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CFD Analysis on Different Shapes of winglet at Low Subsonic Flow

Shivam Kapil Ahluwalia, Vaibhav Negi, Nayan Anand, Varun Goyal, Raj Kumar Singh
Department of Mechanical Engineering, Delhi Technological University, Delhi-42, India

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Abstract

This paper focuses on aerodynamic characteristic ofaircraft wing with and without winglet at low subsonic flow.NACA 65_3-218 profile was applied on four models including elliptical, semicircular and straight winglet. CFD analysis was performed to compare the lift to drag ratio in these models. Spallart Allmarus turbulence model and 3D unstructured tetrahedral mesh was used to compute the flow around the winglet prototype. It was found that elliptical winglet gave maximum lift to drag ratio.

1. Introduction

For many years, wing designers have attempted to reduce the induced drag component by special shaping of the wing tips.The Wright Brothers used curved trailing edges on their rectangular wings based onwind tunnel results. In 1897, British engineer Frederick W. Lanchester conceptualized wing end-plates to reduce the impact of wingtip vortices. Scottish-born engineer William E. Somerville patented the first functional winglets in 1910.In mid 1970s, shortly after energy crisis sent fuel prices skyward, Richard Whitcomb [1] of NASA Langley Research Centre used winglet with its modern meaning referring to near- vertical extension of the wing tips. Small and nearly vertical fins were installed on KC-135A and flights were tested.

The parameters for these winglets include an upper winglet with sweep, cant, taper, and a non-symmetric airfoil. The upper winglet is aligned with the trailing edge of the wingtip. There is also a lower winglet with sweep, cant, and taper ratio, which is aligned with the leading edge of the wingtip. Whitcomb's research showed that winglets could improve L/D by 9% and reduce lift induceddrag by nearly 20% at Reynolds
numbers of 5.25×106 (per foot). A wing tip extension with an equivalentimpact on the root bending moment only improved L/D by four percent.

The first application of NASA's winglet technology in industry was on General Aviation business jets, but winglets are now being incorporated into most commercial and military transport jets, including the Gulfstream III, IV and V (Renamed to G550) business jets, the Boeing 747-400 and McDonnell Douglas MD-11 airliners, the McDonnell Douglas C-17 military transport, and Embraer aircraft.

The advantages of single winglets for small transports were investigated by Robert Jones[2],on which they can provide 10% reduction ininduced drag compared with elliptical wings. Another investigation was carried out on wing tip airfoils by J.J. Spillman [3] at the Cranfield Institute of technology in England. He investigated the use of one to four sails on the wing tipfuel tank of aParis MS 760 Trainer Aircraft. Experiments onflight test confirmedthe wind tunnel tests and demonstrated shorter take off rolls and reduced fuel consumption. Spillman [3] later investigated wing tip vortex reduction due to wing tip sails,and found lower vortex energy 400-700m behind the aircraft, although the rate of decay beyond that was some what lower. The multi-winglet design was evaluated by Smith and Komerath[4] to demonstrate to improve the advanced performance potential over the baseline wing and an equivalent single wing let. The results of their wind tunnel testing show that certain multi wing let configurations reduced the wing induced dragandimproved L/D by 15-30% compared withthe baseline 0012wing.Louis B. Gratzer [5] from Seattle has the patentfor blended winglet and intention of thewinglet is to reduce the interference drag dueto sharp edges as seen in the Whitcomb'swinglet. Also, Gratzer [6] has the patent for theinvention of spiroid-tipped wing in April 7,1992. Later, wing grid concept wasdeveloped by La Roche[7] from Switzerland in1996 and got the patent for his invention.

Though variation of optimum cant angle for different angle of attacks has been extensively studied the shape of the winglet and different types of winglets is a subject for literature research.

***Corresponding Author,**
E-mail: 7ramakant@gmail.com

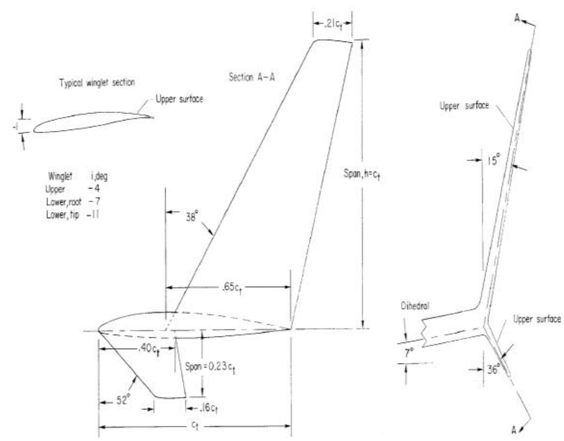

Fig.1: The winglet geometry used by Richard T. Whitcomb [1] in his research at NASA Langley wind tunnel

2. Methodology

The analysis is performed on three shapes of winglets: elliptical, semicircular and straight. The results of these are compared with wing without winglet to study the importance of a winglet. The CFD simulation is done using fluent solver with 8°angle of attack, 45° can't angle at low Reynolds Number of 381,102.

3. Geometry and Modelling

The wing and the winglet were modeled in Solid works by taking same profile of NACA 6 digit series of $65_3$218 as shown in figure 2. In all the cases the chord and semi wing span were chosen to be 121 mm and 330 mm. The angled height for the winglet was 55.55 mm[11]. Major difference in the four models was the curvature of the winglet profile which was elliptical, semi-circular, straight in the three cases and fourth model was made without winglet.

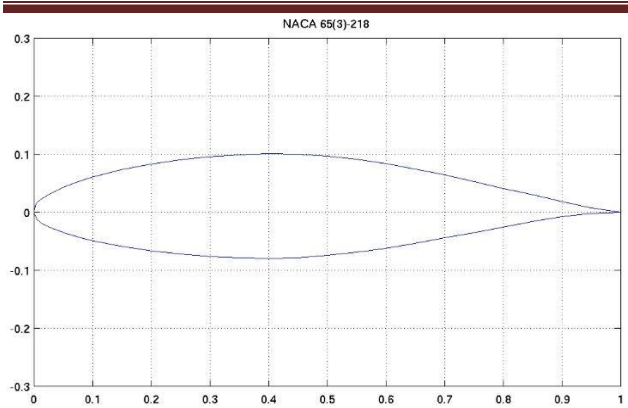

Fig. 2: Profile of NACA 65(3)218

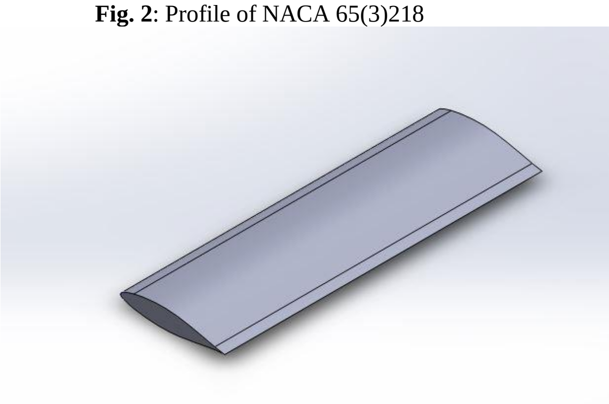

Fig. 3: Wing without winglet

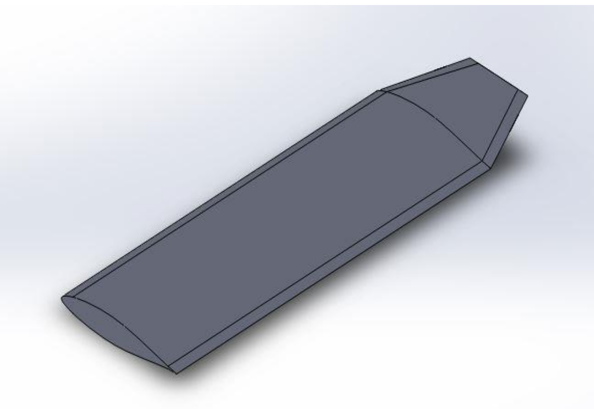

Fig. 4: Wing with Straight Winglet

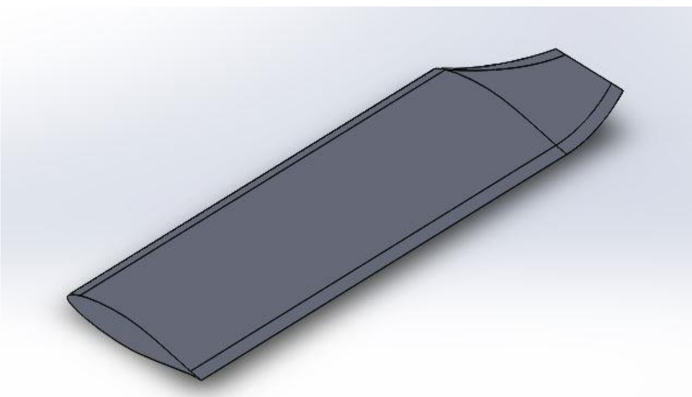

Fig.5: Wing with semi-circular winglet

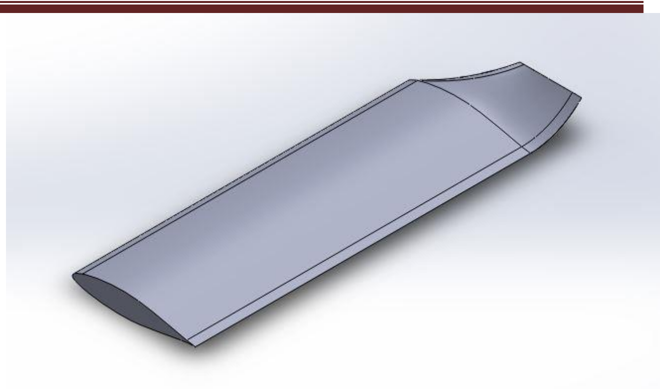

Fig. 6: Wing with elliptical winglet

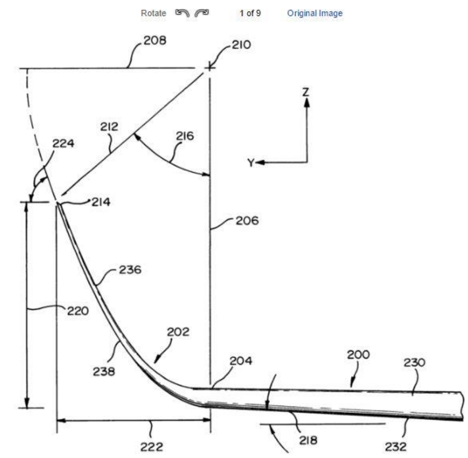

Fig. 7: Winglet shape Boeing patent US6484968 [8]

4. Mesh

The meshing was done in ANSYS 15 Workbench with assistance of Intel i7 5th generation processor and 8.00 GB RAM. A gridrefinement study was performed by running simulationswith different grid resolution, i.e. the number of elements. This was carried out in order to select an appropriaterange for the number of elements in the mesh. In thisparticular case, the mesh consisted of around 2.9 to 3.4 million elements, which was very effective in terms ofcomputational time as well as the results quality.

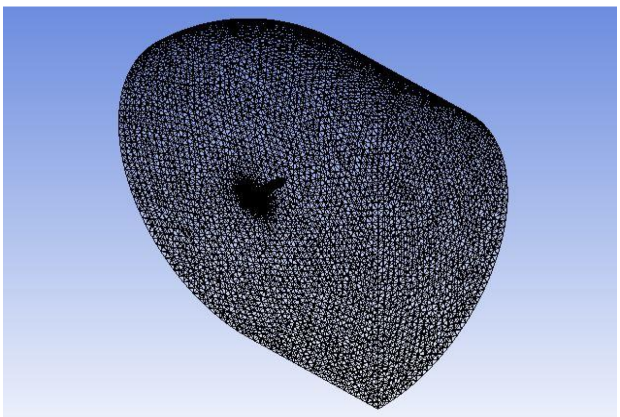

Fig. 8: Mesh for elliptical winglet

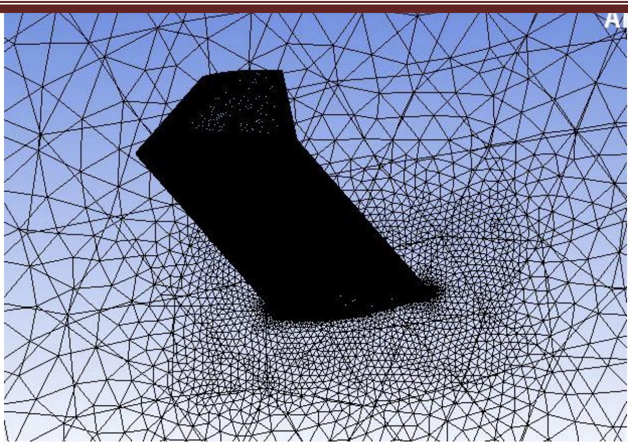

Fig. 9: Body sizing around elliptical winglet

Inflation layer were applied to the meshed geometry to create a layer of structured grids to capture the flow over boundary of the aerofoil. The inflation layer was taken to be of total thickness type where the net thickness was specified as 7 mm with 8 layers having a growth rate of 1.05.

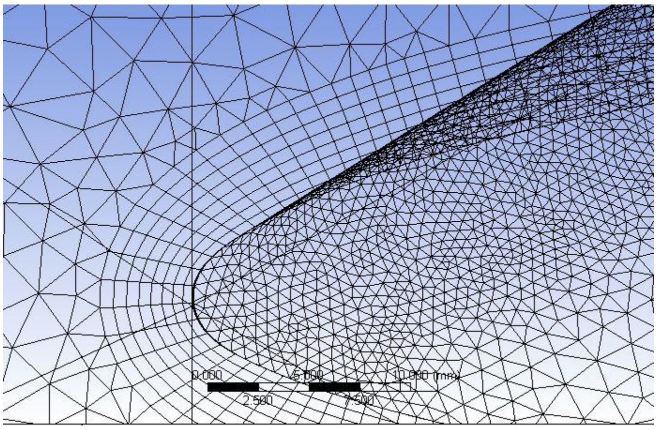

Fig. 10: Inflation layer around wing surface

4.1 Solver Setup

The calculations were performed at freestream velocity of 40 m/s which gave a Reynolds number of about 381,102 (turbulent flow).
The flow region is made of 5 boundaries in a shape of a semi bullet as shown in figure 11, Boundary conditions are specified in Table 1:-

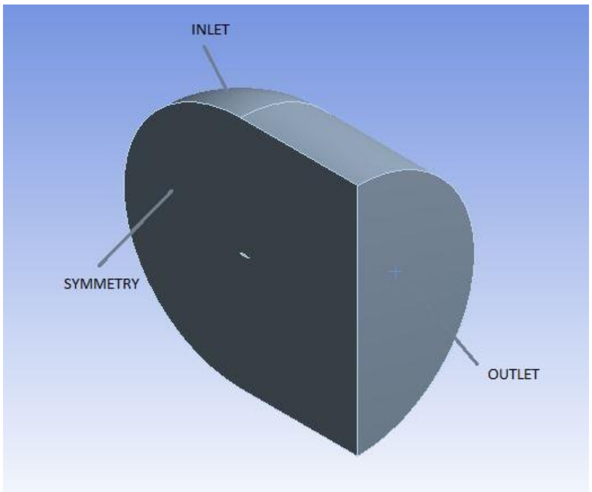

Fig. 11: Boundary conditions on flow field

Table 1: Boundary Conditions

Zone	Boundary Condition
Wing Root	Symmetry
Wing Surface	Stationary Wall
Inlet	Velocity Inlet
Outlet	Pressure Outlet

The calculations were performed using Spallart-Allmarus model. It consists of only one partial differential equation which is used to calculate the velocity component of the model. It solves for turbulent viscosity which is then used to calculate the RANS governing equation.

5. Results and Discussion

Table 2: Comparison of C_L/C_D values between various winglets

Model Type	C_L	C_D	C_L/C_D	% inc. C_L/C_D
Elliptical	0.64375	0.048602	13.2453397	7.119
Semi Circular	0.64308	0.049436	13.0083340	5.203
Without	0.62296	0.050381	12.3649789	0
Straight	0.63257	0.048686	12.9928521	5.077

The result gives highest lift to drag ratio of model containing elliptical winglet which is followed by semi-circular winglet and straight winglet models. This justifies that elliptical winglet is most efficient and produces the least induced drag in its flight.
An airplane has a high L/D ratio if it produces a large amount of lift or a small amount of drag. Under cruise conditions lift is equal to weight. A high lift aircraft can carry a large payload. Under cruise conditions thrust is equal to drag. A low drag aircraft requires low thrust. Thrust is produced by burning a fuel and a low thrust aircraft requires small amounts of fuel be burned. Low fuel usage allows an aircraft to stay aloft for a long time, and that means the aircraft can fly long range missions. So an aircraft with a high L/D ratio can carry a large payload, for a long time, over a long distance. For glider aircraft with no engines, a high L/D ratio again produces a long range aircraft by reducing the steady state glide angle at which the glider descends.
Higher the L/D, the lower the glide angle, and the greater the distance that a glider can travel across the ground for a given change in height. Because lift and drag are both aerodynamic forces, we can think of the L/D ratio as an aerodynamic efficiency factor for the aircraft. Designers of gliders and designers of cruising aircraft want a high L/D ratio to maximize the distance which an aircraft can fly.

Table 3: Verification of results by grid independence

	C_L	C_D	% change C_L	% change C_D
Elliptical	0.6444	0.04885	0.09466758	0.49953
Semi Circular	0.6402	0.04955	-0.4467214	0.238124
Without	0.6214	0.05043	-0.2445932	0.103107
Straight	0.6315	0.04875	-0.1741967	0.133331

At first mesh was made of 2 million elements which provided the above results for CL and CD, this result was compared to the refined mesh with 3 million elements. The result however practically remained same. This shows that the analysis done is independent of grid and mesh and the discretization error is minimal.

5.1 Linearization Error

As we have used second order equations in solution method and the convergence criteria was taken to be up to 10-3, the linearization error produced will be very small.

Table 4: Results from previous research paper [10]

	C_L	C_D	C_L/C_D
Elliptical	0.57929	0.061933	9.353494906
Semi Circular	0.5724	0.064492	8.875519444
Without	0.51212	0.065364	7.834893825

It has been observed that similar trend was observed in previous research which were made on different models of the same profile.
The given boundary conditions were thoroughly checked in post analysis of model, it was found that all the boundary conditions were strictly followed.

5.2 Analysis Discussion

5.2.1 Wingtip Vortices

Wingtip vortices are circular patterns of rotating air left behind a wing as it generates lift.Vortices form because of the difference in pressure between the upper and lower surfaces of a wing that is operating at a positive lift. Since pressure is a continuous function, the pressures must become equal at the wing tips. The tendency is for particles of air to move from the lower wing surface around the wing tip to the upper surface (from the region of high pressure to the region of low pressure) so that the pressure becomes equal above and below the wing. In addition, there exists the oncoming free-stream flow of air approaching the wing. If these two movements of air are combined, there is an inclined inward flow of air on the upper wing surface and an inclined outward flow of air on the lower wing surface. The flow is strongest at the wing tips and decreases to zero at the midspan point as evidenced by the flow direction there being parallel to the free-stream direction.
Indeed, vortices is trailed at any point on the wing where the lift varies span-wise it eventually rolls up into large vortices near the wingtip, at the edge of flap devices, or at other abrupt changes in wing planform.
As wing is viewed from rear; on left side direction of vortex is clockwise and on right its direction is anticlockwise.
Wingtip vortices cause two main problem:
1) Induced Drag
2) Wake Turbulence
Wingtip vortices are associated with induced drag, the imparting of downwash, and are a fundamental consequence of three-dimensional lift generation.The resulting vortices change the speed and direction of the airflow behind the trailing edge, deflecting it downwards, and thus inducing downwash behind the wing.What this means is that the relative flow is such that it decrease effective angle of attack. Thus the lift produced is lesser than needed.To compensate for this the angle of attack is further increased and thus there is increase in induced drag. This tilts the total aerodynamic force rearwards. The angular deflection is small and has little effect on the lift. However, there is an increase in the drag equal to the product of the lift force and the angle through which it is deflected. Since the deflection is itself a function of the lift, the additional drag is proportional to the square of the lift.

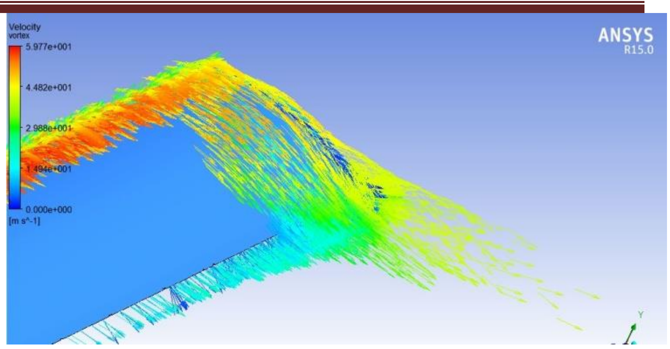

Fig. 12: Vortex formation on wing without winglet

Wingtip vortices is main component of wake turbulence. Wake turbulence is turbulence that forms behind an aircraft as it passes through the air. This turbulence includes various components, the most important of which are wingtip vortices and jet wash. The strength of wingtip vortices is determined primarily by the weight and airspeed of the aircraft.At lower speed and higher attack angle, the spanwise flow component increase and chordwise decrease and thus vortices increase.

5.3 Velocity Contour

From the velocity contour obtained by CFD analysis, it can be easily understood that velocity above the aerofoil is much larger as compared to velocity in Fig. 13.

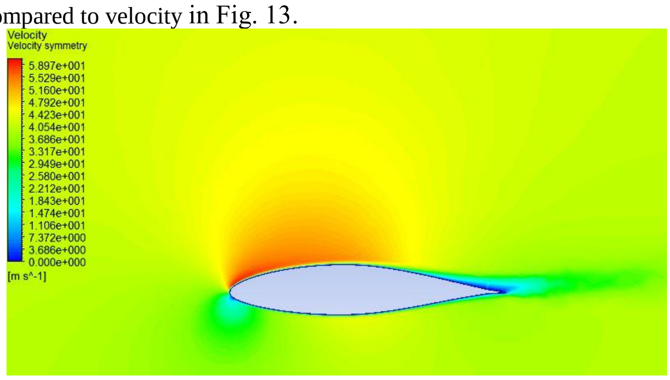

Fig.13: Velocity Contour on symmetry plane of elliptical winglet

There are several theories such as the "Equal Time Transit" theory which explain this velocity difference and thus lift generation. According to this theory, for air flow to travel above the wing, it has to traverse more distance than at below. However it is equally criticized by several including NASA. Wind Tunnel experiments show that above and below airflow does not necessarily reach at same time.

5.4 Pressure Contour and Lift

The lift generated by aerofoil is due to the pressure difference above and below the aerofoil. To create pressure difference the surface of the wing must satisfy one or both the conditions:
The wing surface must be
1) Cambered
2) Incline relative to the airflow direction
The viscosity, however, is essential in generating lift. The airflow when move around the curvature of aerofoil remain attached to the surface even when the surface curves away from the initial flow direction. This is known as Coanda Effect.
The effects of viscosity lead to the formation of the starting vortex,which, in turn is responsible for producing the proper conditions for lift.
The starting vortex rotates in a counter-clockwise direction. To satisfy the conservation of angular momentum, there must be an equivalent motion to oppose the vortex movement. This takes the form of circulation around the wing.

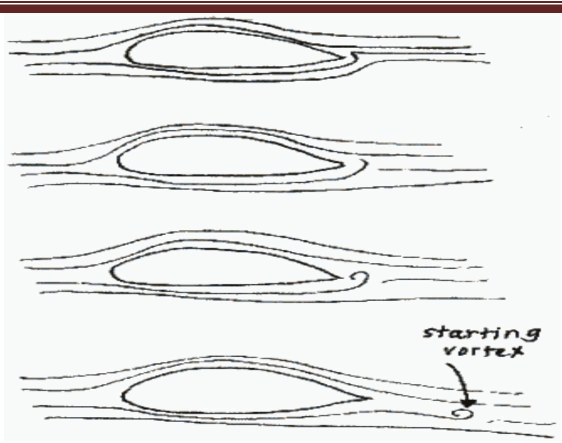

Fig.14: Circulation of air around wind conserving momentum [9]

The velocity vectors from this counter circulation add to the free flow velocity vectors, thus resulting in a higher velocity above the wing and a lower velocity below the wing.

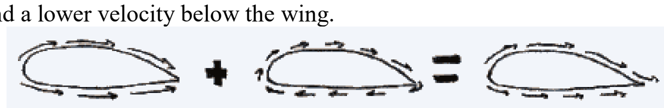

Fig.15: Cause of difference in velocity of air above and below the wing[9]

In the picture below it can be easily understood that pressure above is lesser compared to pressure below.

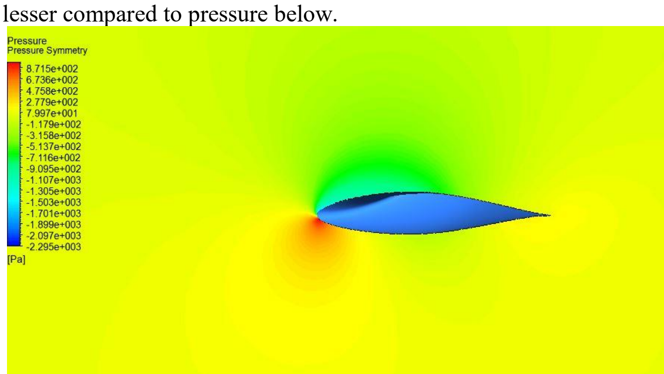

Fig.16: Pressure Contour on symmetry plane of elliptical winglet

The pressure at the bottom of leading edge (red) is the point where the incoming relative airflow hits the aerofoil surface. Thus a local stagnation condition is developed and the kinetic energy is largely converted to pressure.

The air passes over the wing and is bent down. The bending of the air is the action. The reaction is the lift on the wing. As Newton's laws suggests, the wing must change something of the air to get lift. Changes in the air's momentum will result in forces on the wing. To generate lift a wing must divert air down; lots of air. The lift of a wing is equal to the rate of change in momentum of the air it is diverting down. Momentum is the product of mass and velocity. The lift of a wing is proportional to the amount of air diverted down per second times the downward velocity of that air. For more lift the wing can either divert more air (mass) or increase its downward velocity. This downward velocity behind the wing is called "downwash". To the pilot the air is coming off the wing at roughly the angle of attack. To the observer on the ground, it would be coming off the wing almost vertically. The greater the angle of attack, the greater the vertical velocity. Likewise, for the same angle of attack, the greater the speed of the wing the greater the vertical velocity. Both the increase in the speed and the increase of the angle of attack increase the length of the vertical arrow. It is this vertical velocity that gives the wing lift. When the air is bent around the top of the wing, it pulls on the air above it accelerating that air down, otherwise there would be voids in the air left above the wing. Air is pulled from above to prevent voids. This pulling causes the pressure to become lower above the wing. It is the acceleration of the air above the wing in the downward direction that gives lift.

Induced drag can be reduced with wing with long span. But this adds to unnecessary cost, structural weight and also less maneuverability and more parasitic drag.

Winglets only reduce the effects of vortices; they do not get rid of them. Winglets block the path of the higher pressure air and stop it from getting to the lower pressure therefore stopping all forming of large vortices.

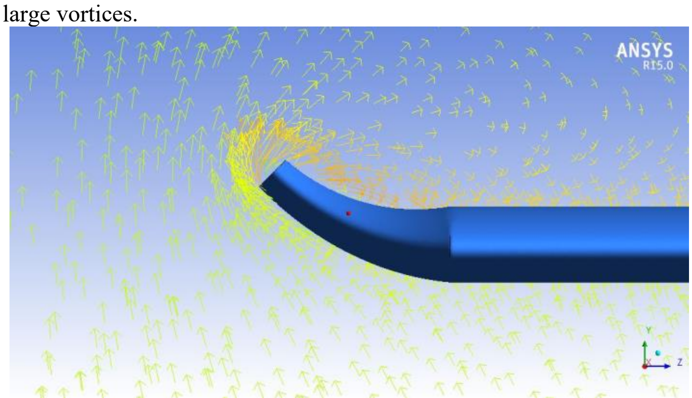

Fig.17: Vortex formation around elliptical winglet

However winglets themselves make tiny vortices because the higher pressure area is now on the outside of the winglet and the low pressure area on the inside. The difference in pressure causes the higher pressure area to move towards the lower pressure area thus making a vortex.

This vortices cause inefficiency however they are far more efficient than not having winglets; up to as much as 6% more efficient. These vortices also cause a small amount of inefficiency because they 'use up' less energy.

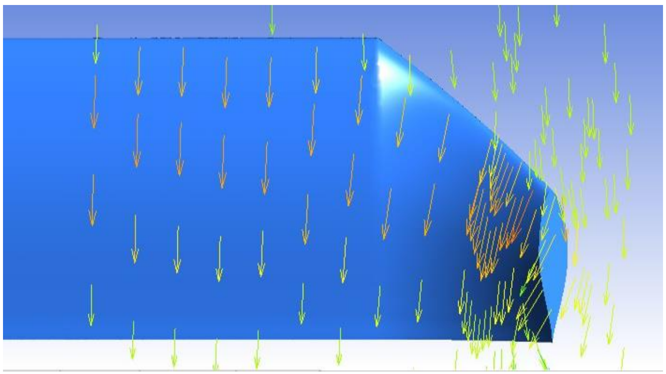

Fig.18: Direction of relative wind in vicinity of winglet surface

Winglets produce a forward thrust vector by being rotated toe-out slightly therefore 'stealing' the energy from the vortices and turning it into a 'thrust' allowing the engines to run at a lower rpm to achieve the same airspeed. The forward thrust vector is formed because the higher pressure on the outside pushes the winglet in and forward due to the toe-out attitude.

6.Conclusions

The present project investigates the aerodynamics effects of winglets of various shapes.

I. When no winglet is provided a vortex is developed due to recirculation of air around the lower and upper faces of the wing.

II. Winglets deflect the air flow towards the fuselage and hence reduces the induced drag caused by lift.
III. Winglet reduces the effective drag on the wing and hence reduces the fuel consumption.
IV. Winglets increases the effective aspect ratio and hence reduces the span wise flow, thus recovering a fraction of energy lost due to vortex formation.
V. Elliptical winglet provides maximum lift and minimum drag which is most desirable and this is followed by semicircular and straight winglets.

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