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Review Article

An overview for effects on aerodynamic performance of using winglets and wingtip devices on aircraft

Şeyda Öztürk[1], İlker Örs[2*]

[1] *Aviation Technologies, Institute of Sciences, Selçuk University, Konya, Turkey*
[2] *Department of Aircraft Maintenance and Repair, School of Civil Aviation, Selçuk University, Konya, Turkey*

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* Corresponding author
ilker.ors@selcuk.edu.tr

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Şeyda Öztürk
0000-0003-2391-5441
İlker Örs
0000-0001-8385-9846

ABSTRACT

In this study, the effects of different types of winglets and wingtip devices on aerodynamic performance in aircraft were investigated. Mostly, CFD analyzes were performed with different turbulence models in the examined studies, as well as experimental studies were also conducted. It has been observed that especially k-ε, k-ω and Sparlat Almaras turbulence models are used in calculations. As a result of the investigations, it has been observed that both the use of winglets and the use of a wingtip devices significantly reduce the vortex formation in the wingtips compared to the plain wing. It has been determined that the most effective method in reducing wing tip vortexes is the use of winglet. The reduction of these vortexes resulted in an increase in lift force and a decrease in drag force. Thus, the L/D ratio has increased and as a result; better fuel economy, longer range and higher payload are provided.

Keywords: Aircraft; Drag force; Lift Force; Winglet; Wingtip device

1. Introduction

The forces acting an aircraft during flight are weight (pulls the aircraft to the earth), lift (pushes the aircraft up), thrust (propels the aircraft forward) and drag (implements the opposite direction to motion) [1]. Figure 1 shows the forces acting on an aircraft in cruise.

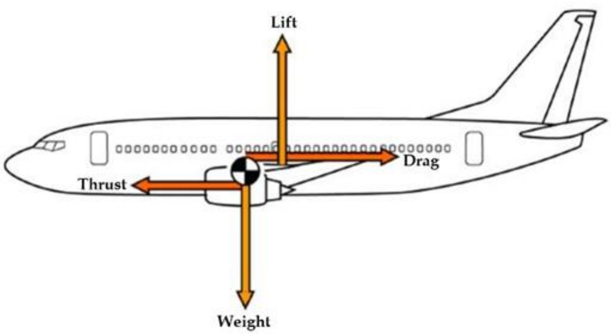


Fig. 1. The forces on an aircraft [1]

Drag is a force reverse of cruise caused by breakdown of airflow by the wing, rotor, fuselage, and other protruding objects [2]. Drag force occurs as two types which are parasite drag and induced drag [3]. Parasite drag consists of structural forces other than lift that work to slow the motion of an aircraft. Parasite drag can be investigated as three kinds which are form drag, skin friction, and interference drag. Form drag arises from the pressure difference created by the flow around objects moving in the opposite direction to the air flow. Streamlining as many of the parts in the outer fuselage of the aircraft as possible is the easiest to reduce of form drag when designing an aircraft. Therefore, form drag can be to minimized thanks to aerodynamic design of aircraft parts. Skin friction drag arises from the contact between the aircraft surface and the air flowing over it. In order to reduce the effect of skin friction drag, flush mount rivets utilized for assembly of parts situated above fuselage. Thus, irregularities on all surface of aircraft is removed. The aerodynamics effects on form drag and skin friction drag of shape design has been seen in Figure 2.

Interference drag occurs by meet of different air flows formed in areas where it joins of different parts such as wings, fuselage and tail [3,5]. Three types of parasite drag have been presented in Figure 3.

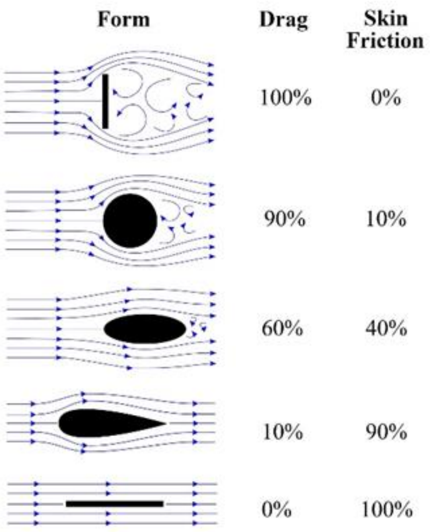


Fig. 2. Form drag and skin friction drag of different body [4]

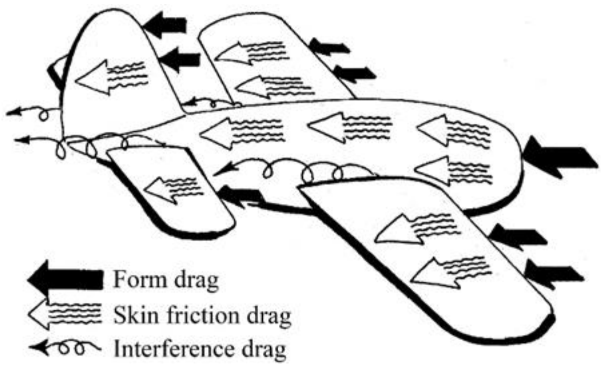


Fig. 3. Form drag, skin friction drag and interference drag [6]

The second main type of drag is induced drag. Induced drag occurs due to the lift force on the wing. During a level flight, induced drag is usual whenever an airfoil (wing or rotor blade) is producing lift. While the lift force is generated by airfoil, the wing colliding with the air pushes the air downwards, leaving a vortex behind, creating a highly mixed flow form. Thanks to the air pushed down due to wing's aerodynamics structure, the pressure on the lower surface of wing is greater than that on its upper surface according to Bernoulli's Principle. The air pushed down flows out from the tip of the wing. The air tends to flow from the high pressure area below the tip upward to the low pressure area on the upper surface. In the vicinity of the tips, there is a tendency for these pressures to equalize, resulting in a lateral flow outward from the underside to the upper surface. This phenomenon imparts a rotational velocity to the air at the tips, causes two large eddies behind both wings of an aircraft [3,5]. Consequently, it can be said that induced drag is the penalty to get the force needed to take off an aircraft. This induced drag that occurs and its formation is shown in Fig. 4. The vortexes occurred behind the wings cause the induced drag force that causes energy loss in aircraft. These vortex formations as a result of lift force is not depend on just the shape of the wing tip, and they are not possible to completely eliminate these vortices. Especially the drag force occurring during straight flight and take-off directly affects the fuel consumption.

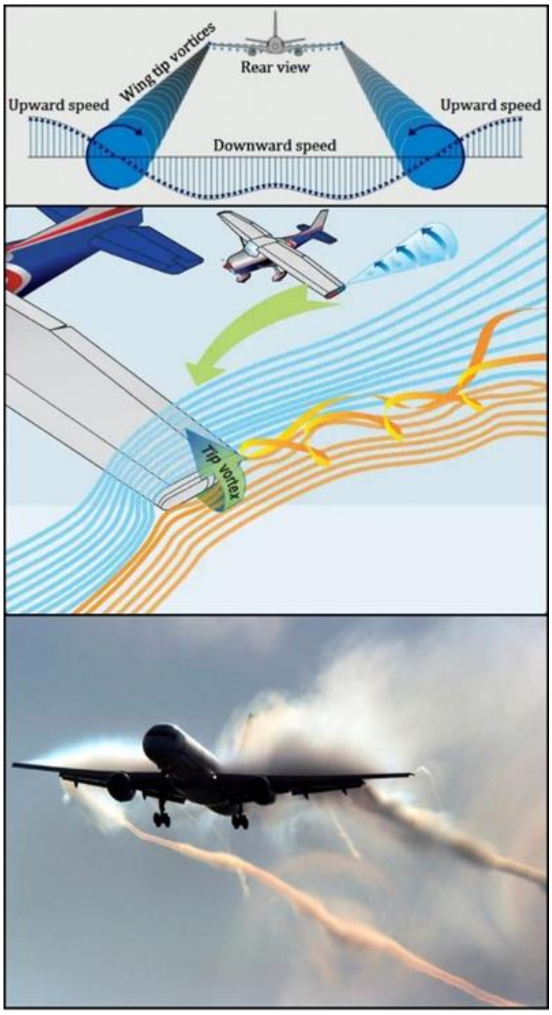


Fig. 4. The induced drag and formation [7-9]

The induced drag force accounts for a significant portion of the total drag forces. A reduction in vorticities caused by drag would be provided an improvement approximately up to 20% for drag force [10]. Besides, passenger and cargo carrying capacities of aircraft will also expand thanks to this improvement [11]. Therefore, many researches have performed in order to reduce of negative effects caused by this force such as increasing the wing span, wingtip devices [12-14], winglets [15,16], and other wingtip structures [17,18].

In this study, studies that numerically and experimentally analyzed different aircraft wingtip designs to reduce drag force in aircrafts were investigated. Thus, the aerodynamic behavior of the winglets and wingtip devices types used today or designed to be usable has been exhibited.

2. Numerical Model of Drag and Lift

It is important to model the drag force of an aircraft numerically. This force is calculated with equation 1 in basic.

$$D = qC_DA \quad (1)$$

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:

$$q = \frac{1}{2}\rho V^2 \quad (2)$$

C_D according to equations 1 and 2 is:

$$C_D = \frac{2D}{\rho V^2 A} \quad (3)$$

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

$$C_L = \frac{2L}{\rho V^2 A} \quad (4)$$

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.

3. Winglets Analysis

Winglets are an aerodynamic improvement often used in today's aircraft. Many experimental and numerical studies have been carried out by examining parameters such as shapes, angles and lengths of the winglets.
The first studies that the wing tip design would reduce the drag force were carried out by Frederick W. Lanchester in 1897. Afterwards, Whitcomb et al. determined the decrease in drag force with wind tunnel tests by placing some vertical pieces on the wing tip as seen in Figure 5. As a result of their study, they predicted that there could be a 20% decrease in induced drag at high cruising speeds and a 6% increase in range [19].

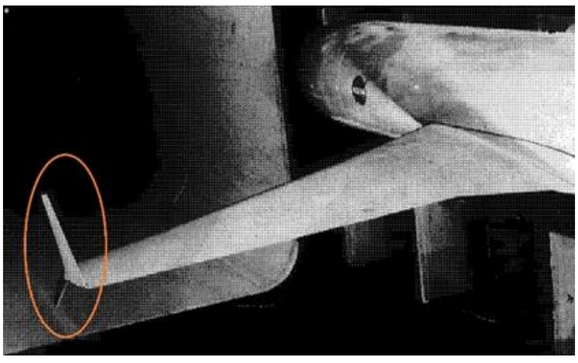


Fig. 5. Winglet designed by Whitcomb et al.

These wing tip designs of Whitcomb et al. have minimized interference drag due to wing and winglet connection points, thanks to the winglet structure designed (in Figure 6.) and patented by Gratzer [20].

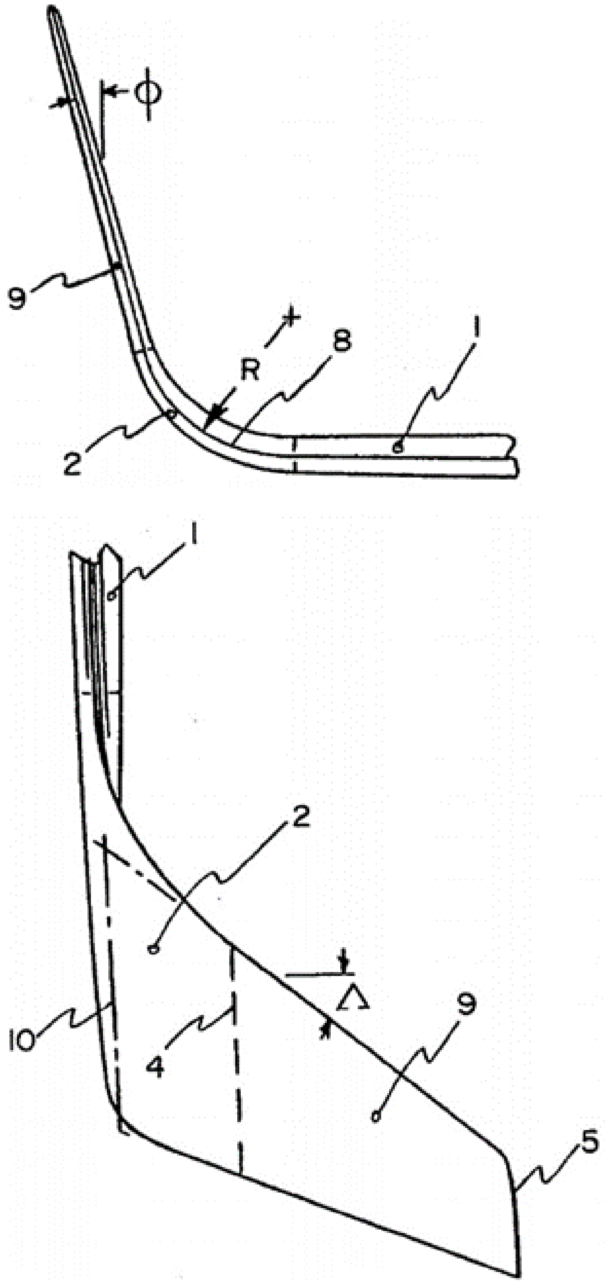


Fig. 6. Winglet patented by Gratzer

Gavrilović et al. [12], in studies aiming to increase the performance of a commercial aircraft by using different types of winglets, they have been investigated to effects on CL/CD ratio, range and passenger capacity parameters of blended winglet and maxi winglet as numeric with CFD simulation of ANSYS-FLUENT. The blended and maxi winglets, and without winglet are presented in Figure 7.
As results, they presented that both blended winglet and maxi winglet improved C_L/C_D ratio by 3.93% and 5.32% respectively, extended of range distances 303 km for blended

winglet and 415 km for maxi winglet. Besides, it has been shown that important decreases in passenger amount and fuel consumption [12]. Bargsten and Gibson [13] also reported that wing tip vortexes were decreased significantly thanks to blended winglet as shown in Figure 8.

Fig. 7. Blended winglet on top, maxi winglet on bottom [12]

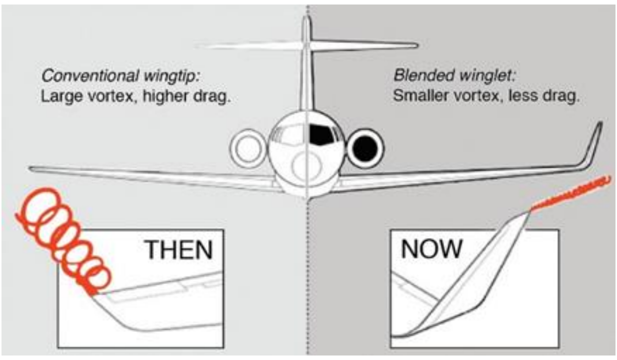


Fig. 8. The effect on wing tip vortex of blended winglet [13]

Panagiotou et al. [15] performed the optimization of different blade angles (50º, 60º, 70º, and 90º) for a Medium-Altitude-Long-Endurance Unmanned-Aerial-Vehicle according to C_D, C_L and L/D values with ANSYS-CFX flow solver. Although they achieved a maximum C_L value of 1.82 at 90º, they found the best L/D ratio at 50º as 22.85. However, they noted that, thanks to the optimization, there was a 7.8% improvement in the L/D ratio, as a result, the total flight time of the vehicle could be increased by about 10%. Figure 9 is shown designed winglet.

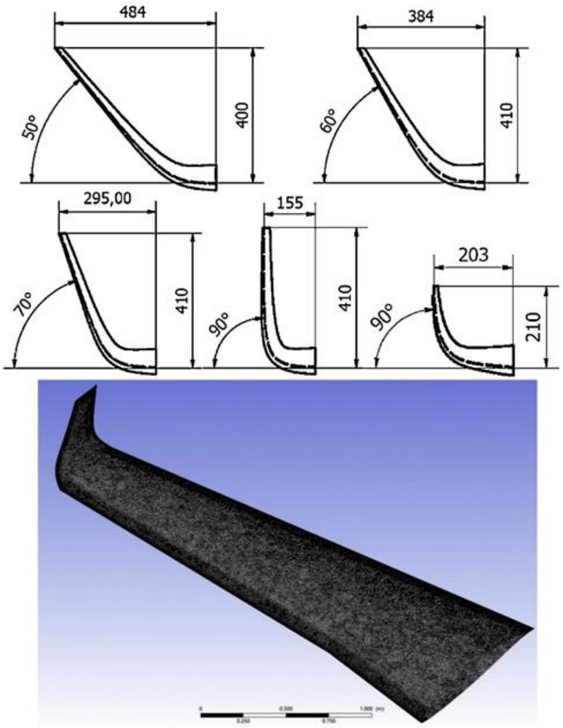


Fig. 9. Difference angle winglets [15]

Babigian and Hayashibara [21] analyzed the intensity of the vortices formed by winglet in the wingtip as three dimensions with FLUENT using the Spalart-Allmaras turbulence model. As a result, they found that the formation of vortices at the wing tips of an aircraft in motion is reduced as seen in Figure 10. and thus the drag force also decreases. They have also shown that a wing with a curvature angle winglet can be used effectively.

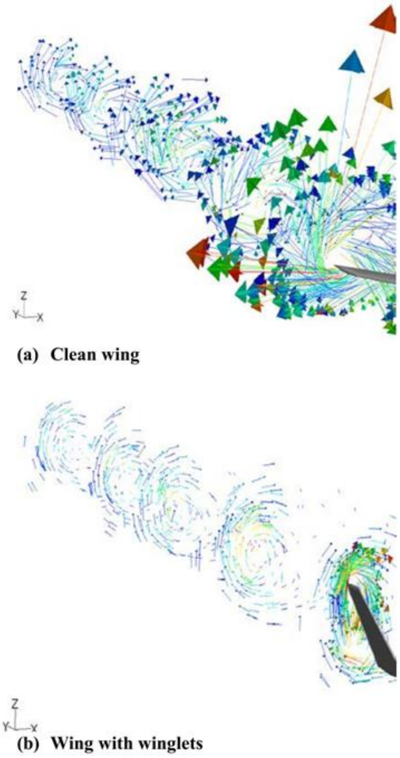


Fig. 10. The effects on the vortices intensity of winglet [21]

Mattos et al. [22], examined the effect of winglets in the wing tips on the drag force of an Embraer 170 model airplane (in Figure 11) in three dimensions with FLUENT (in Figure 12). As a result, they stated that there was a 4.5% reduction in the total drag force tanks to the winglets.

Fig. 11. The Embraer 170 model airplane

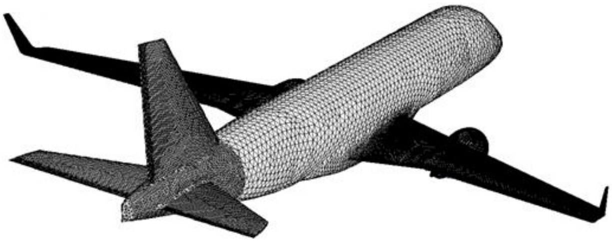


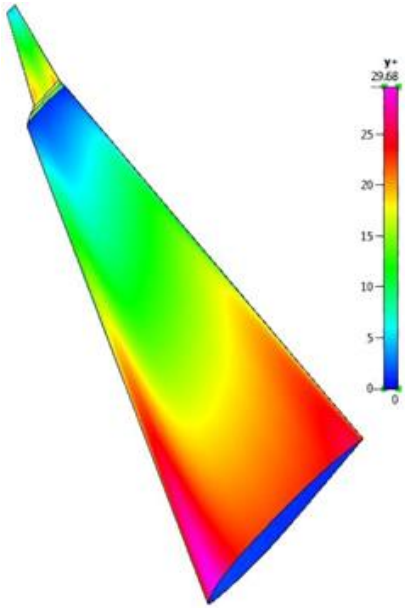
Fig. 12. Triangular surface mesh of an Embraer 170 computational model

Kim optimized three different winglet designs for a Boeing 747-100 model aircraft. He used "Athena Vortex Lattice (AVL)" software for CFD simulation. He made CFD calculations with using called "Reynolds Averaged Navier-Stokes" or RANS, and the k-ε turbulence model which is using two partial differential transport equations. It demonstrated that the induced drag was reduced by 12.5% thanks to the optimized winglet shown in Figure 13 [23].

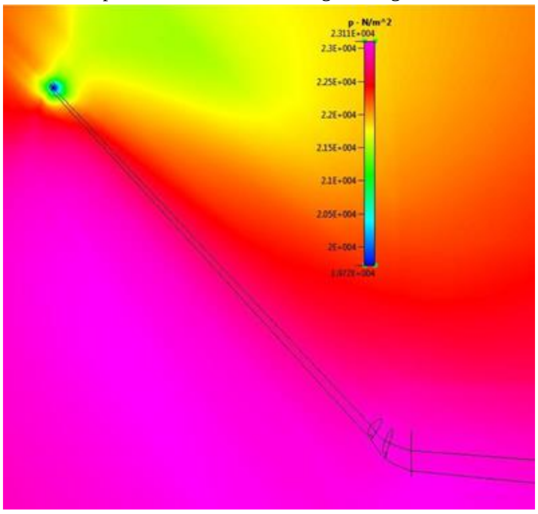
The distance from the wall to the first grid line of the mesh is a function of the y+ value, which defines how coarse or fine a mesh is for given turbulent conditions.

Yahaya et al. [24] examined the flow around Whitcomb winglets both numerically and experimentally at a Reynolds number of 2.33x106. They used FLUENT methods for numerical analysis and PIV (Particle Image Velocimetry) methods for experimental analysis. As a result, they have shown in Figure 14 that the vortex formation around the Whitcomb winglets is less than the vortex formation at the wing tip without the winglets, so that the induced drag is reduced.

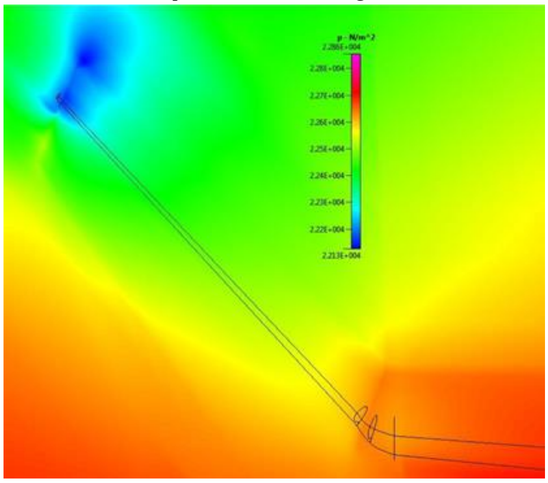
Brüderlin et al. [25] placed vortex generators on the winglet bottom surface as shown in Figure 15 to increase the effectiveness of the winglet control surface. A solver named TAU developed by "German Aerospace Center (DLR)" was used for simulation analysis in their studies. This solver is designed to solve the time-dependent compressible RANS equations for perfect gases. Vortex generators are modeled as slender cuboids. Vortex generators change flow towards the wing tip and create eddies. These eddies increase the kinetic energy in the boundary layer, causing the flow separation to be delayed. Vortex generators redirect the flow, increasing lift.



Y+ contour plot on the surface of winglet wing in laminar flow



Pressure contour plot 0.5m behind winglet in laminar flow



Pressure contour plot 3.5m behind winglet in laminar flow

Fig.13. CFD analysis of the fin optimized by Kim

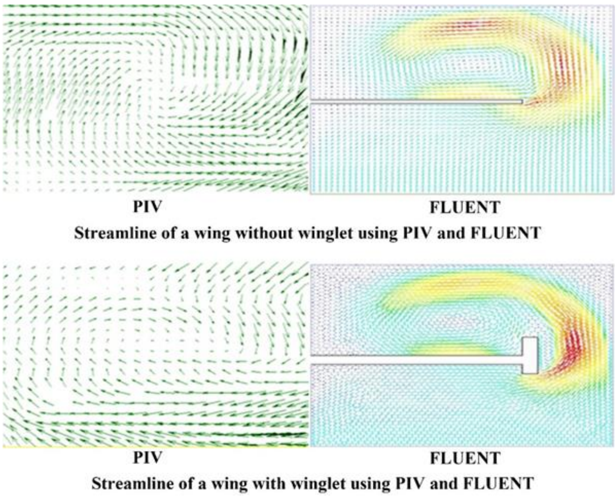


Fig.14. The flow around Whitcomb winglet and clean wing

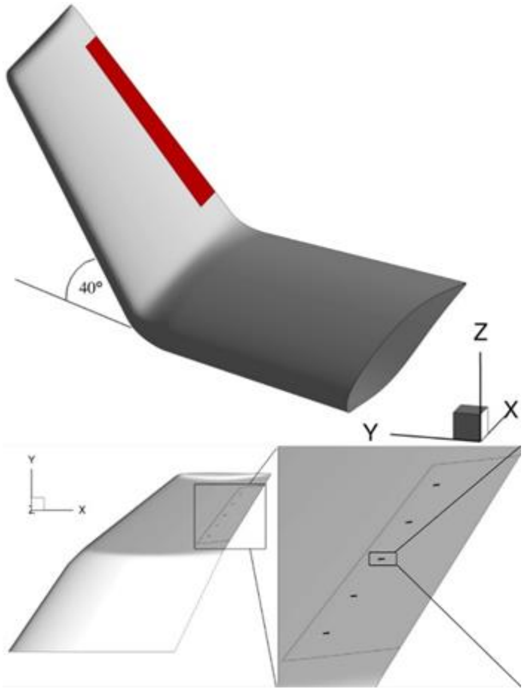


Fig. 15. Winglet and vortex generators

In their study, Narayan and John [18] analyzed the formation and distribution of vortices at the tips of wingleted wings using Ansys Fluent and the k–ω Shear Stress Transport (SST) turbulence model. L/D ratio has been examined as aerodynamic performance during flight. Figure 16 shows the different winglets analyzed. As a result, they have reported a 3.54% improvement with the blended winglet, and 14,81% improvement with the BMAX, and 11.03% improvement with the Multi-Tip-2, and 22.59% improvement with the Multi-Tip-3, and 20.24% improvement with the Multi-Tip-4. Hossain et al. [27] analyzed an elliptical winglet and circular winglet application on the wings of a CN-235 model aircraft in a wind tunnel as seen in Figure 17. They obtained the highest L/D ratio with 60° angular elliptical winglet. Thanks to the elliptical winglet, an improvement of 6% and 28% was achieved in lifting and drag forces, respectively.

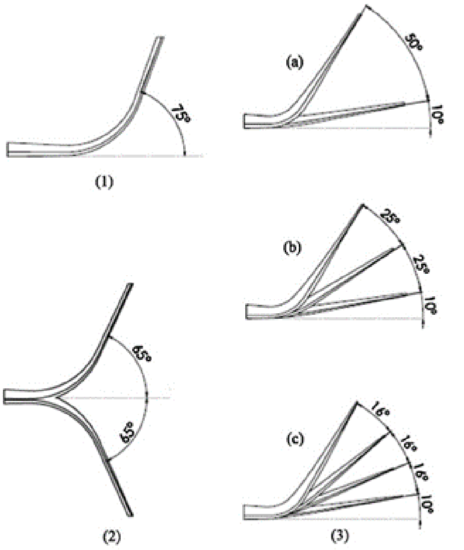


Fig. 16. Different winglet designs 1. Blended 2. BMAX 3. a) Multi-tip-2; b) Multi-tip-3; c) Multi-tip-4

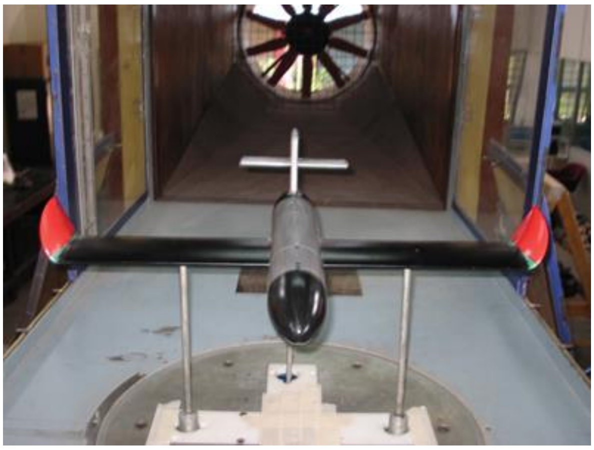


Fig. 17. Airplane model with winglet in wing tunnel

Karaoğlu analyzed the 60° pointed angle winglet model of the CN-235 CASA aircraft seen in Figure 18 with the CFD method. CFD analyzes were performed in k-ε, k-ω and Sparlat Almaras models at 1.7, 2.1 and 2.5 Reynolds numbers. The highest C_L/C_D values were obtained at 2.5 Reynolds number for all models. Also, the highest C_L/C_D values for k-ε, k-ω and Sparlat Almaras models were found to be approximately 9.07, 3.28 and 14.68, respectively.

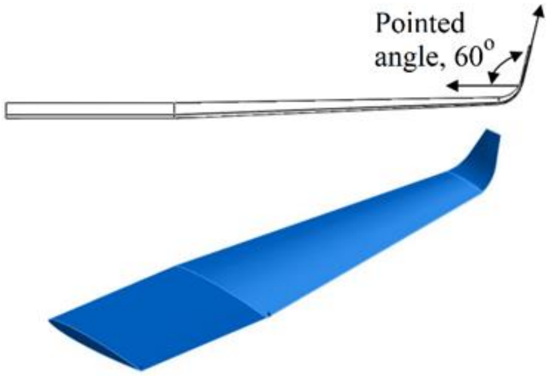


Fig. 17. The model of wing with winglet

Ekinci [3], in order to control the formation of vortices at the tip of the CN 235 aircraft wing, winglets of different angles (5, 10, 25, 45, 60, 75, 85 and 90°) are used in four different turbulence models (Spalart-Allmaras, SST k-ω, k-ε Realizable and Transition SST) analyzed with ANSYS FLUENT. As a result, the best L/D value was obtained with 45° winglet inclination angle. In addition, L/D values for Spalart-Allmaras, SST k-ω, k-ε Realizable and Transition SST turbulence models are 28.425, 27.9, 27.82 and 28.85, respectively. Figure 18 shows the model of the 45o winglet inclination angled wing, velocity streamlines, vortex formation of wing with winglet, and vortex formation of the plain wing. In addition, he calculated that the range of the aircraft raised by 4.78%, an increment 208 km.

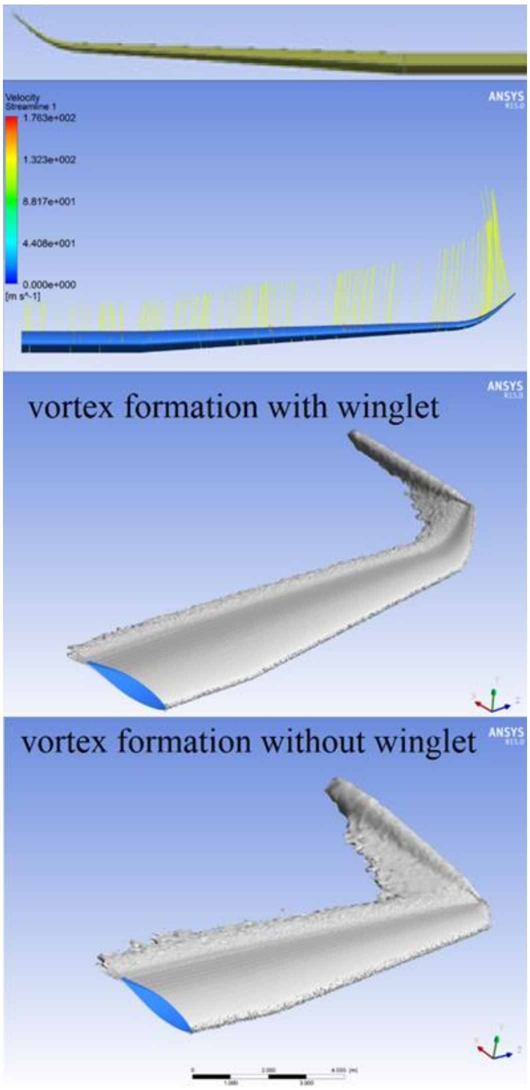


Fig. 18. The compare of vortex formation on wing with and without winglet

4. Analysis of Different Shaped Wingtip Designs and Wingtip Devices

Figure 19 shows examples of different wingtip designs. Apart from these designs, many wingtip designs are available. Under this heading, the effects of some of these designs on aerodynamic properties are examined.

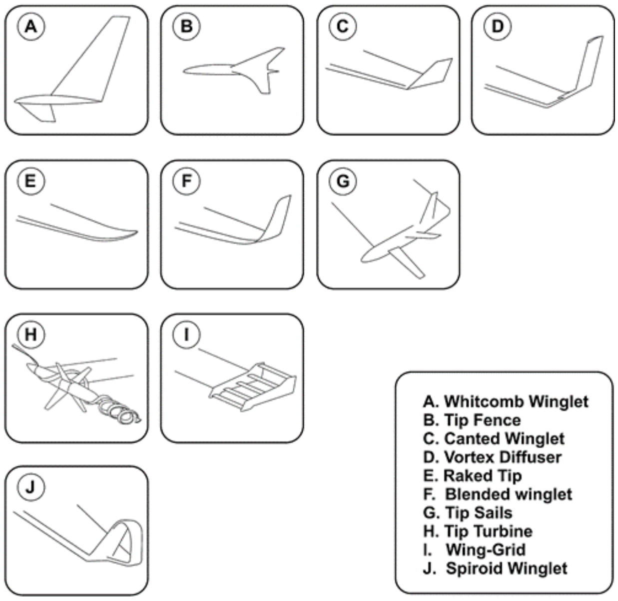


Fig. 19. Some wingtip design examples [17]

Ekinci investigated the aerodynamics analysis of different wing tip devices applications on the tip of the CN 235 aircraft wing, shown in Figure 20, with CFD at ANSYS FLUENT. As a result, it was revealed that POD and FENS wingtip devices decreased the L/D ratio approximately 0.91 and 0.93 times, respectively, while SCIMITAR wingtip device increased approximately 1.4 times [3].

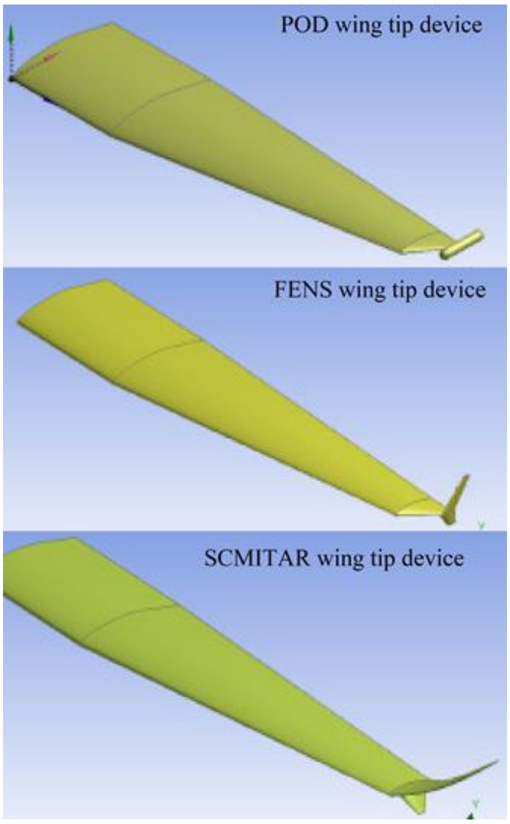


Fig. 20. Different wing tip devices

Wan et al. [29] compared the aerodynamic properties of a modern spiroid winglet with a conventional winglet at seven different angles of attack (0, 2, 4, 7, 10, 13 and 16 degrees) for an airplane wing. Figure 21 shows the pressure distributions over the spiroid winglet and the conventional winglet. As a result of the CFD analysis made with ANSYS FLUENT, the highest L/D ratios were obtained at 4-degree angle of attack. However, they found that compared with the plain wing, the L/D value of the conventional winglet improved approximately 3.06% and the modern spiroid winglet improved by 5.68%, while the L/D value of the modern spiroid winglet increased by 2.55% compared to the conventional winglet.

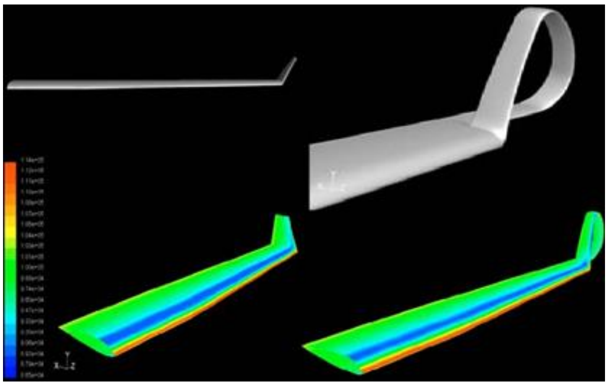


Fig. 21. The pressure distributions over the spiroid winglet and the conventional winglet

In the studies of Reddy et al. [30], where they analyzed the aerodynamic effect of scimitar winglet type wing tip design numerically with the standard k-ε turbulence model in OpenFOAM Navier-Stokes solver, the optimized scimitar winglet with C_L/C_D ratio was increased 14.48% compare to the plain wing, and 6.23% compared to blended winglet. Figure 22 shows the streamlines of the wings analyzed together with the optimized scimitar winglet.

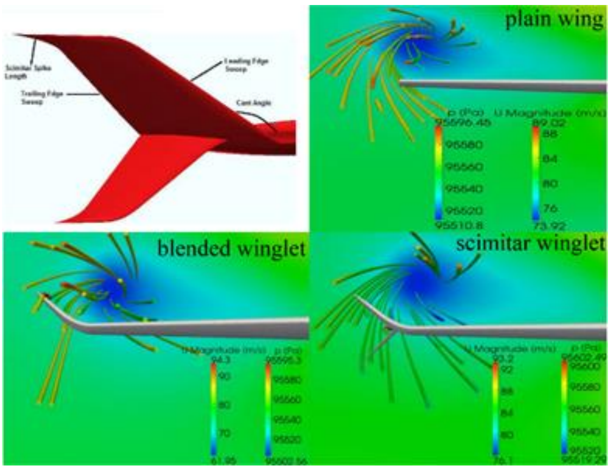


Fig. 22. The optimized scimitar winglet design and streamlines of all wings

Falcao et al. [31], by examining an adaptive and controllable winglet they developed under different cruise conditions, achieved improvement for 25.32% in C_L value at minimum stall speed, 2.58% in C_D value at minimum turn radius and 4.02% in C_D value at maximum top speed. This winglet is shown in Figure 23.

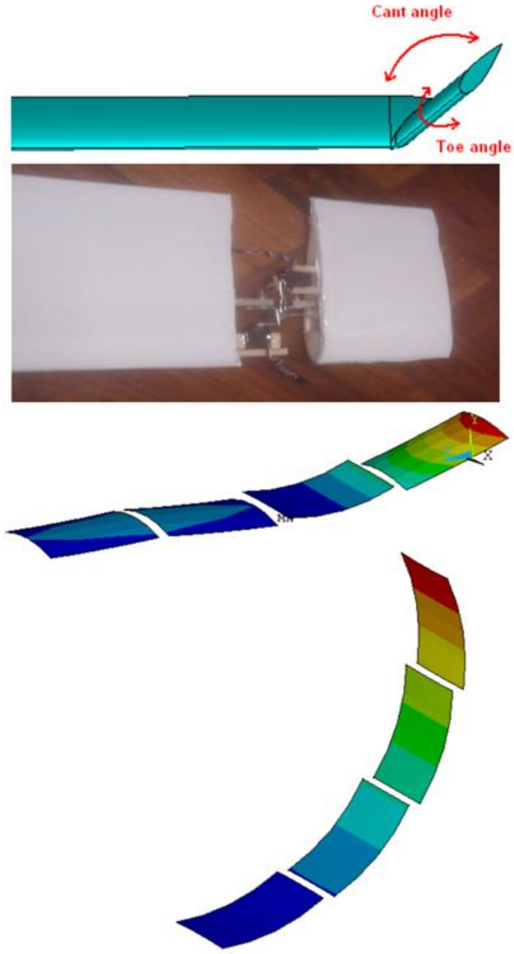


Fig. 23. The adaptive and controllable winglet

Ashrafi and Sedaghat [32] examined the effect of using a semi-circular winglet on aerodynamic performance. As a result, as can be seen in Figure 24, they stated that the wingtip vortexes decreased, the drag coefficient decreased while the lift coefficient increased, higher cruise speed was achieved, fuel economy improved and noise decreased.

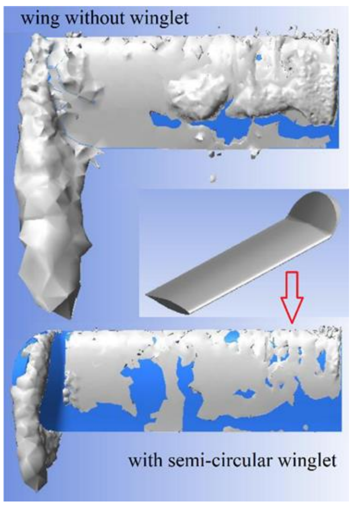


Fig. 24. The vortex formation on wings with and without winglets

In order to increase the aerodynamic performance of unmanned aerial vehicles, wingtip design applications were analyzed. As an example of these applications;

Shelton et al. [33] designed active multiple winglets shown in Figure 25 to increase the performance of an unmanned aerial vehicle. As a result, they showed that with the use of active multiple winglets, the range increased by 40%, and the load carrying capacity increased by rising the L / D ratio. In addition, thanks to the active winglets, the effects of wind impact on the vehicle have been removed and the driving improvement ability has been increased. Thus, they demonstrated that active winglets are applicable for unmanned aerial vehicles.

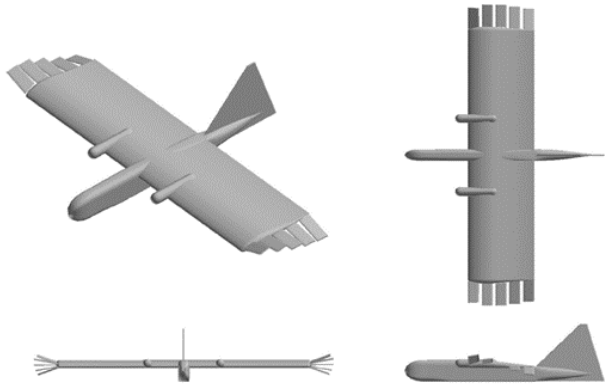


Fig. 25. The active multiple winglets designed for UAV

Gölcük [34] designed winglets in different angle of inclination for the unmanned aerial vehicle wingtip which have a rectangular profile, and reduced drag force by 4.5%. Figure 26 shows the unmanned aerial vehicle after design and the winglet which is 45 ° ellipse rotation at winglet cant 59.4 °.

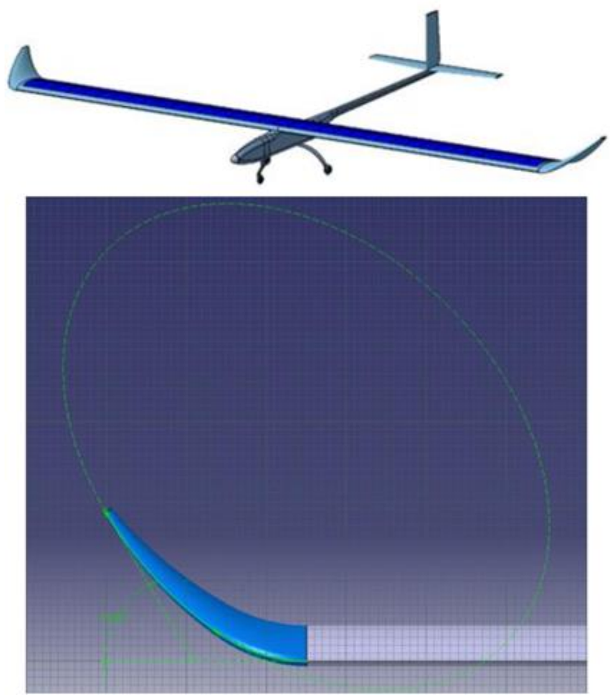


Fig. 26. Unmanned aerial vehicle and designed winglet

Panagiotou et al. [35], using the ANSYS CFX program with the Spalart-Allmaras turbulence model, compared the wing of a medium-altitude-long-flight unmanned aerial vehicle with a 60° winglet angle wing design. They stated that the use of winglet increased the flight time by 10%. Figure 27 shows the model of the unmanned aerial vehicle with winglet.

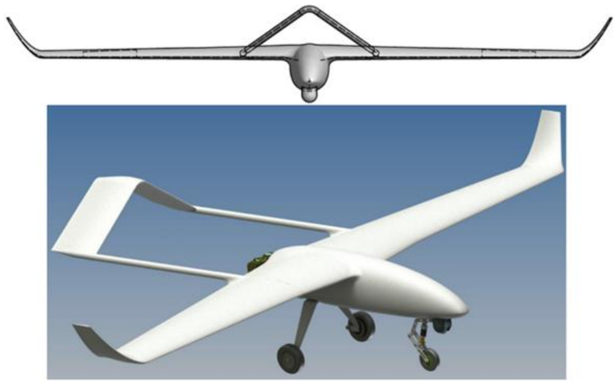


Fig. 27. The model of the unmanned aerial vehicle with winglet

Turangöz [36] compared the aerodynamic characteristics of three different wingtip designs in Figure 28 used in an unmanned aerial vehicle with those of the plain wing. It found the best C_L/C_D ratio with the use of blade winglet as 22 at cruise time and 24.4 at maximum.

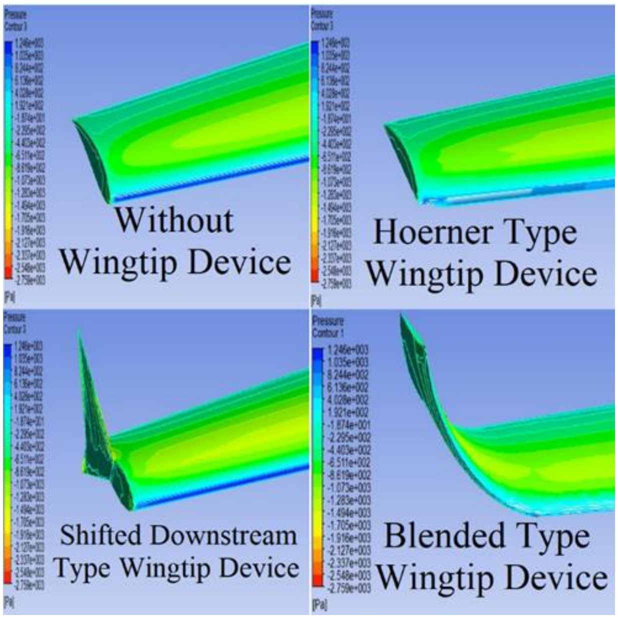


Fig. 28. Various wingtip geometries

5. Conclusion

Many theoretical, numerical and experimental studies on the optimization and aerodynamic performances of numerous winglet and wingtip devices applied for various aircraft wings have been studied. In most of these studies, the main goal is to improve lift and drag forces, and therefore increase the L/D ratio. Thus, fuel savings will be achieved and range and load capacity will be increased. All this can be achieved by reducing the vortexes occurring at the wing tip.

It has been found that both the use of winglet and the wingtip device have an important effect on increasing the L/D ratio. However, it has been shown in the studies examined that the most effective method is the use of winglet. On the other hand, it is seen that the angle of attack is also effective in winglet and wingtip devices.

Currently, the parameters of the winglets such as angle, curvature, shape and size need to be developed and optimized. Similarly, there are many types of wingtip devices that have not yet been studied. The applicability of the design is also an important consideration while designing both the winglet and wingtip device.

Acknowledgment
This paper has been occurred from Msc. Thesis of Şeyda Öztürk.

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