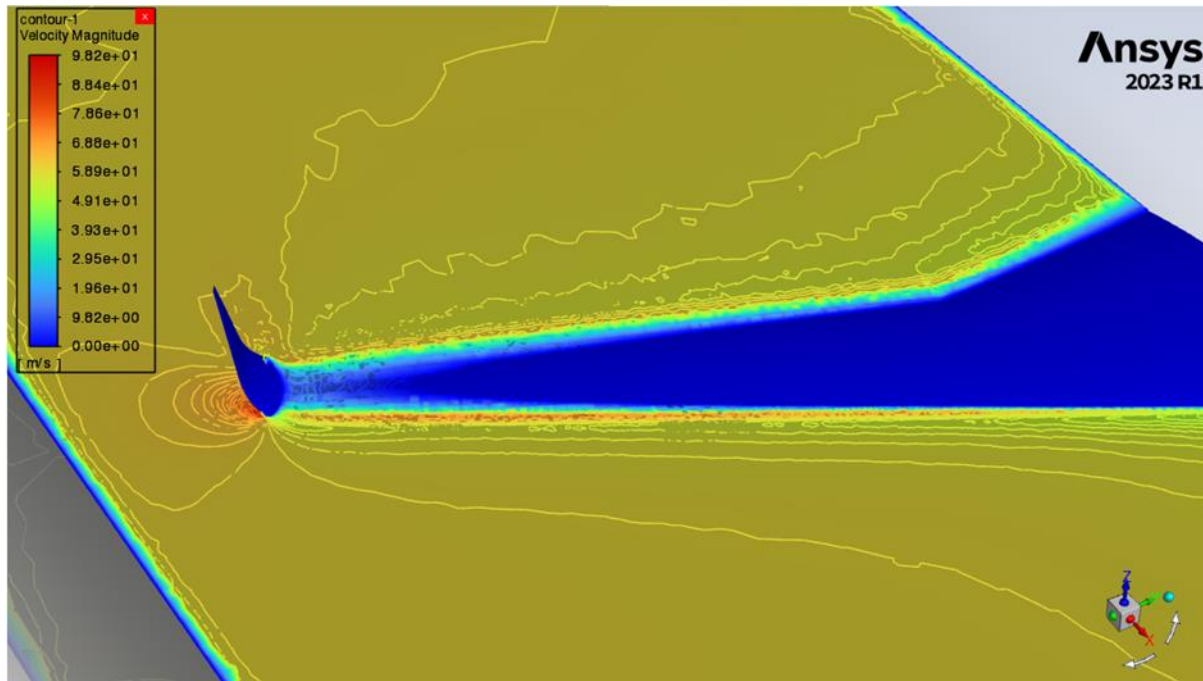


Figure 24. Velocity Contours of Sharklet Winglet

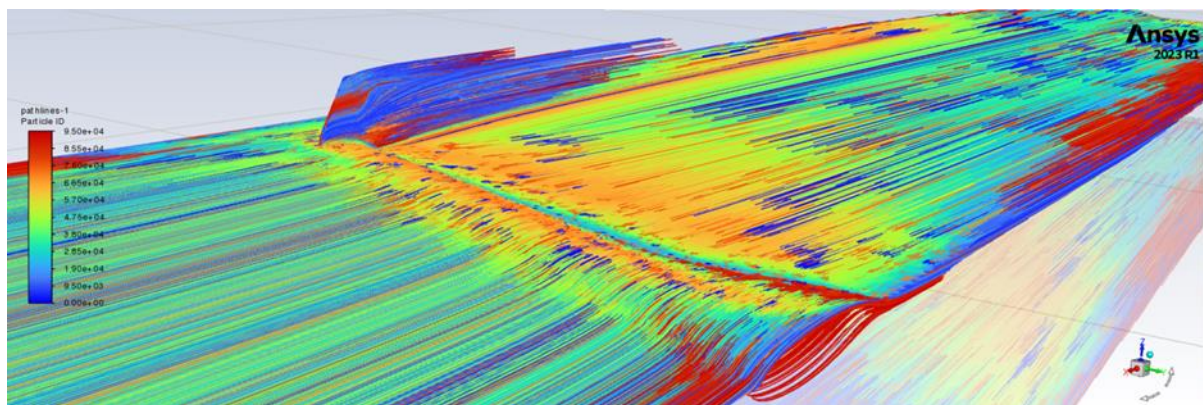


Figure 25. Pathlines over the Wing with Sharklet Winglet

In Figure 26 the velocity vectors around the sharklet winglet.

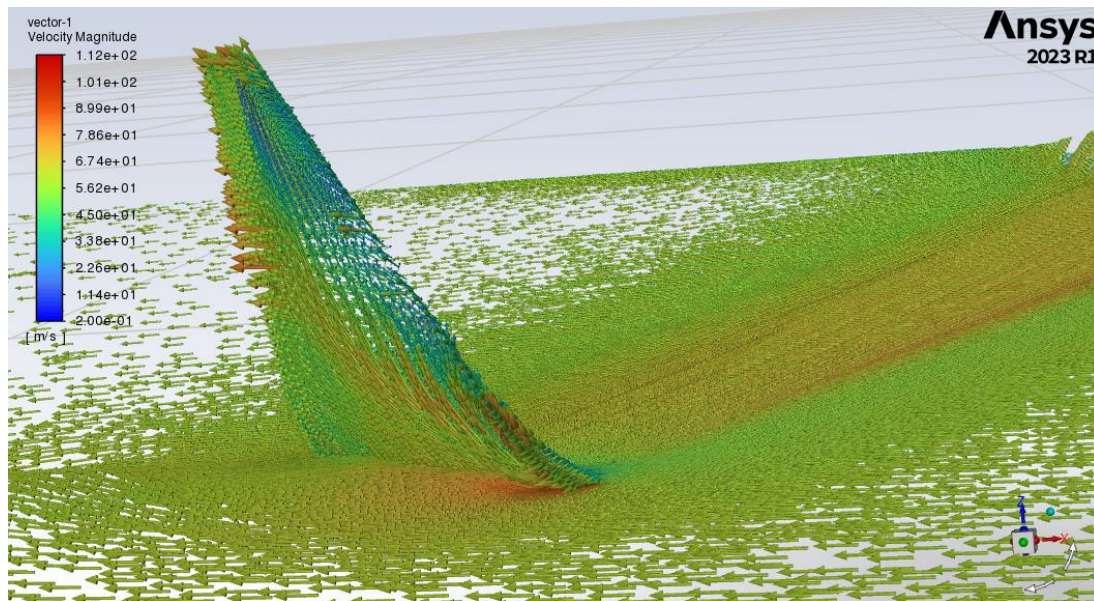


Figure 26. Velocity Vectors on the Sharklet Wingle

4.4.1 Sharklet Winglet Data

The following Figures 27 and 28 show the Residuals vs Iterations of the simulation and the Drag Coefficient plot.

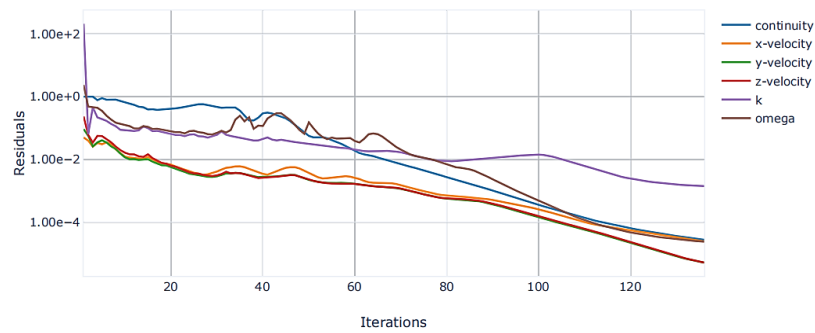


Figure 27. Residuals vs Iterations of the Sharklet Winglet Simulation

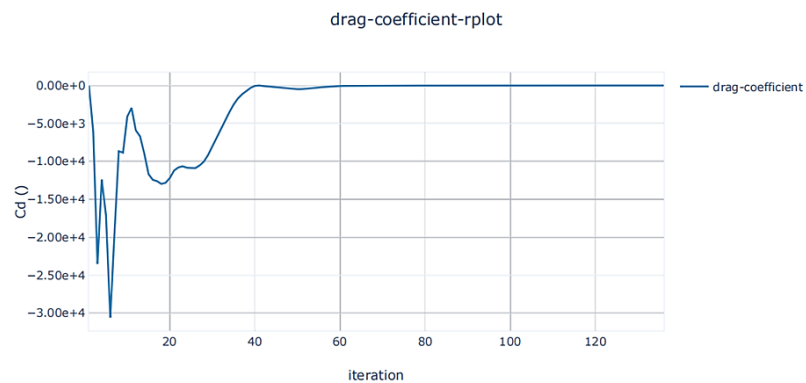


Figure 28. Drag Coefficient Plot

5. Conclusion

These findings in our research align with theoretical expectations of winglet functionality, particularly in minimizing the drag. The customized winglet not only enhanced the aerodynamic efficiency but also optimized the overall lift distribution along the wingspan. For future work further refinement of winglet geometry or improvising the angle of winglets could yield even greater performance improvements. Testing under various operational conditions would also provide insights into the design's adaptability and effectiveness across different flight regimes.

As a takeaway from this research reaffirms the value of custom designed winglet in enhancing aerodynamic efficiency, and it suggests that tailored designs can offer distinct advantages over standard configurations. Further testing is encouraged to optimize and validate these preliminary results across different scenarios.

6. Future Goals

Our future goals will focus mainly on improving the efficiency and design of winglets through both computational and experimental studies.

Material Innovation: We will investigate the new materials which can be used to enhance winglet performance mainly by using lightweight material as well as the adaptive material that can respond to the aerodynamic forces. Some materials like shape memory alloys can allow the winglet to change its shape during the flight which can provide the drag reduction at different flight phases.

Energy efficiency and Fuel Consumption Reduction: We would like to conduct the studies on how our winglet design can affect the overall fuel efficiency in different aircrafts. Winglets can improve fuel efficiency by reducing the drag and mitigating the formation of wingtip vortices, winglets can contribute to fuel consumption reduction of up to 5%.

Experimental Validation and Wind Tunnel Testing: We know that computational models are important but to validate the designs by physical testing can give us better results. We are looking forward to involving scaled wind tunnel testing for our designed winglet.

Design Strategies: Our strategy is to design/modify the Cant angle or the angle between the winglets and the main wing, to find out at which angle the induced drag is at its lowest.

7. References

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