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Application of CFD Simulation in the Design of a Parabolic Winglet on NACA 2412

Arvind Prabhakar, Ayush Ohri

Abstract—Winglets are angled extensions or vertical projections at the tip of a wing, they are widely used in conjunction with plain airfoils on commercial airplanes for the purpose of reducing induced drag, vortices, and increasing lift. In this paper parabolic shaped configuration winglets at cant angles 45 and 55 degrees are analyzed on rectangular NACA 2412 airfoil sections using CFD analysis at Reynolds number $2*10^5$ and $4*10^5$ to compare aerodynamic characteristics. The wing is of 6 inch chord and 12 inches span, airfoils have been created using CATIA V5 and CFD analysis has been carried out using commercial code software ANSYS FLUENT 14.0, it is found that the L/D ratio increases by 13.447% and the coefficient of lift (C_L) increases by 1.958% for a parabolic winglet at 45 degrees cant angle at $2*10^5$ Reynolds number causing a maximum reduction in coefficient of drag (C_D) by 10.125% and thereby reducing fuel consumption of the aircraft.

Index Terms—CFD, Parabolic Winglets, Cant Angle, Coefficient of Lift (C_L), Coefficient of Drag (C_D), Lift to Drag ratio (L/D).

I. Introduction

Winglets are wingtip devices used in conjunction with plain airfoils for the purpose of reducing induced drag, vortices, and increasing lift. Winglets are angled extensions or vertical projections attached to the tips of wings. Winglets reduce vortices at wingtips which are twin tornados formed by the pressure difference on the upper surface and lower surface of a wing. The cause of the vortices formation is the high pressure at the lower surface of the wing that makes its way to the wingtip and then curls around it towards the lower pressure region on the upper surface, this curled flow streams out from the wingtip trailing edge causing formation of vortices.

Vortices are energy loss and a source of induced drag .Winglets do not permit the flow from high pressure region at bottom surface to curl towards the low pressure upper surface thereby not permitting the curl to stream out at the wing tip and cancelling the effect of vortices.

Wingtips were invented and pioneered by Richard Whitcomb in mid 1970's and have been successfully applied to commercial airplanes since then.

A vast amount of research has been ongoing to optimize and select the best shaped winglet configurations for the purpose of achieving minimum drag and maximum lift.

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Winglets are used currently on a number of aircrafts like the Boeing 747-400, Boeing 737, Airbus A-319, Beechcraft, Learjet 60 etc. Whitcomb revealed that winglets can provide improvements in efficiency of full size aircrafts by more than 7%. This helps in saving millions of dollars for airlines.

The motivation behind this research is the exploration of the parabolic shape configuration winglet as an efficient shape for winglet design.

Various shape configurations like Spiroid Winglets, Scimitar Blended Winglets, Blended Split-Tip Scimitar Winglet have been studied but not much and sufficient data is available on parabolic winglets. Hence, Parabolic Winglets were designed for the purpose of this paper at cant angles of 45 and 55 degrees to study their aerodynamic characteristics and compare them with other existing designs. First CFD analysis was carried out on rectangular NACA 2412 airfoils of chord 6 inch and span 12 inches for Reynolds Number $2 * 10^5$ and $4 * 10^5$. The CFD values of lift and drag coefficients achieved were found to be in good agreement with the experimental data thus, the CFD analysis was further extended to analyze NACA 2412 airfoils of chord 6 inch and span 12 inches with Parabolic Winglets attached at tips at cant angles 45 and 55 degrees for Reynolds number $2 * 10^5$ and $4 * 10^5$. The thickness of winglet was half of the airfoil chord. Spalart-Allmaras model was used for the purpose of CFD analysis , coefficient of lift (C_L), coefficient of drag (C_D), lift/drag L/D ratio were determined for these winglets at various angle of attacks and their aerodynamic characteristics were compared to plain rectangular NACA 2412 airfoils.

II. Methodology

The methodology for computation involved designing the plain rectangular NACA 2412 airfoils and the Parabolic Winglets on commercial cad software CATIA V5, the computational fluid domain was created on CATIA v5 and ICEM CFD ANSYS workbench meshing was used to generate the grid. CFD analysis was carried out using commercial code ANSYS FLUENT 14.0 and the values first obtained were compared with the experimental results for validating the CFD code. The post processing of results obtained was done using ANSYS CFD post.

Design of Rectangular Wing:-

Geometry setup of the wing was done on CATIA V5 using part design to draw the three dimensional model of the winglet as shown in figure1.

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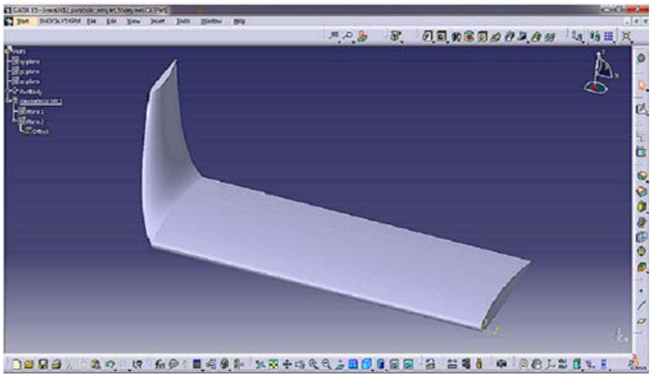

Fig 1: 3D modeling of the winglet on CATIA V5

Design of Fluid Domain:-

The geometry setup of the fluid domain was designed using part design in CATIA V5, the domain was created so as to replicate the experimental setup of the wind tunnel whose experimental results have been used to validate the CFD code.

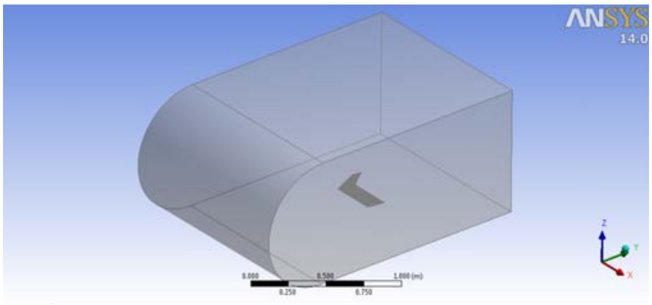

Fig 2: Design of Fluid Domain and Boolean Subtraction on ANSYS workbench

Design of Grid:-

Grid was generated using ICEM CFD in ANSYS workbench. The grid was generated using tetrahedral meshing with finer sizing and refinement done on the leading and trailing edges of the boundary of the wing. The Minimum Element Size at the leading and trailing edge was set to 0.001m. Tetrahedral mesh was generated on the fluid domain. Tetrahedral meshing takes lesser computational time keeping accuracy within the optimum range for complex structures to be analyzed. The Maximum Size, Maximum Face Size, and Growth Rate were set to 3m, 3m, 1.08 respectively are shown in figure 3.

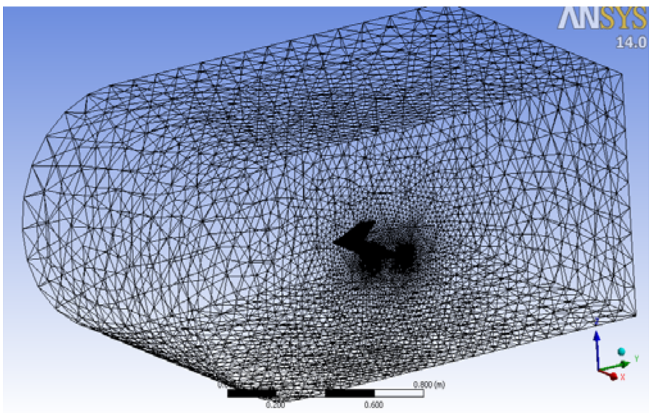

Fig 3: Generation of Grid on ICEM CFD

The design was numerically simulated in the FLUENT solver after the mesh had been generated in workbench. All the parameters which govern the simulation process such as model equation, material type and boundary conditions were defined and entered. Spalart-Allmaras model was used for the purpose of this CFD analysis. After all the parameters had been specified, solution was initialized and iterated till all the computations had been solved. The results that were obtained after the solution converged were analyzed and examined.

Grid Independence Test:-

A grid independence test was carried out to ensure that there is no effect on the solution due to the size of the grid. This was achieved by considering three different grid configurations and studying their convergence behavior at Reynolds Number $2*10^5$.

Grid configuration 1 was a coarse grid that had 502201 number of cells and a Minimum Orthogonal Quality = 0.0495650 it showed inaccurate results due to a deviation of about 15.16% from the experimental value.

Grid configuration 2 was finer grid that had 2833755 number of cells with Minimum Orthogonal Quality = 0.183307 it consisted of refinement at the leading and trailing edges of the wing, this showed realistic behavior and solution obtained was closer to the experimental data. A deviation of about 4.36% was observed.

Grid configuration 3 was the finest mesh and had 4014540 number of cells with a Minimum Orthogonal Quality = 0.168672 and showed a behavior not much different than configuration 2 and also, produced a solution similar to configuration 2 hence, grid configuration 2 was selected for all further analysis, considering computation time and size constraints in mind. The plot of solutions obtained with these three different grid configurations and experimental results has been shown in figure 4.

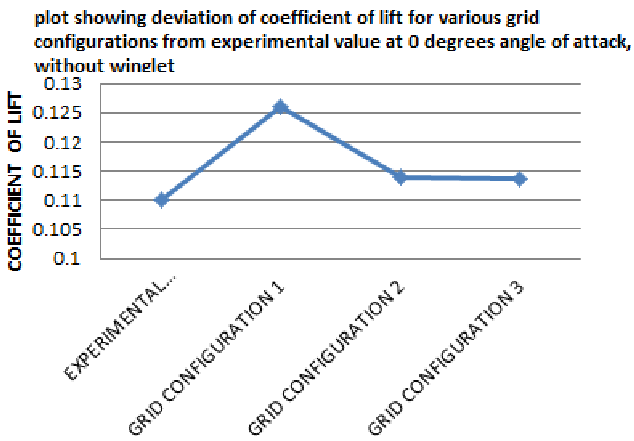

Fig 4: The plot of solutions

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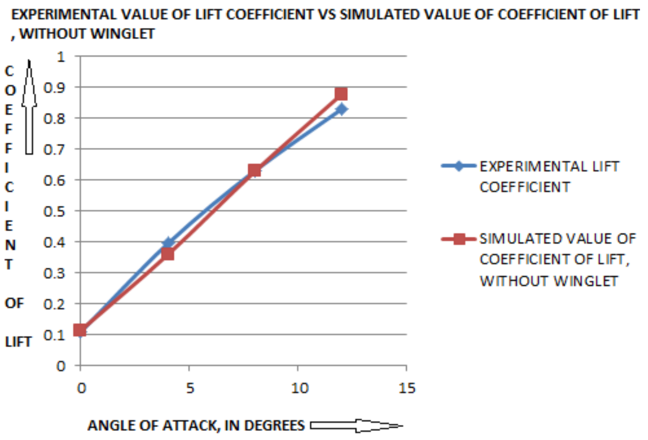

Fig 5: Validation of CFD, a plot of experimental vs simulated Coefficient of Lift.

III. RESULTS AND DISCUSSIONS

After the simulation of the 3d wings was successfully completed, their results were compared in terms of lift-coefficient, drag coefficient and the L/D ratios obtained which are primary indicators of aerodynamic performance. A comparison was made between the three different types of wing configurations which were wing without winglet, wing with parabolic winglet at 45^0 cant angle, and wing with parabolic winglet at 55^0 cant angle. The simulation was carried out at an inlet velocity of 21.24377 m/s which corresponded to $2*10^5$ Reynolds Number and 42.4875 m/s which corresponded to $4*10^5$ Reynolds Number. The Reynolds Number was kept constant for all the simulations that were carried out on different types of wings as mentioned above. The different wing configurations were simulated at 0^0, 4^0, 8^0, & 12^0 angle of attack.

1) Lift-Coefficient Analysis:

a) Angle of attack 0^0 :- At $2*10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 4.185% compared to that of without winglet. Whereas the C_L value for wing with parabolic winglet at 55^0 cant angle increased by 8.713% compared to the wing which had no winglet attached to it.

At $4*10^5$ Reynolds Number the value of C_L for wing with parabolic winglet at 45^0 cant angle decreased by 1.949% compared to that of without winglet. Whereas, the C_L value for wing with Parabolic Winglet at 55^0 cant angle increased by 4.065% compared to the wing which had no winglet attached to it.

b) Angle of attack 4^0 :- At $2 * 10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 1.958% compared to that of the wing without any winglet. There was an increase in the value of C_L by 1.527% for wing with Parabolic Winglet at 55^0 cant angle compared to the wing without any winglet.

At $4 *10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 0.447% compared to that of without winglet. Whereas, the C_L value for wing with Parabolic Winglet at 55^0 cant angle increased by 3.420% compared to the wing which had no winglet attached to it.

c) Angle of attack 8^0 :- At $2*10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 3.628% compared to the wing without any winglet. Whereas the value of C_L for wing with Parabolic Winglet at 55^0 cant angle jumped up by 5.037% compared to the wing which had no winglet attached to it.

At $4*10^5$ Reynolds Number the value of C_L for wing with parabolic winglet at 45^0 cant angle increased by 5.350% compared to that of without winglet. Whereas the C_L value for wing with parabolic winglet at 55^0 cant angle increased by 7.422% compared to the wing which had no winglet attached to it.

d) Angle of attack 12^0 :- At $2*10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 0.627% compared to the wing which had no winglet attached to it. There was an increase in the value of C_L for wing with Parabolic Winglet at 55^0 cant angle by 2.150% compared to the wing without any winglet.

At $4*10^5$ Reynolds Number the value of C_L for wing with Parabolic Winglet at 45^0 cant angle increased by 0.0409% compared to that of without winglet Whereas, the C_L value for wing with Parabolic Winglet at 55^0 cant angle increased by 1.849% compared to the wing which had no winglet attached to it.

Table 1: Lift Coefficient comparison for various wing configurations, Reynolds Number = $2*10^5$

WING CONFIGURATION	VELOCITY (m/s)	LIFT COEFFICIENT (C_L)			
		0^0	4^0	8^0	12^0
WITHOUT WINGLET	21.24377	0.11485636	0.35945018	0.62823054	0.87788515
PARABOLIC WINGLET AT CANT ANGLE 45^0	21.24377	0.1196644	0.3664917	0.65102308	0.8833928
PARABOLIC WINGLET AT CANT ANGLE 55^0	21.24377	0.12486484	0.37472372	0.66010691	0.89676306

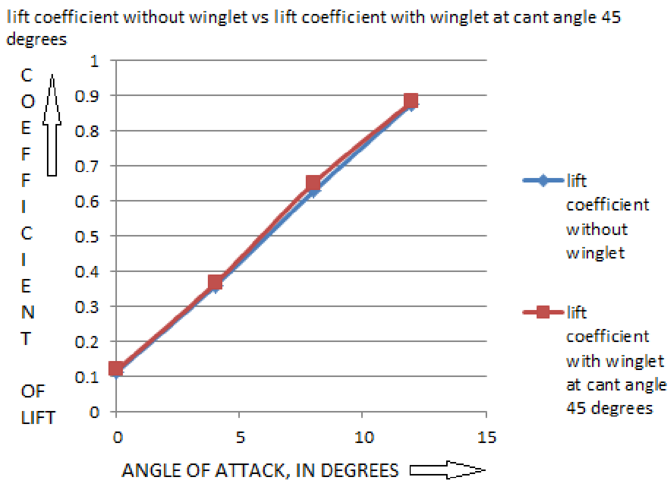

Fig 6: Graph of lift coefficient without winglet vs lift coefficient with winglet at 45 degrees cant angle.

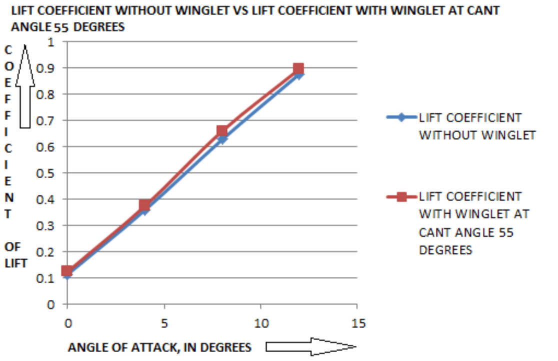

Fig 7: Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

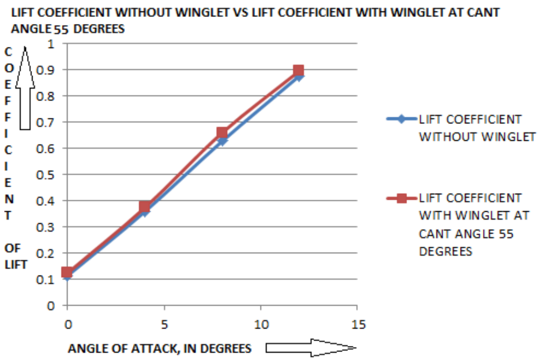

Fig 8, Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

Table 2, Lift Coefficient comparison for various wing configurations at Reynolds Number = $4*10^5$

WING CONFIGURATION	VELOCITY (m/s)	LIFT COEFFICIENT (C_L)			
		0^0	4^0	8^0	12^0
WITHOUT WINGLET	42.4875	.1240263	.36526516	.61815523	.88517215
WITH PARABOLIC WINGLET AT 45^0 CANT ANGLE	42.4875	.12160866	.36689881	.65123198	.88553462
WITH PARABOLIC WINGLET AT 55^0 CANT ANGLE	42.4875	.12906883	.37776075	.66403989	.90154615

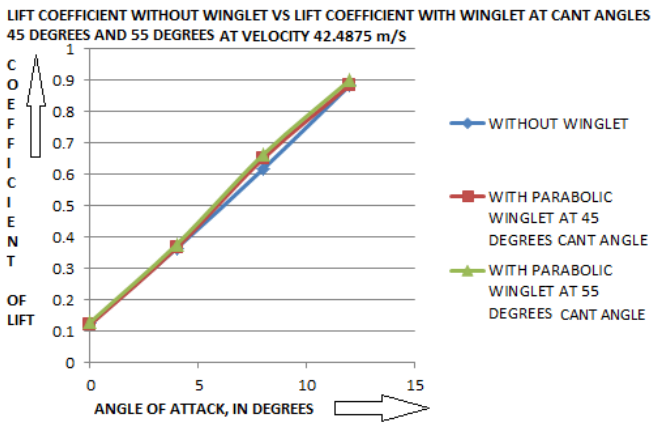

Fig 9: Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

2) Drag Coefficient Analysis :

a) Angle of attack 0^0 :- At $2*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 3.456% compared to the wing without any winglet. Whereas the value of C_D for wing with Parabolic Winglet at 55^0 cant angle decreased by 3.862% compared to the wing which had no winglet attached to it.
At $4*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 5.171% compared to the wing without any winglet Whereas the value of C_D for wing with Parabolic Winglet at 55^0 cant angle decreased by 4.907% compared to the wing which had no winglet attached to it.

b) Angle of attack 4^0 :- At $2*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 10.125% compared to the wing which had no winglet attached to it. There was a decrease in the value of C_D for wing with Parabolic Winglet at 55^0 cant angle by 9.213% compared to the wing without any winglet.
At $4*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 7.845% compared to the wing without any winglet Whereas, the value of C_D for wing with Parabolic Winglet at 55^0 cant angle decreased by 6.193% compared to the wing which had no winglet attached to it.

c) Angle of attack 8^0 :- At $2*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 5.763% compared to the wing which had no winglet attached to it. There was a decrease in the value of C_D for wing with Parabolic Winglet at 55^0 cant angle by 5.517% compared to the wing with no winglet.
At $4*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 2.919% compared to the wing without winglet Whereas, the value of C_D for wing with Parabolic Winglet at 55^0 cant angle decreased by 1.383% compared to the wing which had no winglet attached to it.

d) Angle of attack 12^0 :- :- At $2*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 7.610% compared to the wing without any winglet. There was a decrease in the value of C_D for wing with Parabolic Winglet at 55^0 cant angle by 6.189% compared to the wing without any winglet.
At $4*10^5$ Reynolds Number the value of C_D for wing with Parabolic Winglet at 45^0 cant angle decreased by 8.073%compared to the wing without any winglet Whereas the value of C_D for wing with Parabolic Winglet at 55^0 cant angle decreased by 6.182% compared to the wing which had no winglet attached to it.

Table 3: Drag Coefficient comparison for various wing configurations at Reynolds Number = $2*10^5$

WING CONFIGURATION	VELOCITY (m/s)	DRAG COEFFICIENT (C_d)			
		0^0	4^0	8^0	12^0
WITHOUT WINGLET	21.24377	0.02279445	0.035435663	0.060684782	0.099039102
PARABOLIC WINGLET AT CANT ANGLE 45^0	21.24377	0.022006598	0.031847603	0.057187279	0.091501456
PARABOLIC WINGLET AT CANT ANGLE 55^0	21.24377	.021913941	0.032170752	0.057336521	0.092908888

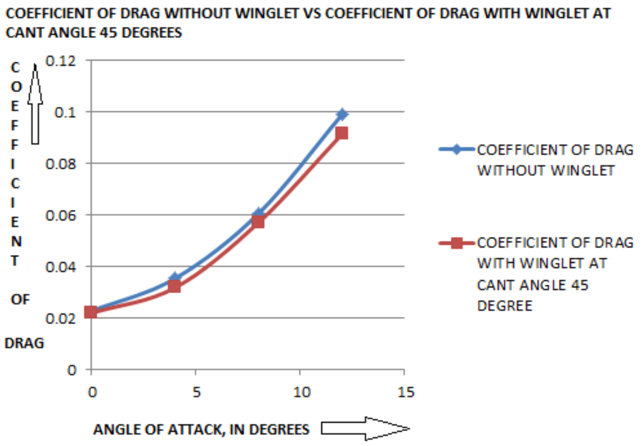

Fig 10: Graph of lift coefficient without winglet vs lift coefficient with winglet at 45 degrees cant angle.

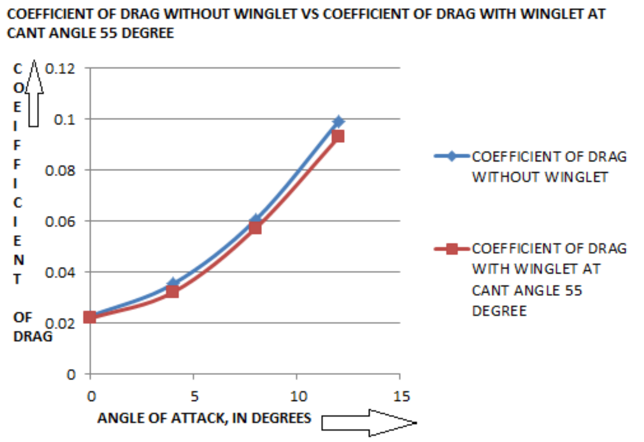

Fig 11: Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

Table 4: Drag coefficient comparison for various wing configurations at Re = $4 * 10^5$

WING CONFIGURATION	VELOCITY (m/s)	DRAG COEFFICIENT (C_D)			
		0°	4°	8°	12°
WITHOUT WINGLET	42.4875	.020090414	.031651315	.05623456	.096952583
WITH PARABOLIC WINGLET AT 45° CANT ANGLE	42.4875	.019051367	.029168133	.054593034	.089125485
WITH PARABOLIC WINGLET AT 55° CANT ANGLE	42.4875	.019104435	.029690859	.055456515	.090958442

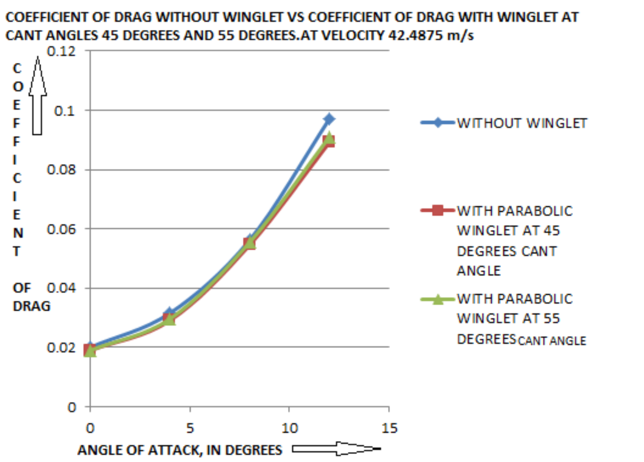

Fig 12, Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle

3) L/D Ratio Analysis:

a) Angle of attack 0^0 :-At $2*10^5$ Reynolds Number the value of L/D for wing with Parabolic Winglet at 45^0 cant angle increased by 7.919% compared to the wing without any winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 13.080% compared to the wing with no winglet attached to it.
At $4*10^5$ Reynolds Number the value of L/D for wing with Parabolic Winglet at 45^0 cant angle increased by 3.396% compared to the wing without any winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 9.435% compared to the wing with no winglet attached to it.

b) Angle of attack 4^0 :- :-At $2*10^5$ Reynolds number the value of L/D increased for wing with Parabolic Winglet at 45^0 cant angle by 13.447% compared to the wing with no winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 14.827% compared to the wing which had no winglet attached to it.
At $4*10^5$ Reynolds Number the value of L/D for wing with Parabolic Winglet at 45^0 cant angle increased by 8.998% compared to the wing without any winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 10.250% compared to the wing with no winglet attached to it.

c) Angle of attack 8^0 :- At $2*10^5$ Reynolds Number the value of L/D increased for wing with Parabolic Winglet at 45^0 cant angle by 9.969% compared to the wing which had no winglet attached to it. There was an increase in the value of L/D for Parabolic Winglet at 55^0 cant angle by 11.205% compared to the wing which had no winglet attached to it.
At $4*10^5$ Reynolds Number the value of L/D for wing with Parabolic Winglet at 45^0 cant angle increased by 8.518% compared to the wing without any winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 8.929% compared to the wing with no winglet attached to it.

d) Angle of attack 12^0 :- :- At $2*10^5$ Reynolds Number the value of L/D increased for wing with Parabolic Winglet at 45^0 cant angle by 8.912% compared to the wing which had no winglet attached to it. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 8.889% compared to the wing which had no winglet attached to it.
At $4*10^5$ Reynolds Number the value of L/D for wing with Parabolic Winglet at 45^0 cant angle increased by 8.827% compared to the wing without any winglet. There was an increase in the value of L/D for wing with Parabolic Winglet at 55^0 cant angle by 8.561% compared to the wing with no winglet attached to it

Table 5: Lift/Drag ratio comparison for various wing configurations at Reynolds Number = $2*10^5$

WING CONFIGURATION	VELOCITY (m/s)	L/D RATIO			
		0°	4°	8°	12°
WITHOUT WINGLET	21.24377	5.038	10.143	10.352	8.864
PARABOLIC WINGLET AT CANT ANGLE 45°	21.24377	5.437	11.507	11.384	9.654
PARABOLIC WINGLET AT CANT ANGLE 55°	21.24377	5.697	11.647	11.512	9.652

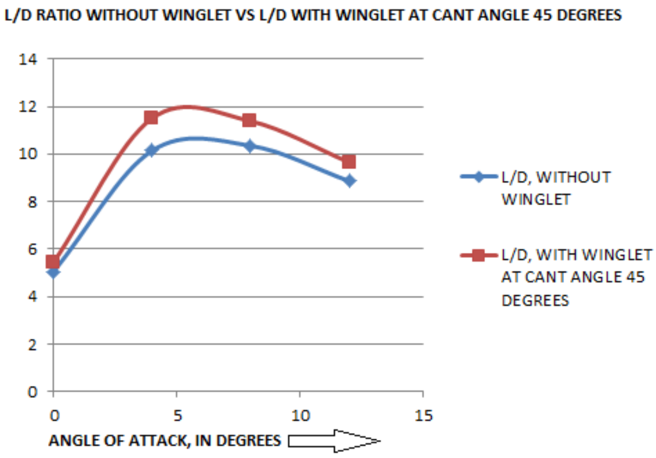

Fig 13: Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

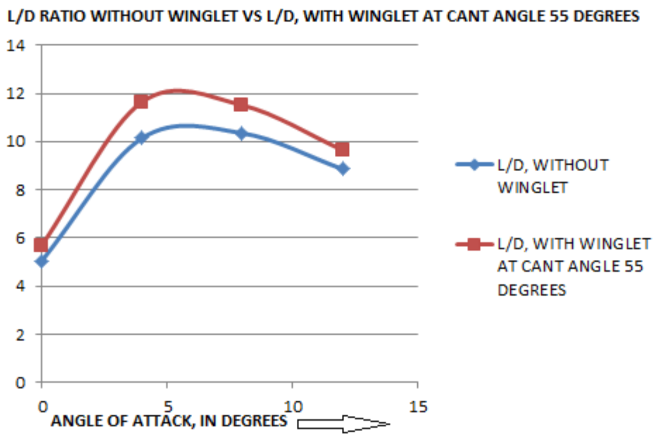

Fig 14: Graph of lift coefficient without winglet vs lift coefficient with winglet at 55 degrees cant angle.

Table 6: Lift/Drag Ratio comparison for various wing configurations at Reynolds Number = $4*10^5$

WING CONFIGURATION	VELOCITY (m/s)	L/D RATIO			
		0°	4°	8°	12°
WITHOUT WINGLET	42.4875	6.1734	11.5402	10.9924	9.1299
WITH PARABOLIC WINGLET AT 45° CANT ANGLE	42.4875	6.3831	12.5787	11.9288	9.9358
WITH PARABOLIC WINGLET AT 55° CANT ANGLE	42.4875	6.7559	12.7231	11.9740	9.9116

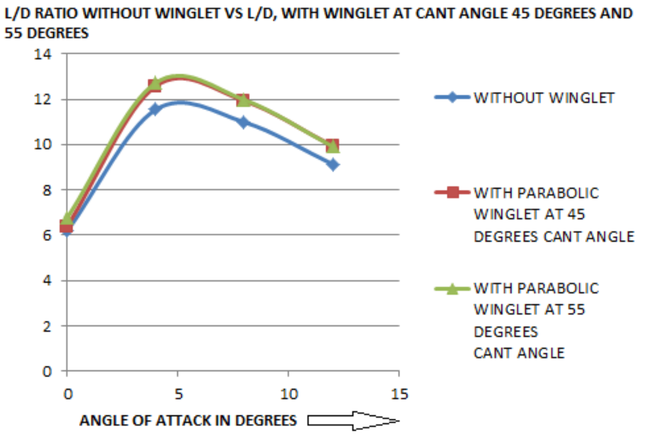

Fig 15: Graph of lift coefficient without winglet vs lift coefficient with winglet at 45 degrees cant angle.

4) Contours of Coefficient of Pressure :- The plot of Coefficient of Pressure for a Parabolic Winglet is shown from figures 5 to 12. The figures suggest that with increasing angle of attack from 0 to 12 degrees the low pressure coefficient area tends to shift towards the leading edge on the upper surface. The magnitude of this Pressure Coefficient is lesser than the Pressure Coefficient on the wing without a winglet thus, causing higher lift generation.
The intensity of this Pressure Coefficient decreases with increasing angle of attack suggesting lower values of Pressure Coefficient and indicating a high lift generation at such positions.

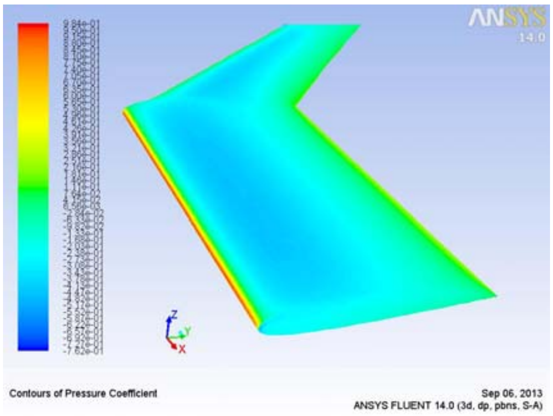

Fig 16: Top surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 0 degrees angle of attack, Reynolds Number = $2*10^5$

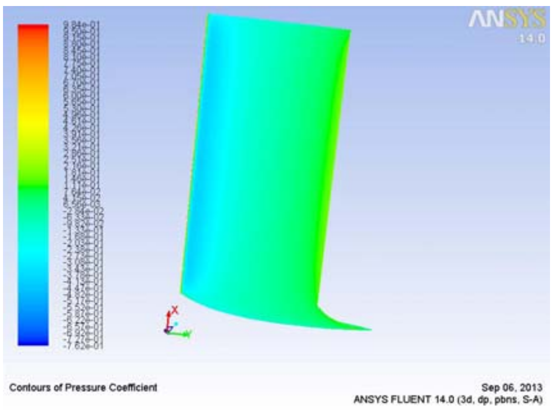

Fig 17: Bottom surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 0 degrees angle of attack, Reynolds Number = $2*10^5$

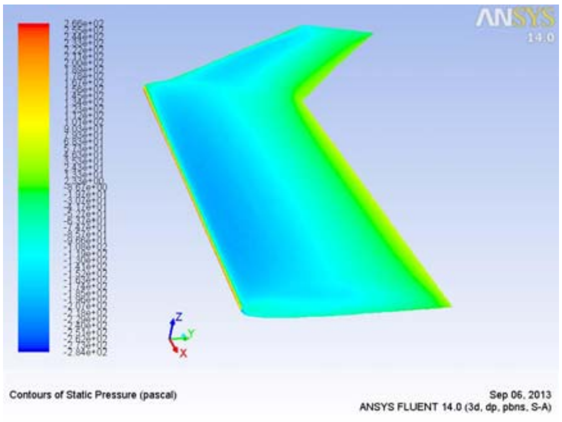

Fig 18: Top surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 4 degrees angle of attack, Reynolds Number = $2*10^5$

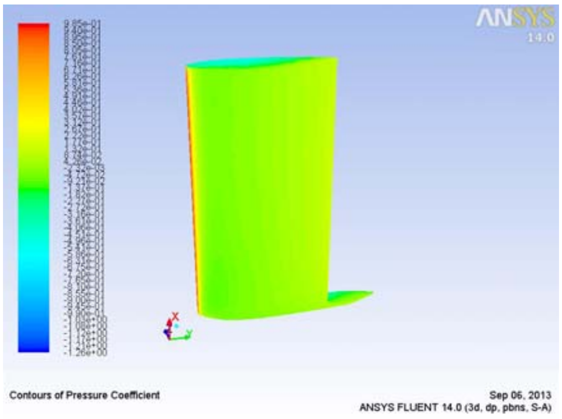

Fig 19: Bottom surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 4 degrees angle of attack, Reynolds Number = $2*10^5$

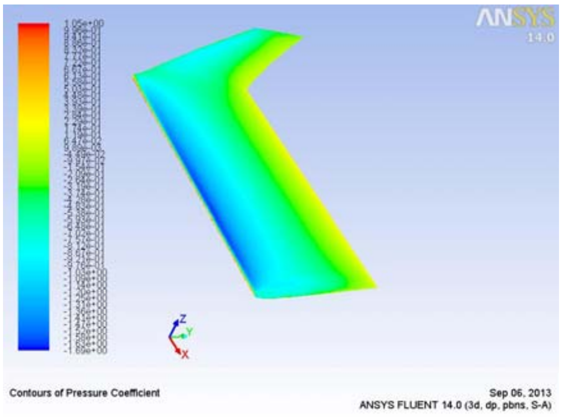

Fig 20: Top surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 8 degrees angle of attack, Reynolds Number= $2*10^5$

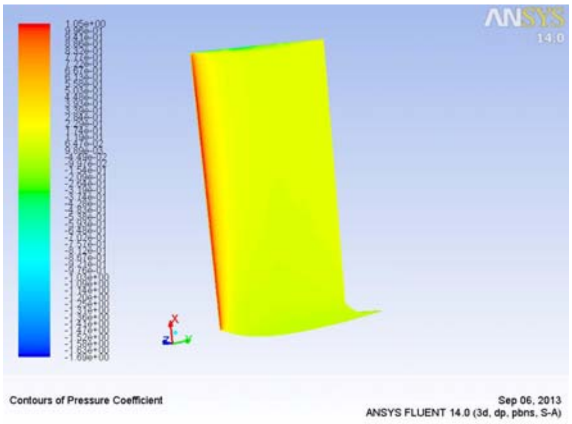

Fig 21: Bottom surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 8 degrees angle of attack, Reynolds Number = $2 * 10^5$

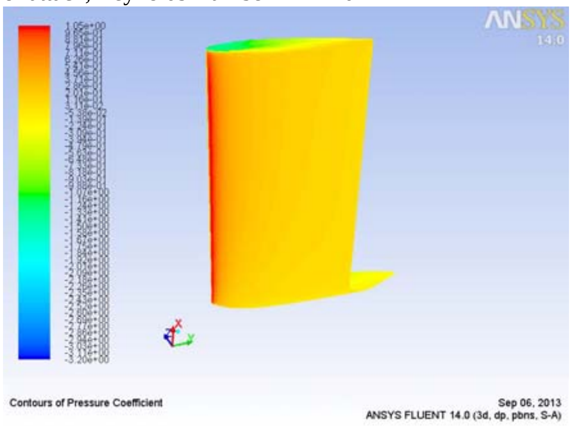

Fig 22: Bottom surface Coefficient of Pressure contours on wing with Parabolic Winglet at cant angle 45 degrees, at 12 degrees angle of attack, Reynolds Number = $2*10^5$

5) Pathlines :- These are coloured lines which define the behavior of the flow of a fluid over a particular object which is being analysed during the graphical post processing of the converged simulation. Each colour represents a particular magnitude of velocity, pressure, energy etc. as the case may be. The figures below show Pathlines of velocity magnitude. These Pathlines are mainly focused to give a graphical representation of the vortices being formed at the trailing edge of the wing without any winglet and wing with a winglet attached to it at some cant angle. The Pathlines visualize as to how the vortices have shifted from one trailing edge of the wing with no winglet attached to it to the top portion of the wing (top part of the winglet) when it has a Parabolic Winglet attached to it at that particular trailing edge. Therefore it can be observed that the turbulence on the plain wing reduces to a considerable extent and shifts to the top portion of the winglet which thereby results in reduction of induced drag and increase in the lift of the wing which has a winglet attached to it. The winglets have to be carefully designed keeping in mind the amount of structural load they would add to the aircraft. If the above mentioned parameter is not kept in mind during the designing of winglets, it will lead to an increase in viscous drag and thereby the purpose of the winglets would fail. The Pathlines shown below have been analysed at an inlet velocity of 21.24377m/s. figures 13 and 14 show velocity Pathlines.

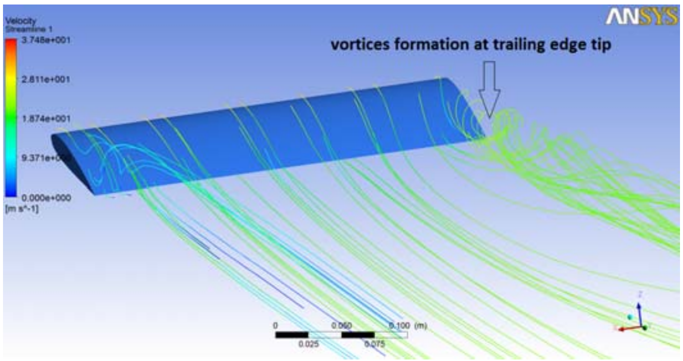

Fig 23: Velocity Pathlines from airfoil without winglet at angle of attack 12 degrees, Reynolds Number = $2*10^5$

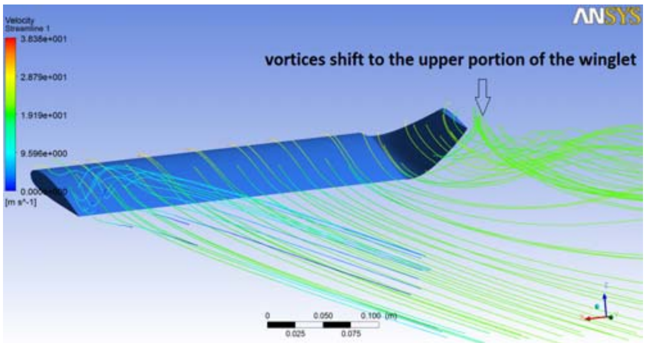

Fig 24: Velocity Pathlines from airfoil with Parabolic Winglet cant angle 45 degrees at angle of attack 12 degrees, Reynolds Number = $2*10^5$

IV. CONCLUSION

The results that were obtained after the simulation was completed on each of the wing configurations proved that the parabolic winglets designed for this project did serve the purpose of a winglet. The results after being analysed numerically showed a considerable reduction in the value of drag coefficient, an increase in the value of lift coefficient, and an increase in L/D Ratio of a wing which had the Parabolic Winglet attached to it at 45 & 55 degrees cant angle when compared to the wing which had no winglet attached to it. Hence it is proved that if parabolic winglets are attached to the plain wing it would result in lesser fuel consumption of the aircraft and more over the lift of the wing would also increase.

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