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Investigation of Adaptable Winglets for Improved UAV Control and Performance

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

***Keywords*—** Aircraft, rolling, wing, winglet.

I. Introduction

AIRCRAFT control through the use of traditional discrete control surfaces has achieved widespread success over many years [1]. These traditional methods, widely accepted on the vast majority of aircraft, however can be detrimental to an 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" technologies and techniques.

Morphing technologies 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 or '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 morphing concepts still suffer significant challenges. These include added weight, costs, and/or complexity. Jha and Kudva [3] summarised 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 has been around for many years [4], being first introduced by Whitcomb. Results obtained from this work showed winglets could increase aerodynamic performance of an aircraft through a 20% reduction in induced drag and 9% increase in lift/drag ratio). From this seminal work, more and more subsequent studies 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 indicated that sharp or swept edge winglets (triangular) are capable of decreasing induce 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 improvement in lift coefficient (approximately 10-20%). Unfortunately, fixed positioned winglets do not provide the optimum solution for aircraft performance in all flight regimes as the lift requirements for aircraft can change within a typical flight due to fuel burn. Some more recent studies on have started to investigate possible ways of alleviating this fixed condition through incorporating methods to actively optimise winglet position at different flight conditions. These variable wingtip devices have included the use of variable cant-angle winglets for aircraft control [7], [8], which show some promise over more traditional methodologies.

The motivation of this study is to explore concepts of adaptable winglets for morphing aircraft control and performance on a small scale UAV platform. The primary variables investigated involved changing winglet angle of twist, sweep, and dihedral angle with the main aim to identify degrees of movement within each of the variables considered that set encompass a flight profile where significant benefits to performance and control can be achieved.

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, and 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. The winglet has 0.15m winglet tip chord, and a span of 0.15m. In order to investigate winglet performance for different flight conditions, predetermined values of winglet sweep ($-40< \Lambda <40$), twist ($-10< \phi <10$) and dihedral angle ($-90<\Gamma<90$) were investigated.

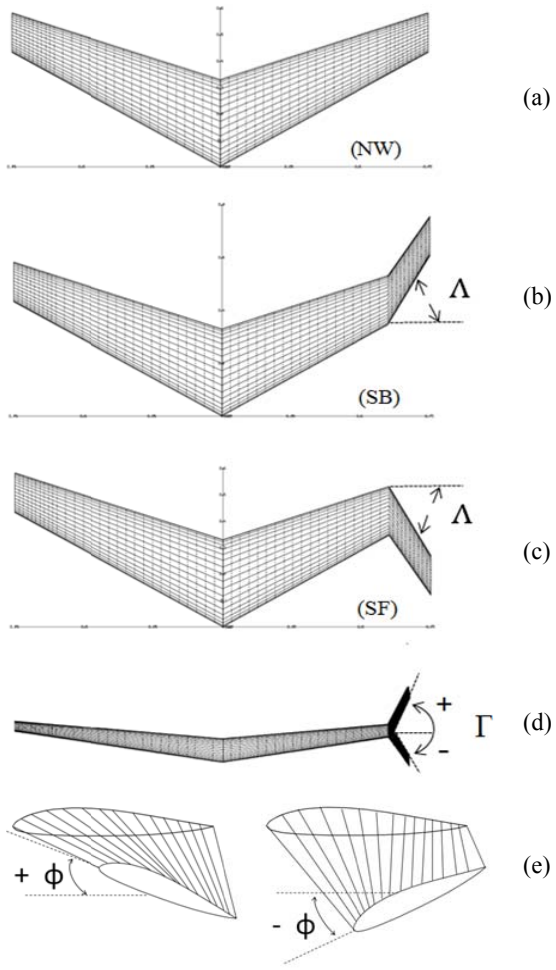

Fig. 1 Schematic View of Variable Winglet Structures: (a) Normal positioned winglet (NW), (b) swept back winglet (SB), (c) swept forward winglet (SF), (d) winglet dihedral angle (Γ), and (e) winglet twist angle (ϕ)

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" [9]. 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 Winglet Dihedral Angle on Aerodynamics

The change in static force and moments coefficients obtained from single winglet (port side) deflection between $-90° \leq \Gamma \leq 90°$ are shown in Fig. 2. From Fig. 2 (a), it can be clearly seen that deflecting the winglet through both $\Gamma<0°$ and $\Gamma>0°$ creates an overall reduction in lift coefficient which would shift of the aerodynamic load inboards (for Γ = +90 ΔC_L= -0.043, Γ = -90° ΔC_L= -0.048) in agreement with previous work [7], [8]. This mechanism is manifested through a reduction in effective lift production as the winglet rotates out of the wing plane [8]. Increasing the winglet's cant angle therefore, also results in a reduction in lift curve slope. Moreover, in agreement with [8], there is also a tendency of asymmetrical lift reduction at Γ = -90° relative to Γ = 90° (NW), due to the use of an unsymmetrical airfoil shape. This lift coefficient reduction asymmetry (particularly evident at large winglet twist angles ϕ >0°) is seen to favour movement to positive dihedral as both the flow is expected to more effective at the maintaining the upper surface low pressures as well as the loss of lift production effectiveness for large twist angles with Γ < 0°. Fig. 2a also shows the influence of increasing winglet twist on ΔC_L to be almost linear at any particular position of dihedral angle with the possible exception of Γ = -90°.

Comparing Fig. 2 (a), with Figs. 3 (a) and 4 (a), adding both sweepback and forward sweep to the winglet has a marked effect on wing performance. For the swept back configuration (Fig. 3 (a)), the change in lift coefficient continues to show the trend seen in Fig. 2 (a) with the asymmetric decrease with change in dihedral angle, favouring Γ < 0°, however results for large angles of sweepback show this asymmetrical decrease to be further exacerbated over the normal winglet configuration with a maximum difference in ΔC_L from Γ = -90° to Γ =90° of -0.014 at SB= 40° ϕ = +5° from -0.010 for NW at ϕ = +10°. For the forward swept winglet configuration (Fig. 4 (a)), there seems to be much less of a variation when compared to the swept back configuration with maximum lift reduction asymmetry being ΔC_L= -0.044 and ΔC_L= -0.047 at Γ = 90 and Γ = -90° respectively. One possible reason for this may lie in the increased effectiveness of sweptback winglets at interacting with the developed wingtip vortices [10].

Similar to ΔC_L, and in general agreement with [7], [8], overall drag (C_D) reductions of up to 15 and 7 drag counts for Γ = 90° and Γ = -90° respectively were obtained for the normal winglet configuration shown in Fig. 2 (b). The influence of twist angle on change in drag coefficient for this configuration was also found to be substantial with maximum differences of more than 22 drag counts when winglet twist is varied from $-10° < \phi < 10°$. The characteristic asymmetric bias with winglet dihedral angle, evident in the results for ΔC_L, also seems to also exist for ΔC_D, however the influence of linear increase in winglet twist to maximum, as would be expected, clearly shows an non-linear dependency on ΔC_D, particularly as ϕ > 0°. With the inclusion of both winglet sweep forwards

and backwards, similar behaviour with regards to drag reduction is observed relative to the normal winglet configuration. Comparing the normal winglet configuration to the swept back configuration (Fig. 3 (b)), the degree of drag reduction has increased for most configurations at maximum negative dihedral angle position with the largest sweep angles, with no inherent twist, providing a maximum additional drag reduction of more than 10 drag counts. The influence of increasing sweep back angle at maximum positive winglet dihedral placement is also shown to be relatively insensitive to changes in drag for the cases presented. For the forward swept configuration, results from the analysis showed levels of drag reduction very similar to the normal winglet configuration with drag reductions (ΔC_D) of 15 and 12 drag counts found at Γ = -90° and Γ = 90° respectively (Λ=20° at ϕ =-5° condition).

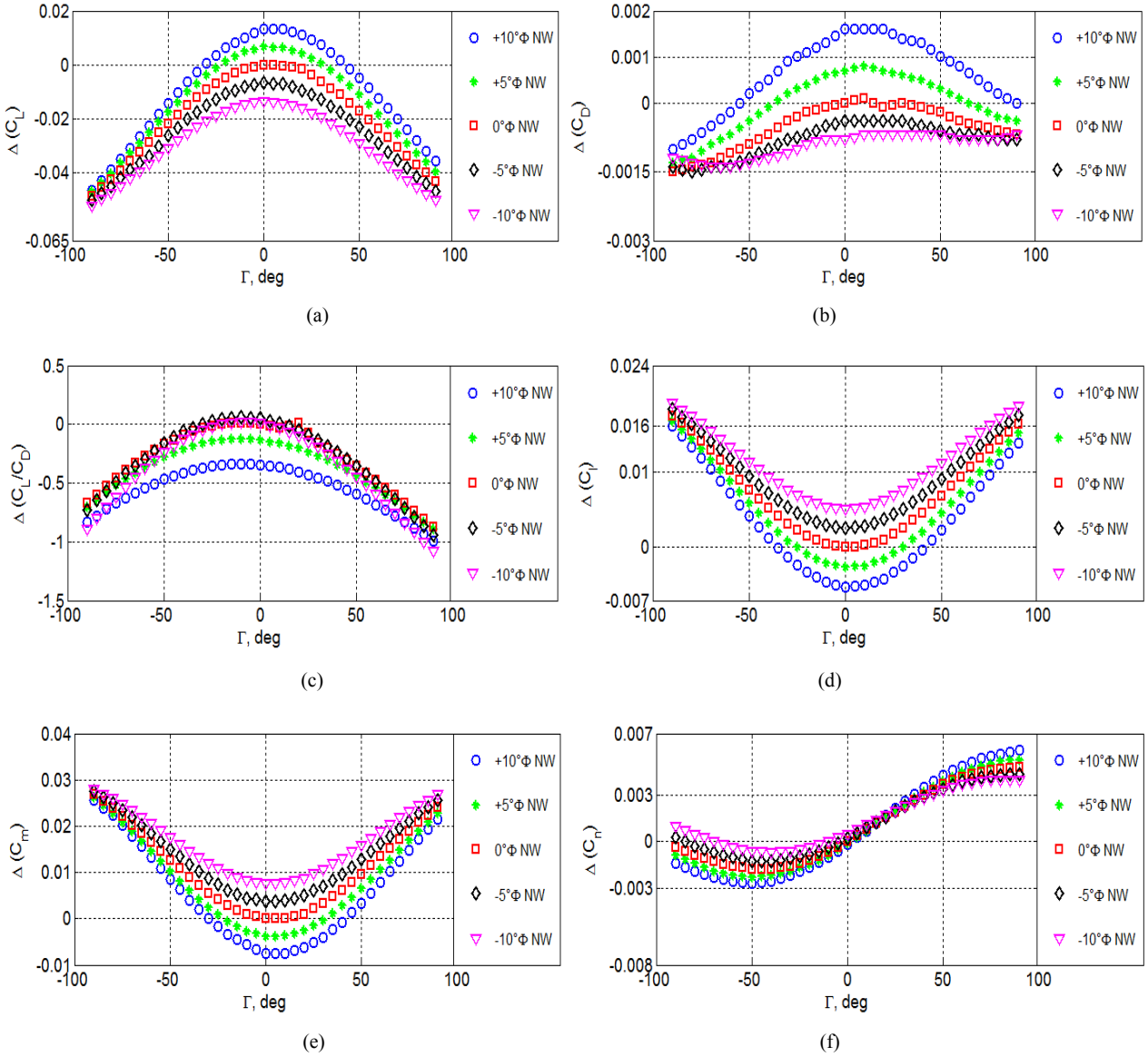

Fig. 2 Effects of changing winglet dihedral and twist angle in normal winglet (NW) configuration at $C_{L_o} \cong 0.6$ (a) ΔC_L, (b) ΔC_D, (c) $\Delta C_L/C_D$, (d) ΔC_l, (e) ΔC_m , and (f)ΔC_n.

Lift to drag ratio plays significant role in the aerodynamic performance of an aircraft. Figs. 2, 3, and 4 (c) detail the $\Delta C_L/C_D$ for normal winglet, swept back and swept forward 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 dihedral angle away from planar configuration (Γ = 0°). 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 dihedral angles from -20°<Γ<0°, particularly for the sweptback configuration, there is evidence of an increase in $\Delta C_L/C_D$ (SB=

30°, ϕ = 0°, Γ = -5°) of approximately $\Delta C_L/C_D$ = 0.2 over all other configurations tested. From Figs. 2 and 4 (c), there seems to be little extra benefit in terms of increased aerodynamic efficiency with either increasing wing twist or sweeping forward the winglet, however additional rearward sweep (Fig. 3 (c)) does show nominal but discernable improvements in aerodynamic efficiency for most of the conditions included.

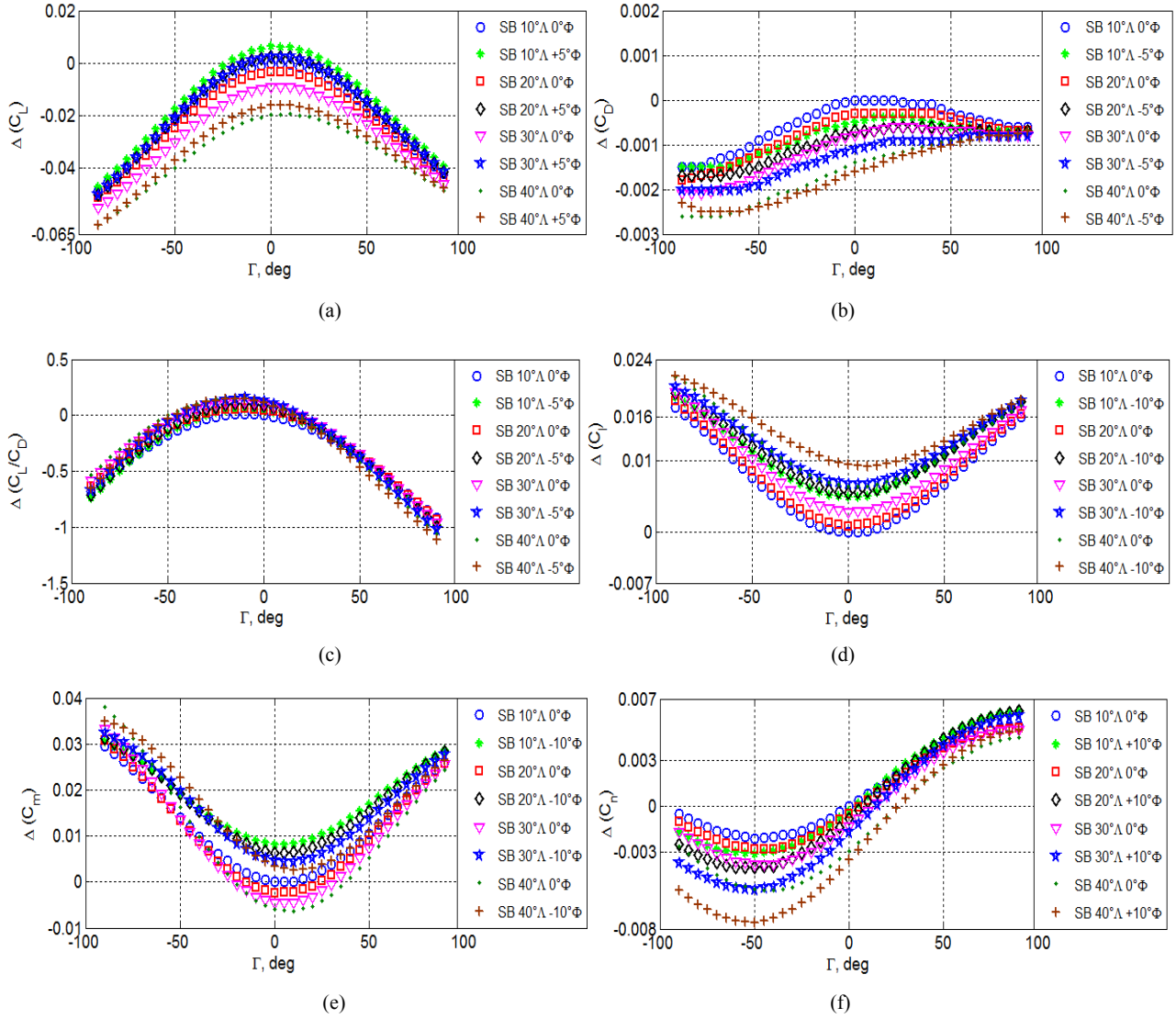

Fig. 3 Effects of changing winglet dihedral, sweep, and twist angle in sweep back winglet (SB) configuration at $C_{L_0} \cong 0.6$ (a)ΔC_L, (b)ΔC_D, (c) $\Delta C_L/C_D$, (d)ΔC_l, (e) ΔC_m , and (f)ΔC_n.

Interestingly, the asymmetric bias evident for both the changes in lift and drag coefficient with increasing or decreasing dihedral angle has switched to favouring positive dihedral for $\Delta C_L/C_D$ with the degree of asymmetry reducing as the winglet is swept more forward. Similar results were also presented in [11]; with small dihedral angles resulting in the production of the lowest lift-induced drag.

Figs. 2, 3, and 4 (e) highlight the influences of dihedral angle change on the change in pitching moment coefficient. As can be seen in these figures, nose up pitching moments were the predominant action on the wing/winglet configuration with change in dihedral angle either side of the planar case (Γ = 0°). However, for some cases presented for the normal and swept back configurations, additional negative pitching moments were found to exist with both, further increases in winglet twist (up to ϕ = 10° for the NW case), as well as at increased, untwisted, values of sweepback (Λ = 40). This would be expected as winglet twist added at the near planar case would increase the pitching down moment as the winglets in this configuration are more effective at producing lift behind the c.g. rotating the winglet from the near-planar case would therefore reduce this augmentation. Additional

sweep back, observed to produce a similar result, has a comparable flow dynamic through the movement of the aerodynamic centre forward with dihedral angle increase. It is this behaviour that has been put forward as a possible means for aircraft pitch control augmentation [7].

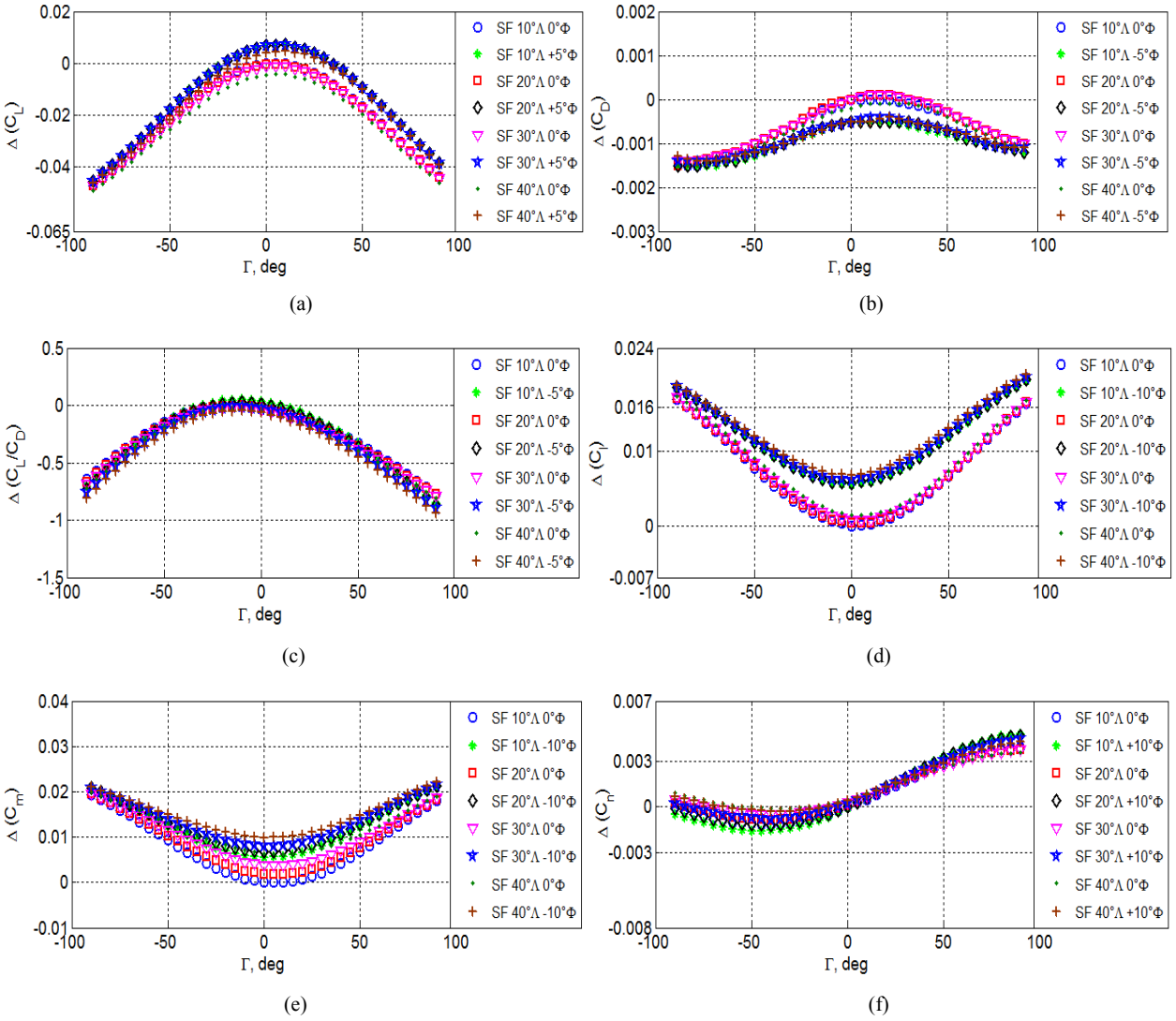

Fig. 4 Effects of changing winglet dihedral, sweep, and twist angle in sweep forward winglet (SF) configuration at $C_{L_0} \cong 0.6$ (a)ΔC_L, (b)ΔC_D, (c) $\Delta C_L/C_D$, (d)ΔC_l, (e) ΔC_m , and (f)ΔC_n.

It has been shown previously that increases in winglet dihedral angle away from the planar configuration can provide substantial roll authority suitable for aircraft roll control [7]. Figs. 2, 3, and 4 (d) illustrate the change in roll coefficient results for the three winglet configurations. As is shown in all of these figures, roll authority is significant with dihedral changes from Γ = +90° and Γ = -90°. Interestingly, for all three configurations, the maximum amount of roll coefficient change generated from dihedral angle movement is relatively invariant with either winglet sweep forward or back, however from Fig. 2 (d), for -40°<Γ<40°, large levels of winglet twist angle are seen produce the opposite effect on change in rolling moment coefficient with the production of a roll moment component acting to oppose the nominal winglet dihedral deflection dynamics outlined earlier for the normal winglet configuration. Overall, however, results using this control methodology do show in agreement with [7], [8] that comparable roll control moments relative to traditional aileron systems (ΔC_l=0.0152-0.0531 where $C_{L_0} \cong 0.6$) [12] can be produced. The dynamics of change in yawing moment coefficient with dihedral angle change also show similar characteristics for the three main test cases considered. For the normal and swept forward winglet cases, there is again very little perceptible difference in the maximum control forces generated with ΔC_n being significantly larger for Γ = 90° than Γ = -90°. Interestingly, for Γ < 0°, the production of effective

yawing moment change is much more varied than for Γ > 0°, with a maximum change generated at approximately Γ = 45-50° in agreement with previous studies. For the swept back case, (Fig. 3 (f)), values of change in yawing moment with winglet dihedral change were found to be markedly more scattered of an increased magnitude, particularly for Γ<0° when compared other test cases investigation. Clearly, adding winglet sweepback, particularly with additional winglet twist, increases generated yawing moment due to the further rearward displacement of the aerodynamic centre behind the c.g.

B. Effects of Changing Winglet Twist Angle on Aircraft Control and Performance

Overall, high winglet twist angle performed well as a mechanism for control, and at up to winglet twist angles of ϕ =±5°, comparable to good aerodynamic efficiency was achieved. With regards to ΔC_L, and as would be expected, positive twisted winglets provides good lift force production performance compared to negative twisted winglets, although, negatively twisted winglets to a small degree, do provide, in some cases, improved aerodynamic efficiency. As discussed already for ΔC_L and ΔC_D, winglet twist of ϕ = 10° has a different impact on lift and drag with positive and negative dihedral angle change. This conflicting result when combined was found to reduce efficiency. For some cases investigated, the overall lift characteristics could be reduced with negative twist and increased with positive twist angle. Quite distinct from the swept back and normal winglet configurations, winglet twist for the swept forward configuration was found to have a minor influence on various aerodynamic and control metrics with the most notable contributions occurring at small levels of winglet twist angle ϕ = ±5.

For the moment coefficient values, increasing winglet twist angle typically increases the degree of moments generated with maximum values occurring at maximum degrees of twist. Inducing additional winglet twist in the swept back and swept forward configurations has a similar influence as discussed for normal winglet configuration in terms of control with increasing twist angle up to ϕ = ±10° found to increase roll, pitch, and yaw moments. Overall, increasing winglet dihedral angle either side of the planar case, further increases the change in moment coefficient, however, the generation of maximum yawing moment coefficient does not occur at maximum winglet deflection, but at approximately -40° to -50 degrees from planar.

C. Effects of Changing Winglet Swept Angle on Aircraft Control and Aerodynamic Performance

For the most part, with respect to ΔC_L changing winglet sweep angle does have a detrimental effect on lift production with for the most part, a positive influence on drag with the highest $\Delta C_L/C_D$ found at Λ= 30° compare to other values of swept configurations. This is further supported by work done in [13] where different winglet sizes with different winglet sweep were investigated showing swept back winglets of approximately $\Lambda = 25°$, gave the highest C_L/C_D.

With forward swept winglets, change in lift coefficient was found be reasonably invariant; however at this condition, increases in lift production were found at low to moderate sweep angles. Unlike the sweptback winglet configuration, forward sweep was also found not to yield a significant increase C_L/C_D with typically, an overall reduction evident.

From the perspective of control moment production, swept-back configurations offer augmented control moment generation with increasing sweep angle. For pitching moment in particular, the basic mechanism of increased pitch-up moment via changing dihedral angle from the planar configuration is also amplified.

IV. Conclusion

An investigation of changing various winglet configuration parameters for augmented UAV control and performance has been investigated. Of the various winglet configurations investigated, selected cases do provide good evidence that adaptable winglets through morphing could provide benefits for small scale aircraft control and performance as well as offer an acceptable alternative aircraft control methodology to current discrete, 3-axis control philosophies.

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