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Computational Analysis of Adaptable Winglets for Improved Morphing Aircraft Performance

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***Abstract*—**An investigation of adaptable winglets for enhancing morphing aircraft performance is described in this paper. The concepts investigated consist of various winglet configurations fundamentally centered on a baseline swept wing. The impetus for the work was to identify and optimize winglets to enhance the aerodynamic efficiency of a morphing aircraft. All computations were performed with Athena Vortex Lattice modelling with varying degrees of twist and cant angle considered. The results from this work indicate that if adaptable winglets were employed on aircraft's improvements in aircraft performance could be achieved.

***Keywords*—**Aircraft, drag, twist, winglet.

I. Introduction

AIRCRAFT control through the use of traditional discrete control surfaces has achieved widespread success over many years [1]. However, these traditional methods, widely accepted on the vast majority of aircraft can be detrimental to aircraft aerodynamic performance as they rely on hinged control surfaces which can generate significant flow separation when actuated fully. To meet the ever increasing demands for more efficient, robust, and cost effective designs, there is an argument that conventional control surface methodologies need to be re-examined in favour of more "morphing-based" technologies and techniques.

Morphing concepts applied to aircraft typically revolve around adaptive geometry structures and mechanisms and are very attractive to aircraft designers as they can provide substantial benefits to aircraft performance. The concept of 'morphing' however is not new. Wing warping techniques were employed by the Wright Brothers to control the first powered, heavier than air, aircraft through wing twist via subtended cables [2]. However, even with the substantial research efforts over the last few decades in particular, morphing concepts still suffer significant challenges. These include added weight, cost, and/or complexity. Jha and Kudva [3] summarized some of the technical challenges and classifications of morphing aircraft, with the most significant challenges tending to be in the structural design of the concepts and mechanisms employed. For instance, to accommodate comparable control surface deflections of traditional techniques, high levels of structural design and analysis are needed, often requiring heavy actuators which increase overall weight.

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The use of winglets to increase the aerodynamic efficiency of an aircraft through the production the forward thrust have been around for many years [4], being first introduced by Whitcomb. Results obtained from his work showed winglets could increase aerodynamic performance of an aircraft through up to a 20% reduction in induced drag and a 9% increase in lift/drag ratio. From this seminal work, more and more subsequent studies have considered various types of winglet configurations and wingtip devices, both theoretically and experimentally. A study using triangular, rectangular, and circular winglets was presented in [5]. Results from this work indicated that sharp or swept edge winglets (triangular) are capable of decreasing induced drag by up to 31%. Various winglet concepts were also studied in [6] with a 60° cant angle winglet achieving a reduction in drag coefficient (approximately 25-30%) and an improvement in lift coefficient (approximately 10-20%). Unfortunately, fixed positioned winglets do not provide the optimum solution for aircraft performance in all flight phases as the optimal lift requirements change with fuel burn. However, some recent studies have started to investigate possible ways of alleviating this fixed condition through incorporating methods to actively optimize winglet position at different flight conditions both for improved efficiency and/or alternative aircraft control. One such investigation was done by [9] and showed that a -3° twisted wingtip winglet configuration increased aerodynamic performance. Other variable wingtip devices have also been used as a primary means of aircraft control, utilizing variable cant angles to generate comparable control forces and moments that would be normally evident through the use of traditional methods [7]-[8].

In this study, work is presented that extends the concept of adaptable winglets for enhancing aircraft performance considered in [10]. The primary variables investigated were winglet angle of twist and cant angle with the main aim to identify degrees of movement within each of the variables that provide benefits to performance. All computations were performed with Athena Vortex Lattice modelling and for all simulations, the Reynolds number was set to 5.53×10^5.

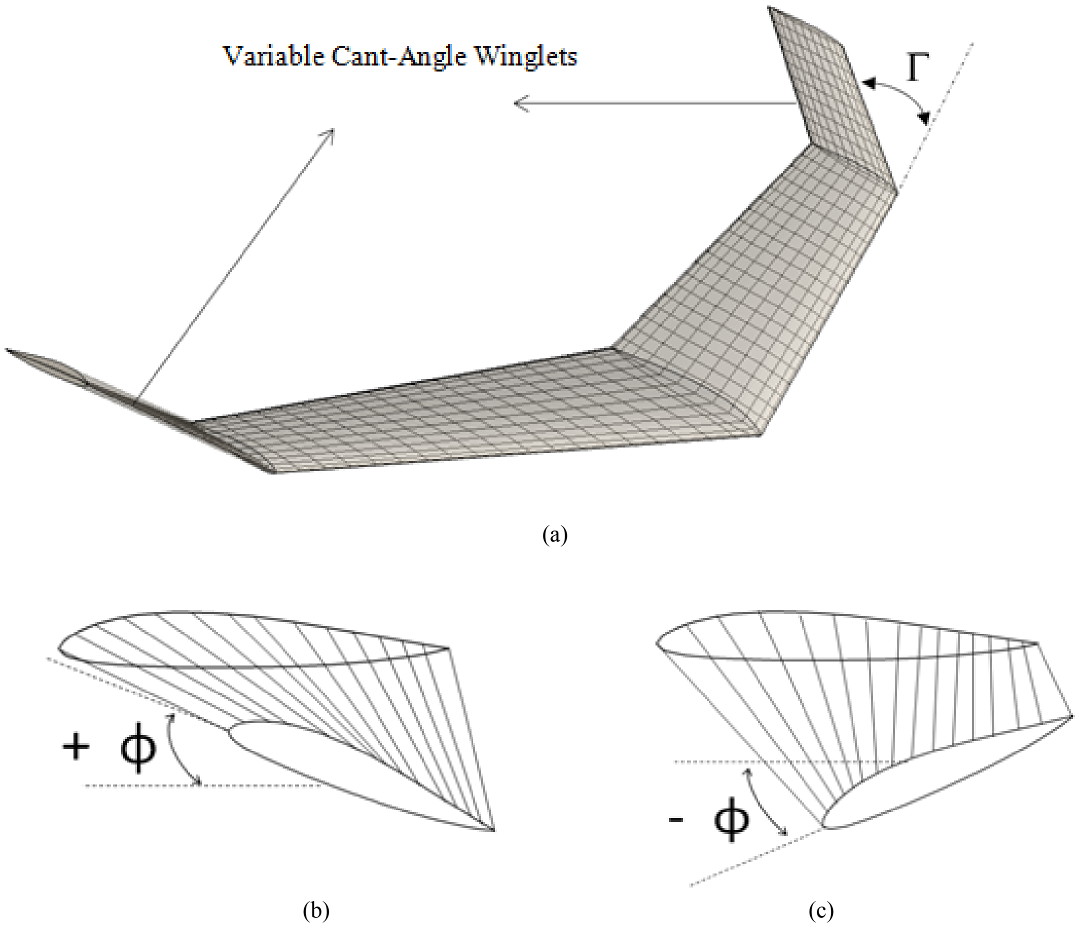


Fig. 1 Schematic View of Swept Wing: (a) Winglet Cant Angle (Γ), (b) Winglet Positive Twist Angle (+ϕ) and (c) Winglet Negative Twist Angle (-ϕ)

II. Design and Methodology

A. Wing/Winglet Geometry

The model chosen for this study was a flying wing (Fig. 1). The baseline wing configuration (without winglet) comprised a 12% thick, Zagi airfoil section, with 30° leading edge sweep angle, 1.2m wing span, 0.33m root chord, 0.185m tip chord, with aspect and tip ratios of 6.19 and 0.47 respectively. Each winglet had a 0.15m tip chord, 30° sweep, and a span of 0.15m. In order to investigate winglet performance for different flight conditions, predetermined values of winglet twist (-10°< ϕ <10°) and cant angle (-60°<Γ<60°) were investigated.

B. Numerical Method

The aerodynamic modelling and numerical computations were carried out using Athena Vortex Lattice (AVL) software. Athena Vortex Lattice is a simulation package that determines the solutions to a linear aerodynamic flow model. For all simulations, modelling was performed from a set of wing panels along the wing span and chord axes. Each surface panel was assigned as a single horse-shoe vortex with velocities induced by each vortex evaluated at certain control points using the "Biot-Savart law". Forces and moments were obtained from the solved load distribution by applying the "Kutta-Joukowski Theorem" [11]. For all simulations, the free-stream velocity was set to 30 m/s and all results were calculated without the influence of compressibility. In order to be computationally efficient, a grid refinement study was performed on the baseline configuration prior to widespread use of the developed model. Subsequent to this activity, all computations were thereafter based on 18 horseshoe vortices along the wing and winglet chord, and 58 along the semi-span of the baseline wing and winglet.

III. Results and Discussion

A. Effects of Changing Cant Angle on Performance

The change in static force coefficients and C_L/C_D obtained from the winglet deflection between -60°≤ Γ ≤60° are shown in Figs. 2-4. It can be clearly seen from Fig. 2 (a) that deflecting the winglet through both Γ<0° and Γ>0° in a positive-twisted configuration creates an overall reduction in lift coefficient, shifting the aerodynamic load inboards (for Γ = 60° ΔC_L= -0.02, Γ = -60° ΔC_L= -0.028 at ϕ = +10°) in agreement with previous work [8], [10]. This mechanism is manifested through a reduction in effective lift production as the winglet rotates out of the wing plane [8]. Moreover, in agreement with [8], [10], there is also a tendency of asymmetrical lift reduction at Γ = -60° relative to Γ = 60°, due to the use of an unsymmetrical airfoil shape within the swept wing configuration. This lift coefficient asymmetry (particularly evident at large winglet twist angles ϕ = ±10°) is seen to reduce less for movement to positive cant angle as both a non-symmetrical airfoil was used and the flow is expected to be more effective at the maintaining the upper surface low pressures for Γ=60°. Fig. 2 (b) shows the change in lift coefficient for negatively twisted winglet configurations. It can also be seen that the change in lift coefficient continues to show the trend seen in Fig. 2 (a) with reductions in lift coefficient as cant angle increases or decreases. As would also be expected, results in Fig. 2 (b) show overall net lift reductions compared to Fig. 2 (a) as less lift is produced in the negatively-twisted winglet configurations.

Similar to ΔC_L, and in general agreement with, [8], [10], maximum overall drag (ΔC_D) reductions of up to 15 and 6 drag counts (for Γ = -60° and Γ = 60° respectively Γ = 0° baseline) were obtained for the ϕ = 10° winglet configuration shown in Fig. 3 (a). When cant angle increases from Γ = 0° to 60°, winglet twist angles of up to ϕ = 3° show little benefit in terms of drag reduction with further increase in twist angle (ϕ > 3°) tending to produce drag reductions of up to 6 drag counts at maximum cant angle (Γ = 60° relative to Γ = 0°). This result gives some indication of the influence of the winglet's movement (at large twist angles) out of the wing plane on overall performance. However, there seems to be some exception to this finding, particularly for Γ > 20° (low twist) where the results seem to be relatively constant. Additionally for Γ > 0°, there seems to be a much more subtle linear reduction in drag coefficient with cant angle change as opposed to the results shown for Γ < 0° where a maximum drag reduction of 15 drag counts at Γ = -60° (ϕ = 10°) exists.

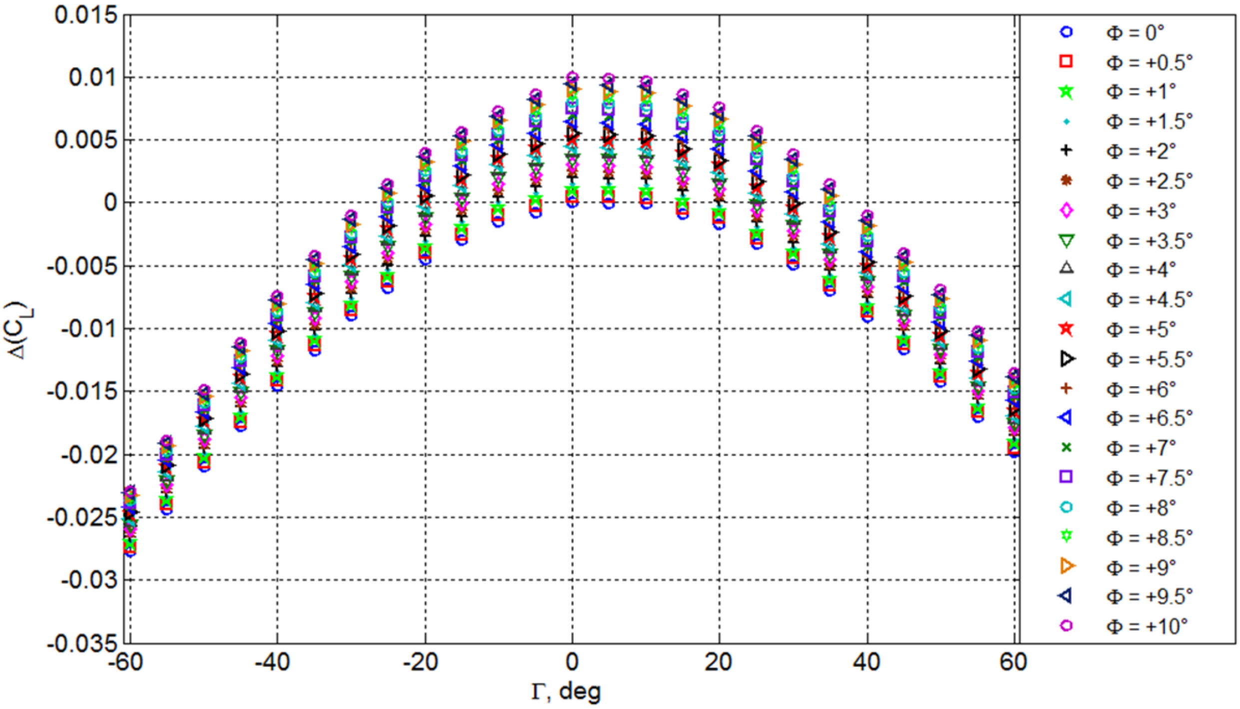
Considering results for ϕ < 0° as shown in Fig. 3 (b), there seems to be much less of a variation in change in drag coefficient when compared to the ϕ > 0° winglet configurations (Fig. 3 (a)) with the influence of winglet twist angle being much less pronounced than that found for ϕ > 0. One possible reason for this may lay in the increased effectiveness of negative twist winglets at both producing less overall lift (and therefore less lift-dependent drag) as well the ability of negatively-twisted winglet configurations to maintain lower effective angles of attack relative to the freestream flow. For all test cases presented negative cant angle seems to have a much more pronounced effect on changing the overall aerodynamic performance with (particularly for ϕ > 0°) large amounts of variation in change in drag coefficient with twist angle change. Results for Γ > 60° in both cases are much less variable.

Lift to drag ratio plays significant role in the aerodynamic performance of an aircraft. Figs. 4 (a) and (b) detail the change in C_L/C_D coefficients obtained from winglet deflection between -60°≤ Γ ≤60° for all the winglet configurations. In all of these configurations, and as would be expected, it can be clearly seen that the principle effect on C_L/C_D is one of a reducing magnitude with movement of cant angle away from planar configuration (maximum $\Delta C_L/C_D$= - 0.57, Γ = -60° Fig. 4 (a) and $\Delta C_L/C_D$= - 0.72 for Γ = +60° Fig. 4 (b)). In saying this however, there exist subtle characteristics within the computed results that show a small degree of augmentation around this baseline planar flow case. In the region of cant angles from -20° < Γ <0°, there is evidence of a small increase in $\Delta C_L/C_D$. Moreover, in agreement with [10], there is also a tendency for asymmetric $\Delta C_L/C_D$ reductions of up to $\Delta C_L/C_D$ =-0.1 at Γ = 60° relative to Γ = -60° for ϕ > 0° (Fig. 4 (a)).

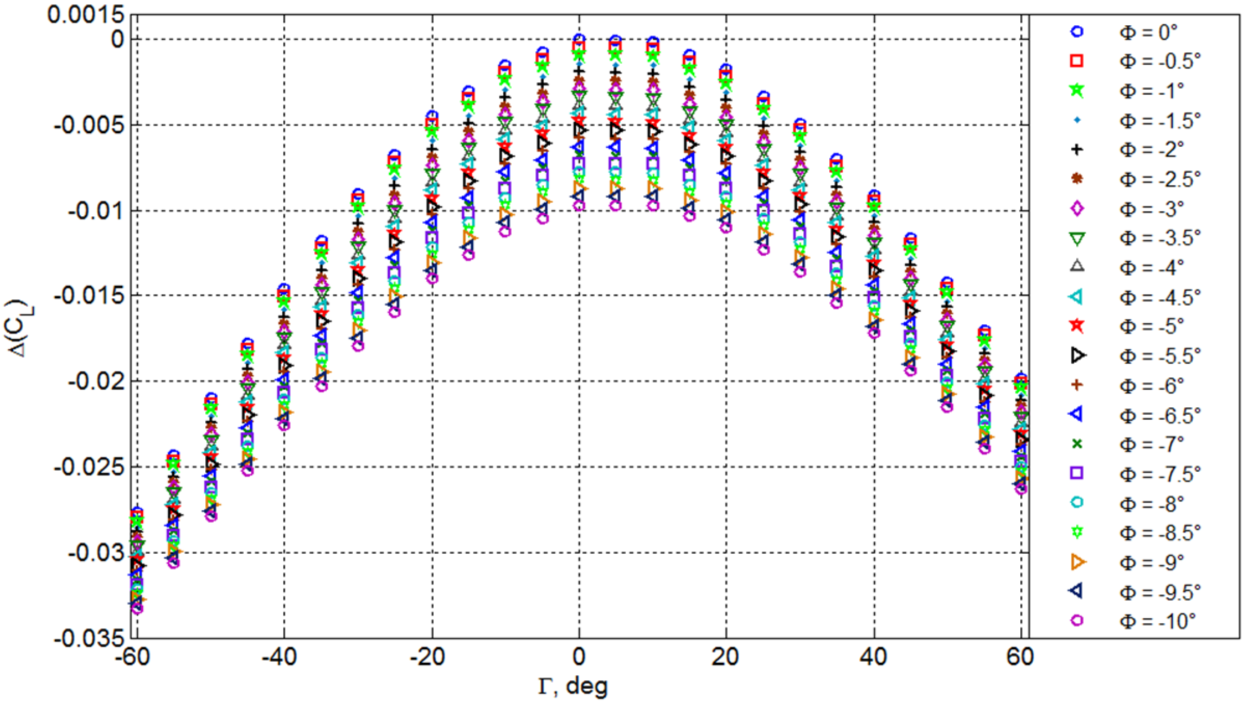
Fig. 4 (b) highlights the change in C_L/C_D for negative twist winglet configurations. Similar to ϕ > 0°, in all of these configurations, and as would be expected, reductions were observed in the change of C_L/C_D when winglet cant angle deviates from the planar configuration (Γ = 0°). Although globally, efficiency tends to reduce, as was the case for ϕ > 0°, for some local cases presented (-20°<Γ<0°) for the negative winglet twist angle configurations, minor improvements ($\Delta C_L/C_D$=0.07 at ϕ = -5°) over that observed from the baseline flow case exist. Similar results were also presented in [12], with in effect a small range of negative cant angles resulting in the best values of C_L/C_D. Furthermore, the asymmetric bias evident in Fig. 4 (a) for the change in C_L/C_D with increasing or decreasing cant angle also exists for negative twist winglet configurations (Fig. 4 (b)) although for this case, the degree of asymmetry has tended to increase further with some examples showing differences of up to $\Delta C_L/C_D$ =-0.31 (ϕ =- 10°, Γ = -60° to 60°). Moreover, from comparing Figs. 4 (a) and (b) directly, results do show much more variability with positive winglet twist (particularly for Γ < 0°) on $\Delta C_L/C_D$ than that observed for the negatively twisted configurations. This is most notable when comparing results in Fig. 4 (a) at Γ=-60°.

B. Effects of Changing Winglet Twist Angle on Performance

From Figs. 2 (a) and (b), as winglet twist angle increases or decreases, the net effect on change in the lift coefficient varies almost linearly up to ϕ = ±10° with the maximum changes with winglet twist occurring at the baseline flow case of Γ = 0° (ΔC_L= ±0.01 ϕ = ±10°). This would be expected as the maximum effectiveness of winglet angle twist occurs at Γ = 0° and is the subsequent position of maximum lift enhancement. This effect reduces with change in dihedral angle from the planar case, due to both net reductions in effective angle of attack as the winglet moves out of the wing plane and the winglet contribution to overall lift development reduces.

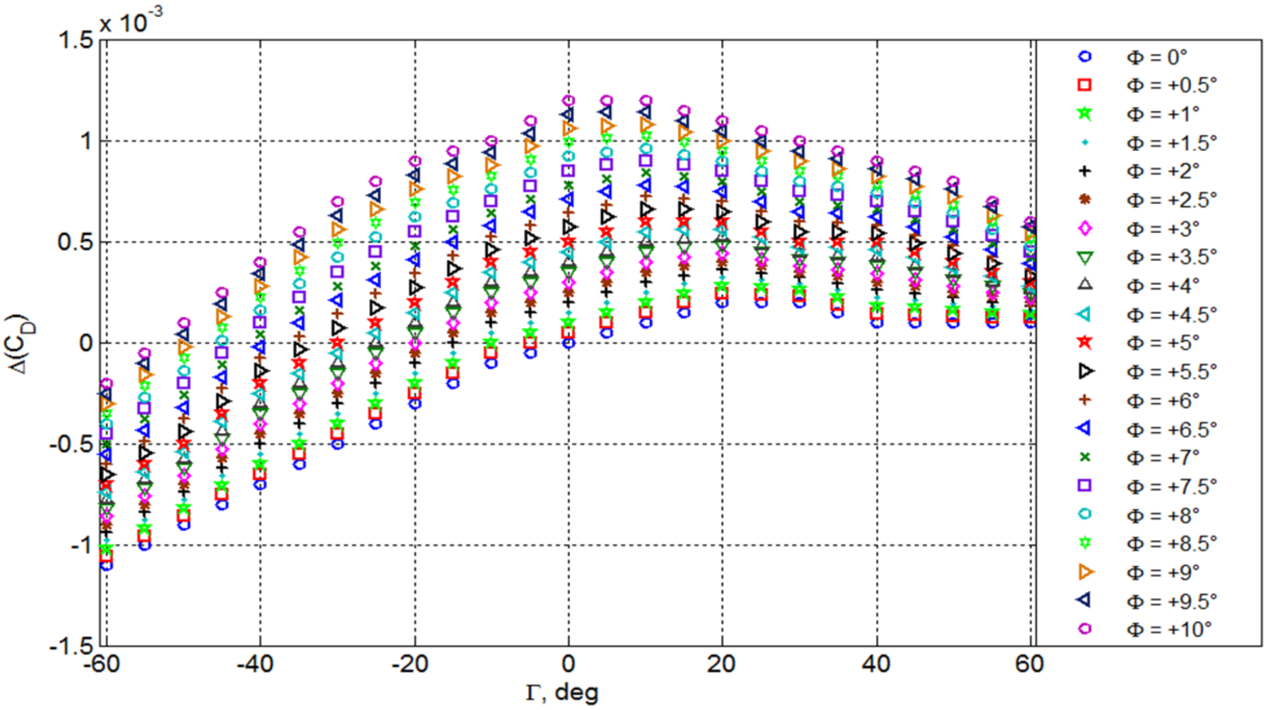


(a)

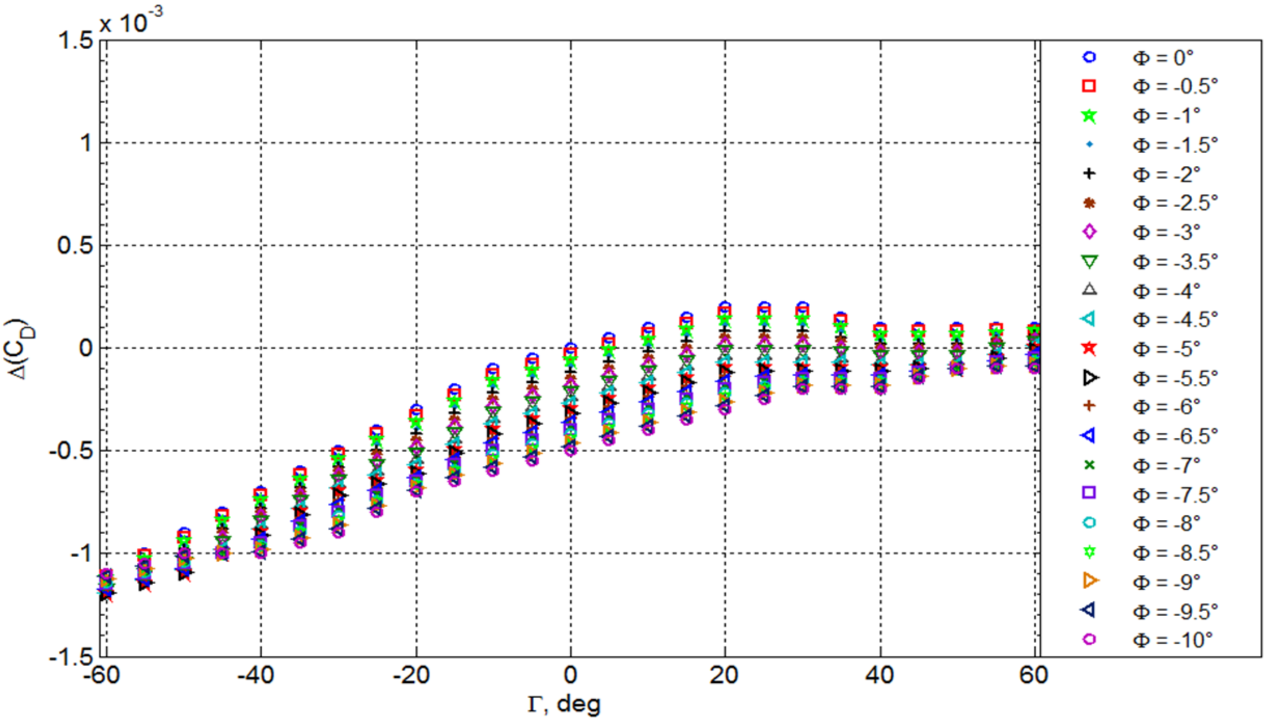


(b)

Fig. 2 Effects of Changing Winglet Cant and Twist angle on Aircraft Performance (ΔC_L) at $C_{L_0} \cong 0.6$: a) Wash-in (Positive Twist) and b) Wash-out (Negative Twist).

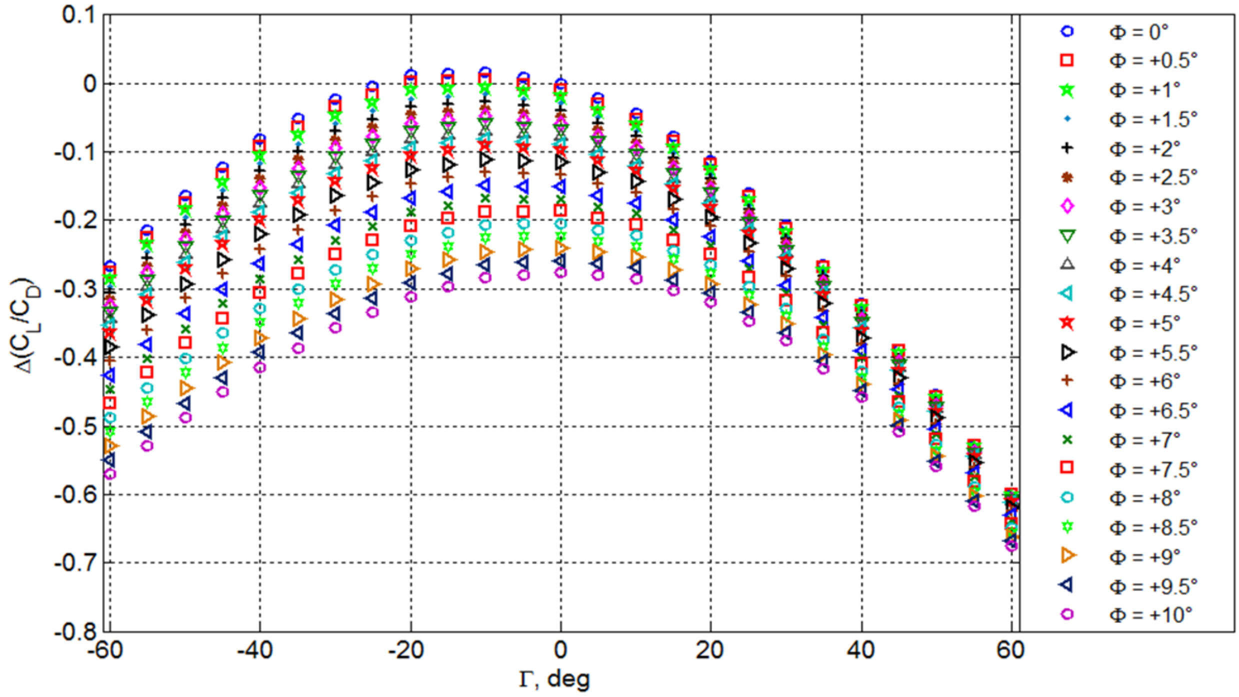


(a)

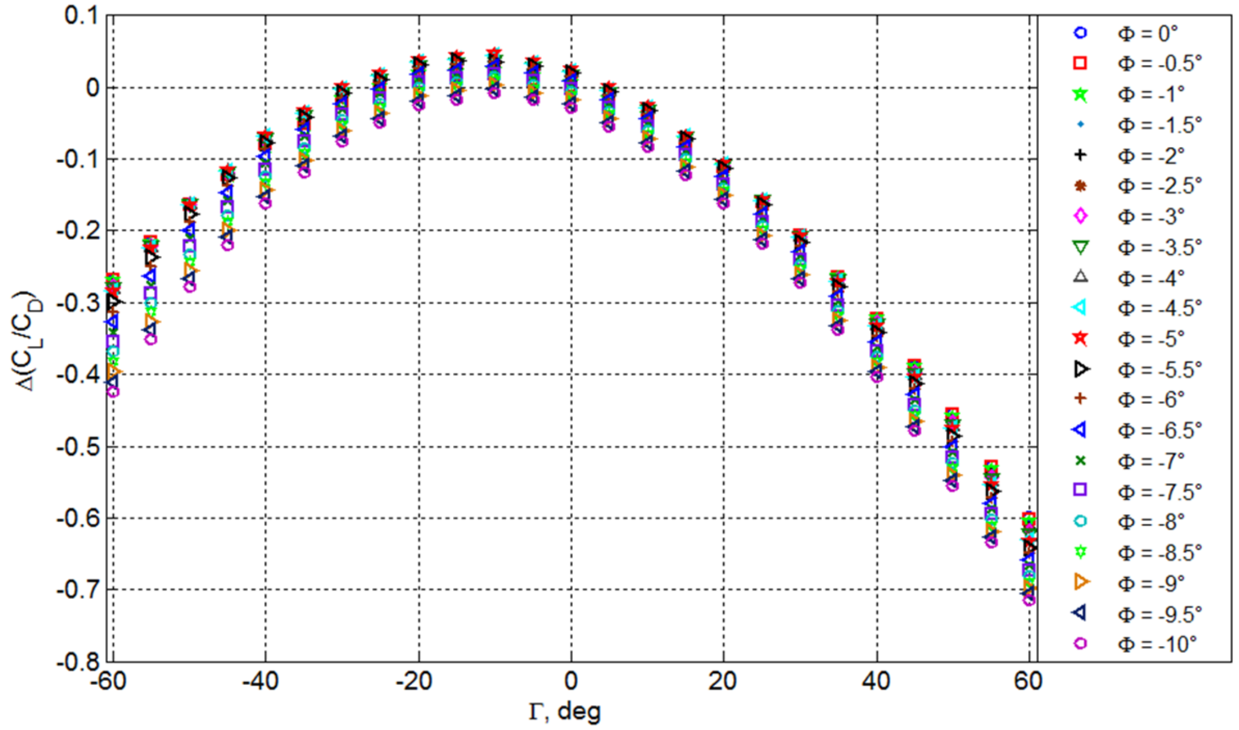


(b)

Fig. 3 Effects of Changing Winglet Cant and Twist angle on Aircraft Performance (ΔC_D) at $C_{L_0} \cong 0.6$: a) Wash-in (Positive Twist) and b) Wash-out (Negative Twist).



(a)



(b)

Fig. 4 Effects of Changing Winglet Cant and Twist angle on Aircraft Performance ($\Delta C_L/C_D$) at $C_{L_0} \cong 0.6$: a) Wash-in (Positive Twist) and b) Wash-out (Negative Twist).

Similar to ΔC_L, the influence of twisting the winglets has a marked influence on the production of drag, however in this particular case, there exists a very non-uniform degree of change that is heavily dependent on the degree of winglet cant angle. For positive winglet twist angles, there is a clear bias and significantly more influence on the drag with changing winglet twist angle for $\Gamma < 0°$. The results in this case suggest that change in drag varies significantly less for $\Gamma > 0°$. Maximum drag coefficient change for these conditions were obtained at a maximum twist angle of $\phi = 10°$ and represented up to an additional 10 drag counts compared to non-twisting winglet configurations ($\Gamma = 0°$).

Comparing the features seen in Fig. 3 (a) with negative twisted winglets (Fig. 3 (b)), change in drag coefficient was found to be much less with winglet change from $\phi = \pm 10°$ with maximum differences of approximately 5 drag counts with winglet variations from $\phi = 0°$ to $\phi = -10°$ ($\Gamma = 20°$). Together with these results, while Fig. 3 (b) displays much more non-linear behavior with change in dihedral angle, the influence of changing winglet twist angle still remains relatively linear at any particular dihedral angle when the winglet is twisted about $\phi = 0°$ at that set dihedral angle. These effects are most notable at $\Gamma = 20°$ to 40° with similar results also presented in [9].

As discussed previously, and confirmed in the results shown here, positive twisted winglets provide a greater lift force production capability than those obtained for negative twisted winglets. However, it should be noted that, under the same conditions, the influence on drag coefficient is much more complex [9-10] with the overall result, for the majority of test cases considered, representing a reduction in aerodynamic efficiency. However, according to the results presented here, increases in aerodynamic efficiency were achieved up to twist angles of $\phi = -5°$ ($-20° < \Gamma < 0°$) with these winglet angle configurations seeming to give some enhancement of $\Delta C_L/C_D$. Similar results were also presented in [9], [10] with small twist angles resulting in the production of the lowest lift-induced drag. However, considering further increases in twist angle, this influence tended to diminish the aerodynamic performance.

IV. Conclusion

An investigation of changing various winglet configuration parameters for augmented morphing aircraft performance has been investigated. Of the various winglet configurations investigated, selected cases do provide good evidence that adaptable winglets through morphing could provide benefits to overall aerodynamic performance and efficiency.

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