DESIGN AND COMPUTATIONAL FLUID DYNAMIC ANALYSIS OF SPIROID WINGLET TO STUDY ITS EFFECTS ON AIRCRAFT PERFORMANCE

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Abstract - *In aerodynamic applications usual demands are reduction in overall drag and increase in lift. This constitutes a major challenge in any aerodynamic application or study. The same is true for a typical aircraft application. The drag profile of most aircrafts has a major portion of its drag consisting of lift induced drag. This drag can be reduced by using wingtip devices such as winglets etc. One such winglet is bio-inspired and is known as spiroid winglet. Present study deals with the investigation of the effects of spiroid winglets geometric modifications on aerodynamic performance of aircraft. The study consists of modifying the design of existing spiroid winglet based on paper [2] and carrying out numerical simulations using Computational Fluid Dynamic (CFD) methods to simulate a modified spiroid winglet design consisting of a 360^0 blended wingtip and having enhanced aerodynamic performance.*

Key Words: spiroid winglets, spiroid-tipped wings, lift-induced drag, parasitic drag, stalling angle, co-efficient of lift, co-efficient of drag

1. INTRODUCTION

This is evident that aviation industry has been striving to increase efficiency and performance of aircrafts for so long in order to make fuel efficient journeys which can drastically increase profit and open doors for new routes. Winglets have known to be used on aircraft for so long to reduce lift-induced drag. Winglets are one of the most important yet simple innovation in aviation industry. These are actually extension of wings at the tip to avoid flow to move span-wise from under to the wing to the top of the surface. If this span-wise flow is not avoided then wingtip vortices are generated and they can be strong enough to reduce the aircraft lifting capabilities and these vortices also generate lift induced drag which is one of the major portion of drag. Several winglets have been designed, tested and modified on aircrafts and they have served their purpose to quite an extent but there is always room for improvement in design features to improve aerodynamic performance. Present study deals with one of the recent winglet which is bio-inspired and is known as spiroid winglet. Spiroid winglet is one the most modern designs and also not significant work has been done on such winglets. Furthermore, spiroid winglets have shown to be very efficient in increasing lifting capabilities of wing by further reducing the strength of wingtip vortices [2]. An estimated 1% improvement in fuel burn, an aircraft has the capability to gain 75 nm in range, almost 10 more passengers or 24, 00 pounds of cargo [12]. So increasing in wingtip efficiency with the help of spiroid winglets could open door for new routes for operators around the world. This served for the motivation to choose one such topic for present study.

Spiroid winglets forms a closed loop at the wingtip. This loop has variations of cross section at different locations causing variations in lifting capabilities of wing. These type of winglets have known to be very efficient as compared to other known winglets [1] and that is the reason the study of such winglets is chosen to know it's the effects of its geometric modifications on aerodynamic performance of aircrafts. The present study includes the study of existing spiroid design, generation of base design and further modifying it using the same approach present in previous research [2]. In the end a modified spiroid winglet design having increased aerodynamic performance will be presented.

2. LITERATURE REVIEW

The first US patent on spiroid winglets was published by *Louis* et al. by the name of 'Spiroid-Tipped Wing'. It incorporated the very first spiroid wingtip design which was intended to be used for the minimization of lift induced drag and to alleviate noise effects associated with vortices that trail behind lifting objects. This basic design comprised a closed loop which initiates from wingtip at appropriate sweep and included angles to form a continuous and closed loop at the wingtip [8]. In this design it was established that the spiroid configuration should be such that for fixed wing aircraft the spiroid configuration on the right is opposite to that of left hand side. This design incorporates airfoil cross section with specified thickness, camber and twist [8]. Further organized study on spiroid winglets was published by the name of 'Parametric investigation of non-circular spiroid winglets' [4]. This paper presented the detailed study of spiroid winglets that produced efficient aerodynamic performance results in terms of L/D and induced drag etc. In this paper heuristic approach was carried out to modify basic spiroid design by changing its semi-circular/ovular shape to rectangular & parallel-piped and then introducing sweep angle to it. In this paper various simulations were carried out to check for the aerodynamic performance of each design and research was concluded by establishing the fact that FWD spiroid gave better results when compared to other types of winglets. This study also concluded that spiroid winglets are superior when compared to other two wingtip configurations in terms of vortex suppression and drag reduction.

In another paper by GiftonKoil et al. titled as Design and Analysis of Spiroid Winglets the fact was established that induced drag comprises 40% of the total drag in cruise phase and 80-90% of the total drag in take-off phase of flight so it's a serious threat to the performance of aircraft in both phases [7].

Study was further enhanced to compare the performance of spiroid winglets with the dual feather winglets by Vinay et al. titled as 'CFD Analysis of Spiroid Winglets and Dual Feather Winglets'. In this study potential of spiroid and dual feather winglets are taken into consideration by using biomimetic abstraction principle of a bird's wingtip feathers, study of spiroid and dual feather winglets which look like extended blended winglets [5]. Both the types of winglets were tested on Boeing 737 wing for various AoA and this study concluded that spiroid winglets show better performance than dual feather winglets in terms of stalling angle, L/D ratio etc.

A study was carried out by Juel et al. titled as 'Biniometric spiroid winglets for lift and drag control'. This study included many benefits of spiroid winglets which incorporated reduction in lift-induced drag, increase in slope of 9.0 % in co-efficient of lift vs AoA curve and lift-to-drag enhancement [2]. This research also concluded that introduction of spiroid winglets in aircrafts has few shortcomings as well. This include increase in parasitic drag and weight of the aircraft but these factors can be compromised because benefits of introduction of spiroid winglets overcome its shortcomings.

3. NUMERICAL METHODOLOGY

Fluid flow equation of general use in any study involving fluid as medium as discussed in this section. Continuity equation in its most basic form can be obtained by applying the principle of conservation of mass to a finite control volume fixed in space [12]. Ref to (1) ρ is density and V is volume

$$\frac{\partial \rho}{\partial t}\oiiint_{V} \rho d\forall + \oiint_{S} \rho \boldsymbol{V}.\boldsymbol{dS} = 0 \qquad (1)$$

Momentum equation is based on Newton's second law which says that the rate of change of momentum of an object is equal to net force applied on that object. In equation form this can be written as follows. Ref to (2) F is force, m is mass and V is velocity.

$$F = \frac{d}{dt}(m\boldsymbol{V}) \qquad (2)$$

Momentum equations in partial differential form are given as Eq. (3), (4) & (5)

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u\boldsymbol{V}) = -\frac{\partial p}{\partial x} + \rho f_x + F_{x,viscous} \qquad (3)$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v\boldsymbol{V}) = -\frac{\partial p}{\partial y} + \rho f_y + F_{y,viscous} \qquad (4)$$

$$\frac{\partial(\rho w)}{\partial t} + \nabla.(\rho w\boldsymbol{V}) = -\frac{\partial p}{\partial z} + \rho f_z + F_{z,viscous} \qquad (5)$$

Energy equation is based on the first law of thermodynamics which states that energy can neither be created nor be destroyed, it can only change its form. Energy equation in partial differential form is given as Eq. (6)

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right] + \nabla.\left[\rho\left(e+\frac{V^2}{2}\right)\boldsymbol{V}\right]$$
$$= \rho\dot{q} - \nabla.(p\boldsymbol{V}) + \rho(\boldsymbol{f}.\boldsymbol{V}) + \dot{Q}'_{viscous} + \dot{W}'_{viscous} \qquad (6)$$

4. METHODOLOGY

First a scheme of CFD analysis that best fits our purpose must be analyzed. The first step of this procedure is to identify a CFD scheme that gives reasonably accurate results for our intended application. This is done by reproducing results of a research [2] whose data is available for validation. For this purpose, one such paper [2] was used to establish a working scheme for our purposes. The paper [2] does a study on a clean wing and spiroid-tipped wing with the following parameters and same parameters were established for present research.

Table -1: Clean wing parameters present and previous research [2]

Wing Planform Area=S	3.58 m^2
Wing Span=b	4.0 m
Wing root chord	1.0 m
Wing tip chord	0.79 m
Wing taper ratio	0.79
Wing Aspect Ratio	4.4692
Wing Sweep around LE	3.01^0
Wing dihedral angle around c/4	0.2^0
Wing twist angle	0.0^0
Wing cross section	NACA 2412

The reproduction of the results of the paper [2] were followed closely and the following parameters were established with the chosen CFD software (Fluent ®).

Table -2: Parameter established in CFD Software (Fluent ®)

SOLVER	Pressure based incompressible
State	Steady State
Turbulence Model	Spalart Allmaras
Solution Methods (Pressure velocity coupling)	SIMPLE scheme
Spacial discretization	Momentum 2nd order Pressure 2nd order

The approach as defined by the paper [2] consists of RANS (Reynolds-Averaged Navier Stokes) model with SA model based on TVD (Total Variation Diminishing) scheme for convictive terms in the RANS model using the OPEN FORM finite volume method and the scheme used in present study only eliminates TVD scheme. The reason is that the software (Fluent ®) used in present research does not have TVD capabilities. However, reasonable results matching with the paper [2] were expected due to a finer mesh and mesh independence study that was performed later on. An error of 10-15 % was expected between the two mentioned studies and a selection of method was made based on approach that satisfied this range of error.

4.1 Model

Model for clean wing was made using Creo ® and to the same geometric specifications as of paper [2].

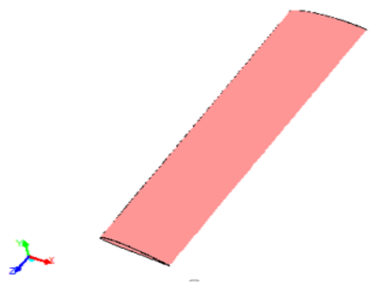


Fig -1: Clean wing model

4.2 Solver setup and solution

The operating conditions mentioned in Table 3 were chosen both by previous research [2] and present study.

Table -3: Operating conditions

Density	1.225 kg/m³
Reynold's Number	100000
Dynamic Viscosity	0.000018375 pascal second

4.3 Criterion for parameter selection

4.3.1 Viscous / Turbulence model selection

S-A Model showed high degree of convergence to experimental values and on density base numerical solver usually 700 to 1200 iterations are involved in each analysis. Also the reason to choose second order discretization is that it uses higher order equation thus increasing the accuracy of results obtained.

4.3.2 Solver Selection

Pressure based SOLVER was used because present research included incompressible flow and pressure based SOLVER is best suited for such flows.

4.3.3 Pressure Velocity Coupling Method Selection

SIMPLE is an acronym for Semi-Implicit Method for Pressure Linked Equations. For low velocity applications, convergence is limited in accordance with pressure velocity coupling. A quicker convergence in such a case is guaranteed due to the fact that the direct effect of velocity corrections is ignored in the pressure correction equations. This causes large deviations in pressure correction equations however it gives better velocity correction values which are more suitable for low velocity applications.

4.3.4 Spacial Discretization Selection

Higher order discretization equations are used to get finer results. This however increases the time of simulations but this fact can be compromised over the fact that finer results are produced.

5. RESULTS AND DISCUSSIONS OF CLEAN WING

5.1 Comparison of graphs

5.1.1 C_L v/s Angle of Attack (AoA) comparison

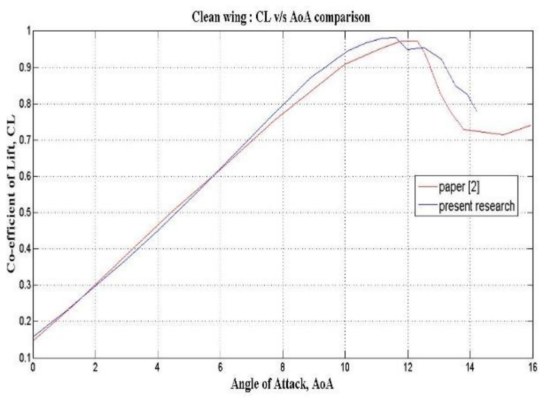


Fig -2: C_L v/s AoA comparison clean wing present and paper [2]

It can be clearly seen in Fig 2 that C_{Lmax} is about 0.95 and stalling angle is almost 12^0. In Fig 2 it is also observed that values of lift slope curves are matching in both curves. Also the values of C_{Lmax} and stalling angle are almost same in both cases. This establishes the fact that the scheme used in present research is validated by comparing the result with previous research [2]. Furthermore, it gives us the liberty to advance our research and use this scheme on modified spiroid winglet designs.

5.1.2 C_D v/s AoA comparison

For the purpose to compare overall drag v/s AoA curves of both present and previous research clean wing case [2], Fig 3 was generated. As it has been an established fact that present research scheme and results are validated by the comparison of C_L v/s AoA in Fig 2 above. However, few deviations were observed in the results of C_D v/s AoA when results of present and previous research [2] are compared in Fig 3 for clean wing case. These deviations were expected because previous research [2] used TVD (Total Variation Diminishing) scheme to carry out analysis while 2nd order pressure and momentum scheme is used in present research due to non-availability of TVD (Total Variation Diminishing) scheme in Fluent ®. The deviation in results can be seen while comparing in higher AoA only however, the results at AoA below 12^0 nearly matches each other in every manner. This comparison further validates present research scheme and results generated.

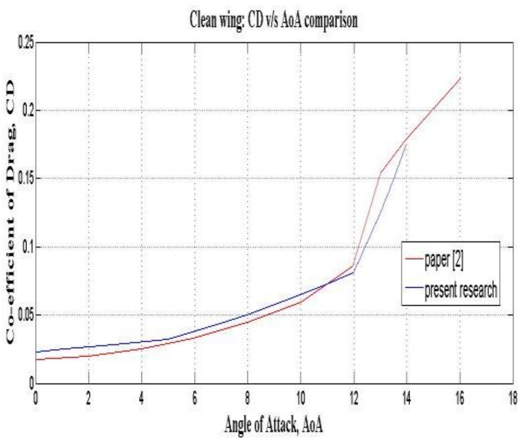


Fig -3: CD v/s AoA comparison clean wing present and paper [2]

6. THEORETICAL APPROACH

As discussed earlier, wingtip vortices are the major cause of producing downstream and eventually increasing the lift-induced drag in aircraft applications. The effect of wingtip vortices and downwash on lifting capabilities of wing is illustrated in Fig 4.

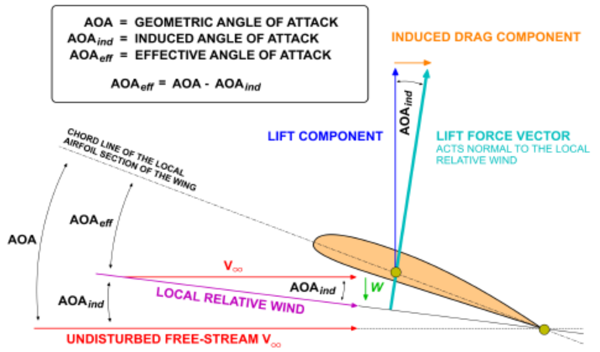


Fig -4: Lift induced drag generated due to downwash [2]

Fig 4 illustrates that lift-induced drag actually reduces AoA to effective AoA thus reducing the lifting capabilities of the aircraft wing. So in order to cater for stronger wingtip vortices a special approach was used by research [2] to modify spiroid winglet design. As already mentioned that wing has been generated of NACA 2412 airfoil in both present and previous research [2] so design was modified by the introduction of cambered NACA 2412 airfoil in the spiroid winglet design in research [2]. The introduction of NACA 2412 airfoil is only in the upper surface of the spiroid winglet as illustrated in Fig 5.

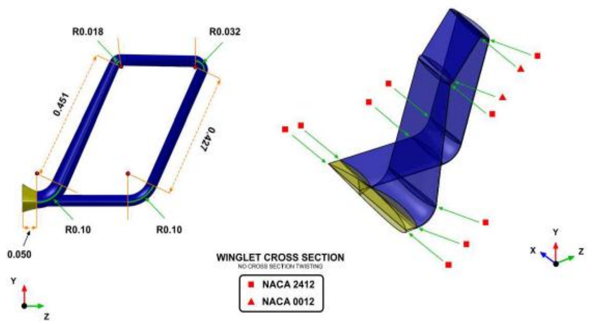


Fig -5: Spiroid winglet design [2]

The wingtip vortices for the wing with spiroid winglet design [2] close to the wing, is made up by two/three coherent patches of vorticity which are shed from the upper corners of the spiroid wingtip. The effect of vortex shedding of modified spiroid winglet design [2] as compared to clean wing [2] is illustrated in the Fig 6.

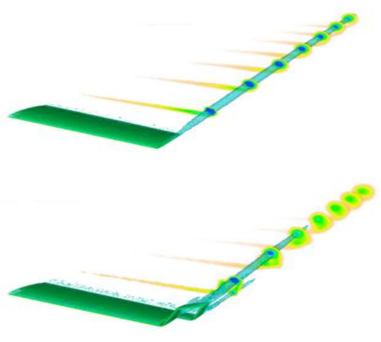


Fig -6: Wingtip vortices visualization [2]

The intensity of spiroid-tipped wing [2] vortices is less than the intensity of the single vortex for the clean wing [2], and as they are convected downstream, which presumably is the reason why these flow structures dissipate much faster [2].

Same approach was contemplated upon in present study and both the lower and upper surfaces of spiroid winglet were made oppositely cambered of NACA 2412 airfoil. The idea to do so was to reduce vortices strength trailing downwards. The vortex strength trailing downwards might be minimized due to the interference of upper and lower surface flows. The upper and lower cambered surfaces will produce coherent and less strong wing-tip vortices which might shed away easily by interference as observed in previous research [2]. Also cambered NACA 2412 lower surface of spiroid winglet has more lift than symmetric NACA 0012 airfoil used in previous research [2]. Another justification to introduce this idea was to further reduce parasitic drag which could have been higher in case of symmetric airfoil NACA 0012 in previous research [2]. The model of improved spiroid winglet present research was generated in Creo ® and to the same geometric specifications as mentioned in paper [2]. Only the lower surface of spiroid winglet was also kept positively cambered and made up of NACA 2412 airfoil. Fig 7 illustrated improved spiroid winglet design.

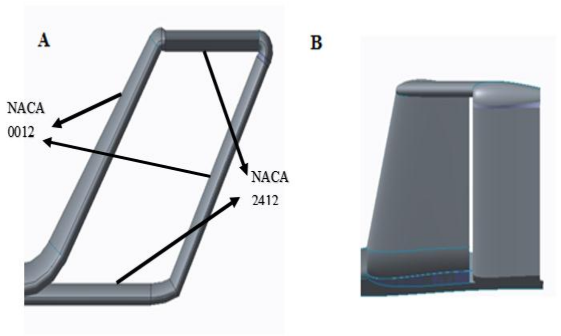


Fig -7: Improved spiroid model present study A) front view B) top view

The methodology and scheme used for improved design is kept same as that of clean wing present research and paper [2]. Mesh independence study was also carried out which will be discussed in detail later on.

6.1 C_L v/s AoA comparison

The C_L v/s AoA curves of improved design present research are compared below with the graphs of spiroid winglet design of research [2].

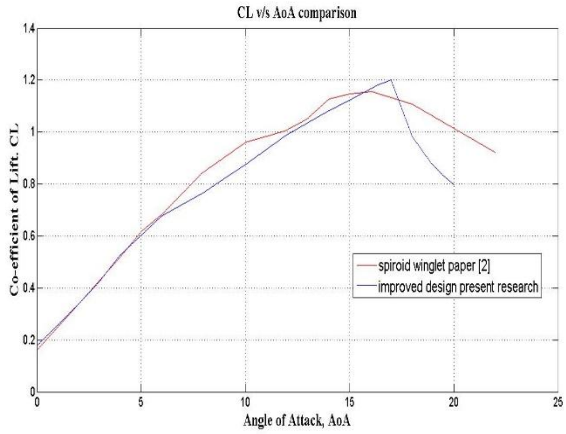


Fig -8: C_L v/s AoA improved spiroid winglet design present research v/s spiroid winglet design paper [2]

Quantitative and qualitative study on C_{Lmax} and stalling angle improvement in improved design will be discussed later on.

6.2 C_D v/s AoA comparison

The C_D v/s AoA curves of improved design present research are compared below with spiroid winglet design of research [2].

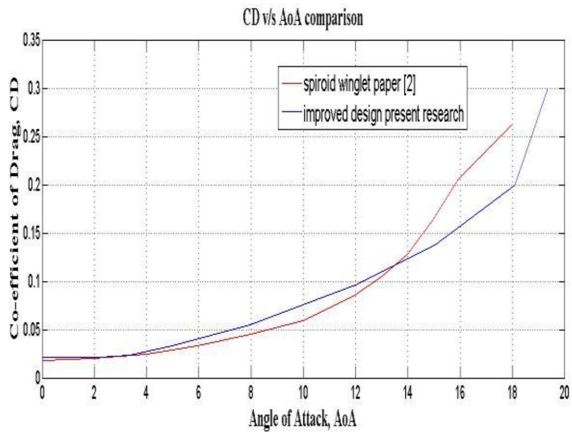


Fig -9: C_D v/s AoA improved spiroid winglet design present research v/s spiroid winglet design paper [2]

By comparing the above curves of C_D v/s AoA in Fig 9, it can be clearly seen that overall drag at various AoA for present improved spiroid design is almost same as compared to overall drag values of previous spiroid winglet design [2]. However, C_D values for AoA greater than 13^0 are found to be lower in present study as compared to previous research [2].

7. FINAL DESIGN

Introduction of sweep angle of 45^0 from leading edge of wing in spiroid winglet design of present research, which is 5^0 as compared to previous research [2], causes the wetted surface area of spiroid winglet to decrease eventually reducing parasitic drag.

In previous research [2], cambered NACA 2412 airfoil was already tested to show its effect on diminishing the wingtip vortices. Also same approach was utilized to modify spiroid winglet design in present research earlier and cambered NACA 2412 airfoil was used on both lower and upper surfaces of the wing instead of only on upper surface in case of previous research [2]. The introduction of cambered NACA 2412 airfoil in present research ensures that the degree of flow disturbance is neutralized by causing interference in wingtip vortices. As mentioned earlier, symmetric airfoil NACA 0012 were used for the formation of vertical walls and lower surface of spiroid winglet design in previous research [2]. The effect of symmetric airfoil in case of increased parasitic drag was reduced by the introduction of oppositely cambered NACA 2412 airfoils in both lower and upper surfaces of spiroid winglet design in present research. The above discussion leads to the conclusion that there is dire need to scrutinize the performance of spiroid winglet design after the introduction of oppositely cambered NACA 2412 airfoil in both lower / upper surfaces & also cambered (in same direction) vertical surfaces / walls which would cause the formation of less strong side vortices which will shed away easily while trailing downwards and also these side vortices will interfere to neutralize the effect of each other as seen in previous modified spiroid winglet design of present research.

7.1 Model of final design

Based on the above discussion a final model of spiroid winglet design was generated in Creo ®. This final model has same geometric specifications as mentioned in previous research [2]. Cambered NACA 2412 airfoil is introduced in all four surfaces (upper, lower and vertical) of final winglet design such as lower surface is positively cambered and upper surface is negatively cambered. Also the vertical walls of final spiroid winglet design are cambered (in same direction) for the formation of co-rotating vortices that will cancel the effect of each other.

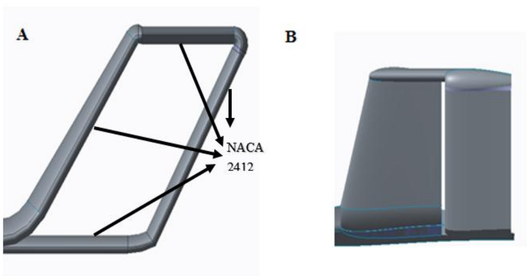


Fig -10: Final Spiroid winglet model A) front view B) top view

The methodology to test for final spiroid winglet design present research is same as simulated for validating previous research [2] and for previous improved model of spiroid winglet in present research.

7.2 Grid Independence Study

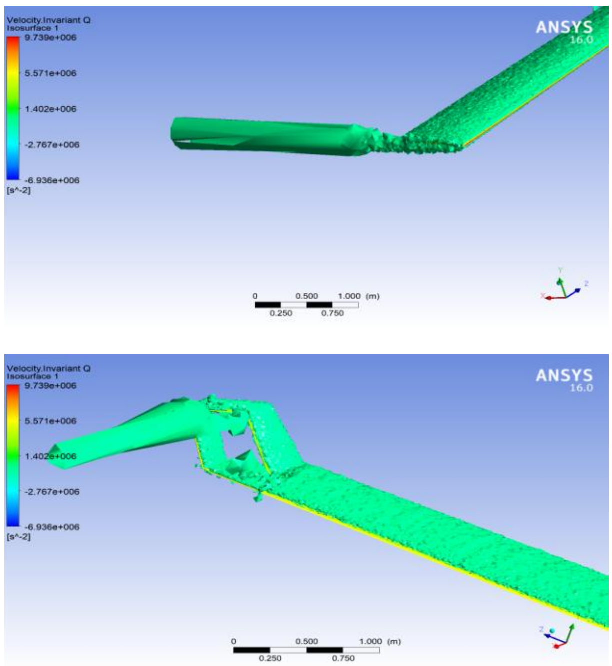
Mesh size required to get reasonable results is dependent on type of problem being solved. Heuristic approach of finding correct mesh size suitable for problem in consideration is called as mesh independence study. In this study, a problem with lesser number of grid points is first solved. Then the number or grid points is increased. Both the results are noted down as velocity difference, pressure difference etc. values. This method is a repetitive one with increased number of grid points each time until the difference between results for two consecutive mesh size is almost negligible. 2^{nd} Last mesh size is selected and further study is performed on that mesh. For mesh independence study in present research, meshes having 150, 250 & 500 mesh intervals were generated and results were simulated on same AoA. Finally, mesh of 250 intervals were used keeping the fact that they served better results in limited time duration. The results of C_L for different mesh interval sized is given below in table 4.

Table -4: C_L results at different mesh intervals

AoA	Mesh Interval 150	Mesh Interval 250	Mesh Interval 500
3^{o}	0.401	0.430	0.434
5^{0}	0.589	0.620	0.626
12^{0}	1.073	1.130	1.141

7.3 Results & discussions of final design

The vortices cancellation effect can be clearly seen in Fig 11 below.



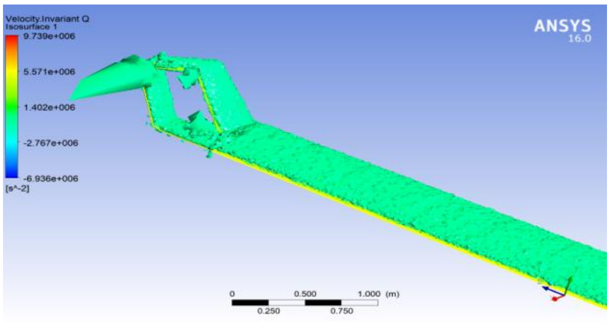


Fig -11: Vortices clean wing, improved & final design

7.3.1 C_L v/s AoA comparison

The comparison of curves of C_L v/s AoA for both previously improved winglet design present research and final spiroid winglet design present research are illustrated in Fig 12.

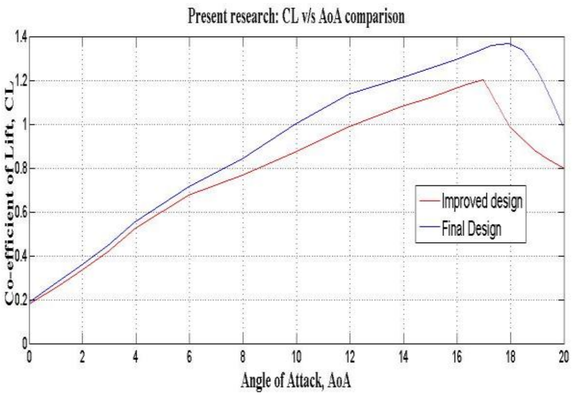


Fig -12: C_L v/s AoA final spiroid winglet design present research v/s improved design present research

7.3.2 C_D v/s AoA comparison

The comparison of curves of C_D v/s AoA for both previously improved winglet design present research and final spiroid winglet design present research are illustrated in Fig 13.

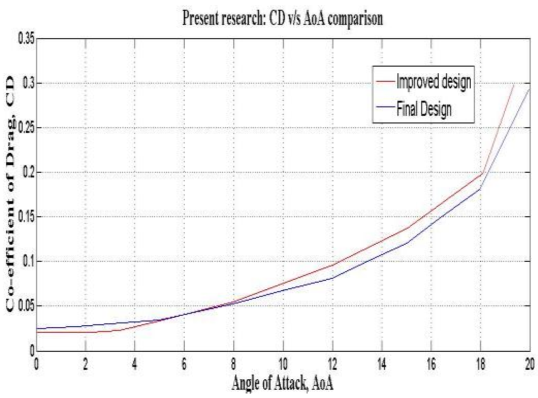


Fig -13: C_D v/s AoA final spiroid winglet design present research v/s improved design present research

8. CONCLUSIONS

The primary objectives of present research are certain and can be summed up in the increment of C_{Lmax}, stalling angle and lift-slope curve and overall drag reduction at higher AoA. Before showing quantitative improvements, C_L v/s AoA curves of clean wing present previous research [2], improved design present research, final spiroid winglet design previous research and final design present research are illustrated in single graph to give clear insight of overall $C_{Lmax,}$ stalling angle and lift-curve slope improvement. Fig 14 illustrates all C_L v/s AoA curves used and generated in present study.

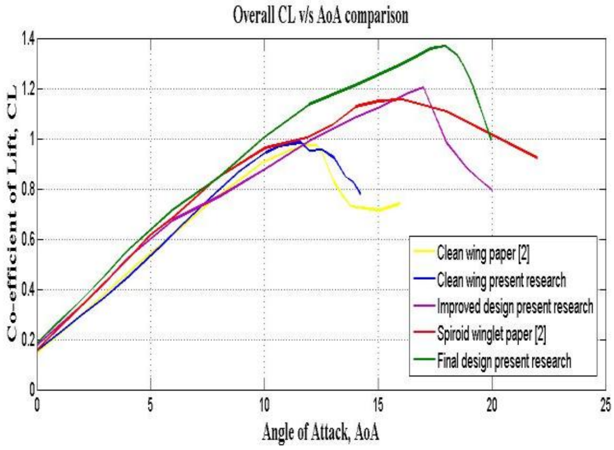


Fig -14: C_L v/s AoA overall comparison

Fig 15 concludes that curves of clean wing present and previous research [2] graphs are matching which eventually served the benchmark for present research. Moreover, in improved design present research only C_{Lmax} & stalling angle increment was achieved. However, in the final design of present research, increment in $C_{Lmax,}$ stalling angle and lift-curve slope can clearly be seen.

Fig 15 illustrates C_D v/s AoA curves of clean wing present and previous research [2], improved design present research, final design previous research [2] and final design present research. Fig 14 concludes that curves of clean wing present and previous research [2] graphs are almost matching which eventually served the benchmark for present research. Few deviations in both above cases are due to different schemes used in both cases.

Also, overall drag reduction could only be achieved in higher AoA above 12^0 in both improved and final design of present research when compared with previous research [2]. At lower AoA, overall drag showed almost same values in case of improved, final design present research and previous research [2].

The increment in overall drag at lower AoA was clogged due to the introduction of sweep and cambered airfoils in spiroid winglet design of present research.

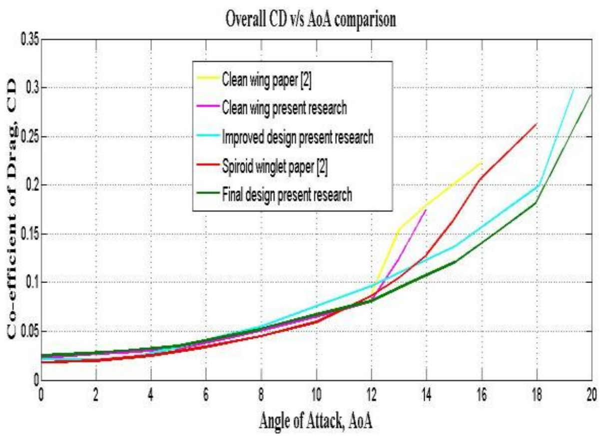


Fig -15: C_D v/s AoA overall comparison

The quantitative comparisons of final spiroid winglet design present research when compared to improved spiroid winglet design present research is given below in Table 5.

Table -5: Comparison of improved v/s final spiroid winglet designs present research

	Improved Spiroid winglet present research	Final Spiroid winglet present research	% increase
C_{Lmax}	1.20	1.38	15.0
α stall	17.1^0	18^0	5.2

Also the quantitative comparisons of final spiroid winglet design present research when compared to spiroid winglet design previous research [2] is given below in Table 6.

Table -6: Comparison final spiroid winglet designs v/s research paper [2]

	Spiroid winglet design research paper [2]	Final Spiroid winglet present research	% increase
C_{Lmax}	1.18	1.38	16.9
α stall	16.0^0	18.0^0	12.5

The discussions above can have numerous advantages in aircraft applications.

1. Improved take-off performance can be one of the main benefits of present research. Aircrafts with higher C_{Lmax} and stalling angle will show better performance in initial climb.

2. Also with stalling angle increased, increased climb rate will be introduced in aircrafts equipped with spiroid winglets.

3. Higher C_{Lmax} warrants shorter take-off run to aircrafts. It also guarantees shorter landing distances. Aircrafts equipped with spiroid winglets will have access to take-off and land to / from even shorter runways.

4. Stall delay will be introduced in aircrafts having higher stalling angle.

5. In case present research is advanced to larger aircrafts, introduction of spiroid winglets warrants even more MTOW (Maximum take-off weight) eventually benefitting operators around the world in terms of increased passengers or cargo.

6. The landing speed prior to landing can be reduced further for even safer landings in case of higher CLmax.

7. Study of noise reduction in aircrafts is of contemporary nature and spiroid winglets have proved to have better noise suppression abilities [2]. By reducing the strength of wingtip vortices, increased noise suppression might have been achieved. The detailed study on noise suppression by spiroid winglets can be carried out in future studies.

8. In busy airports, numerous landings take place in few minutes time. Turbulent wake behind aircrafts poses serious threat to aircrafts coming behind it to land after. With the introduction of spiroid winglets, number of landings can be increased at busy airports by reducing the distances between aircrafts and saving more time.

9. Reduced overall drag increases range of aircrafts by reducing fuel-consumption. This eventually benefits operators around the world.

9. REFRENCES

[1] T. Wan and K. Lien, "Aerodynamic Efficiency Study of Modern Spiroid Winglets," Journal of Aeronautics, Astronautics and Aviation, 2009.

[2] Joel E. Guerrero, "Biomimetic spiroid winglets for lift and drag control," University of Genoa. Department of Civil, Environmental and Architectural Engineering, DICAT, 2016.

[3] T. Sumanth, "Design and analysis of winglets with modified tip to enhance performance by reducing drag," Anveshana's International Journal of Research in Engineering and Applied Sciences, 2016.

[4] S. Mostafa, S. Bose, A. Nair, M. A. Raheem, T. Majeed and A. Mohammed, Y. Kim, "A parametric investigation of non-circular spiroid winglets," Department of Aeronautical Engineering, Emirates Aviation College, Dubai, UAE, 2014.

[5] V. K. Bada, K. Monika, A. Hussain, P. Chikoti, "CFD Analysis and Comparison of Spiroid and Dual Feather Winglets" Department of Aeronautical Engineering, Vardhaman College of Engineering, 2016.

[6] N. N. Gavrilović, "Commercial Aircraft Performance Improvement Using Winglets," University of Belgrade Faculty of Mechanical Engineering, 2014.

[7] W. G. Raj, T. A. Thomas, "Design and Analysis of Spiroid Winglet," International Journal of Innovative Research in Science, Engineering and Technology, 2015.

[8] L. B. Gratzer, "US Patent on Spiroid-Tipped Wings," 1992.

[9] Maksoud, T. M. Andrew and Seetloo, "Wingtips and multiple wing tips effects on wing performance: Theoretical and experimental analyses," 10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, 2014.

[10] N. Balakrishnan, Ganesh, "Design modification of winglet concept to increase aircraft's efficiency," International Journal OF Engineering Sciences & Management Research, 2015.

[11] A. Hossain, A. Rahman, A.K.M. P. Iqbal, M. Ariffin, and M. Mazian, "Drag Analysis of an Aircraft Wing Model with and without Bird Feather like Winglet," International Journal of Aerospace and Mechanical Engineering, 2010.

[12] J. D. Anderson, Fundamentals of Aerodynamics, Third Edition ed.: McGraw Hill, 2001.R. W. Lucky, "Automatic equalization for digital communication," Bell Syst. Tech. J., vol. 44, no. 4, pp. 547–588, Apr. 1965.