Design and Analysis of Winglets on GOE767-il Aerofoil

Sayuj G K, Rishabh Almel, Rohan G, Shashank Naik, Chandru A

Abstract

Aerodynamic efficiency is defined as a ratio of co-efficient of lift to co-efficient of drag. Reduction of aerodynamic efficiency is a result of wing tip vortices which attributes to induced drag. These vortices are formed due to the difference in pressure between the top and bottom surfaces of the wing. Winglets can be used to improve overall aerodynamic efficiency of a wing. In this study, we will compare the effect of different configurations of winglets – Canted, Fenced, Raked and Spiroid on the aerodynamic efficiency of the wing. A GOE767-il aerofoil wing made of aluminium is modelled and retro-fitted with the above mentioned winglet configurations. CFD analysis for the wing and winglets will be done in three flight conditions – Take-off, Cruise and Landing, to calculate co-efficient of lift and drag. This computational analysis will be done on Ansys Fluent using Spalart – Allmaras turbulence model. The CFD results obtained will be compared based on the efficiency to determine the best winglet configuration for said aerofoil structure and wing parameters.

Keywords: Winglets, Induced Drag, Wingtip Vortices, co-efficient of lift, co-efficient of drag, Aerodynamic Efficiency

1. Introduction

For an aircraft one of the most important components is its wings, as it produces the lift required. However, this lift also creates ‘lift induced drag’ at the wing tips. To reduce this drag, wingtip devices also called winglets are used [1-4]. Winglets help do this by moving wingtip vortices (which are responsible for the ‘lift induced drag’) outwards.

1.1. Canted Winglet

Canted winglets are short, upward-sloping wedges. The cant angle cannot be decreased too much, as the flow separates more easily, affecting the properties of the wing at higher angles of attack (AoAs/α) [2][3].

1.2. Fenced Winglet

Fenced winglets are ones that extend both downward and upward from the tip of the wing and perpendicular to it. The smaller size results in a smaller bending moment at the fuselage.

1.3. Raked Winglet

Raked wingtip design is where the tip of the wing is given a further sweep angle than the rest of the wing. Raked wingtips increase the wingspan and thereby produce higher bending stresses.

1.4. Spiroid Winglet

Spiroid winglet technology was developed by former Boeing chief Dr. Louis Gratzer. It looks like a wingtip that has been bent through 360° to form a loop. This winglet will enhance the lift and reduce the drag [4][5]. Nikola N. Gavrilović, carries out CFD analysis of wing with and without winglets to compare the two results. It will be observed that wing without winglet produces
larger vortices, which induces more drag, compared to wings with winglets [5]. A study by Hanlin Gongzhang Eric Axtelius on lift and drag of various winglet design showed spiroid and fenced winglets to be the least effective design [7]. Saravanan Rajendran conducted a theory based study and parameterized all associate parameters of the wing model. At optimal parameters, the payload of the aircraft could be increased [6]. Based on the survey, the expected ranking of the winglets in decreasing order of aerodynamic efficiency is [7] Raked, Canted, Spiroid and Fenced. This study aims to improve the aerodynamic efficiency of GOE 767-il aerofoil by introducing four winglet designs, namely – Canted, Raked, Spiroid, Fenced winglets. The team will carry out theoretical and CFD analysis of the wings and winglets in three flight conditions namely – Take-off, Cruise and Landing. During the analysis, different parameter such as density, altitude and viscosity will be considered. The wing and winglets will be designed on Solid Edge and then the winglets will be retro-fitted onto the wing. It will then be analysed on Ansys Fluent.

2. Governing Equations
2.1. Navier Stokes Equation
Continuity equation
\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \] (1)

X Momentum equation
\[ \rho \frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = \rho F_x - \frac{\partial p}{\partial x} + 2\mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \mu \left( \frac{\partial^2 u}{\partial x \partial y} + \frac{\partial^2 u}{\partial x \partial z} + \frac{\partial^2 u}{\partial y \partial z} \right) \] (2)

Similarly, y and z momentum equations can be framed.

\[ C_L = \frac{L}{\frac{1}{2} \rho V^2 S} \] (3)

\[ C_D = C_{DSF} + FF \times C_{DSF} + K \times C_L \] (4)

\[ C_{DSF} = \frac{0.455}{(\log(Re))^{2.58} (1+0.144M^2)^{0.65}} \] (5)

\[ AE = \frac{C_L}{C_D} \] (6)

| Notation  | Meaning                        |
|-----------|--------------------------------|
| AE        | Aerodynamic Efficiency         |
| C_D       | Drag Coefficient               |
| C_{DFD}   | Form Drag Coefficient          |
| C_{DI}    | Induced Drag Coefficient       |
| C_{DSF}   | Skin Friction Drag Coefficient |
| C_L       | Coefficient of Lift            |
| FF        | Form Factor                    |
| K         | Constant                       |
| L         | Lift Force (N)                 |
| M         | Mach Number                    |
| Re        | Reynolds’ Number               |
| \rho      | Density (kg/m^3)               |
| S         | Surface Area (m^2)             |
| V         | Velocity of incoming air (m/s) |
| W         | Weight of wing                 |
| u         | Velocity in x – direction (m/s)|
| v         | Velocity in y – direction (m/s)|
| w         | Velocity in z – direction (m/s)|
| t         | Time period (s)                |
| \mu       | Dynamic Viscosity (m^3/s)      |
| \rho      | Pressure (Pa)                  |

3. Methodology
3.1. CAD Modeling

The wing and winglets will be modelled using solid edge 2019 academic version. To create the aerofoil structure in Solid Edge, ‘Curve by Table’ function can be used. The co-ordinates of the aerofoil-GOE767-il are imported using this function and scaled. The curves are aligned and spaced to incorporate the wingspan and other parameters mentioned in ‘Table. 2. Dimensions of Wing’. Lastly, ‘Loft Protrusion’ is done to obtain the final feature. Similarly, the winglets are modelled with appropriate dimensions.
Table. 2. Dimensions of Wing

| Parameter                        | Value  |
|---------------------------------|--------|
| Area                            | 214.45m² |
| Left Wing Length                | 21.27m  |
| Mean Aerodynamic Chord Length   | 6.98m  |
| Taper ratio                     | 0.267  |
| Aspect ratio                    | 7.99   |
| Chord Length                    |        |
| -At root                        | 8.57m  |
| -At tip                         | 2.29m  |
| Trailing Edge Sweep Angle       |        |
| -1st sweep                      | 84°    |
| -2nd sweep                      | 22.3°  |
| Leading Edge Sweep Angle        | 31.5°  |
| Dihedral Angle                  | 6°     |
| t/c ratio                       | 11.5   |

3.2. CFD Analysis

Once modelling is completed, the analysis will be carried out on Ansys Fluent 2020 academic version. The turbulence model used in this analysis is Spalart-Alamas equation. But first, the geometries will first be imported into the Ansys workbench module. An artificial wind tunnel will be created around the wing(s). Next step is to create a discrete mesh and set appropriate boundary conditions based on the flight conditions as shown in ‘Table.3.Input Parameters’. Lastly, the calculation will be completed and the results will be obtained and discussed in the coming chapters.

Table.3. Input Parameters

|                     | Take-off | Cruise          | Landing          |
|---------------------|----------|-----------------|------------------|
| Geo. AoA (deg)      | 10       | 3               | 6.5              |
| Op. Cond. Op Pres (Pa) | 101325   | 19740.97        | 101325           |
| Mater. Prop. Density (kg/m³) | 1.225    | 0.32079         | 1.225            |
|                     | Viscosity (kg/m-s) | 1.46E-05 | 4.56E-05 | 1.46E-05 |
| Bound. Cond. Inlet velocity (m/s) | 62.762   | 249.9           | 67.99            |
|                     | Temp (K) (Inlet) | 288.15 | 248.2854 | 288.15 |

4.1.1. Wing

![Fig. 1.1. Pressure Pathlines at Take-off](image1)

![Fig. 2. Pressure Pathlines at Cruise](image2)

4. Results and Discussions

4.1. Theoretical & CFD Results

As shown in figure the various plots such as velocity magnitude and the pressure distribution were plotted. It was observed that the wing tip vortices which attribute to the induced drag and resulted in lower aerodynamic efficiency of the wing was improved upon retrofitting the winglets on to the wing. We can see a general trend where the wingtip vortices are reduced however from the values obtained. We can see that winglets help in increasing the efficiency in specific flight conditions.
Table 4. Table of values

| Flight Condition | C_L | C_D | Efficiency |
|------------------|-----|-----|------------|
| Take-Off         | 0.9302 | 0.1181 | 7.87638    |
| Cruise           | 0.2704 | 0.0265 | 10.20377   |
| Landing          | 0.7003 | 0.0559 | 12.52773   |

4.1.2. Winglet – Canted

Table 5. Table of values

| Flight Condition | C_L | C_D | Efficiency |
|------------------|-----|-----|------------|
| Take-Off         | 0.93915 | 0.10266 | 9.14816    |
| Cruise           | 0.323 | 0.01781 | 18.13588   |
| Landing          | 0.89139 | 0.063 | 14.14905   |

4.1.3. Winglet – Fenced

Fig. 3. Pressure Pathlines at Landing

Fig. 6. Pressure Pathlines at Landing

Fig. 4. Pressure Pathlines at Take-off

Fig. 7. Pressure Pathlines at Take-off

Fig. 5. Pressure Pathlines at Cruise

Fig. 8. Pressure Pathlines at Cruise
Fig. 9. Pressure Pathlines at Landing

Table 6. Table of Values

| Flight Condition | CFD Values | Efficiency |
|------------------|------------|------------|
| Take-Off         | 0.75675    | 0.07810    | 9.68980    |
| Cruise           | 0.29339    | 0.02835    | 10.34881   |
| Landing          | 0.55275    | 0.04673    | 11.82959   |

4.1.4. Winglet – Raked

Fig. 10. Pressure Pathlines at Take-off

Fig. 11. Pressure Pathlines at Cruise

Fig. 12. Pressure Pathlines at Landing

Table 7. Table of Values

| Flight Condition | CFD Values | Efficiency |
|------------------|------------|------------|
| Take-Off         | 0.51865    | 0.09004    | 5.76022    |
| Cruise           | 0.18632    | 0.01678    | 11.10369   |
| Landing          | 0.39855    | 0.04305    | 9.25784    |

4.1.5. Winglet – Spiroid

Fig. 13. Pressure Pathlines at Take-off

Fig. 14. Pressure Pathlines at Cruise
4.2. Comparison of Winglets

One can see that Spiroid offers the least efficiency when it comes to the cruise phase of the flight to a point where the efficiency is lower than that of the wing without winglets by 9%. Canted winglet shows the maximum efficiency when it comes to the cruise phase of the flight whereas the gains obtained from fenced and raked winglets are 1% and 9% respectively. Speaking of the take-off phase Spiroid shows the maximum gain in efficiency of 34% and canted showing a 13% rise in efficiency in the landing phase of the flight as shown in the table below.

Table 8. Table of Values

| Flight Condition | CFD Values | Efficiency |
|------------------|------------|------------|
| Take-Off         | 0.77436    | 0.07346    | 10.54186   |
| Cruise           | 0.31950    | 0.03430    | 9.31487    |
| Landing          | 0.52356    | 0.04389    | 11.92828   |

Conclusion

- Canted winglet was found to show most improvement in cruise condition. Therefore, Canted winglet is best configuration of all the other configurations analyzed.
- After Canted winglet, Raked and Fenced winglet configurations gave desirable results.
- Spiroid winglet was found to give negative improvement in cruise condition and is therefore not a viable configuration for wing parameters used in this project.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank Department of Mechanical Engineering, PESU – Electronic City Campus, for their constant support and guidance through this study.

References

[1]. Nikola N. Gavrilović, University of Belgrade (2015), “Commercial Aircraft Performance Improvement Using Winglets”, Vol. 43, No 1 , 1-8.

[2]. Beechook, J. Wang from Department of Aerospace, Electrical & Electronic Engineering, Coventry University and School of Aerospace and Aircraft Engineering, Kingston University (2013), Proceedings of 19th International Conference on Automation and Computing, Brunel University, “Aerodynamic Analysis of Variable Cant Angle Winglets for Improved Aircraft Performance”, 13-14, 1-6.
[3]. Nicolas El Haddad, Embry-Riddle Aeronautical University (5-2015), “Aerodynamic and Structural Design of a Winglet for Enhanced Performance of a Business Jet”, 1-98.

[4]. W. Giftonkoil Raj, T. Amalseba Thomas, Dept. of Aeronautical Engineering, Hindustan Institute of Technology and Science, (2015), “Design and Analysis of Spiroid Winglet”, DOI: 10.15680/IJJSET.2015.0403070, Vol. 4, Issue 3, 1139-1147.

[5]. Louis B. Gratzer, Spiroid-tipped wing, Publication of US5102068A, 1992-04-07.

[6]. Saravanan Rajendran, Linkoping University, Department of Management and Engineering (2012), “Design of Parametric Winglets and Wing tip devices – A Conceptual Design Approach”, 1-61.

[7]. Hanlin Gongzhang, Eric, KTH Royal Institute of Technology School of Engineering Sciences, Sweden (2020), “Aircraft Winglet Design”, 1-30.

[8]. John D. Anderson Jr, Introduction to Flight, 8th Edition, McGraw-Hill, 2016, Ch. 5, pg. 296, eqn. 5.16.

[9]. Mohammad Sadraey, Aircraft Design: A Systems Engineering Approach, Wiley, Ch.5.4.6, eqn. 5.11.

[10]. John D. Anderson Jr, Introduction to Flight, 8th Edition, McGraw-Hill, 2016, Ch. 6, pg. 526, eqn. 6.102

[11]. John D. Anderson Jr, Introduction to Flight, 8th Edition, McGraw-Hill, 2016, Ch. 6, pg. 530, eqn. 6.110.

[12]. John D. Anderson Jr, Introduction to Flight, 8th Edition, McGraw-Hill, 2016, Ch. 5, pg. 358.

[13]. Mohammad Sadraey, Aircraft Design: A Systems Engineering Approach, Wiley, Ch.5.9, eqn. 5.27b.

[14]. Daniel P. Raymer, Aircraft Design: A Conceptual Approach, AIAA, 2004, Ch. 12.5, pg. 282, eqn. 12.27.

[15]. Ohad Gur, *William H. Mason, †and Joseph A. Schetz‡Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0203, Full-Configuration Drag Estimation, Journal of Aircraft Vol. 47, No. 4, July–August 2010, DOI: 10.2514/1.47557, eqn. 5.

[16]. P.R. Spalart & S. R. (1992), “A one-equation turbulence model for aerodynamic flows. 30th Aerospace Sciences Meeting and Exhibit”. doi:10.2514/6.1992-439.