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Diagnostic Investigation of Aircraft Performance at Different Winglet Cant Angles

Dinesh M., Kenny Mark V., Dharni Vasudhevan Venkatesan, Santhosh Kumar B., Sree Radesh R., V. R. Sanal Kumar

Abstract**—**Comprehensive numerical studies have been carried out to examine the best aerodynamic performance of subsonic aircraft at different winglet cant angles using a validated 3D k-ω SST model. In the parametric analytical studies NACA series of airfoils are selected. Basic design of the winglet is selected from the literature and flow features of the entire wing including the winglet tip effects have been examined with different cant angles varying from 15^0 to 60^0 at different angles of attack up to 14^0. We have observed, among the cases considered in this study that a case, with 15^0 cant angle the aerodynamics performance of the subsonic aircraft during takeoff was found better up to an angle of attack of 2.8^0 and further its performance got diminished at higher angles of attack. Analyses further revealed that increasing the winglet cant angle from 15^0 to 60^0 at higher angles of attack could negate the performance deterioration and additionally it could enhance the peak C_L/C_D on the order of 3.5%. The investigated concept of variable-cant-angle winglets appears to be a promising alternative for improving the aerodynamic efficiency of aircraft.

Keywords**—**Aerodynamic efficiency, Cant-angle, Drag reduction, Flexible Winglets.

I. Introduction

THE main purpose of any winglet is to improve the aircraft performance by reducing its drag [1]-[25]. The term *winglet* was previously used to describe an additional lifting surface on an aircraft. Wingtip devices are usually intended to improve the efficiency of fixed-wing aircraft [1]. 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. Such devices increase the effective aspect ratio of a wing without materially increasing the wingspan. Note that an extension of span would reduce the lift-induced drag, but would increase parasitic drag and would require boosting the strength and weight of the wing.

It is well known that any sort of body exposed in a viscous flow experiences profile drag, whether it produces lift or not. The induced drag is a different type of drag. It is caused by the pressure imbalance at the tip of a finite wing between its upper (pressure side) and lower (suction side) surfaces. That imbalance is necessary in order to produce a positive lift force. However, near the tip the high pressure air from the lower side tends to move upwards, where the pressure is lower, causing the streamlines to curl (see Fig. 1). This three-dimensional motion leads to the formation of a vortex, which alters the flow field and induces a velocity component in the downward direction at the wing, called downwash [2]-[4]. The induced flow pattern causes the relative velocity to cant downwards at each airfoil section of the wing, thus reducing the apparent angle of attack. The lift vector is tilted backwards and a force component in the direction of the drag appears, called induced drag. Reducing the size of this tip vortex and minimizing the induced drag is of great importance for the modern aircraft designers. For this purpose designers developed the winglet concept. Winglets are specially designed extensions adjusted to the wingtip that alter the velocity and pressure field and reduce the induced drag term, thus increasing aerodynamic efficiency.

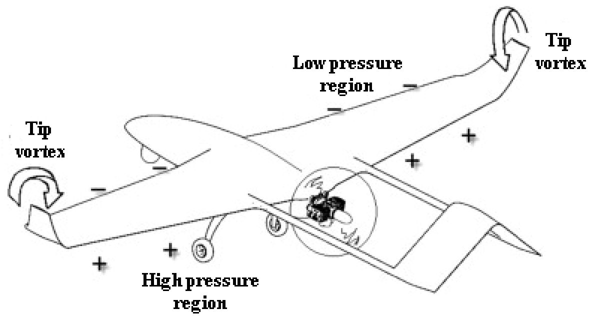


Fig. 1 Demonstrating the tip vortex of a fixed wing aircraft

Bourdin et al. [5] reported that the investigated concept of variable-cant-angle winglets appears to be a promising alternative to conventional control surfaces such as ailerons, elevators, and rudders as far as basic maneuvers are concerned. The concept consists of a pair of winglets with adjustable cant angle, independently actuated and mounted at the tips of a baseline flying wing. A potential application for the adjustable winglets would be for surveillance aircraft, for which enhanced low-speed maneuverability is required. Note that deflecting a winglet when the wing is flying near its stall angle is unlikely to cause the wing to stall (in contrast to the effect of an aileron). Hence, variable cant-angle winglets can be used for effective low-speed roll control (instead of spoilers

Dinesh was an undergraduate student of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore – 641 049, Tamil Nadu, India; (e-mail: dineshaero555@gmail.com).
Kenny Mark, Dharni Vasudhevan, Santhosh Kumar, and Sree Radesh are Undergraduate Students of Mechanical Engineering, Kumaraguru College of Technology, Coimbatore – 641 049, India (Phone: +91-9894467086, e-mail:kennymarkv@gmail.com,vasudhevan.d@outlook.com,santhosh.dice07@gmail.com, radesh94@gmail.com).
Sanal Kumar is Professor and Aerospace Scientist and currently with the department of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore – 641 049, Tamil Nadu, India; (Corresponding Author, phone: +91 – 938 867 9565; + 91 – 875 420 0501, e-mail: vr_sanalkumar@yahoo.co.in).

which are traditionally preferred to ailerons in that flight regime).

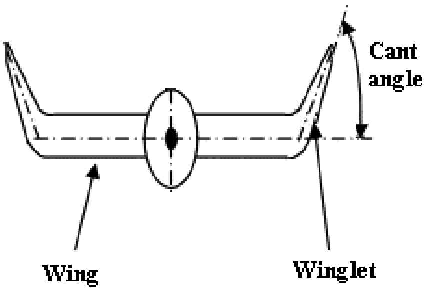


Fig. 2 Front view of a fixed wing aircraft with fixed winglet

Fig. 2 shows the front view of a typical aircraft with winglet at fixed cant angle. Numerical and experimental studies conducted by the earlier investigators on a flying wing configuration showed that adjustable winglets enable control moments about multiple axes, forming a highly coupled flight control system, which is in contrast to conventional control surfaces, which form a decoupled control system. Although many studies have been carried out for winglets design a generalized geometry is still not proposed by any aircraft designer under variable flying conditions [1]-[25]. In this paper diagnostic investigation of aircraft performance at different winglet cant angles has been carried out to examine the best cant angle for the winglets at variable lucrative flying conditions.

II. Literature Review

The initial concept of winglet dates back to 1897, when English engineer Frederick W. Lanchester patented wing end-plates as a method for controlling wingtip vortices [6]. In the United States, Scottish-born engineer William E. Somerville patented the first functional winglets in 1910. Somerville installed the devices on his early biplane and monoplane designs. 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 [1].

The literature review reveals that the United States Air Force studies could come up with the improvement in fuel efficiency, which correlates directly with the causal increase in the aircraft's lift-to-drag ratio. In flight, induced drag results from the need to maintain lift. It is greater at lower speeds where a high angle of attack is required. As speed increases, the induced drag decreases, but parasitic drag increases because the fluid is striking the object with greater force, and is moving across the object's surfaces at higher speed. As speed continues to increase into the transonic and supersonic regimes, wave drag enters the picture. Each of these drag components changes in proportion to the others based on the speed. The combined overall drag curve therefore shows a minimum at some airspeed; an aircraft flying at this speed will be close to its optimal efficiency. Fig. 3 found in literature is reproduced herewith for a critical review. It shows that lowest total drag is at a particular airspeed. Note that Pilots will use this speed to maximize the gliding range in case of an engine failure. However, to maximize gliding endurance, aircraft's speed should be at the point of minimum power, which occurs at lower speeds than minimum drag.

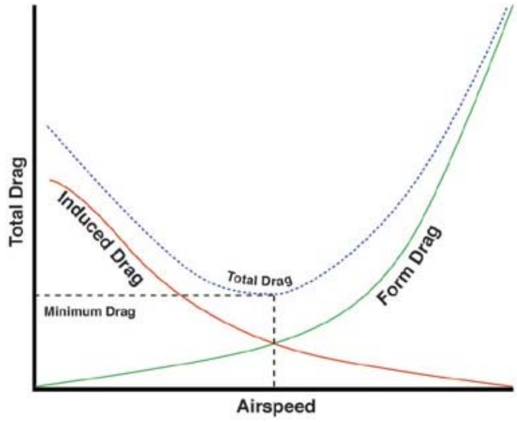


Fig. 3 The typical drag curves at different airspeed

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 [7]. It has already been reported that 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 generally classified by weight 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 takeoff distance [8]. Winglets and wing fences also increase efficiency by reducing vortex interference with laminar airflow near the tips of the wing [7], 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. These are succinctly reported in the open literature [1]-[25].

TABLE I
SPECIFICATIONS OF WING

Sl. No.	Description	Dimension
1	Airfoil Type	NACA 0012
2	Wing Type	Swept Back
3	Sweep Angle	32.43^0
4	Wing Span	22 cm
5	Taper Ratio	0.292553
6	Aspect Ratio	3.62139
7	Wing Area	133.65 cm^2
8.	Maximum Chord	9.4 cm
9.	Minimum Chord	2.75 cm

TABLE II
SPECIFICATIONS OF WINGLET

Sl. No.	Description	Dimension
1	Winglet Type	Blended Winglet
2	Winglet Span	3 cm
3	Winglet Height	3 cm
4	Winglet Area	9.255 cm^2
5	Winglet Sweep Angle	47.29^0
6	Winglet Taper Ratio	0.109
7	Maximum Chord	2.75 cm
8	Minimum Chord	0.3 cm

Aircraft such as the Airbus A340 and the Boeing 747-400 use winglets. Other designs such as some versions of the Boeing 777 and the Boeing 747-8 omit them in favor of raked wingtips. Large winglets such as those seen on Boeing 737 aircraft equipped with blended winglets are most useful during short-distance flights, where increased climb performance offsets increased drag. Note that the raked wingtips are a feature on some Boeing airliners, where the tip of the wing has a higher degree of sweep than the rest of the wing. The stated purpose of this additional feature is to improve fuel efficiency and climb performance, and to shorten takeoff field length. It does this in much the same way that winglets do, by increasing the effective aspect ratio of the wing and interrupting harmful wingtip vortices. This decreases the amount of lift-induced drag experienced by the aircraft. In testing by Boeing and NASA, raked wingtips have been shown to reduce drag by as much as 5.5%, as opposed to improvements of 3.5% to 4.5% from conventional winglets [9]. While an equivalent increase in wingspan would be more effective than a winglet of the same length, the bending force becomes a greater factor. A three-foot winglet has the same bending force as a one-foot increase in span, yet gives the same performance gain as a two-foot wing span increase [10]. For this reason, the short-range Boeing 787-3 design called for winglets instead of the raked wingtips featured on all other 787 variants.

Winglets are also applied to several other business jets to reduce take-off distance, enabling operation out of smaller secondary airports, and allowing higher cruise altitudes for overflying bad weather, both of which are valuable operational benefits for corporate travel. In addition to factory-installed winglets on new aircraft, aftermarket vendors developed retrofit kits, for popular jets and turboprops, to improve both aerodynamics and appearance. Winglets became so popular on this class of aircraft that the Dassault Group, whose French designers resisted applying them on their Falcon line until recently, were forced to run a contrarian marketing campaign. Of late Cessna disclosed to test a new wingtip device called Elliptical Winglets, which are designed to increase range and increase payload on hot and high departures. It has been revealed through this literature review that winglet designs must be optimized to be able to get maximum benefits during cruise and non-cruise flight conditions; and for that 3D design optimization is inevitable. Therefore, 3D numerical studies have been carried out for examining the possibilities of increasing the aerodynamics efficiency of a typical wing with variable-cant-angle winglets.

Fig. 4 Physical model of a wing with winglet Cant-Angle 15^0

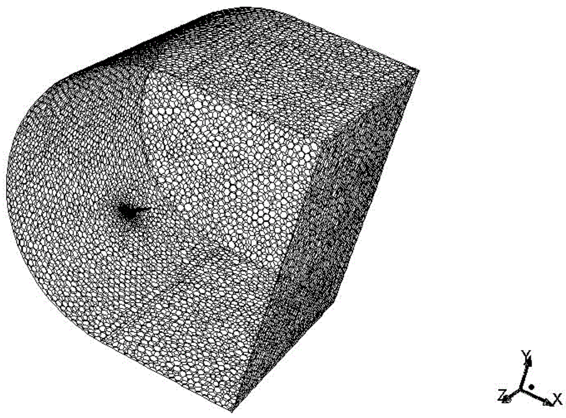


Fig. 5 3-D grid system in the computational domain

III. NUMERICAL METHODOLOGY

Numerical simulations have been carried out with the help of a steady 3D, double precision, pressure-based, SST k-ω turbulence model. This model uses a control-volume based technique to convert the governing equations to algebraic equations. The viscosity is determined from the Sutherland formula. The wing geometric variables and material properties are known *a priori*. Initial wall temperature and inlet temperature are specified. At the exit, far field boundary condition is prescribed. At the solid walls no-slip boundary condition is imposed. The Courant-Friedrichs-Lewy number is chosen as 1.0 in all of the computations. The turbulent kinetic energy and the specific dissipation rate are taken as 0.8. Ideal gas was selected as the working fluid. Inlet velocity is taken as 55.55 m/s, with turbulence intensity of 5 %. Tables I and II show the geometric details of the wing and the winglet considered in this study. Fig. 4 shows the physical model of an aircraft wing with 15^0 winglet cant angle. Fig. 5 shows the 3D grid system in the computational domain. Grid are selected after a detailed grid refinement history (Cells: 140144, Faces: 929653, Nodes: 780461). The grids are clustered near the solid walls using suitable stretching functions. Orthogonal Quality ranges from 0 to 1, where values close to 0 correspond to low quality. Minimum orthogonal quality was 7.28711 E-01 and maximum aspect ratio was 2.60710 E+01.

IV. Results and Discussion

It is well known that winglets application is one of the most noticeable fuel economic technologies on aircraft. The diagnostic investigation reveals that the winglet designs must be optimized to be able to get maximum benefits during cruise and non-cruise flight conditions. In this paper comprehensive numerical studies have been carried out to examine the best aerodynamic performance of subsonic aircraft at different winglet cant angles using a validated 3D k-ω SST model. In the parametric analytical studies NACA series of airfoils are selected. Basic design of the winglet is selected from the literature and flow features of the entire wing including the tip effects have been examined with different cant angles varying from 15^0 to 60^0 at different angles of attack up to 14^0.

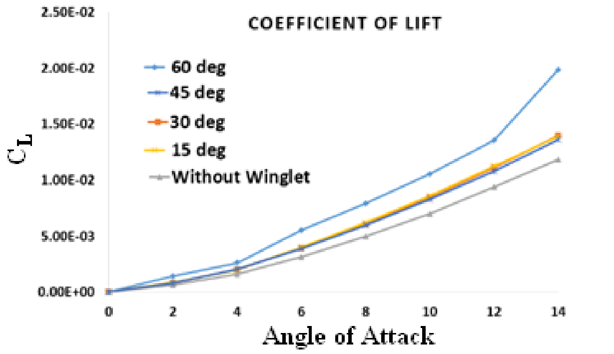


Fig. 6 Comparison of lift coefficient (C_L) at different angles of attack without and with winglet at four different cant angles

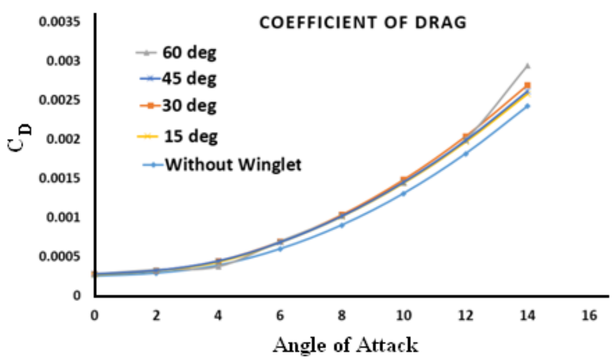


Fig. 7 Comparison of drag coefficient (C_D) at different angles of attack without and with winglet at four different cant angles

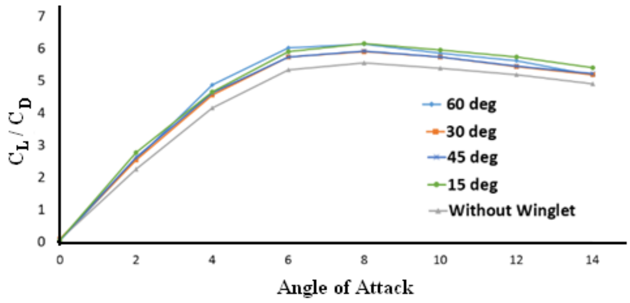


Fig. 8 Comparison of aerodynamic performance (C_L/C_D) at different angles of attack without and with winglet at different cant angles

Fig. 6 shows the comparison of lift coefficient (C_L) at different angles of attack without and with winglet orienting at four different cant angles viz., 15^0, 30^0, 45^0 and 60^0. It is evident from Fig. 6 that a case with cant angle 60^0 is giving the highest coefficient of lift at various angles of attack (0-14). Nevertheless, as evident in Fig. 7, this trend is not seen while comparing the drag coefficient (C_D) at different angles of attack. One can discern from Fig. 7 that a case with 60^0 cant angle C_D is relatively high up to 2.8^0 than a case with 15^0 cant angle and further it diminishes up to 12^0 angle of attack and again it increases due to change in flow features. These variations are corroborated with C_L/C_D curves, which are shown in Fig. 8. It is evident from Fig. 8 that aerodynamic performance of an aircraft with winglet at a cant angle of 15^0 is giving better performance up to an angle of attack 2.8^0 and further a case with winglet cant angle of 60^0 is giving better performance due to the change in overall flow features and the corresponding drag coefficient variation as discussed in the previous session. Fig. 9 shows the reference plane taken for generating numerical results for comparison. Figs. 10-17 show the pressure and velocity contours corresponding to the reference plane shown in Fig. 9 at two different cant angles and various angles of attack.

In the parametric analytical studies NACA series of airfoils are selected. Basic design of the winglet is selected from the literature and flow features of the entire wing including the tip effects have been examined with different cant angles varying from 15^0 to 60^0 at different angles of attack up to 14^0. We have observed, among the cases considered in this study that a case with 15^0 cant angle the aerodynamics performance of the subsonic aircraft during takeoff was found better up to 2.8^0 angles of attack and further its performance got diminished at higher angles of attack. Analyses further revealed that increasing the winglet cant angle from 15^0 to 60^0 at higher angles of attack could negate the performance deterioration and additionally it could enhance the peak value of C_L/C_D on the order of 3.5 %. A winglet's main purpose is to improve performance by reducing drag. To understand how this is done, it is first necessary to understand the distinction between profile drag and induced drag. Profile drags is a consequence of the viscosity, or stickiness, of the air moving along the surface of the airfoil, as well as due to pressure drag (pressure forces acting over the front of a body not being balanced by those acting over its rear). As a wing moves through viscous air, it pulls some of the air along with it, and leaves some of this air in motion. Clearly, it takes energy to set air in motion.

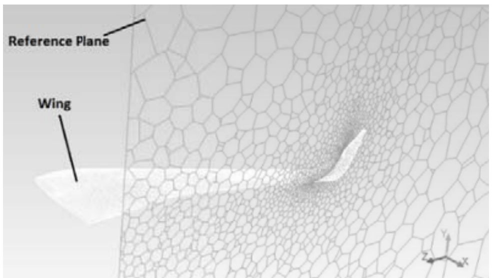
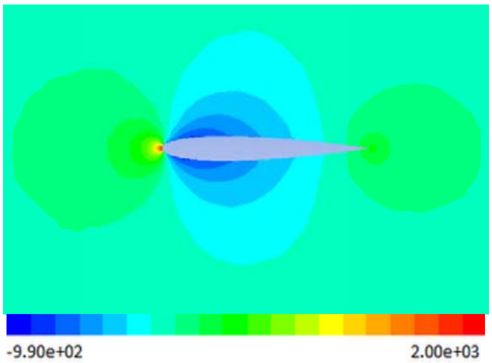
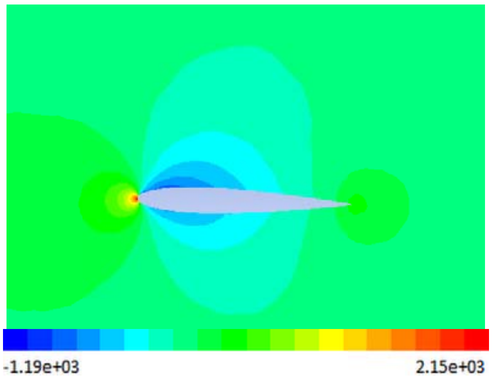


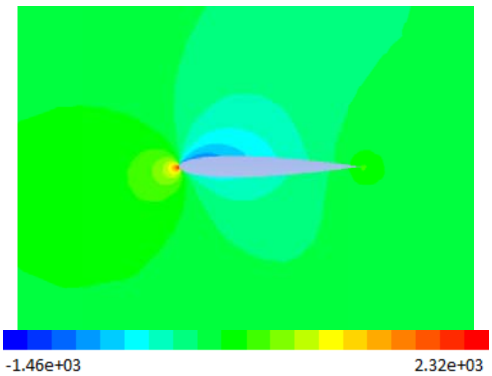
Fig. 9 The selected reference plane for results generation



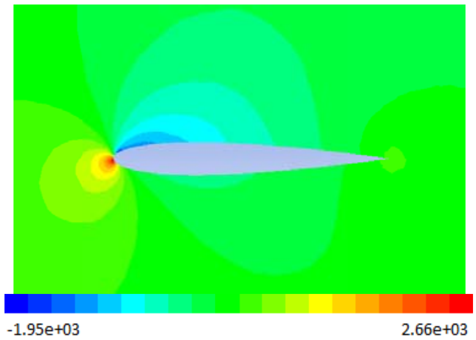
(a) Angle of attack = 0^0



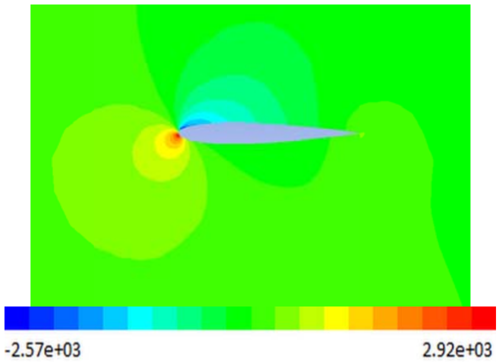
(b) Angle of attack = 2^0



(c) Angle of attack = 4^0

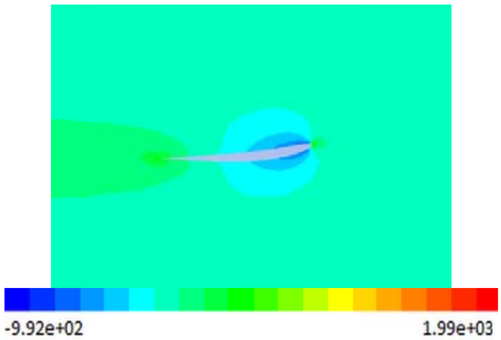


(d) Angle of attack = 6^0



(e) Angle of attack = 8^0

Fig. 10 (a)-(e) Pressure contours (Pascal) at cant angle 15^0 at symmetry plane with different angles of attack



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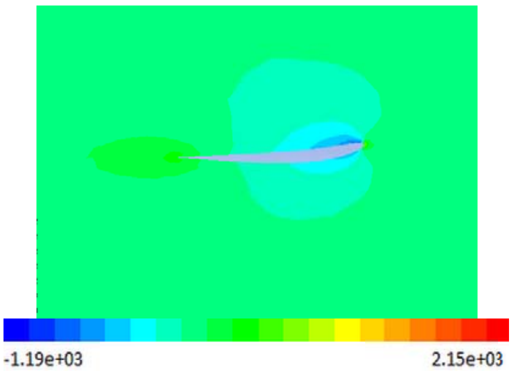

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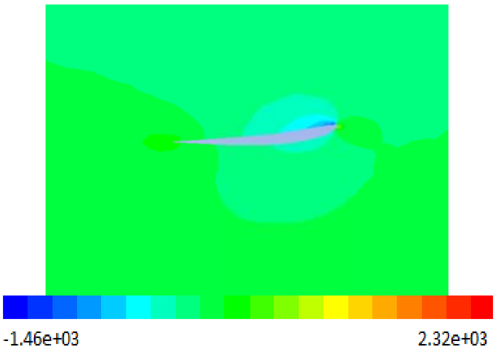

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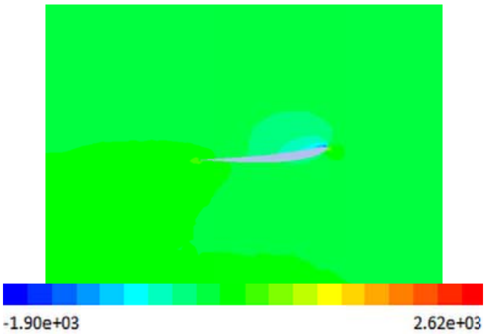

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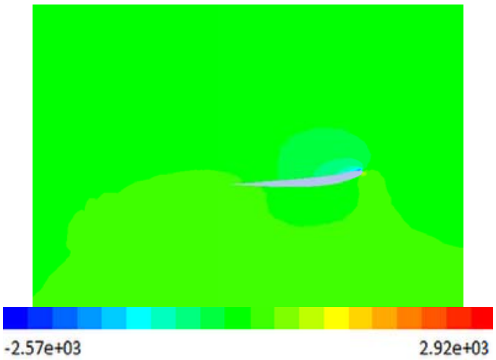
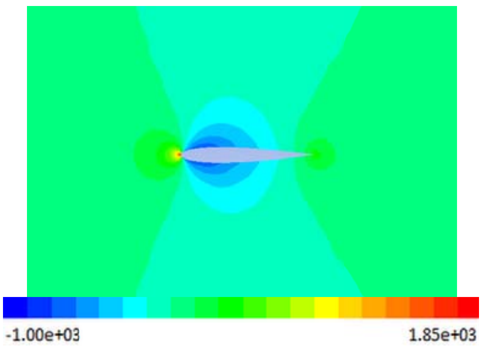


(e) Angle of attack = 8^0

Fig. 11 (a)-(e) Pressure contours (Pascal) at cant angle 15^0 at reference plane with different angles of attack



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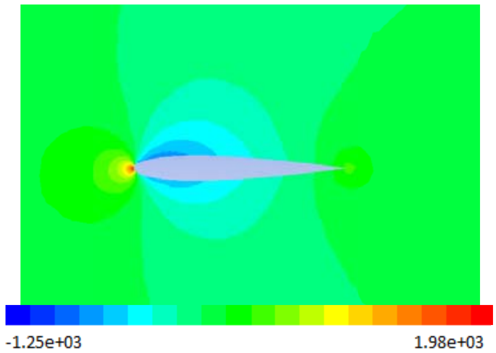

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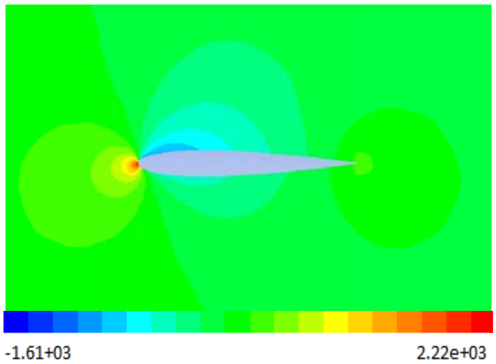

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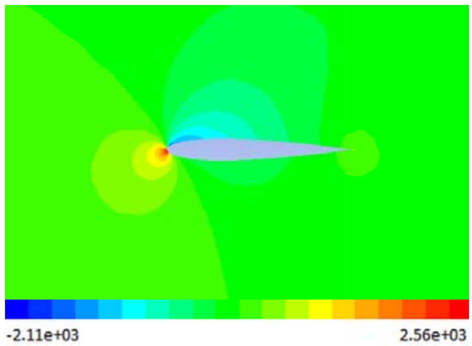

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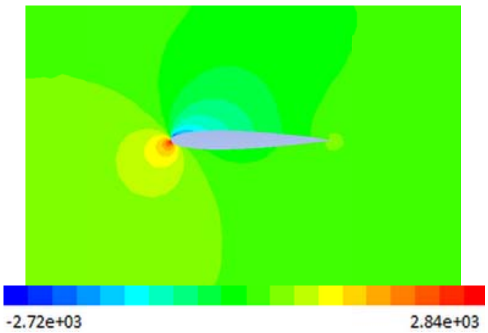
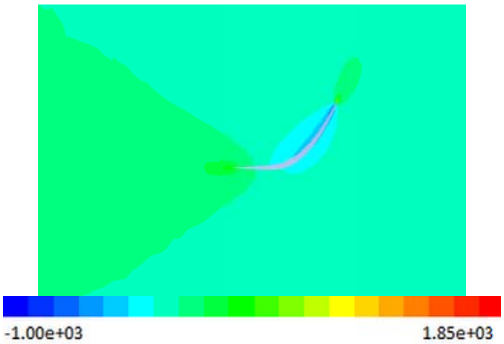


(e) Angle of attack = 8^0

Fig. 12 (a)-(e) Pressure contours (Pascal) at cant angle 60^0 at symmetry plane with different angles of attack



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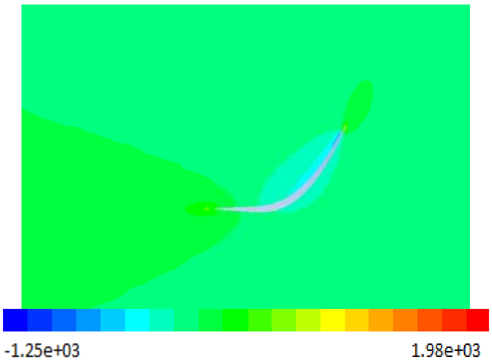

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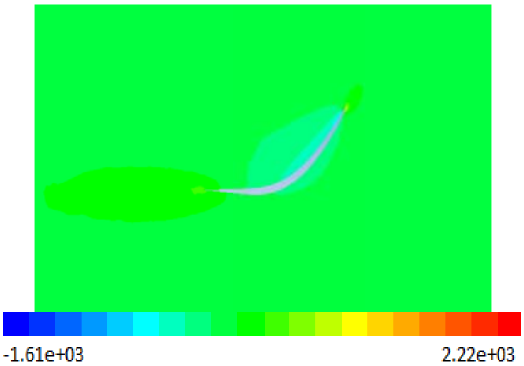

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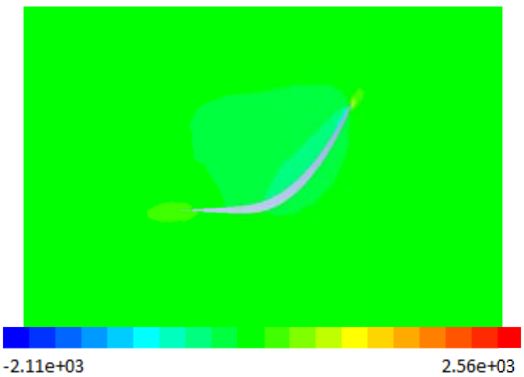

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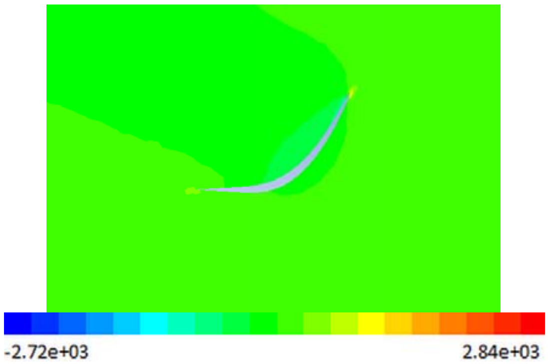
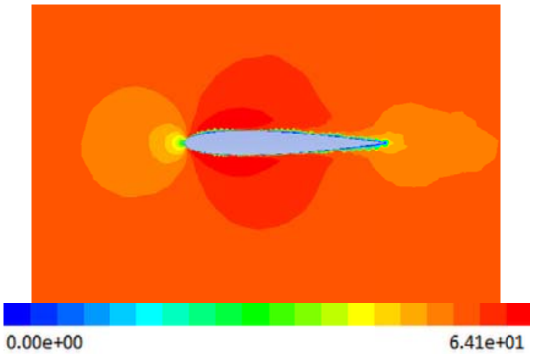


(e) Angle of attack = 8^0

Fig. 13 (a)-(e) Pressure contours (Pascal) at cant angle 60^0 at reference plane with different angles of attack



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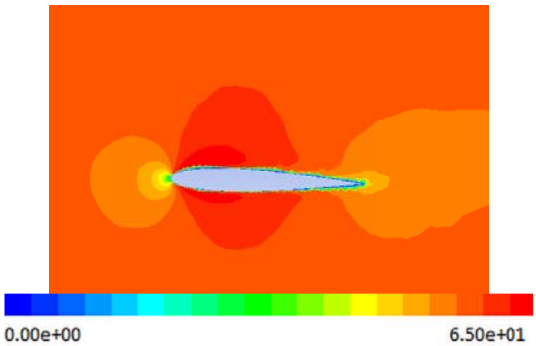

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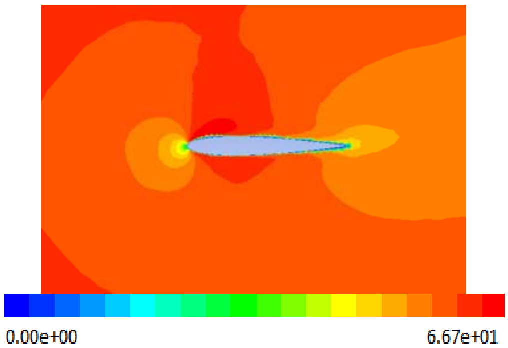

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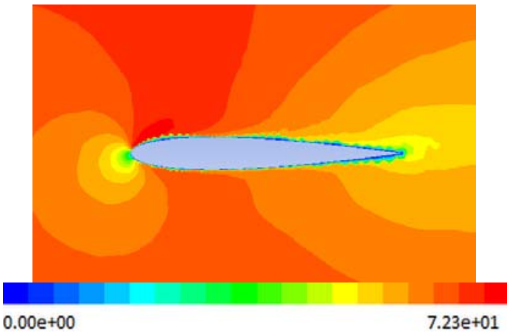
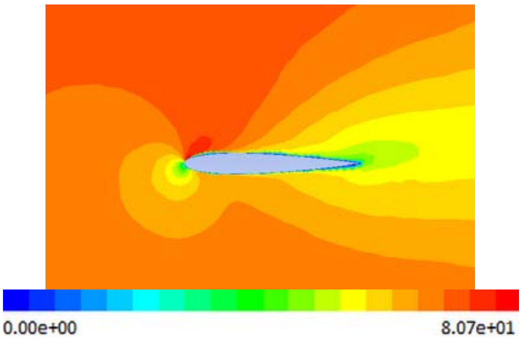
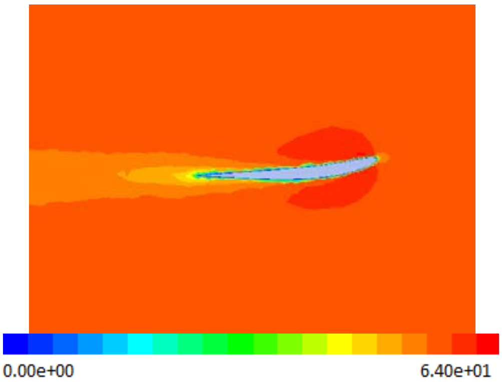


(d) Angle of attack = 6^0

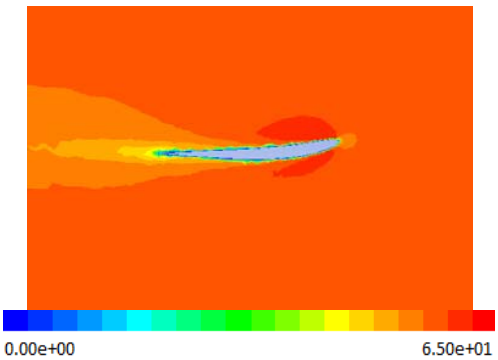


(e) Angle of attack = 8^0

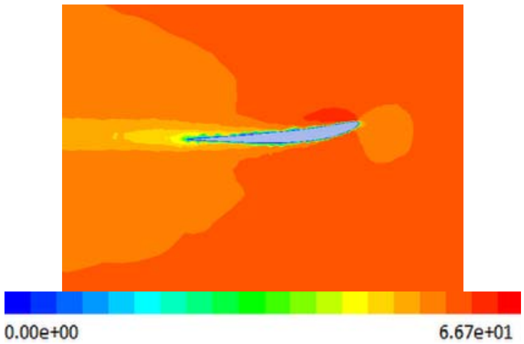
Fig. 14 (a)-(e) Velocity contours (meters per second) at cant angle 15^0 at symmetry plane with different angles of attack



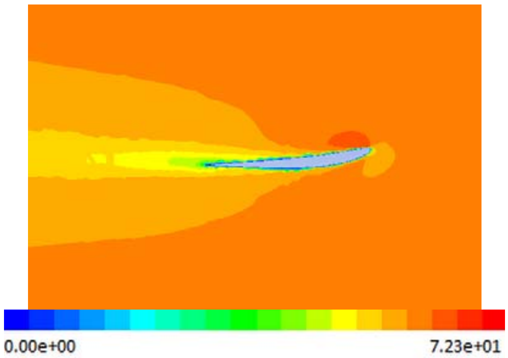
(a) Angle of attack = 0^0



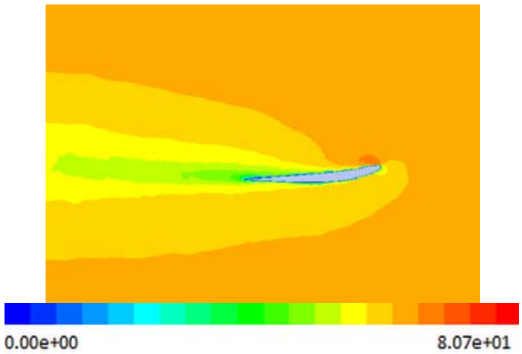
(b) Angle of attack = 2^0



(c) Angle of attack = 4^0

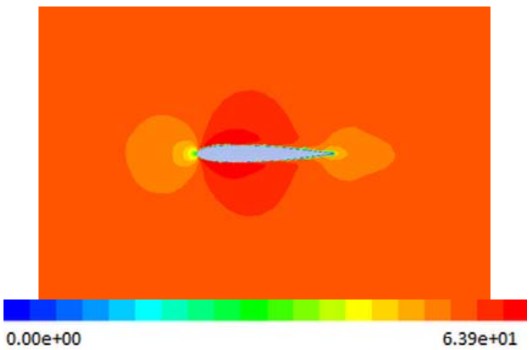


(d) Angle of attack = 6^0

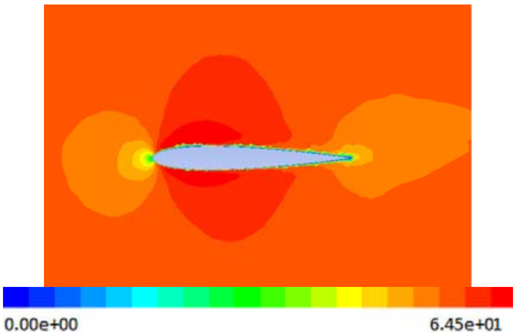


(e) Angle of attack = 8^0

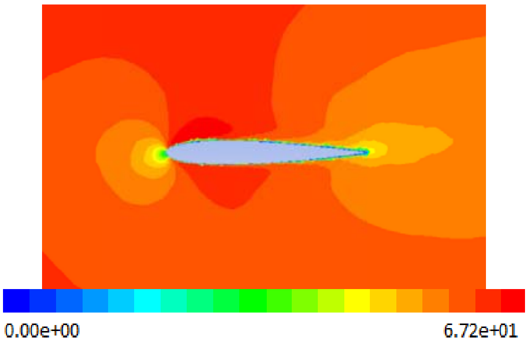
Fig. 15 (a)-(e) Velocity contours (meters per second) at cant angle 15^0 at reference plane with different angles of attack



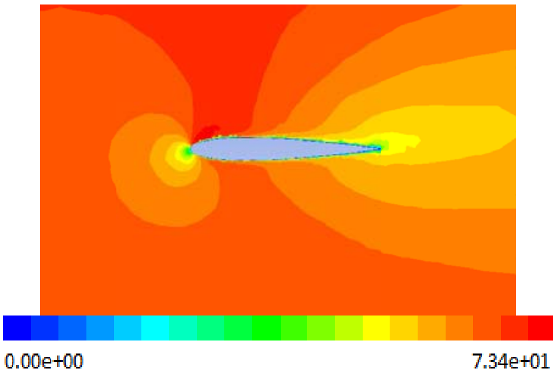
(a) Angle of attack = 0^0



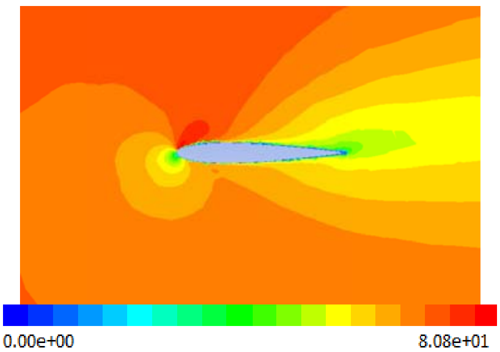
(b) Angle of attack = 2^0



(c) Angle of attack = 4^0

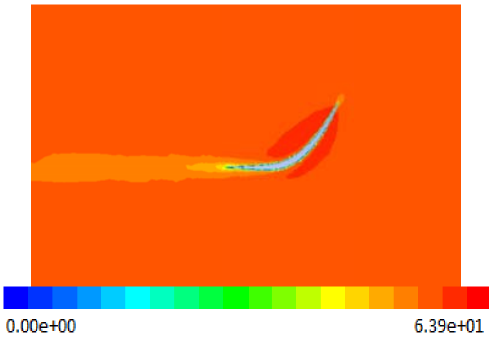


(d) Angle of attack = 6^0

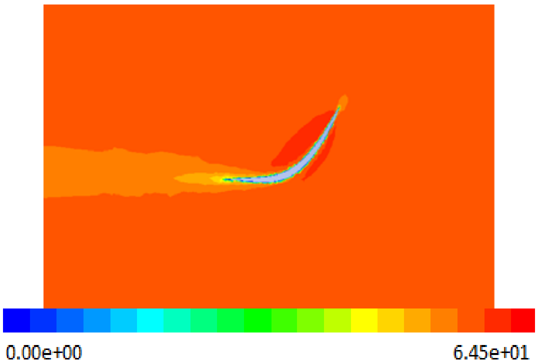


(e) Angle of attack = 8^0

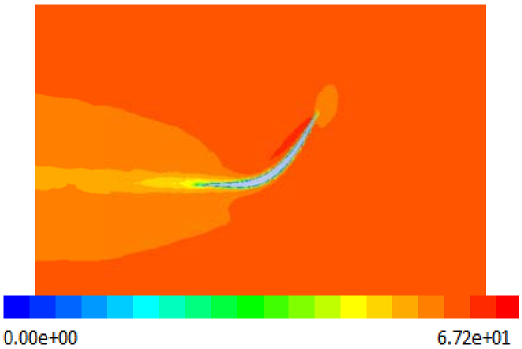
Fig. 16 (a)-(e) Velocity contours (meters per second) at cant angle 60^0 at symmetry plane with different angles of attack



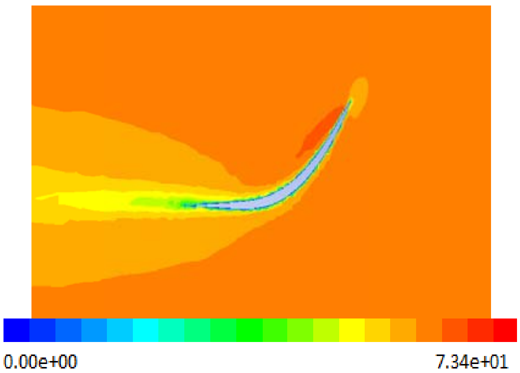
(a) Angle of attack = 0^0



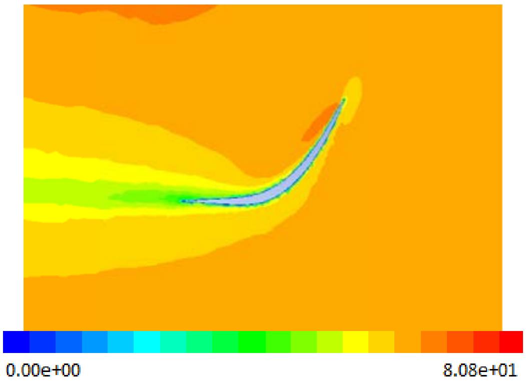
(b) Angle of attack = 2^0



(c) Angle of attack = 4^0



(d) Angle of attack = 6^0



(e) Angle of attack = 8^0

Fig. 17 (a)-(e) Velocity contours (meters per second) at cant angle 60^0 at reference plane with different angles of attack

The transfer of this energy from the wing to the air is profile drag. Profile drag depends on, among other things, the amount of surface exposed to the air (the wetted area), the shape of the airfoil, and its angle of attack. Profile drag is proportional to the airspeed squared. Note that variable cant-angle winglets in disrupts significantly the symmetry of the wing relative to its longitudinal plane, resulting in, conceivably, a more efficient method of lateral/directional control than through the articulation of discrete control surfaces. Through various parametric analytical studies we have conjectured that aircraft with variable winglets, viz., low cant angles at low angles of attack and relatively high cant angles at high angles of attack, could give better performance during takeoff and landing.

V. Concluding Remarks

Although performance gains achieved with winglets are only a few percent, such small differences can be of significant profit to any airline industry. Through various parametric analytical studies we have concluded that aircraft with variable winglets, viz., low cant angles at low angles of attack and relatively high cant angles at high angles of attack, could give better performance during takeoff and landing. Winglet cant angle optimization needs to be carried out case by case. The structural technologies available to achieve the shape and/or cant angle changes in a morphing aircraft is an area that is to be addressed separately for meeting the objective of the variable-cant-angle winglets for practical applications. We concluded that the investigated concept of variable-cant-angle winglets appears to be a promising alternative for improving the aerodynamic efficiency of aircraft.

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