Design and Aerodynamic Analysis of Different Winglets

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Abstract- This paper investigates the aerodynamics characteristic of the wing and the winglet. A winglet is vertical surface placed at the trailing edge of the wing, this helps to increase the aerodynamic efficiency of the wing. The airfoil used to construct the whole wing is NACA 4412.The wing and the winglets are manufactured by using Fiber glass re-enforced composite materials (FRCM). The three types of winglets that are analyzed blended, bird like winglet and finlet. The wing and the winglets were designed using CATIA V6, and analyzed by using UNIFIGUREICS. The experimental analysis was carried out in a low speed subsonic wind tunnel, having a cross section of 0.300 m X 0.300 m X 0.600 m, at a velocity of 40 m/s and 25 m/s. The winglets have been tested at different Cant angles and angles of attack. The conclusion of this experiment shows that the finlet tend to delay the stall, bird winglet is efficient at low speed, and overall the blended winglet was more efficient than the other two types of winglets.

Keywords- Winglet, Aerodynamic Characteristics, Wind Tunnel, Cant Angle

I. INTRODUCTION

High fuel cost and environment concerns provide continuing motivation for research aimed at increasing aircraft efficiency. Vortex drag is a major contributor to aircraft drag, typically accounting for about 40% of the drag in cruise and about 80-90% of the drag in second segment climbs [1]. Since vortex drag is strongly affected by wing tip geometry, wing tip optimization has received a great deal of attention because of its potential for reducing vortex drag. Improved wing tip design can benefit new designs and can be used to improve performance by retrofitting existing wings [2].

The major obstacle in aircraft performance is drag; this drag is mainly caused due to the shear-force which in turn generates vortices. Vortices are formed at the tip of the wing, due to the pressure difference between the upper and lower surface [3]. The flow on the lower surface is higher than that on the upper surface, therefore the flow coincide with the upper surface flow forming vortices, which produces induced drag. In cruise conditions the induced drag is responsible for approximately 30% on entire drag and also 50% in high-lift conditions [4]. Wing with high aspect ratio generate weak vortices compared to wings with low aspect ratio. A favorable device which helps in reducing drag is a winglet.

Winglets are vertical surfaces placed at the tip of the wings. Winglets affect the part of drag called induced drag. As air is deflected by the lift of the wing, the total lift vector tilts back, the aft component of this lift vector is the induced drag. Induced drag can be reduced by increasing the horizontal span or the vertical height of the lifting system [5]. The idea behind all the devices was to diffuse the strong wing tip vortices and to optimize the span wise wing lift distribution. Modern interest in winglets spans the last 25 years. Research in the field of winglets began in 1976, by Robert Whitcomb [6] of NASA Langely Research Centre published a general design approach that summarized the aerodynamic technology involved in winglet design so that lift to drag performance would be increased. Kroo et al [7], [8] did a revision in the basis that described the prediction and reduction of the induced drag. Ruhlin, et al [9] noted that the addition of a winglet substantially reduced the flutter speed of the wing at transonic Mach numbers. Winglets are used at low speeds because the induced drag decreases and the profile drag increases with increase in air speed [10]. Thus the gains in performance that the winglets provide are greatest at low speeds and progressively less as the speed increases. Usually these surfaces have reduced the drag at very high lift coefficients but have resulted, at best, in only slight reductions in drag near cruise lift coefficients [11].

All the commercial aircrafts in today's world use blended winglets as there are efficient compared with other winglets in use. A blended winglet was attached to the wing with smooth curve instead of a sharp angle and is intended to reduce interference drag at the wing/winglet junction. The blended winglet [12] reduces drag by eliminating the discontinuity between the wing tip and the winglet. The blended winglet is used on business jets and sailplanes, where individual buyer preference is an important marketing aspect. A joint partnership of Aviation Partners, Inc. and Boeing, Aviation Partners Boeing offers blended winglets for the Boeing 737 Classic and Next Generation models,[1] 757 and 767 [12].

To improve the winglet performance characteristics two new concepts have been taken into account in this paper. Bird have been inspiring humans for a long time, birds have pin feathers at the ends that produce slotted wingtips. It was found that pin feathers help to decrease the drag, thereby giving the concept of bird winglet [13]. Vance Tucker, a biologist with an aerodynamics background, demonstrated that the tip slots of soaring birds reduce induced drag and increase the span factor of the wings [14]. Cosin et al. [15] worked on a wing with multi winglets, three small fins attached to the salmon timing different for each winglet were used. This device increases the aerodynamic parameters, with a 7.3% gain in efficiency.

Finlet are present on the body of the fish behind the dorsal fin and anal fin. These appear to be in a zig-zag form and help in affecting the flow around them by increasing the thrust. Implementing this concept in winglet called finlet to improve the performance of the winglet. Research done in 2000 and 2001 by Nauen and Lauder indicated that the finlets have a hydrodynamic effect on local flow during steady swimming and that the most posterior finlet is oriented to redirect flow into the developing tail vortex, which may increase thrust produced by the tail of swimming mackerel [16], [17]. This helps in delaying the stall conditions of the wing apart from reducing induced drag. A comparison was made between these three types of winglets to find the efficient one, and also came to a conclusion with the pros and cons on the implemented concept.

II. METHODOLOGY

A. Computational Approach-

The computational steps in this project consist of three stages as shown in the figure 1. In the first stage the design of the wing and the winglet is done using CATIA V5. In the second stage the computational simulation is done by means of UNIFIGUREICS. In the third stage the aerodynamic characteristic of the winglet are determined.

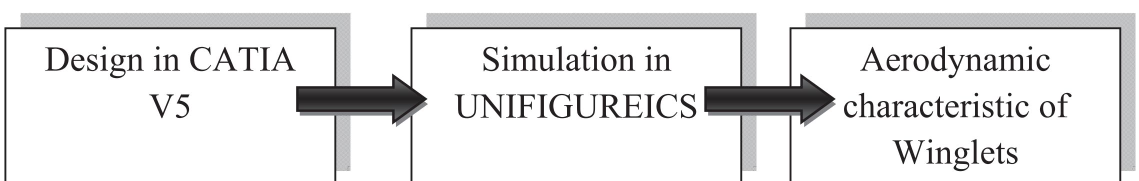

Figure 1. Computational steps

The three types of winglets at different Cant angles were designed in CATIA V5. To design the wing and the winglet NACA 4412 airfoil was used. As in most airfoil design efforts, the goal of the winglet airfoil design is to generate the lift required with the lowest possible drag. The winglets are designed at four different Cant angles i.e. 0^0, 45^0, 60^0, 90^0. The images of these winglets designed by CATIA V5 are shown in figures 2,3, 4.

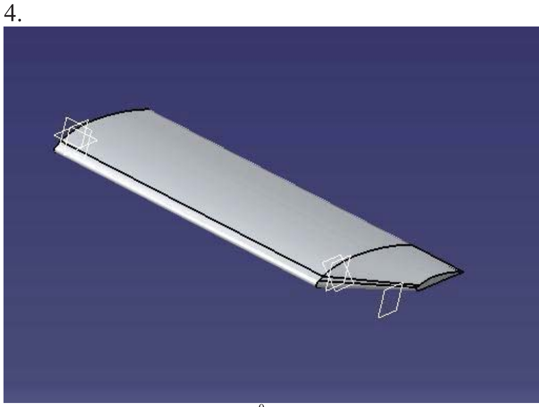
Figure 2. 0^0 (degree) Cant angle

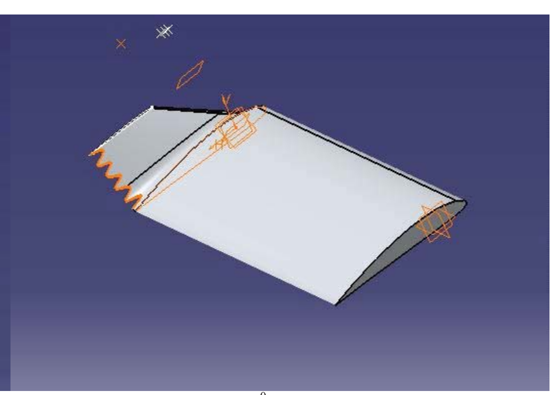
Figure 3. 45^0 (degrees) Cant angle

These CATIA design models were imported in UNIFIGUREICS. The cross section of wind tunnel test section was created and meshed in UNIFIGUREICS as shown in figure 5. The boundary conditions were specified and the values of velocity, density and area were specified. The numerical simulation by the solver was made after specifying the boundary conditions. After all the parameters were specified the model was initialized. The initializing and iteration process stopped after the completion of computations. The results obtained were examined and analyzed.

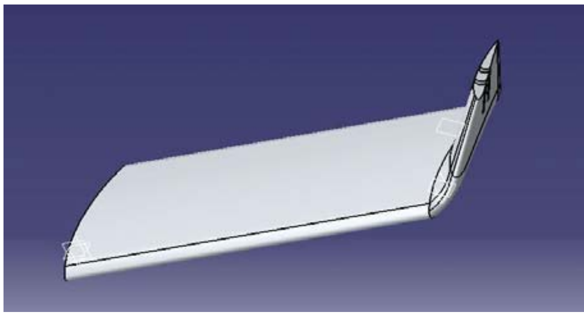

Figure 4. 60^0 (degrees) Cant angle

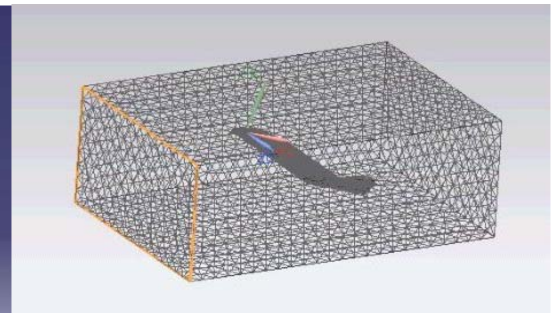

Figure 5. Wing with Winglet Meshing in UNIFIGUREICS

The result of the computational simulation performed is as shown in the figures 6,7,8 and 9.

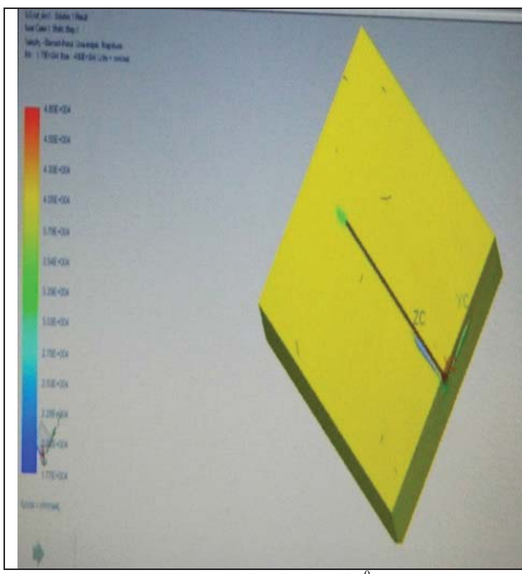

Figure 6. Simulation of 0^0 Cant angle

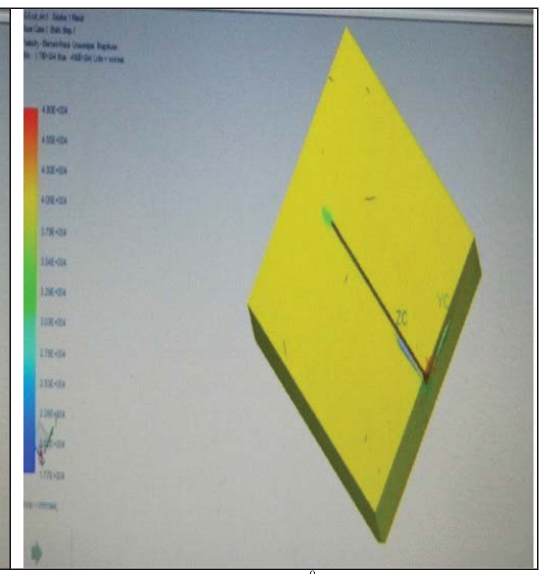

Figure 7. Simulation of 45^0 Cant angle

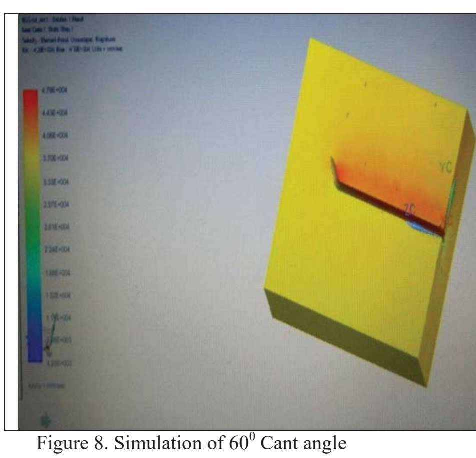

Figure 8. Simulation of 60^0 Cant angle

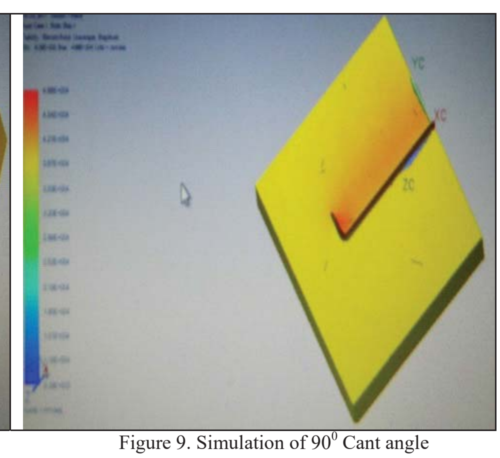

Figure 9. Simulation of 90^0 Cant angle

B. Experimental Approach-

The models of wing and the winglets have been designed and fabricated using wood and Fiber Glass Re-enforced Composite Material (FRCM). Both the wing and the winglets have been designed using NACA 4412. The wing model has a half span of 0.200m and chord of 0.100 m as shown in figure 10.The winglets models of different shapes made of wooden and FRCM using different manufacturing techniques are shown in figure 11. A Low speed subsonic wind tunnel with test section of 0.300m X 0.300m X 0.600m was used to test the aerodynamic characteristic of the semi span wing and winglet as shown in the figure 12. The test was carried out at a free stream velocity of 40m/s with the three different configurations of the winglets. The three component balance is used for measurements of aerodynamic forces. A Pitot static tube is used for measurements of air flow velocity with digital measuring system. The maximum speed of air flow that can be generated by this wind tunnel is 50 m/s.

Figure 10. Wing fabricated with FRCM

Figure 11. Winglets modelled with FRCM

Figure 12. Low Speed Subsonic Wind Tunnel

The test was carried out at an angle of attack ranging from 0^0 to 20^0, with an interval of $5^{0.}$ Along with the angle of attack the Cant angle of the winglets were also varied as 0^0, 45^0, 60^0 and 90^0. The winglets which were attached with wing placed inside the test section by mounting the wing in three component balance strut firmly, leading edge facing toward the wind. The wings along with all three types of winglets during testing are shown in figure 13 to 15.

Figure 13. Blended winglet in the test section

Figure 14. Bird winglet in the wind tunnel

Figure 15. Finlet in the wind tunnel

During the test the actual lift and drag forces were measured using a three component balance. The lift and drag coefficient were obtained by using the following equation

The coefficient of lift is given as $C_L = L/ (0.5 \rho V^2 S)$.

Coefficient of drag $C_D = D/ (0.5 \rho V^2 S)$.

Where,

L =Lift (value obtained from the wind tunnel)

D = Drag (value obtained from the wind tunnel)

V = velocity

S = reference area

ρ = density

III. RESULT AND DISCUSSION

The wind tunnel measurements using the wing and the winglet models with different configuration were tested at a velocity of 40 m/s, and the bird winglet was tested at a velocity of 25 m/s. The values of lift and drag obtained from the wind tunnel and the calculation of the coefficients at different angle of attack are given in table 1.The coefficient of lift versus angle of attack with the different winglets and Cant angels studied in this investigation are shown in the table 1 and Figures 16, 17, 18. As the angle of attack increases the coefficient of lift also increases at a particular point above 10^0 angle of attack the lift decreases suddenly, this position is called stalling position. The lift also varies with the Cant angles as shown in the Figures 16, 17 and 18 respectively.

Table -1 Coefficient of Lift versus Angle of Attack

Winglet configuration	Velocity m/s	Coefficient of Lift				
		0^0	5^0	10^0	15^0	20^0
0 deg blended	**40**	**0.00264**	**0.004755**	**0.00159**	**0.00106**	**0.00079**
0 deg bird winglet	**25**	**0.00271**	**0.007439**	**0.01014**	**0.00541**	**0.00135**
0 deg finlet	**40**	**0.00159**	**0.002642**	**0.0037**	**0.00502**	**0.00159**
45 deg blended	**40**	**0.00282**	**0.005166**	**0.00658**	**0.0047**	**0.00376**
45 deg bird winglet	**25**	**0.00842**	**0.019235**	**0.02164**	**0.01322**	**0.00962**
45 deg finlet	**40**	**0.00704**	**0.010332**	**0.01315**	**0.01597**	**0.0108**
60 deg blended	**40**	**0.00288**	**0.003362**	**0.0048**	**0.00192**	**0.00048**
60 deg bird winglet	**25**	**0.00258**	**0.002951**	**0.00283**	**0.00123**	**0.00062**
60 deg finlet	**40**	**0.00096**	**0.002882**	**0.00432**	**0.00576**	**0.0024**

90 deg blended	**40**	**0.00288**	**0.007204**	**0.01105**	**0.00865**	**0.00672**
90 deg bird winglet	**25**	**0.0123**	**0.022132**	**0.02582**	**0.01107**	**0.00246**
90 deg finlet	**40**	**0.00384**	**0.004803**	**0.0072**	**0.00865**	**0.00192**

The coefficient of drag at different angles of attack for the three types of tested winglets was calculated as given in table 2. According to the results drag values obtained are more for the bird winglet at 90 degree Cant angle and 20 degree angle of attack. The lowest drag is produced for the bird winglet at 60 degree cant angle.

Table -2 Coefficient of drag

		Coefficient of Drag				
Winglet configuration	**Velocity m/s**	**0**	**5**	**10**	**15**	**20**
0 deg blended	**40**	**0.00026**	**0.000264**	**0.00053**	**0.00053**	**0.00053**
0 deg bird winglet	**25**	**0.00068**	**0.000676**	**0.00135**	**0.00203**	**0.00203**
0 deg finlet	**40**	**0.00026**	**0.000264**	**0.00053**	**0.00053**	**0.00079**
45 deg blended	**40**	**0.00047**	**0.00047**	**0.00094**	**0.00094**	**0.00141**
45 deg bird winglet	**25**	**0.0012**	**0.002404**	**0.0024**	**0.00361**	**0.00481**
45 deg finlet	**40**	**0.00047**	**0.00047**	**0.00094**	**0.00141**	**0.00141**
60 deg blended	**40**	**0.00048**	**0.00048**	**0.00048**	**0.00096**	**0.00144**
60 deg bird winglet	**25**	**0.00012**	**0.0002459**	**0.00037**	**0.00037**	**0.00037**
60 deg finlet	**40**	**0.00048**	**0.00048**	**0.00048**	**0.00096**	**0.00144**
90 deg blended	**40**	**0.00048**	**0.000961**	**0.00144**	**0.0024**	**0.00336**
90 deg bird winglet	**25**	**0.00123**	**0.001229**	**0.00246**	**0.00369**	**0.00615**
90 deg finlet	**40**	**0.00048**	**0.00048**	**0.00096**	**0.00144**	**0.00144**

The graphs plotted for the coefficient of drag over the angle of attack (AoA) with the three winglets at different Cant angels that is blended, birds like winglets and finlet are given in Figure 19, 20 and 21 respectively.

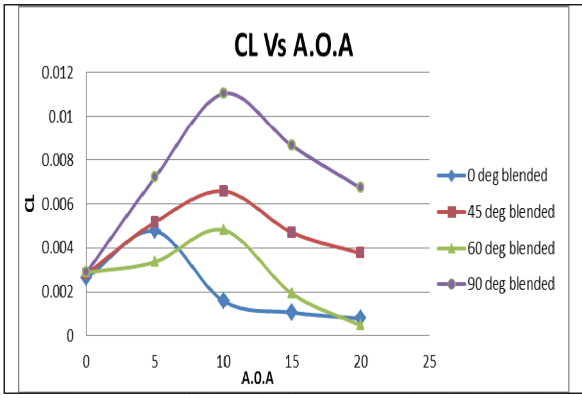

Figure 16. Coefficient of Lift versus AoA for Blended Winglets

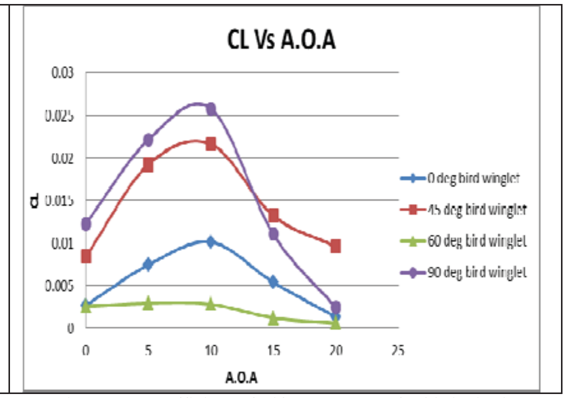

Figure 17. Coefficient of Lift versus AoA for bird winglets

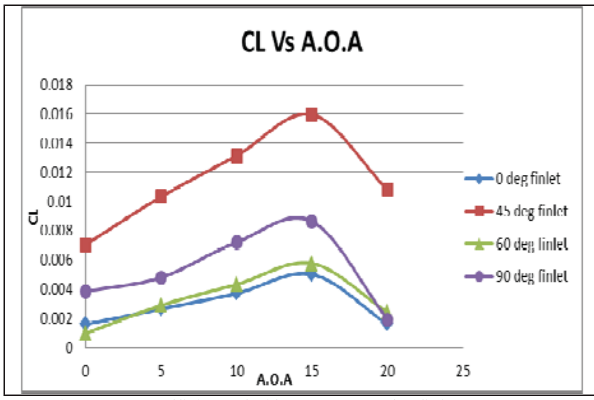

Figure 18. Coefficient of Lift versus AoA for finlets

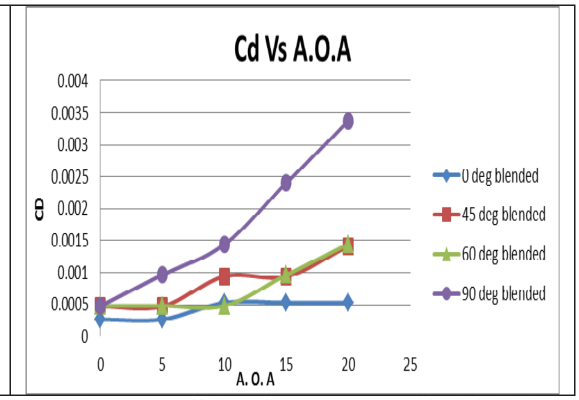

Figure 19. Coefficient of Drag versus AoA blended winglet

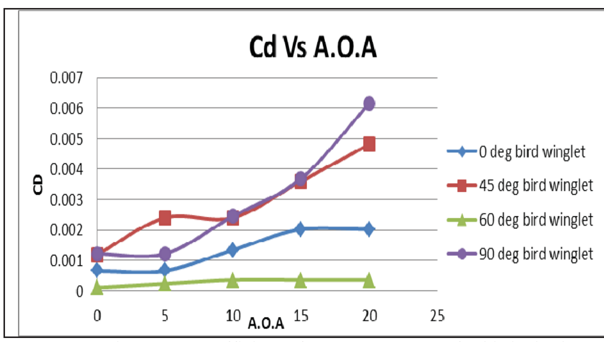

Figure 20. Coefficient of Drag versus AoA for bird winglet

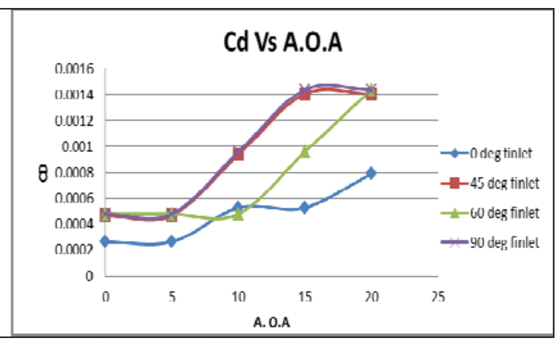

Figure 21. Coefficient of Drag versus AoA for finlet

A. Computational Analysis-

The results obtained from UNIFIGUREICS at different Cant angles are tabulated in the table 3, 4, 5 and 6 respectively.

Table -3 Results for Cant angle of 0^0

A.O.A	winglet type	L	CL	D	CD
0	0 Blended	5.3123	0.229	1.1921	0.05144
5	0 Blended	5.18819	0.223876	1.65056	0.071223
10	0 Blended	5.02459	0.216816	2.09646	0.090464
15	0 Blended	4.82275	0.208107	2.5264	0.109017
20	0 Blended	4.79464	0.254362	3.339701	0.146585

0	**0 Bird winglet**	**1.28462**	**0.055433**	**0.776411**	**0.033503**
5	**0 Bird winglet**	**3.999**	**0.172561**	**2.34904**	**0.101363**
10	**0 Bird winglet**	**5.01622**	**0.216455**	**1.74485**	**0.075292**
15	**0 Bird winglet**	**4.26789**	**0.184164**	**1.97237**	**0.08511**
20	**0 Bird winglet**	**4.39369**	**0.189593**	**2.98368**	**0.128749**
0	**0 Finlet**	**4.76197**	**0.22464**	**1.21005**	**0.056962**
5	**0 Finlet**	**4.753799**	**0.22349**	**1.21005**	**0.056962**
10	**0 Finlet**	**4.70943**	**0.221691**	**1.21005**	**0.056962**
15	**0 Finlet**	**4.92923**	**0.231691**	**1.22005**	**0.058962**
20	**0 Finlet**	**4.5138**	**0.212482**	**1.22005**	**0.058962**

Table -4 Results for Cant angle of 45^0

A.O.A	**winglet type**	**L**	**CL**	**D**	**CD**
0	**45 Blended**	**4.08277**	**0.187921**	**1.36148**	**0.062666**
5	**45 Blended**	**4.16334**	**0.191629**	**1.23593**	**0.056887**
10	**45 Blended**	**4.14761**	**0.190905**	**1.23593**	**0.056887**
15	**45 Blended**	**3.91182**	**0.180053**	**1.23593**	**0.056887**
20	**45 Blended**	**3.76289**	**0.11281**	**1.23593**	**0.056887**
0	**45 Bird winglet**	**4.08277**	**0.187021**	**1.36148**	**0.062666**
5	**45 Bird winglet**	**4.03769**	**0.185846**	**1.36148**	**0.062666**
10	**45 Bird winglet**	**4.96189**	**0.182357**	**1.36148**	**0.062666**
15	**45 Bird winglet**	**3.59128**	**0.165299**	**2.37179**	**0.109168**
20	**45 Bird winglet**	**3.72062**	**0.171252**	**1.36148**	**0.062666**
0	**45 Finlet**	**4.14445**	**0.19076**	**1.25394**	**0.057716**
5	**45 Finlet**	**4.18129**	**0.1755**	**1.23787**	**0.056977**
10	**45 Finlet**	**4.14674**	**0.190866**	**1.25394**	**0.057716**
15	**45 Finlet**	**3.90598**	**0.179784**	**1.25394**	**0.057716**
20	**45 Finlet**	**3.76599**	**0.17334**	**1.25394**	**0.057716**

Table -5 Results for Cant angle of 60^0

A.O.A	**winglet type**	**L**	**CL**	**D**	**CD**
0	**60 Blended**	**5.1729**	**0.243508**	**1.25331**	**0.058998**
5	**60 Blended**	**5.04398**	**0.23744**	**1.69939**	**0.079997**
10	**60 Blended**	**5.04398**	**0.23744**	**1.69939**	**0.079997**
15	**60 Blended**	**4.67225**	**0.219941**	**2.54945**	**0.120013**
20	**60 Blended**	**4.28959**	**0.249002**	**2.591505**	**0.127844**
0	**60. Bird winglet**	**5.12178**	**0.241102**	**1.37575**	**0.064762**
5	**60. Bird winglet**	**5.98239**	**0.25454**	**1.8169**	**0.085529**

10	60. Bird winglet	5.98507	0.226193	2.24423	0.105645
15	60. Bird winglet	4.59119	0.216125	2.65448	0.124957
20	60. Bird winglet	4.34236	0.204412	3.04453	0.143318
0	60 Finlet	4.11329	0.213157	1.24564	0.0659005
5	60 Finlet	4.6633	0.187164	1.24564	0.057334
10	60 Finlet	3.98329	0.183343	1.24564	0.057334
15	60 Finlet	3.08624	0.188682	1.24564	0.057334
20	60 Finlet	3.04598	0.184562	1.24564	0.057337

Table -6 Results for Cant angle of 90^0

A.O.A	winglet type	L	CL	D	CD
0	90 Blended	4.04659	0.190489	124257	0.05849
5	90 Blended	4.06768	0.185385	1.22992	0.056611
10	90 Blended	4.087775	0.186541	1.24257	0.058492
15	90 Blended	3.59108	0.169046	1.24257	0.05849
20	90 Blended	2.888317	0.135722	3.09939	0.14596
0	90. Bird winglet	3.9458	0.185744	1.37412	0.064685
5	90. Bird winglet	3.8756	0.182411	1.37542	0.064746
10	90. Bird winglet	4.16998	0.196297	1.54052	0.074445
15	90. Bird winglet	3.9109	0.184101	1.46189	0.06881
20	90. Bird winglet	3.84443	0.180972	1.34194	0.06317
0	90 Finlet	4.091418	0.186112	1.24503	0.058608
5	90 Finlet	4.104682	0.193671	1.22609	0.057721
10	90 Finlet	4.115362	0.193694	1.26503	0.058606
15	90 Finlet	3.82785	0.180192	1.24503	0.058606
20	90 Finlet	3.44042	0.161945	2.50778	0.121313

IV. CONCLUSION

This paper suggests alternative in the design of winglet from the conventional designs. An improved winglet design will significantly yield a better performance of an aircraft and reduce the fuel consumption. Following are the conclusions drawn from the investigation:

- Aerodynamic characteristics (lift and drag) of the wing and winglet model with NACA 4412 airfoil have been presented.
- Lift curve slope increases more with the addition of the blended winglet at 90 degrees Cant angle and at the same time the drag decreases more for the aircraft model with blended winglet.
- Finlet helps in delaying the stall at different angle of attack and is also efficient at 45 degree Cant angle.
- The Bird like winglet increases the lift more efficiently there by reducing the drag at lower speeds.
- The experimental and the computational analysis shows the similar results.

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