A CFD ANALYSIS OF WINGTIP DEVICES TO IMPROVE LIFT AND DRAG CHARACTERISTICS OF AIRCRAFT WING

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Abstract. The present study investigates the use of various wingtip devices to analyse the parameters of lift and drag for an aircraft wing. The coefficients of lift and drag are investigated in this research to optimize the wing design for enhancing the aircraft performance. A reduction in the drag produced due to wingtip vortices leads to reduced fuel consumption which contributes to the reduction in fuel emissions. The two-dimensional analysis is carried out for the selection of an apposite aerofoil by comparing the lift/drag characteristics of NACA 0012, 2415 and 23015 respectively at the velocity of 79.16 m/s at the angles of attack of 0°, 4°, 8°, 12°, 16° and 20°. The aerofoil section NACA 2415 is used to design the three-dimensional aircraft wing. For the analysis of the various wing tip devices the three-dimensional wing is incorporated with the spiroid winglet, blended winglet, wingtip fence and a mini-winglet. The CFD analysis for the wing designs is carried out for the take-off and landing phases of an aircraft’s flight because the effect of vortices is the highest during these flight phases. The angles of attack range from 0° to 20°. The CFD results reveal that for the wing designs, the plain wing produced the highest drag and the blended winglet proved to be the wingtip device with the most beneficial design. The results obtained for the 30° cant angled blended winglet and 60° cant angled wingtip fence produces additional lift when compared to the results obtained for the counterpart designs. The results obtained from the analysis are in close correlation to the established use of the wingtip devices.

Keywords: Computational Fluid Dynamics, Wingtip Devices.

1. Introduction
The vortex theory of an airfoil’s lift was developed in the early 1900’s and most notably by Prandtl in 1918. The identification of the wing-tip vortices led to the initial explanation that the spinning mass of air was in the shape of an ellipse. It was Frederick W. Lanchester and Ludwig Prandtl’s insightful notion and investigation of fluid mechanics which elaborated that the cylindrical air entraining a wing is equal in diameter to the span [1]. The creation of the vortices at the wingtip is defined as air’s spillage from the wing’s bottom side to the top surface, owed to the pressure difference between the top and the bottom surface. The production of drag caused by this difference in pressure above and below the wing’s surface, induced drag, poses a great threat to the flight performance. The wingtip...
vortices cause the induced drag to increase hence causing a reduction in lift and a rise in drag. The vortex strength is dependent on the factors of weight, speed and shape of the wing of the aircraft. Owing to the dangerous impact of wake turbulence the take-off, climb and descent phases of flight are the most crucial flight phase. In an effort to achieve reduction in the production of induced drag a variation in the design of the wing tip was suggested as one of the possible techniques. Frederick W. Lanchester, in the year 1897 patented the use of end-plates at the wingtips for monitoring the vortices produced at wingtips [2]. In the early 1970’s NASA’s Richard T. Whitcomb invented wingtip extensions which were almost vertical with the intention to enhancing the wing lift-to-drag performance by producing an increase in the parameters [3]. Winglets effectively avert the flow of air from the tip vortex in turn reducing the drag.

In this research CFD study is performed to investigate the effect of wingtip devices on the coefficients of lift and drag. The values attained are analysed to suggest the most optimum design during take-off and landing. This study also analyses the effect the varying cant angle produces on the flight characteristics of the aircraft. Earlier research has been conducted for blended winglets [4], multiple winglets [5] and spiroid winglets [6] however this research specifically combines the results for the not only the wingtip devices being used but also presents the effects produced by changing the cant angles of the selected devices.

2. Literature Review
During the take-off phase of flight for an aeroplane the formation of wingtip vortices contributes up to 60% of the total drag [7]. Raj and Thomas [8] concluded that for the period of cruise 40% of the total drag and during take-off conditions 80-90% of the over-all drag is owing to induced drag. Mattos, Macedo, and Filho [9] further elaborated that with the addition of wingtip devices to the wings aim at the decrease in the production of induced drag. The induced drag makes up to 30% to 40% of the entire drag for a transport category aircraft at the cruise condition for a long-range flight and also has a noticeable downgrade effect on the climb performance for an aircraft. In 1986 NASA [10] assessed various drag reduction devices at the wing tip; winglets, feathers, and sails, and observed that the use of such devices designed as an integral part of the wing could lead to the decrease in drag created due to lift producing components by 10% to 15%. Analogous research was also carried out by Smith et al. [11] to examine the decrease of induced drag by investigating the capability of multi-winglets for the same aircraft wing’s span.

In 1994, Louis B. Gratzer acquired the patents for the most widely used winglet, blended winglet. Gratzer [12] defined the shape of blended winglets as a wing-like surface encompassing a blended surface for enhancing lift attached to an aircraft’s wingtip for a selected surface size of the wing to attain minimum induced drag. Aviation Partners Inc. was the first to introduce blended winglets for the Gulfstream aircraft in 1992. For the enhancement in the design of blended winglets Aviation Partners Inc. and Boeing collaborated in the year 1999. The finalisation of the design and patent of the blended winglet lead to its installation on a number of Boeing aircrafts and its variants i.e. B737, B757, and B767. The used of these winglets contributed to superior take off performance, reduction in engine maintenance costs and also contribute in lowering noise and emissions along with the 6% reduction in drag. Narayana et al.’s [13] aerodynamic analysis for a rectangular wing using XFLR5 deduced that a 4.33% increase in the Cl/C0 ratio for a wing was recorded for an increase in wing span, for a wing using winglets the calculated increase is 6.63% and 4.83% increase was evident for a wing with blended winglet. The evaluation of five types of wingtip devices for commercial aircraft model for cruise conditions at various angles of attack was investigated by Gavrilović et al. [14]. The analysis included spiroid wingtip, blended winglet, maxi wingtip, wing fence and spiroid 2. The results obtained showed the maximum percentage improvement of 5% due to the use of maxi wingtip and 3.78% for blended winglet. Another CFD simulation emphasised on the wing of a Boeing 737-800 with and without winglet was conducted by Atique et al. [15]. The analysis determined that at an angle of attack of 4° the drag decline was about 40.13% at 0.35 mach in comparison to the lessening of drag for flight between 0.5 Mach number and 0.6 Mach number was a minimum of 3.47%. 

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3. Methodology

3.1. Design of 2D aerofoil and 3D wing

In order to investigate the usage of wingtip devices, the selection of the 2D aerofoil to be used for the construction of the 3D is performed. The 2D aerofoil sections for NACA 0012, NACA 2415 and NACA 23015 have been designed using a CSV file for importing coordinates to make the profile for the selected aerofoils. The 3D wing is constructed by using the CSV coordinate file format in the 3D CAD module of STAR CCM+. The values for the wing design have been postulated by closely following Airbus A320’s wing. The wing span is measured as 15 m. The wing has also been designed with the wingtip devices; blended winglet, wingtip fence, spiroid winglet and mini-winglet for the study. The complete wing design is shown in Fig. 1.

![3D wing completed design](image)

Fig. 1: 3D wing completed design

The basic configuration for the plain wing with an augmented aerofoil profile at the tip of the wing is created for the blended type winglet. The design of the winglet consists of varying cant angles of 30°, 45° and 60° to evaluate the optimum design characteristic. The layouts of the varied cant angled winglets are shown in Fig. 2.

![Blended winglet design](image)

Fig. 2: Blended winglet design

The spiroid winglet is designed with a simplified semi-circular profile, the second design is based on a varying aerofoil chord length and the third design incorporated parallelogram shaped spiroid. The three configurations of the spiroid designed winglets are shown in Fig. 3.

![Spiroid winglet designs](image)

Fig. 3: Spiroid winglet designs

The profile of the wingtip fence incorporates an extended surface above and the other below the wingtip. NACA 2415 is used to form the wingtip fence. The design is further constructed by varying the aerofoil’s upper surface cant angle. The cant angles at 90° and 60° are used for the design of the wingtip fence for the upper surface. Fig. 4 shows the designs of the main wing with the wingtip fence appended.
The tenacity for constructing the mini-winglet is to review the influences that it would produce on the flight performance parameters since the size of the winglet is reduced in comparison to similar winglets i.e. blended winglet. A 60° cant angle has been specified for the mini-winglet as shown in Fig. 5.

3.2. **Computational Domain and Boundary Conditions**

A far-field boundary is bullet shaped as shown in Fig. 6. is shaped for simulating the air flow for the three 2D aerofoils. The computational domain’s inlet and the walls have been sketched to make sure that the flow fully develops past the aerofoil resulting in not any errors caused by reverse flow. For the 2D aerofoil analysis the walls of the computational domain are specified suiting the specification of the simulation. A ‘bullet-shaped’ domain is constructed for the 3D wing analysis similar to the 2D domain. The domain shape and the wing are shown in Fig. 6. The domain size has been specified by using the span of the wing as the reference length.

3.3. **Mesh Generation**

Volumetric control blocks of the shape of block and cylinder have been made for the 2D analysis of aerofoils. The mesh has been refined around the aerofoil and further refinement has been done around leading and trailing edge of the aerofoil while the rest of the computational domain’s mesh is coarse. Further the values for the prism layer stretching the prism layer thickness, number of prism layers, base size have been specified. The computational domain’s mesh is shown in Fig. 7.
The 3D computational domain’s meshing is done keeping in consideration the limitation of the resources available for computations as well as time. Three different mesh refinement options have been used for achieving mesh refinement. The approximate cell size measurement on the wing surface has formed the base size. The largest distance on the surface of the computational domain on the ‘Inlet’ upstream region is specified as the maximum cell size. The mesh generated for the computational domain and the 3D wing with blended winglet are shown in Fig. 8 below.

3.4. Simulation Parameters
The Reynolds number calculated for the simulations is $7.8 \times 10^6$. For the 2D analysis the turbulence model k-ε is selected. The Realizable Two-Layer K-Epsilon model supported with the two layers all y+ wall treatment is also selected as it combines the Realizable K-Epsilon model with the two-layer approach. The values for initial velocity, dynamic viscosity for air and density for both the 2D and 3D models is presented in Table 1. The reference area specified for the two-dimensional aerofoil is 1.5 m$^2$. The turbulence model selected for the three-dimensional wing analysis is Spalart-Allmaras model.

Table 1: Initial conditions used for 3D simulations

| Parameters        | Take-off | Landing |
|-------------------|----------|---------|
| Initial Velocity  | 79.16 m/s| 68.89 m/s|
| Dynamic Viscosity | $1.826 \times 10^{-5}$ N.s/m$^2$ | $1.826 \times 10^{-5}$ N.s/m$^2$|
| Density           | 1.2 kg/m$^3$ | 1.2 kg/m$^3$ |

3.5. Convergence Criteria and Mesh Independence Check
For the fulfilment of the convergence criteria to validate the simulations the magnitude of the simulation residuals should reduce by two or three orders as a first check for the convergence criteria. Fig. 9 shows the converged solution obtained for both the 2D aerofoil and 3D wing designs.
Fig. 9: Converged residuals

The use of higher mesh elements for refinement carried out for the 3D wing model confirms the mesh independence for the final model. The percentage difference of 0.13% is calculated between M2 and M3 while a larger difference is obtained between the coarse mesh, M1 and finer mesh M2 as is seen in Fig. 10. From the results obtained it is established that the values used for M2 will be used to mesh all the models for simulations.

Fig. 10: Mesh Independence check

4. Results and Discussion

4.1. Aerofoil comparison results

The lift and drag coefficients obtained for the three NACA profiles have been presented in Fig. 11.

Fig. 11: Comparison of NACA profiles based on CL and CD

From the values obtained for the 2D analysis, it can be seen that the value of $C_L$ for NACA 2415 is higher as compared to the two aerofoils. Even though similar stalling characteristics can be observed for the three aerofoils, the lift coefficient for NACA 2415 is greater at higher angles of attack.
compared to the NACA 0012 and NACA 23015 aerofoils. Similarly, the value of coefficient of drag is lower for NACA 2415 in comparison to the other studied aerofoil designs. Hence NACA 2415 is used for the construction of the rest of the 3D wings.

4.2. Results comparison for take-off and landing conditions

The comparison of the results obtained for the value of $C_L$ and $C_D$ for plain wing and the wings with wingtip devices is shown in Fig. 12. The design with the best lift characteristics has been presented for the comparison.

The analysis of the coefficient of lift values shows that during take-off the blended winglet provides the highest value of $C_L$ in the range of 0° to 20°. The spiroid parallelogram winglet also provides more lift and stalls later than the plain wing. The least lift increase in comparison with the plain wing is produced by mini winglet. From the results obtained it can thus be deduced that the blended winglet provides the best lift due to the reduction in wingtip vortices. The values obtained for coefficient of drag exhibits similar increase in the value for all the wing designs. However, the value of drag at higher angles of attack is smaller than the others for the parallelogram spiroid winglet.

![Fig. 12: CL and CD comparison for different wingtips- Take-off](image1)

The results of the wingtip devices for the landing phase conditions are presented in Fig. 13.

![Fig. 13: CL comparison for different wingtip - Landing](image2)
angles of attack 8°, 12° and 16°. The decrease in $C_L$ is calculated at about 8%, 12% and 5% approximately for the two wingtip devices respectively. The results for the spiroid winglet also show a reduction in the obtained values; however, the values begin to decrease as soon as the angle of attack increases from 0°.

The results for the values of $C_D$ are shown in Fig. 14. The maximum percentage decrease at 0° angle of attack for the values of $C_D$ has been attained for the blended winglet design. The results show a 22% decline in the value of $C_D$ for the blended winglet when compared with the plain wing. For the same angle of attack the spiroid winglet produced only 2.81% decrease for $C_D$. In comparison to the plain wing as the angle of attack increases to 4° the drag also increases. For the blended winglet and spiroid winglet, the decrease is 1.2% and 0.26% respectively. An increase in the drag is observed for all the other simulated wingtip devices. For all the wingtip types, the analysis shows that with the increase in the angle of attack a significant increase in the drag coefficient occurs. The highest increase of about 40% is obtained for the wingtip fence. For 12° and 16° angle of attack the same trend continues. The spiroid winglet at 16° angle of attack is the only wingtip device that shows a decline in the value of $C_D$. At 20° angle of attack decrease in drag is about 9% which is obtained by using the spiroid winglet and 1.2% reduction in $C_D$ is obtained for the blended winglet.

![Fig. 14: Comparison of CD for various wingtips – Landing](image)

The results obtained in this research are in close correlation to the study conducted by Beechooky and Wang [13]. In their study, a comparison is done of the results obtained by conducting a wind tunnel experiment and CFD analysis for a plain wing and a wing with blended winglet is [13]. The conclusion stated that the increase in lift obtained for the blended winglet at 45° cant angle is greater than the lift obtained for blended winglet at 60° cant angle. The result analyses for both the researches show that the trend of increase in lift coefficient and decrease in drag coefficient obtained are identical. The results obtained in this research for the plain wing and blended winglet show the same results with the increase in lift being greater for the winglet with 45° cant angle in comparison with winglet having 60° cant angle and plain wing.

5. Conclusion

The effect of using wingtip devices on wings has been analysed in this CFD study by analysing the values of lift and drag coefficient. The decline in the drag coefficient and increment in the lift reveals the significance of the various wingtip devices. The comparison of coefficients of lift and drag attained from the initial investigation revealed the aerofoil NACA 2415 to be the most suitable aerofoil for the modelling of the wing’s three-dimensional design. The three-dimensional plain wing design without and equipped with devices of wingtips is modelled and designed for two flight stages; take-off and landing. Various cant angles for the selected wingtip devices, blended winglet, spiroid winglet and the wingtip fence, were varied for the analysis. The comparison and analysis of the results obtained concludes that the 30° cant angle blended winglet and the 60° cant angle wingtip fence when compared to their counterpart designs produced more lift. The comparison of the various spiroid
winglet designs reveal that the design configuration of the spiroid winglet with parallelogram produced less drag and more lift. Hence the blended winglet with 30° cant angle can be regarded as the most suitable winglet as it produces the highest rise in lift coefficient and a comparable decrease in drag coefficient.

6. Conclusion

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