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Impact of implementing winglets on the aerodynamic performance of an aircraft: A review

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Abstract
This study reviews into how various winglets and wingtip devices affected an aircraft's ability to fly aerodynamically. The analysis focuses on how the introduction of winglets affects key performance parameters, including drag force, lift-to-drag ratio, and overall efficiency. Various studies and applications related to winglet design are reviewed, shedding light on the potential benefits of this aerodynamic enhancement. Through computational simulations, wind tunnel tests, and empirical data, the research aims to quantify the improvements in aerodynamic efficiency achieved by incorporating winglets into the aircraft design. In the majority of the reviewed investigations, both experimental and computational fluid dynamics (CFD) studies using various turbulence models were carried out. Turbulence models like Sparlat Almaras (SA), k-ε and k-ω have been employed in computational investigations have shown that, in comparison to a plain wing, the introduction of winglets and wingtip devices both greatly reduce the production of vortices in the wingtips. It has been found that using winglets is the most efficient way to reduce the wing tip vortexes. As a result, there is now a bigger payload, longer range, and improved fuel economy due to the enhanced L/D ratio.

Keywords: Winglets, induced-drag, wingtip vortex, aircraft performance

1. Introduction

The elements influencing an aircraft in flight encompass weight, which draws the aircraft toward the ground, lift, responsible for lifting the aircraft, thrust, propelling it forward, and drag, exerting resistance against the direction of motion [1]. Figure 1 illustrates these forces at play during the aircraft's cruising phase.

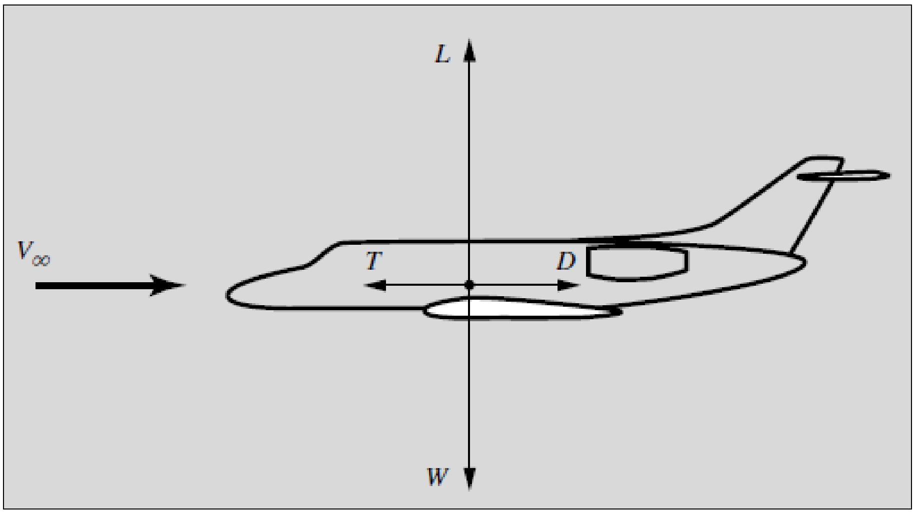

Fig 1: Forces acting on an airplane during Flight [1].

Drag, the opposing force during flight, results from the disruption of airflow around the wing, fuselage, and other protruding elements. This force manifests in two distinct types: parasite drag and induced drag [2].

Parasite drag encompasses non-lift-related structural forces that impede the aircraft's motion, and it can be further classified into three form drag, skin friction, and interference drag. Form drag originates from pressure differentials caused by objects moving counter to the airflow, and optimizing the aerodynamic design of external fuselage components is a key strategy to minimize its impact. Streamlining these parts effectively reduces form drag, making it a crucial consideration in aircraft design. Skin friction drag, on the other hand, arises from the interaction between the aircraft surface and the passing air. To mitigate this, flush mount rivets are employed in assembling components above the fuselage, eliminating surface irregularities and reducing the effect of skin friction drag [3]. The aerodynamic influence on form drag and skin friction drag due to shape design is illustrated in Fig 2.

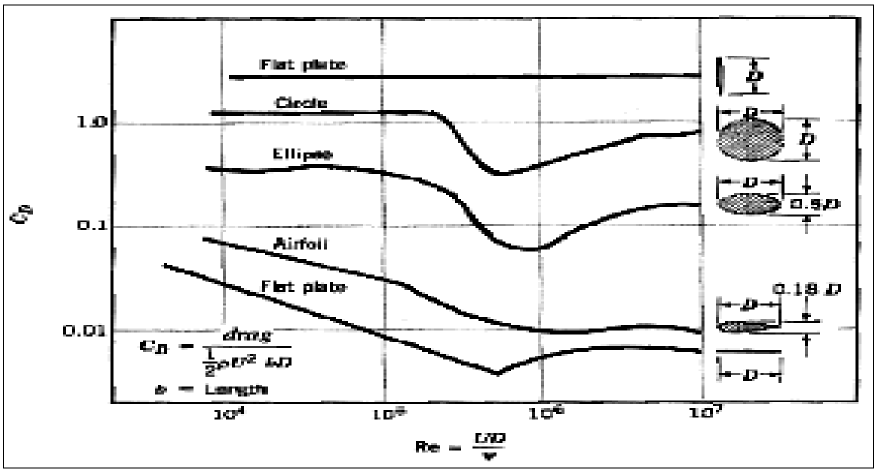

Fig 2: Drag coefficients of blunt and streamlined bodies [4]

Interference drag emerges from the convergence of diverse airflow patterns where different components, such as wings, fuselage, and tail, intersect [3, 5]. Figure 3 presents the three subtypes of parasite drag, offering a visual representation of these drag components.

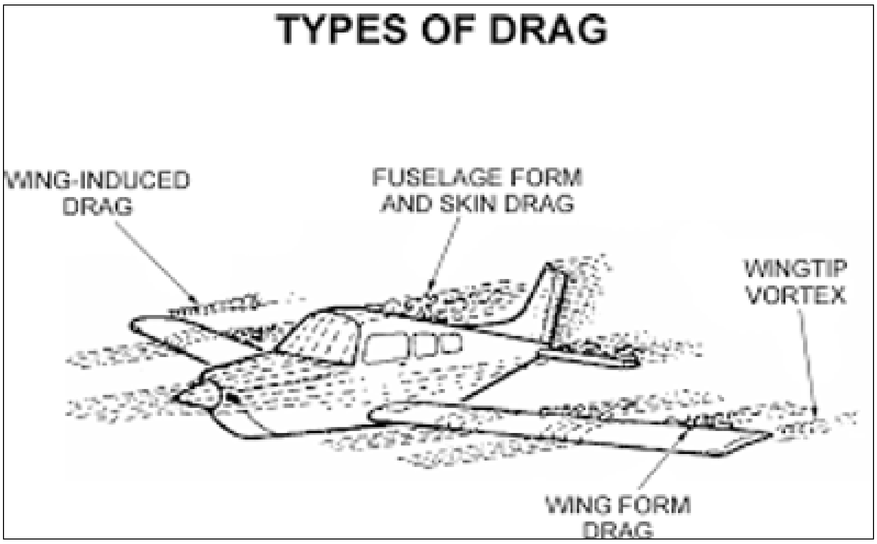

Fig 3: Type of Drag [6]

The second primary form of drag is known as induced drag, and it arises from the lift force generated on the wing. Induced drag is a common occurrence during level flight when an airfoil, such as a wing or rotor blade, is actively producing lift. As the airfoil generates lift, the collision of the wing with the air results in a downward push, creating a trailing vortex that gives rise to a highly turbulent airflow pattern. This turbulent flow is facilitated by the aerodynamic structure of the wing, causing the pressure on the lower surface of the wing to be greater than that on the upper surface in accordance with Bernoulli's Principle.

The air pushed downward escapes from the wing's tip, creating a flow from the high-pressure region beneath the tip to the low-pressure region above the wing's upper surface. In the proximity of the wingtips, there is a tendency for these pressures to balance out, leading to a lateral flow outward from the underside to the upper surface. This phenomenon induces a rotational velocity in the air around the wingtips, resulting in the formation of two large eddies behind both wings of an aircraft [8]. Consequently, induced drag can be regarded as the necessary trade-off for obtaining the lift force required to take off an aircraft. The generated drag force in airplanes is caused by vortexes that form behind the wings. Because of the lift force, these vortex forms are not solely dependent on the wing tip's shape, and they cannot be totally eliminated. Fuel consumption is directly impacted by drag force, particularly during takeoff and straight flight.

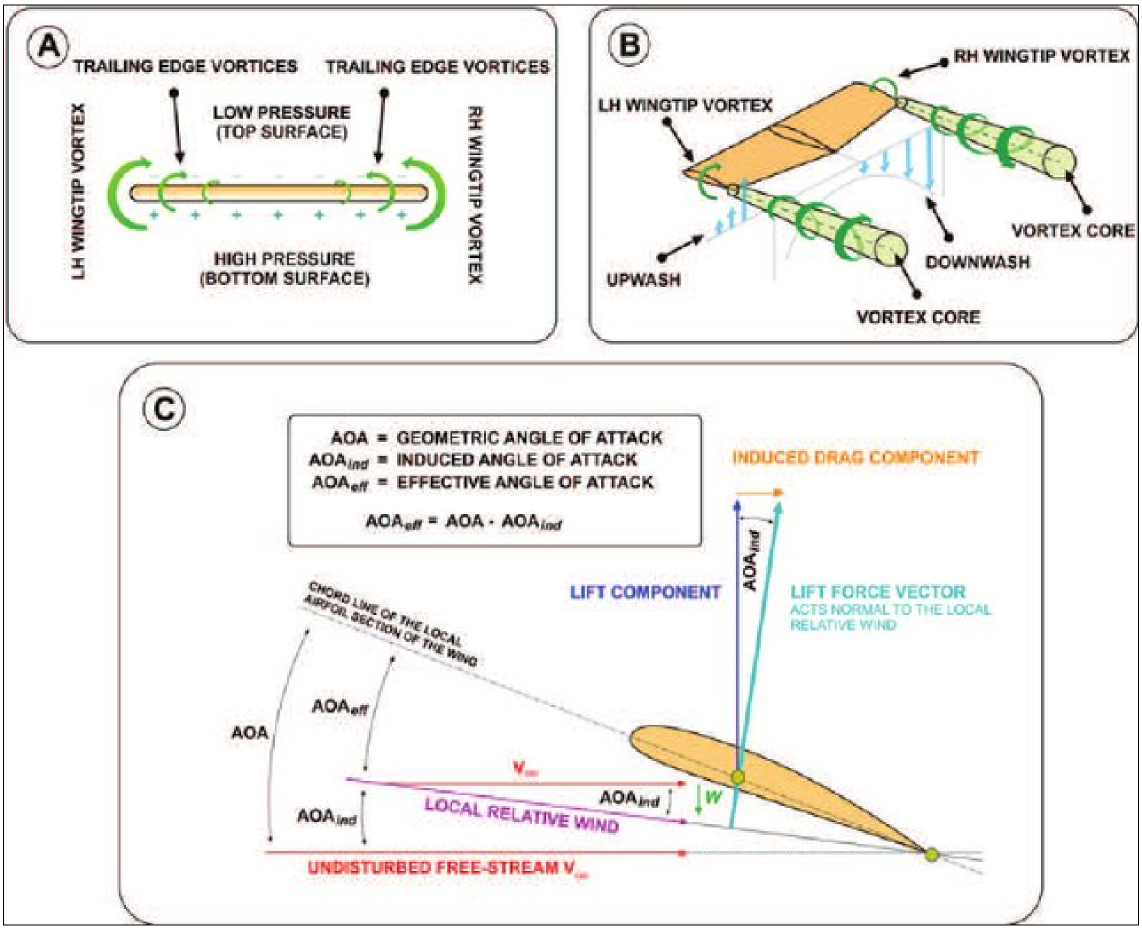

Fig 4: The generation of induced drag [9]

A large percentage of the total drag forces are accounted for by the induced drag force. An improvement in drag force of up to 20% would result from a decrease in drag-induced vorticities. Additionally, this enhancement will allow aircraft to carry more passengers and cargo. As a result, numerous studies have been conducted to lessen the harmful consequences brought on by this force, including those including wingtip devices, winglets and various wingtip structures [10].

This study looked into studies that examined various aircraft wingtip designs to lower drag force in aircrafts by numerical and experimental analysis. As a result, the winglets and wingtip device types that are now in use or that are intended for use have demonstrated their aerodynamic behavior [11].

2. Numerical Methods

Numerical modeling of an aircraft's drag force is crucial. Equation 1 in Basic is used to determine this force.

$$D=qC_DA \tag{1}$$

Where A is a suitable reference area of the body, C_D is drag coefficient, and q is the freestream dynamic pressure. This pressure can calculate with equation below:

$$q= 0.5\, \rho V^2 \tag{2}$$

C_D according to equations 1 and 2 is:

$$C_D=2D/\rho V^2 A \tag{3}$$

C_D is a unitless quantity representing drag force. This coefficient for an aircraft are depend on to the shape of the wing, to the angle of attack and to square of flight speed. Hence, C_D and drag are directly proportional [12].

The lift also can be expressed similarly as in equation 4.

$$C_L=2L\rho/V^2 A \tag{4}$$

C_L is lift coefficient, and *L* is lift force. For an aircraft, the larger the C_L value than the C_D value, the better the performance. For this reason, C_L/C_D ratio is an important parameter in examining the aerodynamic structures of aircraft. This ratio can be increased both by increasing the lift force and by decreasing the drag force. Thus, while the carrying capacity and range of the aircraft will increase, fuel consumption will also decrease [13].

3. Winglets Analysis

Winglets are an accepted aerodynamic feature on modern airplanes. Numerous computational and experimental investigations have been conducted by analyzing winglet parameters like lengths, angles, and forms. Frederick W. Lanchester conducted the first research in 1897 suggesting that the wing tip design would lower the drag force. Then, using wind tunnel studies, Whitcomb *et al.* calculated the decrease in drag force by attaching some vertical pieces to the tip of the wing, as shown in Fig 5.

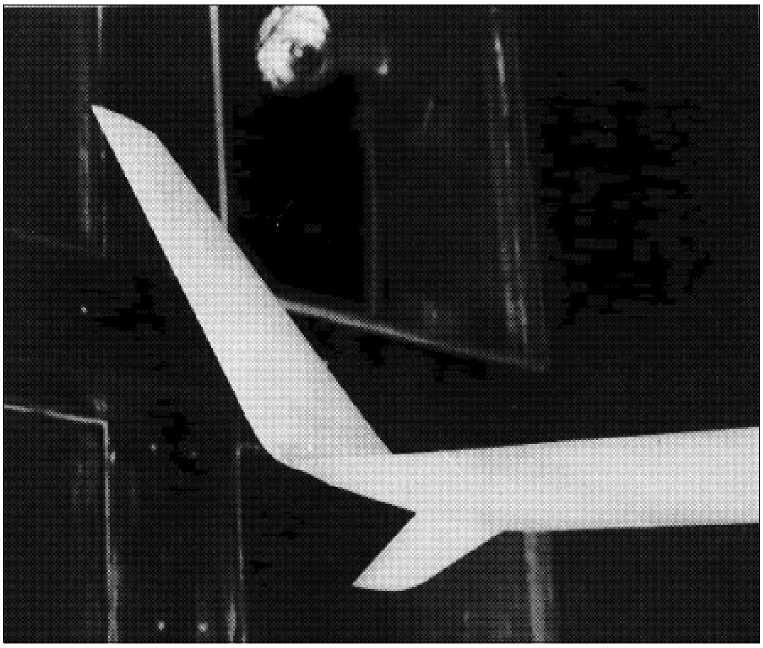

Fig 5: Winglet by Whitcomb [15]

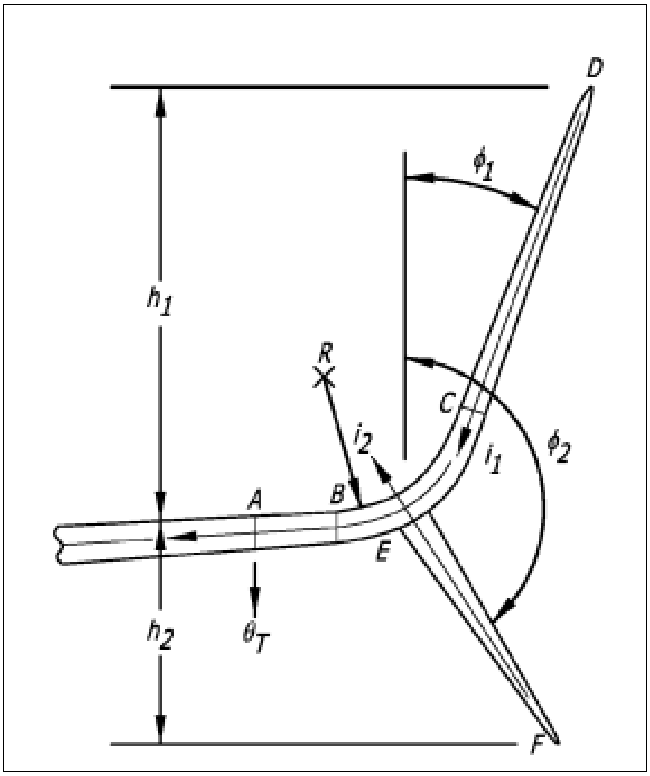

Fig 6: Winglet by Gratzer [16]

Fig 7: Blended winglet [17]

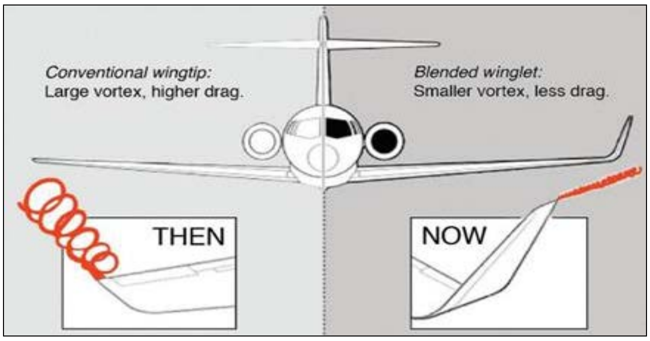

Fig 8: Effect of winglet on Tip Vortex [18]

They estimated that their research may result in a 6% increase in range and a 20% reduction in induced drag at high cruising speeds [15]. Because of the winglet structure created (in Figure 6) and patented by Gratzer [16], the interference drag caused by wing and winglet connection points has been reduced in these Whitcomb *et al*. wing tip designs. In an effort to improve a commercial aircraft's performance through the use of various winglet types, Gavrilović *et al*. looked into the effects of blended and maxi winglets's range, passenger capacity, and C_L/C_D ratio as numerical parameters using ANSYS-FLUENT CFD simulation. Figure 7 shows the blended winglets.

As a result, they were able to extend the range distances by 303 km for blended winglets and 415 km for maxi winglets, respectively, and enhance the C_L/C_D ratio by 3.93% and 5.32%, respectively. Furthermore, significant drops in the number of passengers and fuel usage have been demonstrated [17]. As seen in Figure 8, Bargsten and Gibson [19] also showed that blended winglets greatly reduced wing tip vortexes. Using the ANSYS-CFX flow solver, Panagiotou *et al*. optimized the 50°, 60°, 70°, and 90° blade angles for a Medium-Altitude-Long-Endurance Unmanned-Aerial-Vehicle based on C_D, C_L, and L/D values. They discovered that the optimal L/D ratio was 22.85 at 50 degrees, while reaching a maximum C_L value of 1.82 at 90 degrees. They did point out that the optimization produced a 7.8% improvement in the L/D ratio, which allowed for a roughly 10% increase in the vehicle's overall flight time [20].

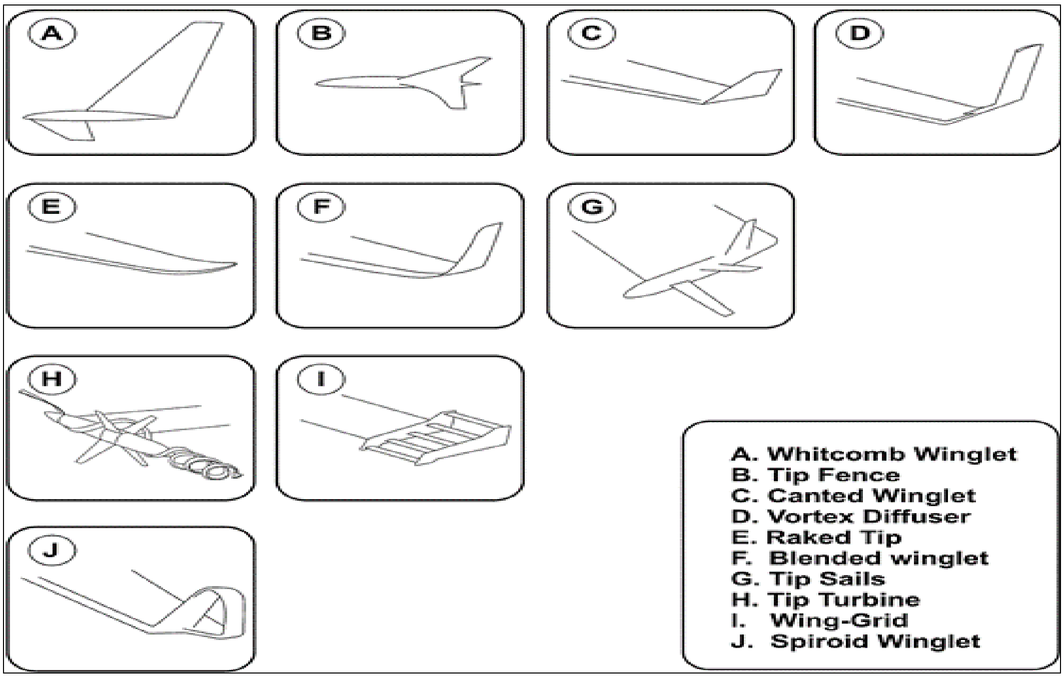

Fig 9: Different Types of Winglet Configurations [14]

Babigian and Hayashibara conducted an analysis on the vortices' intensity generated by winglets at the wingtip, employing FLUENT and the Spalart-Allmaras turbulence model in three dimensions. Their findings indicate a reduction in the formation of vortices at the wingtips during the motion of an aircraft, as illustrated in Figure 10. Consequently, this reduction leads to a decrease in drag force [21]. The study further demonstrated the effective utilization of a wing with a curved-angle winglet.

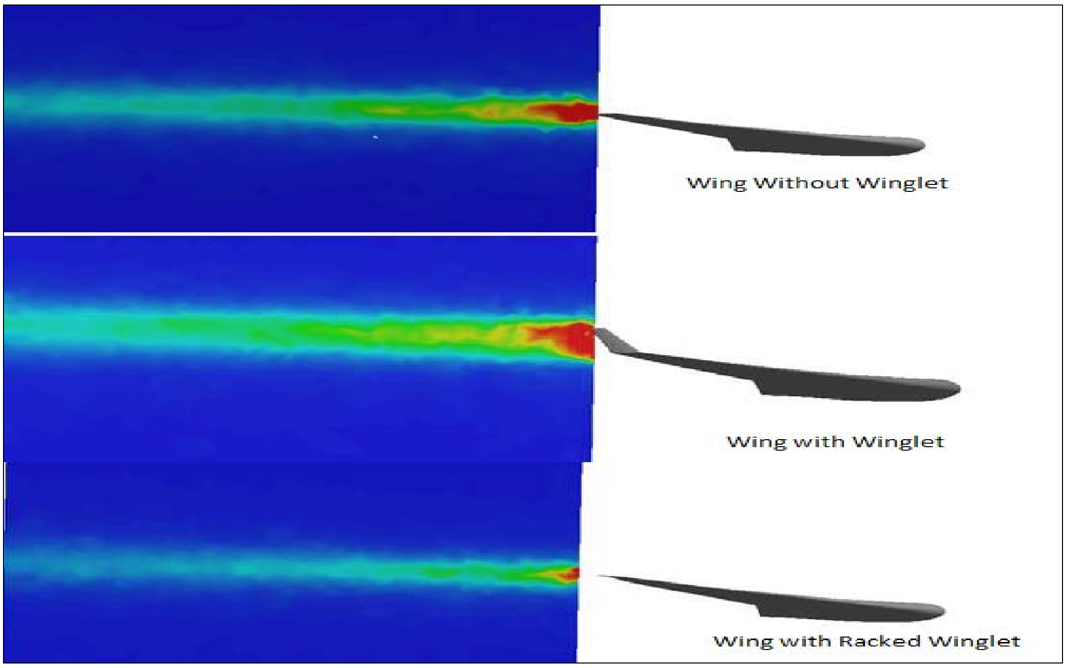

Fig 10: Variation in Tip Vortex due to winglets [21]

In three dimensions using FLUENT, Mattos *et al.* investigated the impact of winglets at the tips of the wings on the drag force of an Embraer 170 model airplane (Figure 11). They claimed that as a result, the overall drag force tanks to the winglets were reduced by 4.5% [22].

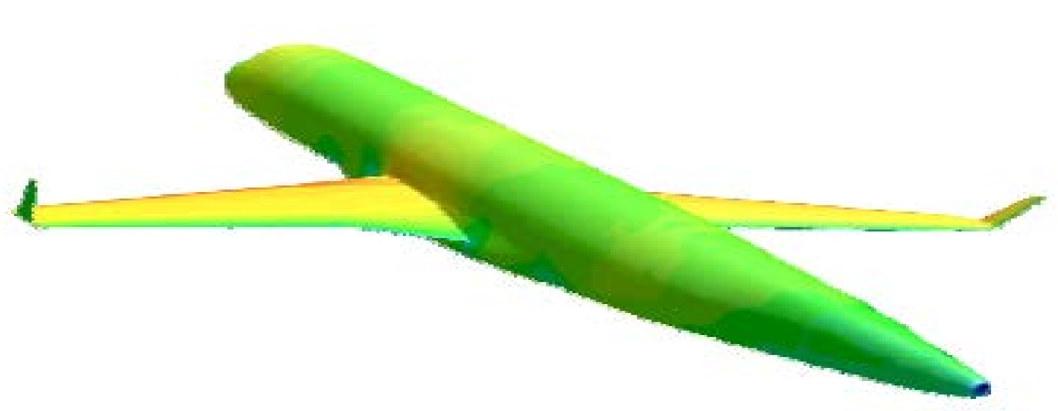

Fig 11: Mach countours on a computational model of Embraer 170 [22]

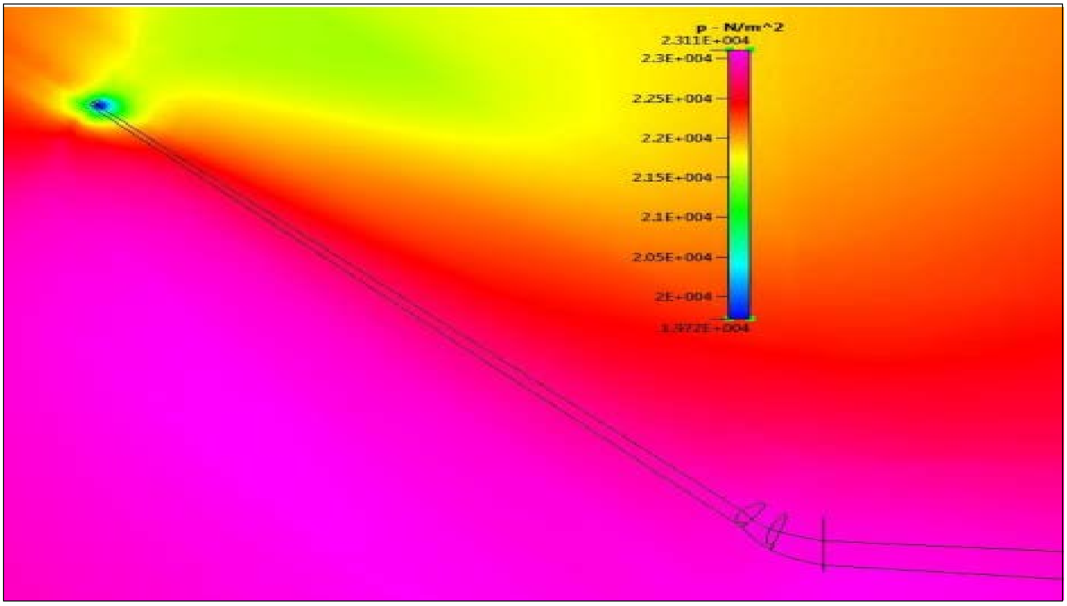

Fig 12: Pressure contour plot behind winglet in laminar flow [23]

Kim refined three distinct winglet configurations for a Boeing 747-100 aircraft model. He simulated CFD using "Athena Vortex Lattice (AVL)" software. Using two partial differential transport equations and the k-ε turbulence model, he performed CFD simulations using the "Reynolds Averaged Navier-Stokes" or RANS method. It proved that the improved winglet seen in Figure 12 was responsible for the 12.5% reduction in induced drag [23].

Yahaya *et al.* used both numerical and experimental methods to study the flow over Whitcomb winglets at a Reynolds number of 2.33x106. They conducted experimental analysis using PIV (Particle Image Velocimetry) techniques and numerical analysis using FLUENT methodologies. In order to lessen the resultant drag, they have therefore demonstrated in Figure 14 that the vortex development around the Whitcomb winglets is smaller than the vortex creation at the wing tip without the winglets [24].

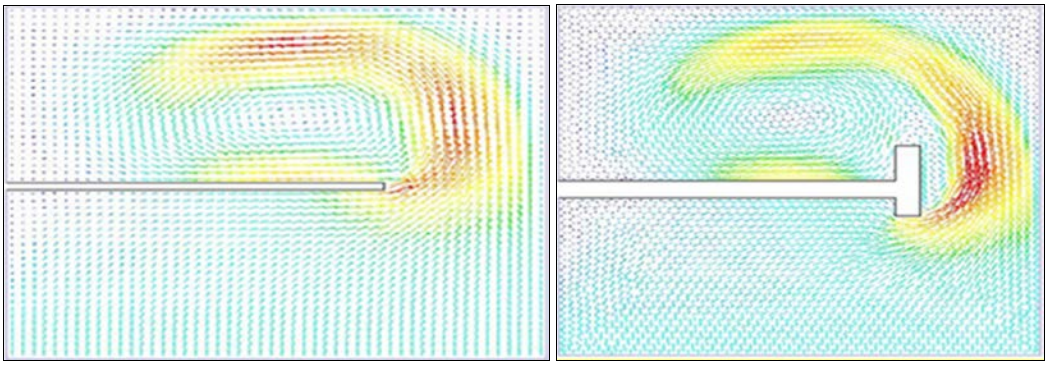

Fig 13: FLUENT Simulation of Wing with and without Winglet [24]

To improve the efficiency of the winglet control surface, Brüderlin *et al*. positioned vortex generators on the winglet bottom surface, as seen in Figure 14. In their research, the "German Aerospace Center (DLR)" solver TAU was utilized for simulation analysis. The time-dependent compressible RANS equations for ideal gases are the focus of this solver. Models of vortex generators are thin cuboids. Vortex generators produce eddies by altering the flow towards the tip of the wing. The kinetic energy in the boundary layer is increased by these eddies, delaying the flow separation. By rerouting the flow, vortex generators increase lift [25].

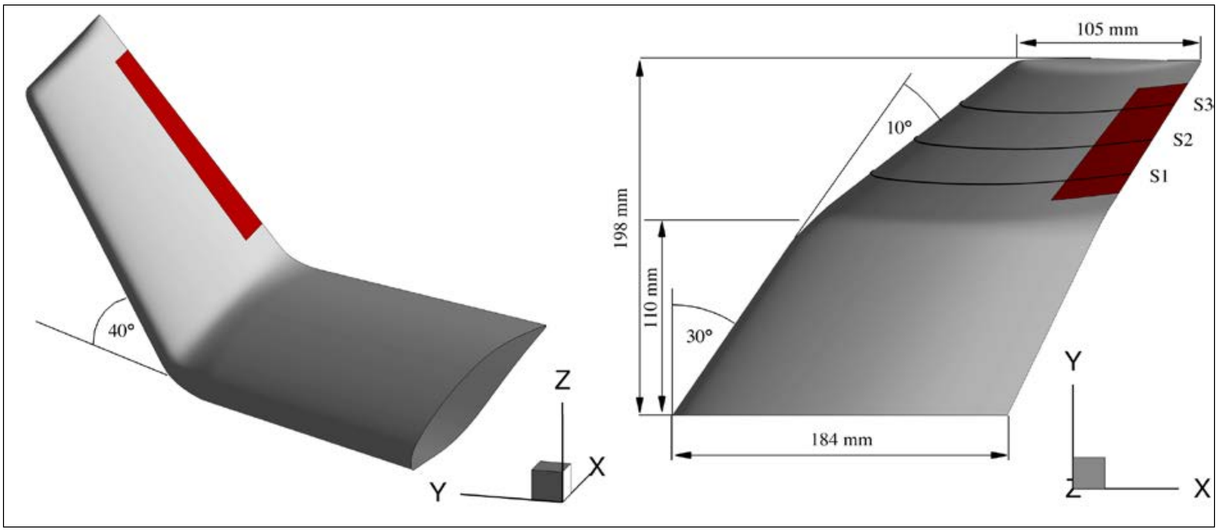

Fig 14: Winglet with control surfaces [25]

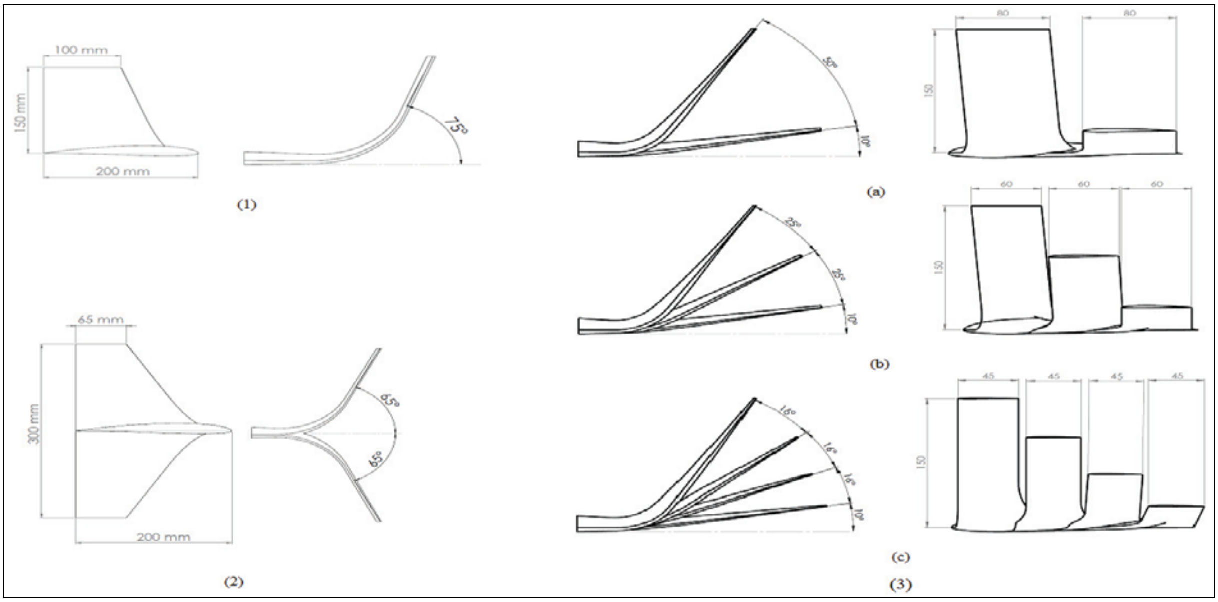

Fig 15: Different winglet designs 1. Blended (side view and front view) 2. BMAX (side view and front view) 3. a) Multi-tip-2; b) Multi-tip-3; c) Multi-tip-4 [19]

Using Ansys Fluent and the k–ω Shear Stress Transport (SST) turbulence model, Narayan and John examined the development and dispersion of vortices at the tips of wingleted wings. The L/D ratio has been studied in relation to flight aerodynamic performance. The various winglets under analysis are displayed in Figure 15. According to their reports, the blended winglet showed an improvement of 3.54%, the BMAX showed an improvement of 14,81%, the Multi-Tip-2 showed an improvement of 11.03%, the Multi-Tip-3 showed an improvement of 22.59%, and the Multi-Tip-4 showed an improvement of 20.24% [19].

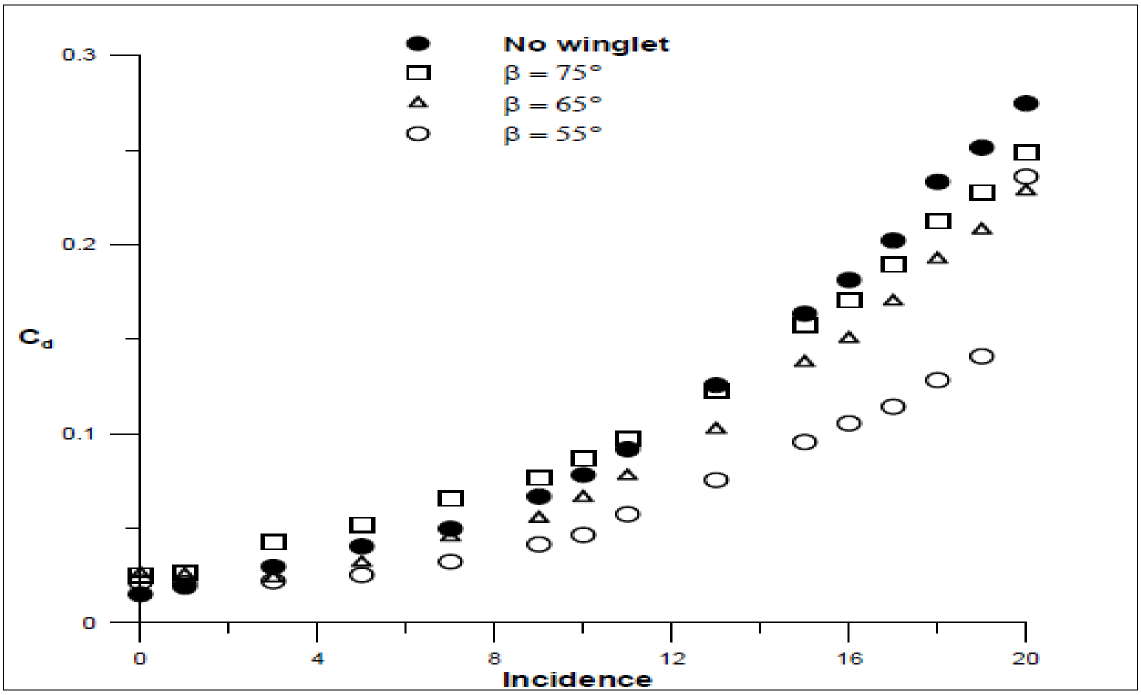

Fig 16: Variation of drag coefficient against incidence [26]

Tests conducted by Belferhat *et al.* (as shown in figure 16) to assess the effectiveness of winglets positioned at different β angles in enhancing the performance of a wing during subsonic flow. The results indicated that the upward placement of the considered winglets at the wingtip contributes to improved efficiency by reducing induced drag and increasing lift. To focus on the aerodynamic optimization of a wing equipped with upward winglets, it was noted that the aerodynamic performance of the winglet at β = 55° is more favorable for positive angles of incidence compared to other scenarios [26].

4. Different Shaped Wingtip Designs and Wingtip Devices

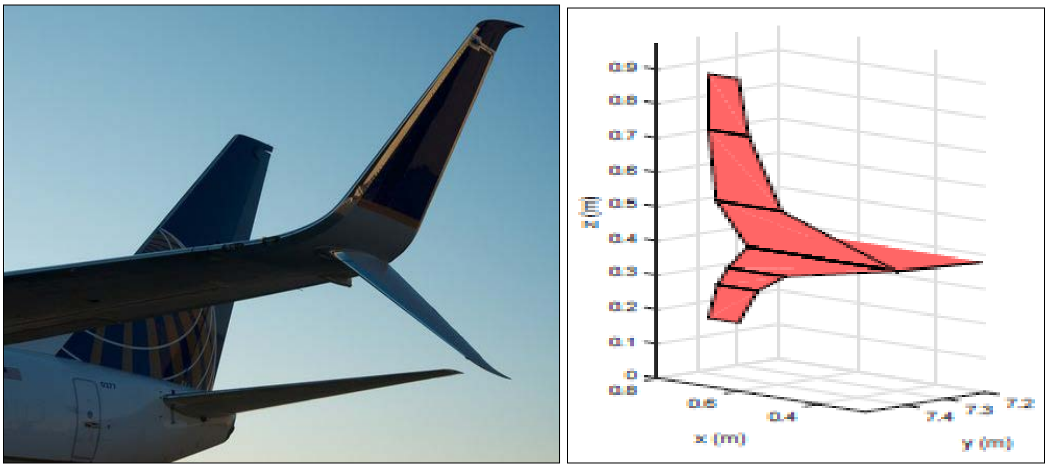

Fig 17: Split winglet by boeing (Left) & Split Winglet modeled by Kerbs [27]

An optimization-driven design approach was employed to create split-winglets for the Standard Cirrus sailplane, with one selected for detailed analysis. Compared to a traditional canted winglet designed under the same process, the split-winglet demonstrated an impressive up to 8.9% increase in the Standard Cirrus' maximum cross-country speed, particularly in low-strength thermals. Notably, the split-winglet effectively reduced sink rates during low-speed flight, with approximately 37% of the benefit attributed to the lower surface. However, the lower surface introduced a parasitic drag penalty, necessitating adherence to recommended inter-thermal cruise speeds to optimize performance. Implementation challenges, such as ground clearance and a retractable lower surface, were identified. The optimization-based design process holds potential for deeper insights into split-winglet dynamics and broader applications in tip sails and wingtip devices for small to medium-sized UAVs. Ongoing exploration of this process could further enhance understanding and implementation in aerodynamic design [27].

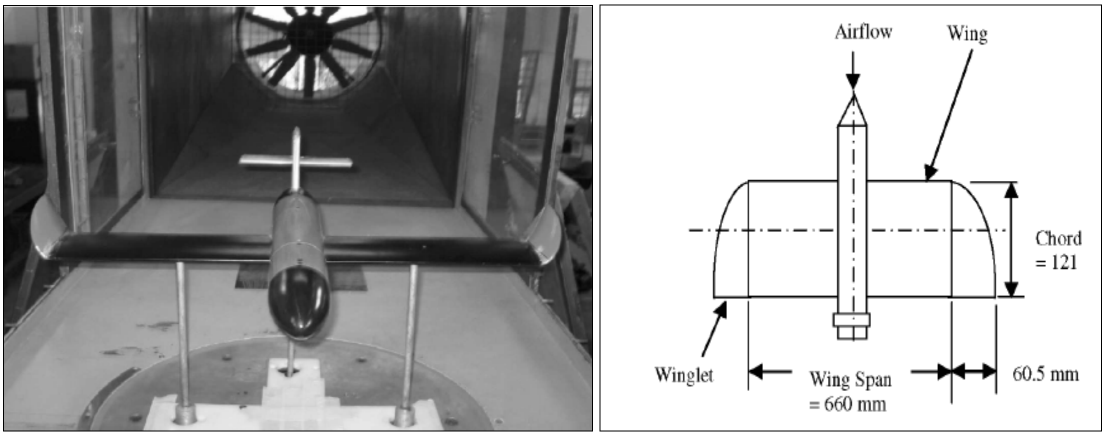

Fig 18: Elliptical winglet experimental model and schematics diagram by Arora *et al*.

The aerodynamic characteristics of the aircraft model equipped (Figure 18) with NACA 65-3-218 are outlined. The lift curve slope experiences a notable increase with the incorporation of an elliptical winglet. Simultaneously, the drag reduction is more pronounced for the aircraft model featuring an elliptical-shaped winglet, providing a distinct advantage over the winglet-less counterpart in terms of lift-to-drag ratio. Specifically, the elliptical winglet of configuration 2, with a winglet inclination of 60 degrees, exhibits the most favorable overall performance. This configuration yields an approximately 6% boost in the lift curve slope compared to the model without a winglet, establishing itself as the optimal choice for achieving the best lift-to-drag ratio among the considered configurations [28].

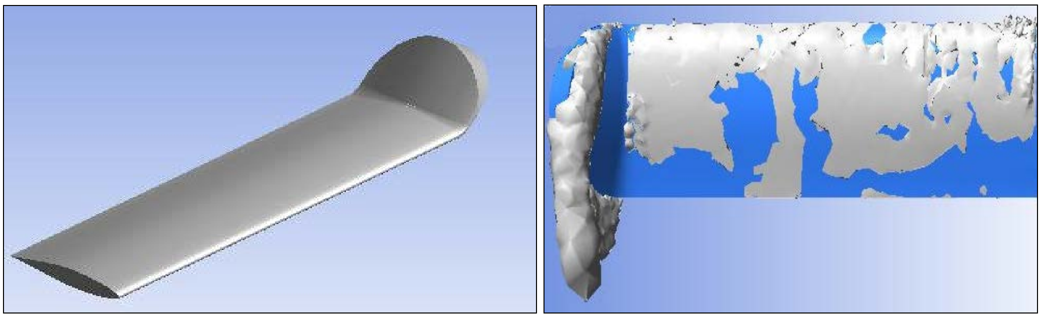

Fig 19: CAD model of semi-circular winglet along with vortex generation simulation [29]

The study by Ashrafi and Sedaghat examined a 3D wing with and without winglets in two scenarios involving simple and semi-circular winglet configurations (shown in Figure 19), employing the Control Volume Method. The results indicated that the installation of winglets led to an increase in lift coefficient and a significant reduction in drag coefficient. The presence of trailing vortices was notably diminished compared to the configuration without winglets.

The cost-effective installation of winglets, coupled with minimal structural alterations to the wing, supports their recommended utilization. The advantages encompass a reduction in wingtip vortices, an increase in lift coefficient, and decrease in drag coefficient, elevated cruise speed, improved fuel economy, and a reduction in noise levels during takeoff around airport areas. Take-off [29]

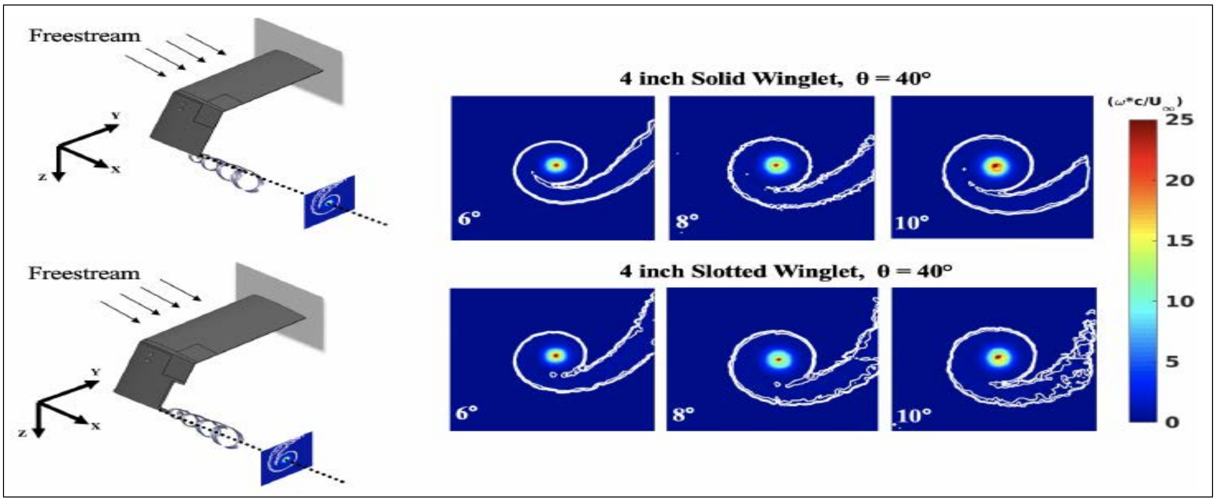

Fig 20: Vorticity contours for both solid and slotted winglets varied with angle of attack [30]

The findings regarding the slotted winglets by Josh & Sidaard indicated an intensified interaction between the wingtip vortex and the Free Stream Line (FSL). This interaction plays a pivotal role in diminishing both the generation of induced drag and the strength of the wingtip vortex. Coupled with an 11% reduction in weight, the attenuation of the wingtip vortex's strength holds substantial aerodynamic implications. This reduction can lead to a shortened duration between takeoff and landings at commercial airports, potentially accommodating increased air traffic. Furthermore, the decrease in weight contributes to diminished loads on the wing structure, leading to lower fuel consumption. Importantly, since winglets are typically implemented as post-design addons, their incorporation does not necessitate extensive modifications to existing commercial fleets, facilitating a practical and efficient integration into operational aircraft [30].

5. Conclusion

Substantial theoretical, computational, and experimental investigations have been conducted on the aerodynamic performances and optimization of various winglet and wingtip devices used on different aircraft wings. Enhancing lift and drag forces in order to raise the L/D ratio is the primary objective of the majority of these investigations. As a result, fuel efficiency will be boosted along with load capacity and range. By lessening the vortexes that form at the tips of the wings, all of this is possible.

It has been discovered that raising the L/D ratio is significantly impacted by the usage of both winglets and wingtip devices. Nonetheless, the research that have been looked at has demonstrated that using winglets is the most successful technique. Should be the major findings of your experiment. You have to compare the results with previous studies done in same.

At present, research and optimization are required for the winglets' shape, size, angle, and curvature. In a similar vein, numerous wingtip gadget types remain unexplored. When designing the winglet and wingtip devices, application of the design is also a key factor to take into account.

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