CFD Simulations of Various Shapes of Winglets

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***Abstract*— The objective of this research work is to reduce the lift induced drag generated due to wing tip vortices at the tip of the wing. The NACA-65(3)-218 is chosen as a clean wing and the computational results are validated with the experimental results. The experimental data is obtained from the journal drag analysis of an Aircraft Wing Model with and without bird feather like Winglet conducted by AltabHossain, AtaurRahman, A.K.M. P. Iqbal, M. Ariffin, and M. Mazian. The unstructured mesh is constructed with the prism layer meshing using ICEM-CFD and the grid independence study has conducted to know the optimum mesh size for all the three wing configuration of clean wing (NACA-65(3)-218), wing with rake winglet and the wing with L-winglet. The RANS (Reynolds averaged Navier stokes equation) numerical studies have conducted by the finite volume method to analyse the physical system modelled. Fluent is used as a common solver for analysing the physical model. The new design changes are implemented with two types of winglets attached at the end of the clean wing. The rake winglet and the L-winglet are used for the computational analysis. The analysis is carried out at the different angles of attack such as -40, 00, +80, +160 and +180 at an inlet velocity of 32m/s with the adiabatic conditions. The obtained results shows that the rake winglet performs better than clean wing at the angles of attack of 8^0 with the L/D ratio of 8 and the L-winglets performs better than clean and rake winglet at the angles of attack of 8 with the L/D ratio of 10.**

Keywords*— *Aerofoil; Winglets; AOA; NACA; CFD

Nomenclature

AOA	**Angle Of Attack**
L/D	**Lift to Drag ratio**
C_L	**Coefficient of Lift**
NACA	**National Advisory Committee For Aeronautics**

I. INTRODUCTION

Winglets are used to reduce the lift induced drag generated due to the formation of wingtip vortices from the third direction flow caused due to flow separation above the wing surface. Winglets are usually in vertical or in angled shapes and are attached to the tips of the main wing. By adding the winglets, it increases the aspect ratio of the wing by maintain the structural weight within the limits. The lift induced drag can also be reduced by increasing the wing span but it will increase the pressure drag and profile drag on the wings and also increases the weight of the wing. Induced drag takes the major share among the total drag of up-to 40% and therefore it consumes large fuel. Thus by adding the winglet it will increase the aspect ratio of the wing and reduces the lift induced drag.In the earlier days in England Frederick W. Lanchester and others have made lot of studies to reduce the wing tip vortices and suggested that the vertical bodies attached to the wing tip will reduces the induced drag. Hand calculations and the results of experimental studies of the vertical bodies attached at the tip of the main wing have proven that it will reduce the induced drag (and Lanchester has patented the concept of endplate in the year 1897). But this was only successful when the aircraft is flying at high speed and in the lower speeds it will increase the profile drag and pressure drag. Thus due to its increase in parasitic drag by adding the endplates it was not much used on later days. Lot of research work had been conducted throughout the world on the concept of winglets design by modifying various shapes.

Here in this work we are focusing to reduce the lift induced drag on the wing i.e., by attaching the different shapes of winglets such as rake winglet and L-Winglet at the tip of the main wing which reduces the vortices generated. In the present work the NACA-65(3)-218 is selected has a base wing and the analysis is carried out for various angles of attack at the velocity of 32m/s and computational results are validated with the experimental results [1]. The computation results matched well with experimental results with a deviation of ±7%. Further the NACA-65(3)-218 wing is attached with two different shapes of winglets to the end of the base wing to carry out the behavioural study of the formation of wing tip vortices which accounts to induced drag. In the first case the NACA-65(3)-218 is attached with the rake winglet of 0 cant angle and the analysis is carried out for various angles of attack such as -4^0, 0^0, $+8^0$, $+12^0$& $+16^0$ at the free stream velocity of 32m/s. In the second case the NACA-65(3)-218 is attached with the L-Winglet of 90^0 cant angle and the analysis is carried out at the same boundary conditions as in the first case. The analysis was focused to study the behaviour of formation of wing tip vortices on both the cases which will lead to the formation of the induced drag. Altab Hossain et al [1] have reported on “Drag Analysis of an Aircraft Wing Model with and without Bird Feather like Winglet”. Their aim is to reduce drag which describes the aerodynamic characteristic for aircraft wing model with and without bird feather like winglet they have conducted the study on NACA 65(3)-218 Rectangular wing and validated with the experimental values. The experimental analysis for the aerodynamic characteristic for rectangular wing without winglet, wing with horizontal winglet and wing with 60^0 inclination winglet for Reynolds number 1.66×10^5, 2.08×10^5

and 2.50×10^5 have been carried out in open loop low speed wind tunnel. The results obtained are by using bird feather like winglet the drag has reduced & the lift co-efficient has increased. And this winglet has reduced wing tip vortex and converted this vortex into additional thrust.P. Bourdin et al [2,3] has investigated a novel method for the controls of morphing aircraft, where the pair of winglets with adjustable cant angle are actuated independently and are mounted at the tips of the main wing. The general idea is by using two control devices will enhance aircraft control. Comparison of CFD with the experimental results showed good agreement. The investigation results showed that by using the concept of variable cant angle winglet can replace the conventional control surfaces. Also the experimental results showed that rolling and pitching will be effected by the winglet concepts and still its direct comparison should be made with conventional control surfaces in terms of moment co-efficient.Mohammad IliasInam et al [4] has conducted the wind tunnel experiments for different winglet shapes such as rectangular, circular and triangular, and the results shown that the induced drag has reduced without increasing the wingspan on the modern aircrafts by using winglets. The wind tunnel tests were carried in a closed-loop wind tunnel for different Reynolds numbers. The experimental results showed that the triangle winglets performs better at 5^0 AOA and the drag has reduced by 30.9% as compared to the results of other winglet configurations carried out.M.A Azlin et al [5] has studied numerical investigation on elliptical and semi-circular winglets at different cant angles and at various angle of attacks. The analysis is conducted at free stream velocity of 40m/s with the unstructured tetrahedral mesh and fluent as a solver. The results obtained showed that the elliptical winglet performs better than semi-circular winglet at 45^0 cant angle and the lift curve gradient has increased by 8%.M.J. Smith et al [6] has conducted Experiments and Numerical analysis on multiple winglet configurations at Georgia institute of technology, Atlanta. The analysis was conducted to study the potential of the multiple winglets to reduce induced drag without increasing the wing span. The results showed that the multiple winglet configuration has reduced lift induced drag and the performance L/D has increased upto 30% as compared to the normal wing of aircraft.R.H. Grant [7] has patented the work on retractable type multiple winglets on the aircraft wing to recycle much of the energy dissipated by the wing trailing edge vortices.J.B. Allen [8] has patented his unique research work on Articulating Winglets type. This unique concept is having foldable type winglets. This work has been carried out with the objective to increase aircraft efficiency and optimise performance at cruise and non-cruise conditions. L.B. Grater, [9] has patented his research work on the Spiroid-tipped wing concept, Spiroid winglets was developed to minimize the induced drag and alleviate noise effects associated with concentrated vortices wakes that trail from lifting surfaces. W.Garvey [10]spiroidwinglets had developed by Aviation partners and was first seen on the Gulfstream 2. R. Hallion et al, [11] editor of the NASA's contribution to Aeronautics. The winglet concept was first developed by Frederick W. Lanchester in 1800's and he had patented his work as endplates which under high lift conditions the wingtip drag can be reduced but it was not that much efficient at cruise and has created large flow separations and increased profile drag. Later at 1974 Dr. Richard whitcomb, an aeronautical engineer at NASA Langely research centre, had installed small vertical fins on a Boeing KC-135A aircraft and experimented. The results obtained showed that the vertical wing like surfaces at the wing tips will reduces the vortices, if it has designed accurately.

II. COMPUTATIONAL METHODOLOGY

A. Computational Domain & Mesh .

The computational domain for the present study mimics the one used in [1]. Figure 1 shows the 3-D domain.

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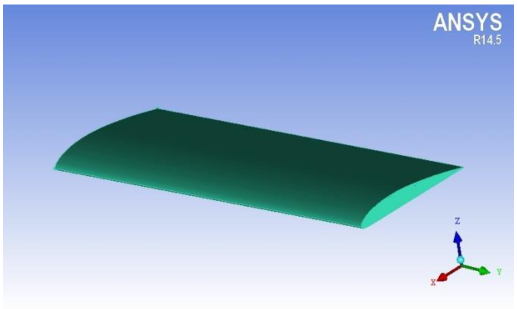

Figure: 1 showing NACA-65_3-218Wing.

TABLE I. EXPERIMENTAL TEST SETUP DETAILS USED IN *[1]*

Dimension	Value
Chord	295mm
Wing span	794mm
Wing Type	No swept back

The present computational model was built as per the specification shown in table I, details used in [1]. Experiments were conducted in the Aerodynamics Laboratory Faculty of Engineering (University Putra Malaysia) with subsonic wind tunnel of 1 m ×1 m rectangular test section and 2.5 m long. The wind tunnel could be operated at a maximum air speed of 50 m/s and the turntable had a capacity for setting an angle of attack of 14^0. The ambient pressure, temperature and humidity were recorded using barometer, thermometer, and hygrometer respectively for the evaluation of air density in the laboratory environment. Details of the experimental results, together with the wing profile used can be seen by the work carried out by AltabHossain et al*[1]*.

Unstructured mesh was generated for the domain using ANSYS® ICEM CFD 14.5. Fine meshes near the wall boundary regions have been developed. The pre-requisite of maintaining a Y^+ value less than 2 is achieved to fulfill the need of turbulence models. Grid independence study was carried out to finalize the mesh density & its details are tabulated in table 2.

TABLE II. EXPERIMENTAL TEST SETUP DETAILS USED IN *[1]*

Type	No. of elements
Coarse	318067
Medium	386368
Fine	420876

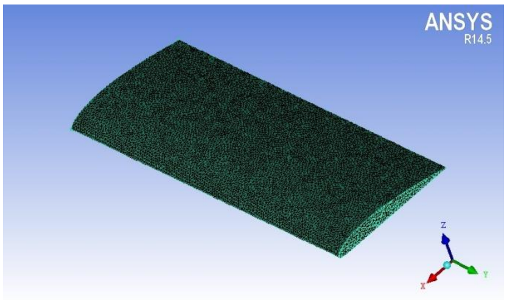

Figure:2ShowingNACA-65(3)-218with unstructured-mesh for present study.

The domain with 386368 mesh density shown in figure 2 is selected which yielded a $Y^{+} \approx 1$& offered reasonably good results taking less computational time

B. Governing Equations

Firstly, ANSYS® FLUENT 14.5 is used for carrying out simulation & following assumptions are made-(i)the flow is steady, (ii) the fluid is incompressible (iii) the fluid properties are constant. The governing equations used are continuity & momentum, S-A is the turbulence model selected as it is best suited for external flow. Coupled algorithm is used for pressure velocity coupling & standard interpolation is used for pressure. Second order upwind scheme is used for, momentum. The convergence criteria fixed is 10^{-3} for continuity & turbulence quantities, 10^{-6} for momentum equations. Double precision solver is activated for the simulation.

C. Boundary Conditions

The brief description of the used boundary conditions are given below

i) No slip boundary condition

$V_w = 0$, at wall

ii) Flow inlet condition,

$V_v, V_z = 0$,

iii) Entrainment condition,

$P = P_{ambient}$, at Outlet

iv) Inlet velocity is maintained constant for all angle of attack for the clean wing configuration (NACA-65(3)-218) and is given in table 3. The temperature is maintained as 300K as STP. Reynolds number is calculated by the formula $\rho V_{oe} D_i / \mu$,which is based on the inlet velocity condition's equations.

III. VALIDATION

The experimental results used for validating the present computational results are taken from [1]. The similar boundary conditions and at various angle of attack is taken into consideration & a comparison of the results taken from [1] & present computational results is carried out.

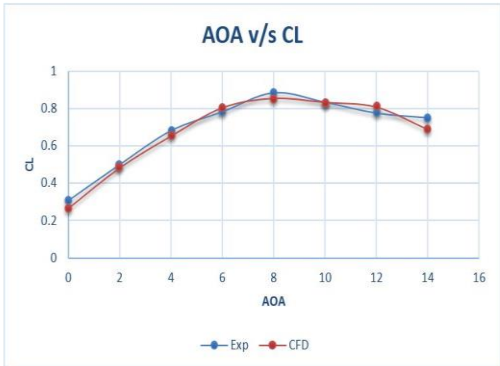

Figure: 3shows the validation of Co-efficient of lift from the CFD with the Experimental results [1].

The use of S-A turbulence model & good quality mesh have rendered values very close to the experimental work done in [1] & is clearly evident from the figure 3. The obtained computational results are in very close proximity, around ±7% with the experimental values.

The computational results for coefficient of lift and drag over wing matches well with the experimental data with ± 7% at all the angle of attacks which validates the work carried out and thus the computational results with the experimental results. SpallartAllmars turbulence model gives the most reliable value to the experimental results.

IV. RESULTS & DISCUSSION.

A. Geometry details

- *NACA 65(3)-218 with Rake Winglet*

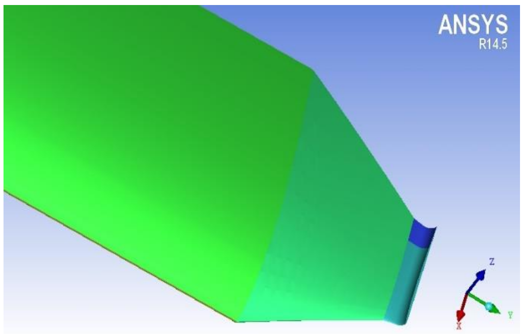

Figure: 4 Shows the geometry of the Rake winglet attached with NACA-65(3)-218.

Table: 3 Shows the details NACA 65(3)-218 with rake winglet

Sl.No.	DESCRIPTION	QUANTITY
1	CHORD	295.11 mm
2	WING SPAN	954 mm
3	VELOCITY	32 m/s

- *NACA 65(3)-218 with L Winglet*

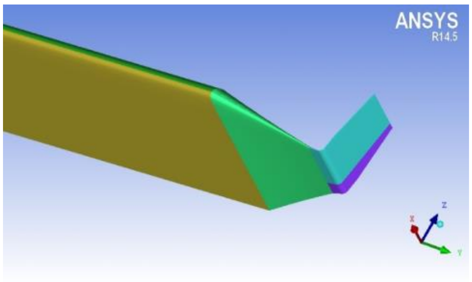

Figure: 5 Shows the geometry of the L-winglet attached with NACA-65_3-218.

Table: 4 Shows the details NACA 65(3)-218 with L - winglet.

Sl.No.	DESCRIPTION	QUANTITY
1	CHORD	295.11 mm
2	WING SPAN	937 mm
3	VELOCITY	32 m/s

B. Results

- *Velocity streamline contours*

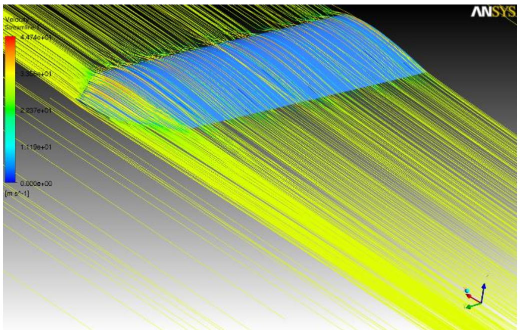

Figure: 6 Shows the velocity streamlines on rake type winglet attached with NACA-65_3-218 at - 4^0 AOA.

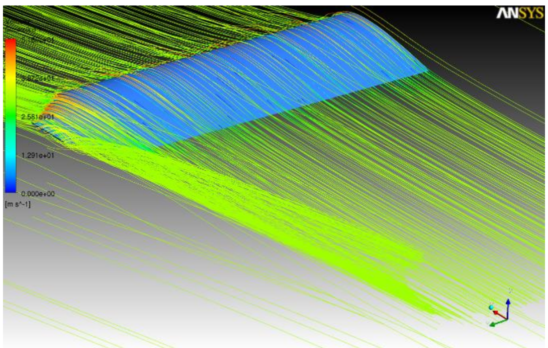

Figure: 7 Shows the velocity streamlines on rake type winglet attached with NACA-65(3)-218 at +8^0 AOA.

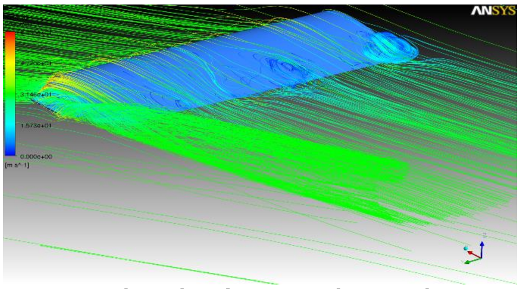

Figure: 8 Shows the velocity streamlines on rake type winglet attached with NACA-65(3)-218 at +16^0 AOA.

From the figures 6, 7 & 8 show the velocity streamline contour of the wing with the rake winglet at -4^0, +8^0& +16^0angle of attack respectively. It is seen from the figure 6 at -4^0AOA that the velocity streamline is not obstructed on anywhere of the wing and mainly at the wing tip, the flow is almost smooth. It is observed from the figure 6 that stream-lines are very straight above the wing surface and at the tip of the wing and hence flow separation and the vortex formation is lesser therefore the pressure drag and the induced drag formation will not be there at the negative angles of attack. In the negative angles air comes steeper and the downwash will be lesser and hence the induced drag and the pressure drag is much reduced.

From the figure 7 it is seen that the velocity streamlines are flowing smoothly and following straight path above the surface of wing without any flow separation but at the tip of the wing, vortex formation is observed which is initiating the lift induced drag on the wing with rake winglet at +8^0 AOA. Wing tip vortices are generated due to the third direction air flow caused by the increase in downwash.

From the figure 8 both flow separation and wing vortices are observed on the surface and at the tip of the wing respectively. At +16^0 AOA the formation of wake and the increase in downwash are causing the flow separation on the wing surface which is observed at the mid region of the wing. Here the wing tip vortices are increased more than which was observed in figure 7 at +8^0 AOA, this is due to the increase in downwash and third direction flow of air from the bottom of the wing at higher angles of attack.

The analysis shows that even with the addition of rake winglet to the clean wing NACA-65(3)-218, the wing tip vortices are not reduced up to the mark and the lift induced drag are still present on the wing while flying at the higher angles of attack.

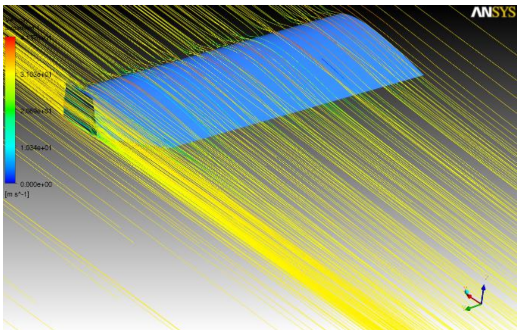

Figure: 9 Shows the velocity streamlines on L - type winglet attached with NACA-65_3-218 at - 4^0 AOA.

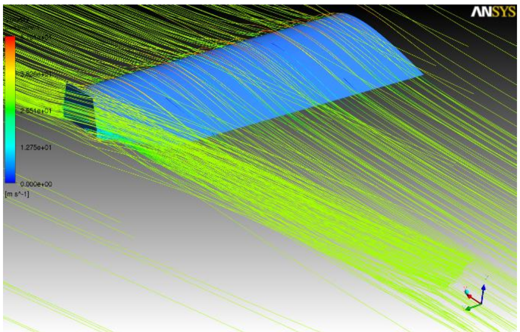

Figure: 10 Shows the velocity streamlines on L - type winglet attached with NACA-65(3)-218 at $+8^0$ AOA.

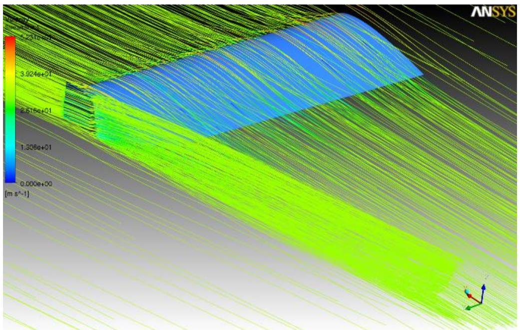

Figure: 11 Shows the velocity streamlines on L - type winglet attached with NACA-65(3)-218 at $+16^0$ AOA.

From the figures 9, 10 & 11 shows the velocity streamline contour of the wing with the "L" – winglet at -4^0, $+8^0$& $+16^0$ angle of attack respectively. It is seen from the figure 9 that the velocity streamline is not disturbed on any part of the wing and mainly at the wing tip, the flow is perfectly straight without any vortices. It is observed from the figure 9 that stream-lines are very straight above the wing surface and at the tip of the wing and hence flow separation and the vortex formation is not present therefore the pressure drag and the lift induced drag is not acting at the negative angles of attack. At the negative angles air comes steeper and the downwash will be lesser and hence the induced drag and the pressure drag is much reduced.

From the figure 10 it is seen that the velocity streamlines are flowing smoothly and following straight path above the surface of wing without any flow separation but at the tip of the wing, a slight formation of vortex is observed which is trying to initiate the induced drag on the wing with L winglet at $+8^0$ AOA, but the presence of L type winglet is reducing the vortex formation, where its presence has observed from the figure 7 on the rake winglet.

From the figure 11 it is observed that both flow separation and wing tip vortices are completely eliminated on the surface and at the tip of the wing respectively, where its presence was observed on the figure 8 at $+16^0$ AOA. At higher angles of attack of $+16^0$ the downwash and the third direction air flow will be more and leads to the formation of the vortices at the wing tip, but L – type winglet is not allowing the third direction flow to mix with the main flow which cause vortex at the tip. Therefore the wing with L winglet is reducing the wing tip vortex formation hence lift induced drag.

The analysis shows that with the addition of L – winglet to the clean wing NACA-65(3)-218, the wing tip vortices are reduced completely and the lift induced drag is reduced on the wing while flying at the higher angles of attack.

- *Comparison graph of all three wing configurations for lift/drag v/s angle of attack.*

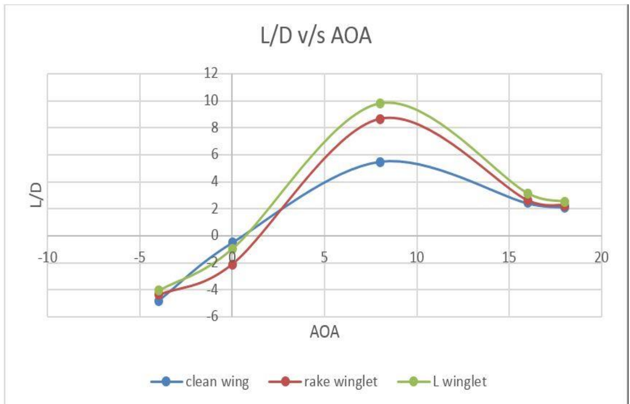

Figure: 12 Shows the lift/drag v/s angle of attack for all three wing configurations.

The graph in figure 12 shows the Lift/Drag versus Angle of attack in comparison with all the 3- configurations of 1) Clean-Wing, 2) Wing with Rake Winglet & 3) Wing with L – Winglet.

From the figure 12, graph it is seen that at lower angles of attack between -4^0 to 0^0 the clean wing performs better than other 2 configurations. Further at higher angles of attacks the L – Winglet & Rake Winglet performs better than clean wing and still the L – winglet holds its performance higher than rake winglet at all higher angles of attack.

Thus the best operating range of the all three wing configurations are as follows.

1) The L – Winglet configuration performance is higher at all higher angles of attacks as compared with other 2 – configurations.
2) The rake winglet also performs better at higher angles of attack from +4 to +16 than clean wing but with slightly lesser than L – winglet at all higher angles.

The performance of clean wing is higher only at lower angles of attacks from -4^0 to $+2^0$.

V. CONCLUSION.

In the present study the computational analysis is carried out on the NACA-65(3)-218 wing with the objective of reducing the lift induced drag, which accounts almost 30 – 40% of the total drag produced by the wing.

From the results it is concluded that Rake and L-winglet performs better than clean winglet at all higher angles of attacks. The Rake winglet performs better than clean winglet with high L/D ratio of 8 at the angle of attack of 8^0. And the L – Winglet performs better than both clean and Rake winglet with the high L/D ratio of 10 at the angle of attack of 8^0 and the performance of all the three wing configuration decreases as the angle of attack increases further higher from 8^0 to 16^0.

Therefore by adding winglets to the clean wing configuration reduces the lift induced drag produced due to the formation of wing tip vortices by the third direction flow.

1) Clean wing produces higher CL between the AOA of $+8^0$ to $+16^0$ but the drag also increases in this range and hence the best operating range for clean wing is at $+8^0$, and as the angle of attack increases the performance starts decreasing.
2) The rake winglet is attached to the clean wing, in this configuration the CL produced by the wing increases than the clean wing configuration with a slight decrease in the drag, therefore the best operating range for the wing with rake winglet is also at +80 but it produces higher L/D of 8.5 which is more than the L/D 5 of clean wing.
3) The L – winglet is attached to the clean wing, in this configuration the CL produced by the wing increases much higher than the clean wing and a slightly higher than the rake winglet. The drag of the L – winglet also decreases predominantly and therefore the performance L/D of the L – winglet increases to 10 than the 5 and 8.5 of clean and rake winglet respectively.

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