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Analysis of Winglets Designed from PSU Airfoils

Sibi A Arul[1], Deva Vibin M[1], Dinesh G[1], Vignesh R[1], Manoj N[2], Murali. K[3]
1-UG Student, Department of Aeronautical Engineering, V.S.B. Engineering college, Karur,
2-Assistant Professor, Department of Aeronautical Engineering, V.S.B. Engineering college, Karur, Tamil Nadu.
3- Assistant professor, Department of Aeronautical Engineering, M.A.M. School of Engineering, Trichy, Tamil Nadu

***Abstract* — Saving fuel has become the task of highest priority in our generation. This in turn has been taken very seriously by commercial airliners which are the largest consumers of fuels. One of the widely applied method of saving fuel is by application of winglets. Out of which blended winglets have become successful and manufacturer friendly. One of the most promising sub-type of blended winglet is the "Sharklet" that proposes about 3.5 percent of additional fuel savings. It is employed in the most sought aircraft in the world (A320) presented by the Airbus Company. This projects aims to produce a design with parameters modified to produce the best optimum flight with reduced trailing vortices. They cause induced drag which is the reason for 40 percent of the total drag of the entire aircraft. Hence increasing the efficiency and reducing noise pollution. The design is based on study conducted on aircraft manuals and related journals. The design is done in a suitable CAD modelling software such as CATIA V5 R20 and then the final design is analyzed in a Cfx software like ANSYS. The results are computed based on the comparison between various airfoils with and without winglets at several angle of attack. The results are computed for various velocities and pressure conditions so as to determine pattern of pressure distribution around the airfoils. Successful design are those with reduced vortices which eventually have low induced drag.**

I. INTRODUCTION

Wingtip devices are usually intended to improve the efficiency of fixed-wing aircraft. There are several types of wingtip devices, and although they function in different manners, the intended effect is always to reduce the aircraft's drag by partial recovery of the tip vortex energy. Wingtip devices can also improve aircraft handling characteristics and enhance safety for following aircraft. Such devices increase the effective aspect ratio of a wing without materially increasing the wingspan. An extension of span would lower lift-induced drag, but would increase parasitic drag and would require boosting the strength and weight of the wing. At some point, there is no net benefit from further increased span. There may also be operational considerations that limit the allowable wingspan (e.g., available width at airport gates).Wingtip devices increase the lift generated at the wingtip (by smoothing the airflow across the upper wing near the tip) and reduce the lift-induced drag caused by wingtip vortices, improving lift-to-drag ratio. This increases fuel efficiency in powered aircraft and increases cross-country speed in gliders, in both cases increasing range. U.S. Air Force studies indicate that a given

improvement in fuel efficiency correlates directly with the causal increase in the aircraft's lift-to-drag ratio. The term "winglet" was previously used to describe an additional lifting surface on an aircraft, e.g., a short section between wheels on fixed undercarriage. Richard Whitcomb's research in the 1970s at NASA first used winglet with its modern meaning referring to near-vertical extension of the wing tips. The upward angle (or cant) of the winglet, its inward or outward angle (or toe), as well as its size and shape are critical for correct performance and are unique in each application. The wingtip vortex, which rotates around from below the wing, strikes the cambered surface of the winglet, generating a force that angles inward and slightly forward, analogous to a sailboat sailing close hauled. The winglet converts some of the otherwise-wasted energy in the wingtip vortex to an apparent thrust. This small contribution can be worthwhile over the aircraft's lifetime, provided the benefit offsets the cost of installing and maintaining the winglets. Another potential benefit of winglets is that they reduce the strength of wingtip vortices, which trail behind the plane and pose a hazard to other aircraft. Minimum spacing requirements between aircraft operations at airports is largely dictated by these factors. Aircraft are classified by weight (e.g. "Light," "Heavy," etc.) because the vortex strength grows with the aircraft lift coefficient, and thus, the associated turbulence is greatest at low speed and high weight.

The drag reduction permitted by winglets can also reduce the required take-off distance. Winglets and wing fences also increase efficiency by reducing vortex interference with laminar airflow near the tips of the wing, by 'moving' the confluence of low-pressure (over wing) and high-pressure (under wing) air away from the surface of the wing. Wingtip vortices create turbulence, originating at the leading edge of the wingtip and propagating backwards and inboard. This turbulence 'delaminates' the airflow over a small triangular section of the outboard wing, which destroys lift in that area. The fence/winglet drives the area where the vortex forms upward away from the wing surface, since the center of the resulting vortex is now at the tip of the winglet.

II. INDUCED DRAG

In flight, air doesn't simply flow over and under the wing, there is also a span wise movement of air under the wing, around the wing tips, and spilling over to the top of the wing. The lower pressure above the wing causes air under the wing to flow around the wingtip to the top of the wing. The reduced pressure differential causes an almost total loss of lift at the wingtip. The effect gets smaller as measured toward the wing root and is known as the "span wise pressure gradient". This disrupts the flow over the wing, causing nasty vortices which reduce lift. To compensate, we can increase the angle of attack to gain more lift. But this tilts the wing's lift vector backwards slightly. Though most of the lift force is still upwards, a portion is now generating a force that tugs rearward on the wing. This is induced drag. Induced drag is proportional to the square of the lift, which also means it's inversely proportional to the square of airspeed. Essentially, the slower we go and the more we increase AoA, the more induced drag we get.

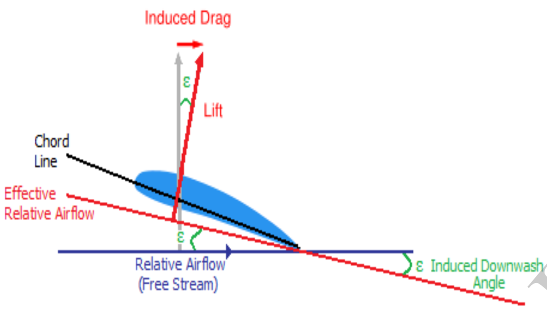

Fig 1. Induced drag downwash

If we had a wing of infinite span, we'd get no induced drag because there are no wingtips to allow air to escape around to the topside. We can't build infinitely long wings, but high-aspect wings still produce less induced drag because wingtip vortex effects are reduced on long wings. In effect, induced drag is inversely proportional to aspect ratio (though technically it's more a function of span loading).

Washout or twist also plays a role by proportionally generating more lift toward the inboard wing segments. It's been found that elliptical wing configurations are best for reducing induced drag, which is why aircraft like the Spitfire and P-38 had such curvy wing shapes. But elliptical configurations are difficult and expensive to make, so designers compromise by building tapered wings and playing tricks with the wingtips to divert vortices away from the wing. Note that induced drag is not the same as parasitic drag, which is generated by bodies moving through the airstream and rises geometrically with airspeed. Induced drag is of particular importance to the takeoff, climb, and landing regions of a flight profile, where it can be more than 20% of the total drag forces, and at takeoff might be as high as 70% for some planes. The cross sectional shape obtained by the intersection of the wing with the perpendicular plane is called an airfoil. The major design feature of an airfoil is the mean cambered line, which is the locus of points halfway between the upper and lower surfaces as measured perpendicular to the mean cambered line itself. The most forward and rearward points of the mean cambered line are the leading and trailing edges respectively. The straight line connecting the leading and trailing edges is the chord line of the airfoil and the precise distance from the leading to the trailing edge measured along the chord line is simply designated the chord of the airfoil, given by the symbol C. The camber is the maximum distance between the mean camber line and the chord line, measured perpendicular to the chord line. The camber, the shape of the mean camber line and to a lesser extent, the thickness distribution of the airfoil essentially controls the lift and moment characteristics of the airfoil.

III. HORSE SHOE VORTEX

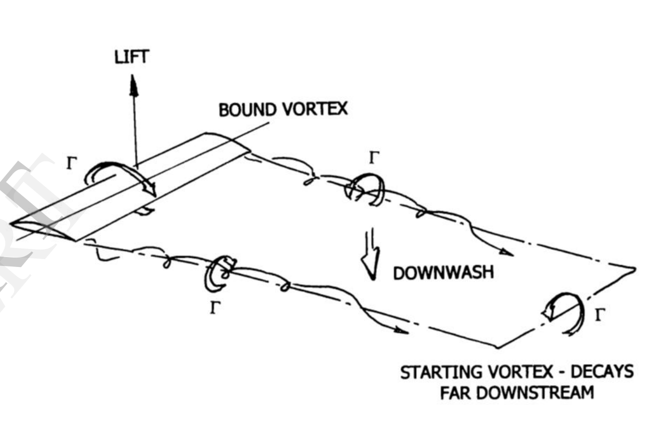

Fig 2. Idealized “horseshoe” vortex system

The horseshoe vortex model is a simplified representation of the vortex system of a wing. In this model the wing vorticity is modelled by a bound vortex of constant circulation, travelling with the wing, and two trailing vortices, therefore having a shape vaguely reminiscent of a horseshoe. (The starting vortex created as the wing begins to move through the fluid is considered to have been dissipated by the action of viscosity, as are the trailing vortices well behind the aircraft). The trailing vortices are responsible for the component of the downwash which creates induced drag. The horseshoe vortex model is unrealistic in implying a constant circulation (and hence by the Kutta–Joukowski theorem constant lift) at all sections on the wingspan. In a more realistic model (due to Ludwig Prandtl) the vortex strength reduces along the wingspan, and the loss in vortex strength is shed as a vortex-sheet from the trailing edge, rather than just at the wing-tips. However, by using the horseshoe vortex model with a reduced effective wingspan but same midplane circulation, the flows induced far from the aircraft can be adequately modelled. The term horse-shoe vortex is also used in Wind Engineering to describe the vortex of strong winds that form around the base of a tall building. This effect is amplified by the presence of a low-rise building just upwind. This was greatly researched in the decade of 1970.

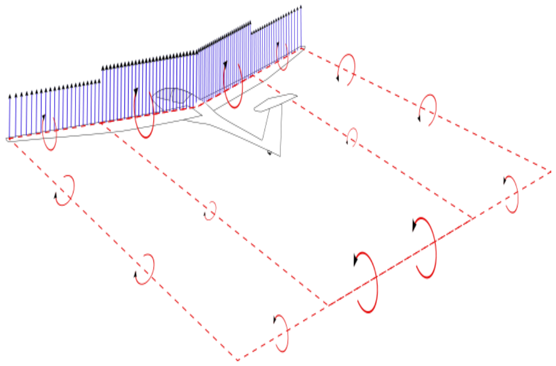

Fig 3. Lifting Line Theory

IV. Winglet Theory

Apart from the selection of a winglet airfoil, there were five key parameters that had to be chosen to optimize the design:
4.1 Cant angle
4.2 Twist distribution
4.3 Sweepback
4.4 Taper ratio
4.5 Ratio of winglet root chord to tip chord

Cant Angle

The selection of cant angle evolved from an unusual consideration specific to sailplanes: the narrow and highly flexible wings pro- vide for a wingtip angle in flight which can approach 30 degrees on some sailplanes when flying with water ballast. A more common angle for modern 15 meter ships is 7–12 degrees.
On winglets that are nominally set to a cant angle of 0 degrees (at right angles to the wing), as the wing deflects, the winglet generates a side load in flight which has a component oriented downward. This is a self-defeatinge situation, since the winglet is generating additional drag by contributing to the weight of the aircraft. Thus a more reason- able approach is to set the winglets at least at a cant angle on the ground of 0 degrees plus the in–flight local tip deflection angle. Sweepback The selection of the sweepback angle was based on experimental observations. It was first believed that the sweepback angle for the winglet should be equal to that for the main wing (0 degrees), however experience proves otherwise. If a vertical winglet with no sweepback is built, it will be observed that the root of the winglet will stall first and that the tip will remain flying.
The optimum situation from an aerodynamic standpoint is to have the aerodynamic loading such that the entire winglet surface stalls uniformly. This can be achieved by sweeping back the winglet, which will increase the loading on the tip. Because of the rapid variation in angle of attack of the winglet as a function of height, a large degree of sweepback is required to load the tip correctly. For our wing- lets, a 30 degree leading edge sweep angle was used to achieve this effect.

Twist Distribution

The twist distribution on a winglet is normally selected so as to provide a uniform load distribution across the winglet span. Since the inflow angle is higher at the base, the winglet is twisted to higher angles of attack toward the tip. This is opposite to the general design methodology for wings, which normally have washout (either geometric or aerodynamic) so as to decrease the angle of attack towards the tips. The determination of optimum twist for our winglets was made by iterating experimentally. When flight tested, the first set of winglets fabricated stalled at the root first with a progressive stall developing upwards towards the winglet tip. By twisting the winglet to in- crease the angle of attack at the tip, the en- tire surface of the winglet could be made to stall simultaneously. Two degrees of twist from root to tip proved to be optimum. The second benefit of positive twist on the winglet is that the high speed performance is enhanced there is less likelihood of developing separation on the outer surface of the winglet at low inflow angles (high speed = low coefficient of lift, Cl).

Sweep Back

The selection of the sweepback angle was based on experimental observations. It was first believed that the sweepback angle for the winglet should be equal to that for the main wing (0 degrees), however experience proves otherwise. If a vertical winglet with no sweepback is built, it will be observed that the root of the winglet will stall first and that the tip will remain flying. The optimum situation from an aerodynamic standpoint is to have the aerodynamic loading such that the entire winglet surface stalls uniformly. This can be achieved by sweeping back the winglet, which will increase the loading on the tip. Because of the rapid variation in angle of attack of the winglet as a function of height, a large degree of sweepback is required to load the tip correctly. For our wing- lets, a 30 degree leading edge sweep angle was used to achieve this effect.

Taper Ratio

The effect of taper ratio on inflow angles and the resulting optimum twist distribution was analyzed theoretically by K.H. Horstmann in his PhD thesis. It was shown that as taper ratio increases, the optimum twist distribution for the winglet varies more linearly from root to tip. From a construction standpoint it is also easier and more accurate to build a wing- let with a linear change in twist angle along the winglet span. This favors a winglet with a larger tip chord. We also try to maximize the tip chord so as to maximize the Reynold's number. Accordingly, a ratio of tip to root chord of 0.6 was selected.

RATIO OF WINGLET CHORD TO TIP CHORD

It would seem that the winglet might ideally be designed as an extension of the wing, and thus the optimum winglet would be a smooth transition of the wing from horizontal to vertical. Experiments suggest otherwise.

If the root chord of the winglet is equal to the tip chord of the wing, then the inflow angle at the tip will be less than when the winglet is a smaller fraction of the tip chord. The result will be that at high speed, the inflow angle may not be sufficient so as to prevent separation of the airflow from the outer (lower) surface of the winglet.

The choice of the root chord of the winglet is also constrained by the nominal tip chord of the wing, and by considering Reynold's number effects. Too small a winglet chord can result in extensive laminar separation and high drag. For the Nimbus III and Discus winglets, the small nominal tip chords force the winglet geometry to be smaller than would be desirable from a Reynold's number consideration.

SELECTED TYPE OF WINGLET NEW DESIGN PROPOSITION

After the invention of winglet by Whitcomb, many types of winglets and tip devices were developed by aircraft designers. Some of the inventions of winglets by the respective aircraft manufacturer are discussed in the following section.

BLENDED WINGLET

Blended winglet was developed by Grazter from Seattle in 1994. The unique design in this winglet is no sharp edge found at the wing/winglet intersection and followed by smooth curve. Aviation Partners Inc. (API) and Boeing Company made collaboration in 1999 for the design of advance blended winglets in 1999. Mike Stowell, Executive vice president of APB mentioned about the interference drag, an aerodynamic phenomenon caused due to intersection of lifting surfaces, hence the winglet design was developed to overcome the interference drag formed at the junction of wing and winglet. The winglets were retrofitted in Boeing business jets and also in B7371. Now these flights have their services in American airlines (Southwest airlines) and also in European airlines (Ryanair).

Fig 4. Blended Winglet

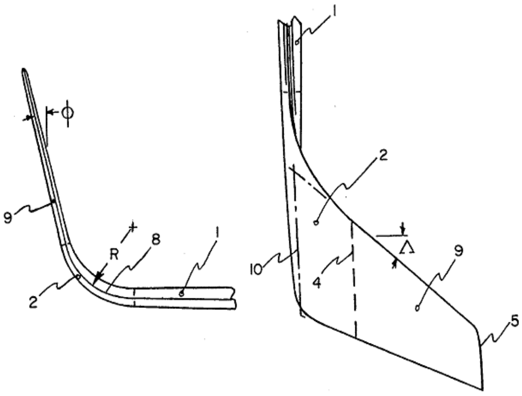

Fig 5. Blended Winglet Curvature.

PSU AIRFOIL

There are two PSU airfoils designed by the Pennsylvania State University. They are termed as PSU90-125wl-il and PSU94-097-il

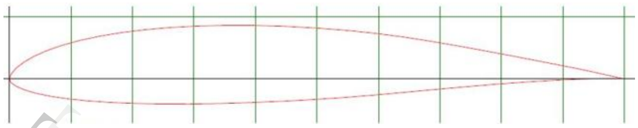

Fig 6. PSU90-125-wl-il
(Obtained from UIUC data site)

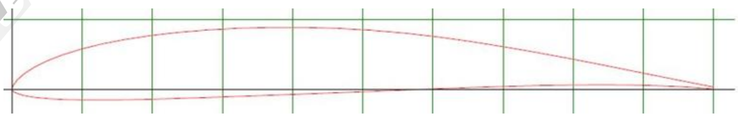

Fig 7 PSU94-097-il
(Obtained from UIUC data site)

The lift drag characteristics are

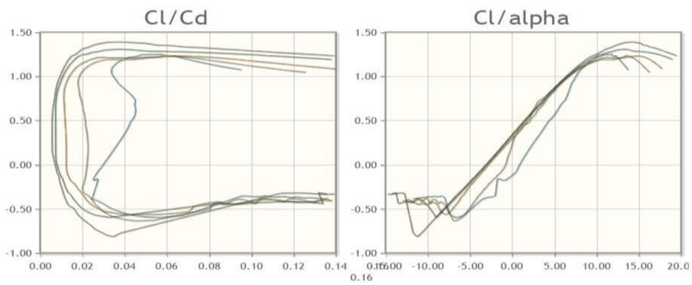

Fig. 8 Cl vs Cd and Cl vs alpha of PSU90-125wl-il

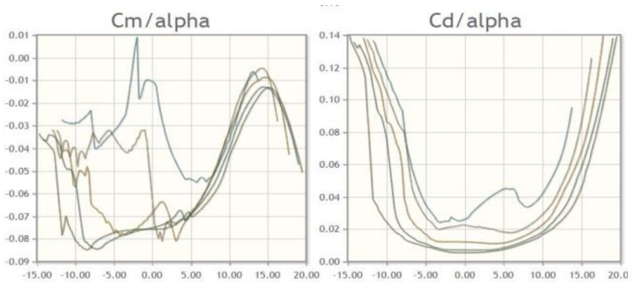

Fig. 9 Cm vs alpha and Cd vs alpha of PSU90-125wl-il

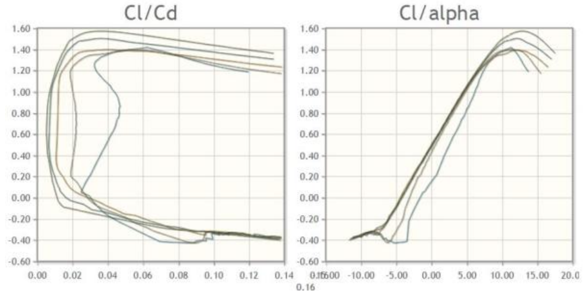

Fig. 10 Cl vs Cd and Cl vs alpha of PSU94-097-il

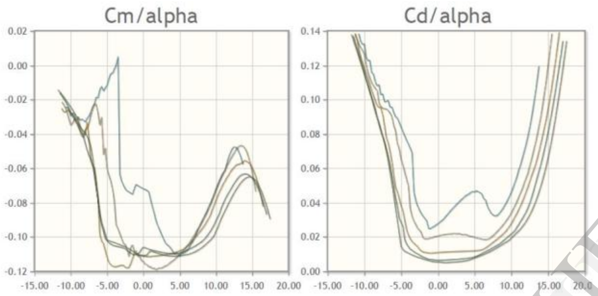

Fig. 11 Cm vs alpha and Cd vs alpha of PSU94-097-il

The efforts at Penn State to develop winglets for high-performance subsonic aircrafts began in the early 1980's as a collaborative effort with Mr. Peter Masak to design winglets for the subsonic aircrafts of that era. Although work had already been done in the area of nonplanar wings and winglets, in practice it was found winglets provided little or no benefit to overall subsonic aircrafts performance. The widely held belief at that time, essentially the same as that held for transport-type aircraft, was that while climb performance could be improved, it could not be done without overly penalizing cruise performance. The first steps taken were directed toward the design of an airfoil specifically intended for use on a winglet. Although not a great deal was known at this time about exactly how a subsonic aircrafts winglet should operate, it was clear that a winglet does not operate exactly as a wing and, consequently, an airfoil intended for use on a wing would not be a good choice for a winglet. Thus, the PSU 90-125 airfoil was designed. This was a robust design that was intended to operate over a very broad range of conditions.

From this point, a trial-and-error process was begun that used flight testing as the primary method of determining the important design parameters. Although vortex-lattice and panel methods were of some value for gaining insight, they were unable to predict drag accurately enough to be of use in the actual design process. Likewise, because the beneficial influence of a winglet is due to it favorably altering the flow field over the entire wing, meaningful

Wind-tunnel experiments require a full- or half-span model. Thus, unless the wind tunnel has a very large test section, the high aspect ratios typical of subsonic aircrafts result in model chords that produce excessively low Reynolds numbers. To address these problems, methods of simulating full-scale flow fields with truncated spans have been explored but, in every case, the necessary compromises produce results that are somewhat questionable. For these reasons, the parameters that were deemed the least important were set to reasonable values, while the more critical ones were determined from flight test. Using some of the results from earlier work on winglets for transport aircraft along with some simple calculations, the winglet height, planform, and cant angle were fixed. Because the basic shape of this loading can be adjusted with either twist or sweep, the twist was set, again being guided by the earlier work on winglets, and the sweep iterated until the desired result was obtained. For minimum induced drag, if the planform is somewhat close to elliptical, the load distribution would have spanwise lift coefficients that are essentially constant. Thus, with the planform set, the sweep was adjusted until yarn tufts indicated a uniform stall pattern in the spanwise direction. The last design parameter to be determined was the toe angle. Because there seemed to be little benefit in having the winglet carry load beyond that of the wing, the toe angle was adjusted until both the wing and the winglet stalled simultaneously, again as determined tufts.

Although it took some time and competition successes, the winglets that were the result of the process were the first ones that were generally accepted as beneficial to overall cross country performance over a wide range of thermal sizes and strengths.8 In 1989, one of these designs was adopted by sailplane manufacturer Schempp-Hirth and became the "factory winglet" for the Venus. In retrospect, with the understanding that has come since, it seems that this process, while systematic and logical, was accompanied with a great deal of luck. It now seems somewhat remarkable that with the tools then at hand, it was possible to configure a winglet that actually worked.

The Winglet Design Process

To obtain the desired results over the entire range of operation of an aircraft, it is necessary to design a new winglet for every application. The area, height, cant angle, sweep angle, twist angle, and the all-important toe angle must be uniquely determined to achieve the desired performance goals. Thus, even though the trial and error process described resulted in a successful winglet, much remained to do in the development of tools and methods for analysis and design. Through the efforts of a succession of excellent students, a great deal has been accomplished at Penn State which has bettered this situation.

The first accomplishment of these efforts was the design and testing of a new airfoil. With a much better understanding of the operating conditions of a winglet, the PSU 94-097 airfoil

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was designed to have much less conservatism than its predecessor. Because of these advantages the PSU airfoil is used as a preferred subject in design.

EXISTING WINGLET INSTALLATION

From the details on research papers and journal text it is evident that the flow pattern formed by PSU can be successfully installed over the high speed subsonic aircrafts. In this article the extensive research and study are done on the aircrafts of Airbus and winglets which have been installed newly in Airbus A320-200 and the ones recently manufactured along with these winglets. It can be seen that A320-200 is one of the highest ordered aircraft in the world with 3565 aircrafts delivered as of February 2014. Most of the aircrafts when manufactured have a blunt wing tip with no winglets installed. The Airbus Company came up with the “Wing Tip Fence”, which is a type of winglet where there are outward projections on the upper and lower side of the wing tip similar to a curvature of a cone. It extends to eliminate the wing tip vortices by means of expanding the curvature of the vortices. Recently the Airbus Company came up with its new type of winglets called the “Sharklets” in the fourth quarter of 2011 and it was made a success in 2012. The company deployed the winglets to its already existing customers by a voluntary fixation in the aircrafts as an external wing tip devices but integrated to the edge of the airfoil in the wing. They were seen to have more than a performance boost to the aircrafts. They have been put on the aircrafts from 2012. Newer aircrafts are fabricated with these Sharklets before they are delivered to their customers. They are about 2.43m tall fence like structures usually at a cant angle of near zero but with a sweep angle i.e. the angle between the vertical axis to the slant on the front edge of winglet. They are usually made of the same profile as that of the wing in subsonic aircrafts and in high speed aircrafts they are of thin airfoils. Moreover the winglets are put to twist on the root to tip. It is accompanied by a taper ratio which could be advantageous at cruising flights.

PROPOSED MODEL AND DESIGN

From the extensive collection of the winglet model and their types a design is done such that the wing section maybe made of any type of airfoil, but only the winglets are designed with PSU airfoils. Both the airfoil section of the wing and the winglet are placed with upper camber on the upper side of wing and outer side of winglet respectively. The arbitrary design consists of the wing design made as per approximate dimensions from the wing design of Airbus A320-200. Then using CATIA V5 R20 the entire model is designed and made suitable for analysis. The design details are such that the wing are an approximate replica of the ones on A320-200. But the winglet placed on the tips are made of the following configuration:
Airfoil: PSU 90-125wl-il
Cant angle- 7°
Sweep angle-40°
Twist-0°
Wing dihedral- 3°

The obtained design is as shown below.

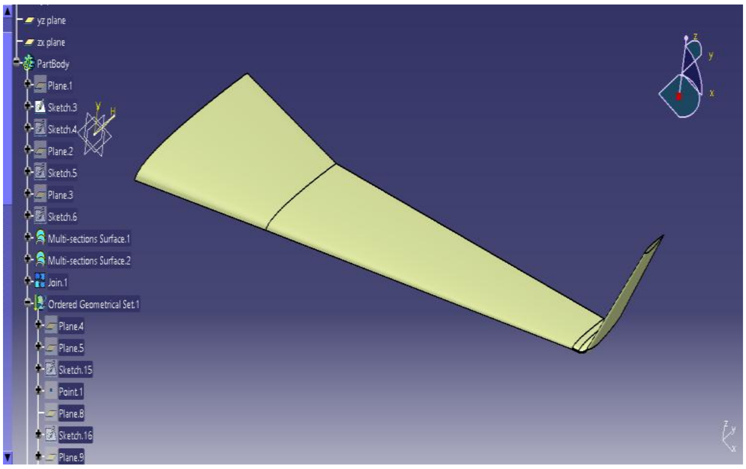

Fig. 12 New Winglet and Wing Design

ANALYSIS

Using ANSYS 14.0 the analysis of the designed model is analyzed for various end conditions and flow conditions

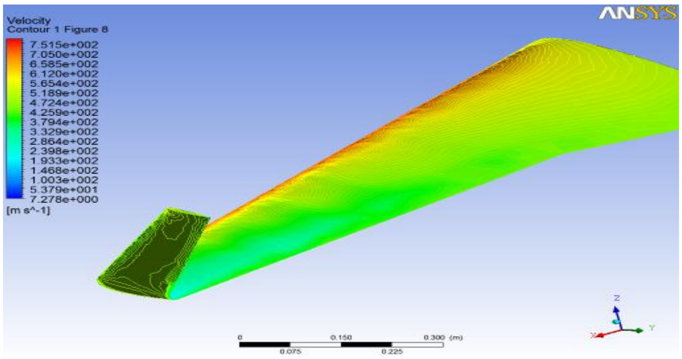

Fig. 13 Velocity over contour at 200m/s

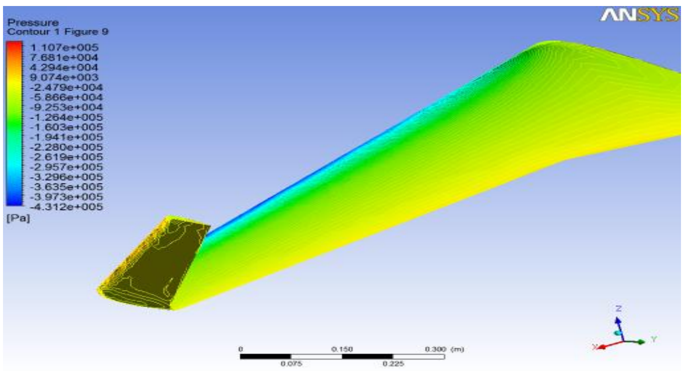

Fig 14 Pressure over contour at 200m/s

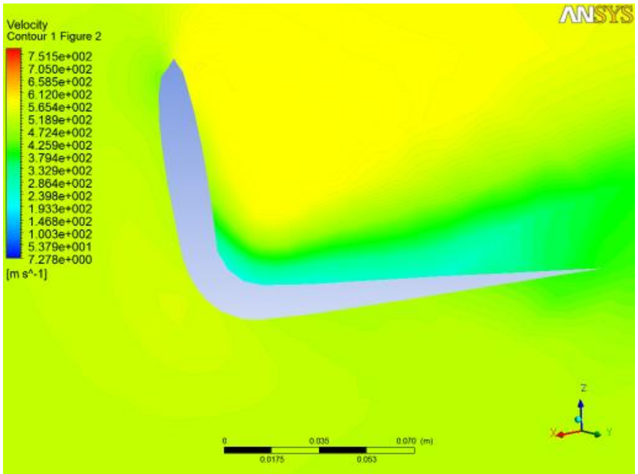

Fig. 15 2-D Analysis of winglet by
Velocity over contour at 200m/s

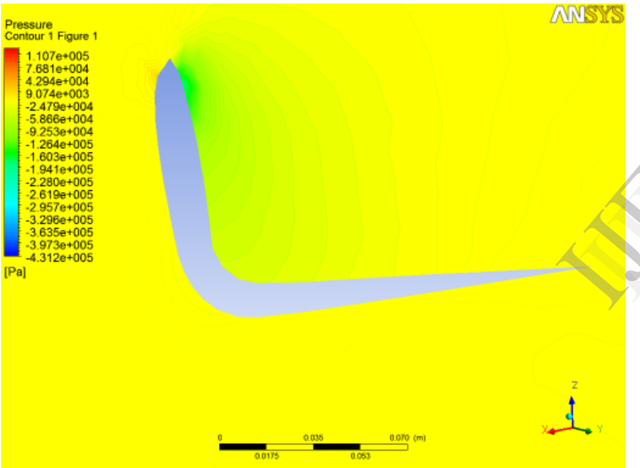

Fig. 16 2-D Analysis of winglet by
Pressure over contour at 200m/s

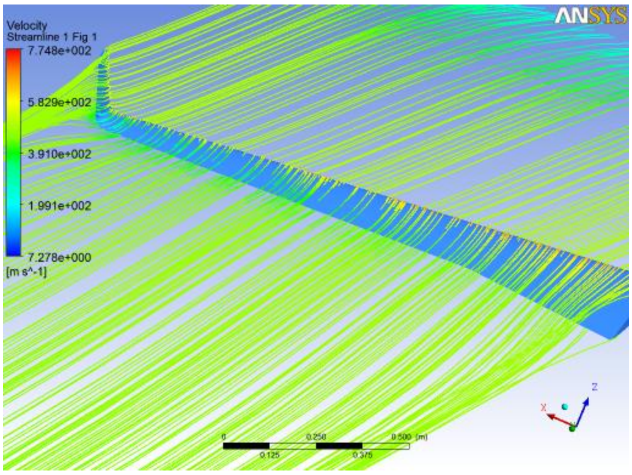

Fig. 17 No vortices formed at end of streamline over contour at 200m/s

CONCLUSIONS

From the analysis figures it can be seen that the vortices formed are negligible or no vortices that can affect the pressure distribution over the wing of the aircraft. This can be applied to low speed to high speed subsonic aircraft wings because of the flexibility of the PSU airfoils over varied flow conditions. From the analysis graph it is also evident that flow are less deviant than its actual wing without the winglets thus proving its efficiency over its applications.

REFERENCES

[1] Altab Hossain, Ataur Rahman, A.K.M. P. Iqbal, M. Ariffin, and M. Mazian (2012), “Drag analysis of an aircraft wing model with and without bird feather like winglet”.
[2] Coiro D. P, F. Nicolosi, F. Scherillo, U. Maisto Department of Aerospace Engineering (DIAS), University of Naples “Federico II”, 80125, Naples, Italy.
[3] David P. Lockard and Geoffrey M. Lilley (2004), “The Airframe Noise Reduction Challenge”.
[4] D. Maughmer, “About winglets”.
[5] Gianluca Minnella,Yuniesky Rodriguez and Jose Ugas (2010), “Aerodynamic Shape Design Optimization of Winglets”.
[6] Levi Neal,Neal Harrison and Dzelal Mujezinovic (2004), “Wingtip Devices”.
[7] Mark D. Maughmer, “The design of winglets for low-speed aircraft”.
[8] Mark D. Maughmer, Timothy S. Swan, and Steven M. Willits, “The design and testing of a winglet airfoil for low-speed aircraft”.
[9] Mohammad Ilias Inam, Mohammad Mashud, Abdullah-Al-Nahian and S. M. S. Selim(2010), “Induced Drag Reduction for Modern Aircraft without Increasing the Span of the Wing by Using Winglet”.
[10] Mohammad Salahuddin, Mohd Obaid-ur-Rahman, Shaik Jaleel (2013), “A report on numerical investigation of wings: with and without winglet”.
[11] M. J. Smith, N. Komerath, R. Ames, O. Wong and J. Pearson, “Performance analysis of a wing with multiple winglets”.
[12] Peter Masak, “Winglet design for sailplanes”.
[13] Prithvi Raj Arora, A. Hossain, Prasetyo Edi, A.A. Jaafar, Thamir S. Younis and M. Saleem (2006), “Drag reduction in aircraft model using ellipticalwinglet”.
[14] Saravanan Rajendran (2012), “Design of Parametric Winglets and Wing tip devices – A Conceptual Design Approach”.
[15] S. Andrew Ning and Ilan Krooy, “Tip Extensions, Winglets, and C-wings:Conceptual Design and Optimization”.
[16] Vance A. Tucker (1998), “Gliding flight: speed and acceleration of ideal falcons during diving and pull out”.
[17] Vance A. Tucker and G. christian parrott (1969), “Aerodynamics of gliding flight in a falcon and other birds”.
[18] Willard Dodds (2002), “Dreams of Flight”.
[19] William Freitag and E. Terry Schulze, “Blended Winglets Improve Performance”.
[20] Aircraft Characteristics Airport and Maintenance Planning, Airbus AC, September 30 1985, Revised June 01 2012.

[21] Effect of Gurney Flaps and Winglets on the Performance of the HAWT, Division of Safety and 108 Fire Engg., SOE, CUSAT
[22] The Design Of Winglets For Low-Speed Aircraft
[23] Maughmer, M.D., "The Design of Winglets for High-Performance Sailplanes," Journal of Aircraft, Vol. 40, No. 6, Nov.-Dec. 2003.
[24] Adjustment and implementation of cad/cam systems being used in polish aviation industry, journal of machine engineering, vol. 10, no. 3, 2010.
[25] NASA Supercritical Airfoils, Charles D. Harris, Langley Research Center Hampton, Virginia, NASA Technical Paper, 1990.
[26] ANSYS CFX Introduction, ANSYS, Inc. Release 14.0,Southpointe October 2012