JOURNAL OF AVIATION

e-ISSN: 2587-1676 J Aviat 2020; 4(1): 31-44

Research Article DOI : 10.30518/jav. 716194

Aerodynamic Analysis of Morphing Winglets for Improved Commercial Aircraft Performance

*Erdoğan KAYGAN[1]**

[1] School of Aviation, Girne American University, Kyrenia, PO Box 5, 99428, Cyprus

Abstract

This article describes the performance benefits of variable winglet configurations. The primary variables investigated involved varying the winglet twist and dihedral angle of a comparable Airbus A330-300 wing structure. Numerical studies have been carried out in AVL (Athena Vortex Lattice Method). In order to illustrate the aerodynamic benefits of morphing winglet concepts for different flight regimes, values of twist (-10°< θ <10°, in steps of ±2.5°) and values of dihedral (-90°< θ <90°, in steps of ±15°) were designed and numerically investigated. The results obtained from this work indicate that by carefully adjusting morphing winglets on air vehicles (Airbus A330-300), the aerodynamic performance benefits could be achieved.

Keywords: Aerodynamics, Aircraft, Drag, Morphing, Winglet

1. Introduction

NASA references morphing as 'efficient, multi-point adaptability' in the forthcoming aerial vehicles research [1]. The morphing aircraft is defined as a vehicle that changes configuration of its geometry during flight to adapt to different flight conditions [2]. In order to meet the ever increasing demand for more competent, robust and cost-effective designs, variable geometry concepts need to be revisited by engineers and/or designers. The variable geometry idea and/or original morphing aircraft effort comes from Wright Brothers' design. Wright Brothers did not have a conventional control surface at had a wing twist phenomena. Wing warping techniques were practically applied to control the first powered, heavier than air, aircraft through wing twist via subtended cables [3]. However, in today's aviation world, this technique is no longer available and replaced by conventional control surfaces which they provide substantial benefits for aircraft control (aileron for roll, elevator for pitch and rudder for yaw control). Lately, there is an argument that conventional wings with these traditional control surfaces do not provide the optimum solution for aircraft performance in all

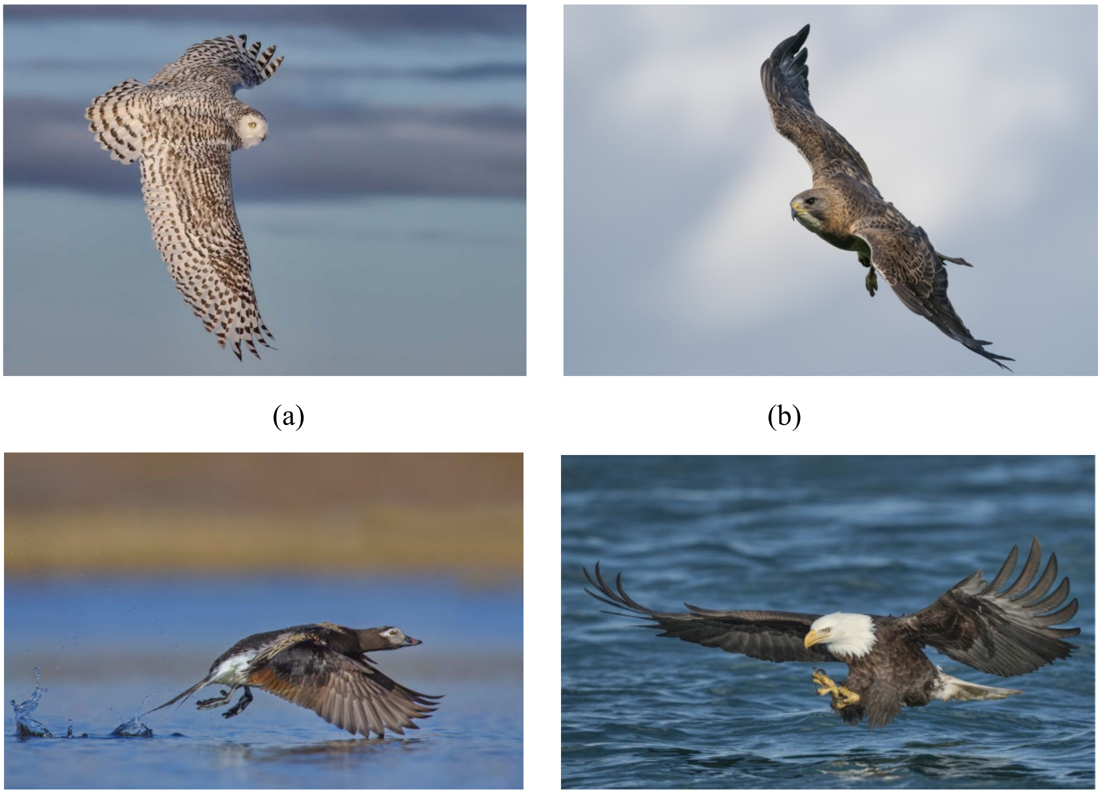
Corresponding Author: Dr Erdogan KAYGAN, erdogankaygan@gau.edu.tr
Citation: Kaygan E. (2020). Aerodynamic Analysis of Morphing Winglets for Improved Commercial Aircraft Performance J. Aviat. 4 (1), 31-44.
ORCID: [1] https://orcid.org/0000-0003-3319-3657
DOI: https://doi.org/10.30518/jav.716194
Received: 8 April 2020 **Accepted:** 7 June 2020 **Published (Online):** 22 June 2020

flight regimes as the lift requirements for aircraft can vary within a typical flight due to fuel burn.

Birds are another motivation for morphing aircraft. They are unique among flying animals in that they display an array of local changes in wing shape due to the deflection of the feather. The best known examples are indicated in Figure 1. It can be clearly seen that they alter their wing shapes to adapt different flight regimes such as take-off, landing, gliding, soaring, and so on [4]. With new results in bio-inspiration and recent advances in aerodynamics, controls, structures, and materials, researches finally converging upon the set of tools and technologies needed to realize the original dream of aircraft which are capable of smooth and continuous shape changing. After recent discoveries in bird flight mechanics, two significant and ambitious research programs that were to have far-reaching and productive effects on morphing aircraft appeared. In 1998, NASA's Morphing Aircraft Program aimed to investigate new shape changing morphing aircraft using adaptive materials, micro control devices, and also biologically inspired material technologies to enhance the manoeuvrability and aerodynamic performance of the aircraft [5]. The research program will continue to develop new aircraft structures using updated materials until 2030. Similar to NASA's Morphing Aircraft Program, DARPA's Morphing Aircraft Structure Program is currently engaged in large-scale coordinated efforts to develop morphing flight vehicles capable of drastic shape change in flight [6]. This program, which is sponsored by NextGen Aeronautics, Lockheed Martin and Raytheon Missile System, started in 2002. Following these programs, more and more researches also conducted to illustrate morphing applications and their benefits on aerodynamics and control of an aircraft. In this regard, a detailed description of past and current morphing aircraft concepts are well summarized by Barbarino et al. [7], and Weissahaar et al.[8]. According to their survey, various shape changing concepts were analysed and all pros and cons of morphing aerial vehicles were clearly expressed. Similarly, Ajaj et al. [9] succinctly mapped out the morphing applications by highlighting the latest research as well as presenting the historical connections of morphing aircraft. [10]

Prandtl's Lifting Line Theory was the first mathematical method to estimate the performance of a wing's lift capabilities for an aircraft [11]; being thereafter modified by Philips [12,13] to estimate the influences of wing twist on lift distribution. Following this seminal work, more studies have considered morphing wing and/or winglet twist configuration both theoretically and experimentally, to investigate influences on the aerodynamic performance of an aircraft. Recent work has detailed of wing twist systems using piezoelectric and pneumatic actuators [14–16]torque rods, adaptive stiffness structures[17], threaded rods [18], and shape memory alloys [19–21].The fishbone active camber wing concepts were introduced by Woods et al. [22]. The core of the Fish Bone Active Camber (FishBAC) concept is a compliant skeletal structure inspired by the anatomy of fish. Wind tunnel testing showed that using the FishBAC morphing structure remarkable increase in the lift-to-drag ratio of 20%–25% was achieved compared to the flapped airfoil over the range of angles of attack.

Similar to wing morphing concepts, the past surveys and investigations have shown that winglets and/or wingtip devices offer possible solutions to both reducing induced drag as well as improve the range and aerodynamic performance of an aircraft [23–28]. Also, many studies have found that winglets can provide up to a 6% reduction in CO_2 emissions and 8% reduction in NO_x emission. Although all winglets have different functionalities, they are all intended improve aerodynamic performance and for that matter wingtip devices. The first major breakthrough was introduced by Whitcomb [29]. Likewise, NASA provided good evidence for the efficiency of winglet devices between 1974 and 1976 [30]. They assessed different drag reducing devices and wingtip devices with results showing winglets can improve aircraft efficiency by 10-15% during cruise. Later on most of the commercial long range aircraft has installed winglet to decrease the induce drag to save more



(a) (b) (c) (d)

Figure 1. Birds' wingtip feathers. (A) Snowy Owl; (B) Swainson's Hawk; (C) Long-Tailed Duck; (D) Bald Eagle. Images courtesy of Ad Wilson (www.naturespicsonline.com) and Rob McKay(http://robmckayphotography.com) [4].

fuel. It is clear that winglets have a beneficial impact on the aerodynamic efficiency of an aircraft during cruise. Unfortunately, fixed position winglets do not provide the optimum solution for aircraft performance in all flight regimes as the lift requirements for aircraft change due to fuel burn. Recent studies have started to investigate possible ways of alleviating this fixed condition through incorporating methods with morphing technology to actively optimize the winglet position under different flight conditions. A novel method of controlling aircraft via adaptable winglet concepts was investigated by several researches. Bourdin et al. [31, 32] and Alvin et al. [33] investigated the adjustable cant angled winglets to increase aerodynamic performance and control of a flying wing aerial vehicles. The concept consists of a pair of winglets with an adjustable cant angle, independently actuated and mounted at the tips of a baseline flying wing. Multi-functional winglets were also investigated numerically and experimentally by Kaygan et al.[34][35]. Recently, active winglet twist concepts investigated by Kaygan et al.[36, 37]. Novel design concepts with multiple morphing elements were utilised and the results illustrate the concept is superior to more conventional methods under designated test conditions such as ϕ=-6° with both sufficient compliance in twist, adequate resistance to aerodynamic bending, and minimal surface distortion all demonstrated successfully in flight [38]. Although substantial improvement has been achieved in morphing wing and/or winglet concepts, the biggest challenging faced in morphing structure is the morphing skin, which has to be flexible for actuation, but also rigid to allow favourable aerodynamic performance to be obtained. Some prior literature on morphing skins, involve variety of structures and materials [39] however none have yet to achieve widespread use. This problem is particularly difficult as there are conflicting requirements.

The goal of the current study is to investigate the aerodynamic characteristics of morphing winglets for improved commercial aircraft performance. The major variables investigated involved changing the winglet twist and dihedral angle of a comparable Airbus A330-300 wing model by assigning the ideal angle of twist and dihedral, hence the rest of this paper will express the numerical analysis of selected twist and dihedral cases.

2. Design and Methodology

2.1 Wing Geometry

The wing model used for this study is shown in Figure 2 and Figure 3. It can be seen that swept wing configuration has been investigated which is a comparable wing structure with Airbus A330-300. Comparing with A330-300 original wing structure, swept wing model has an uniform trailing edge angle [40]. NACA 2415 airfoil profile was chosen for wing structure (as indicated in Figure 3 (e), which is an asymmetrical airfoil that allows the aircraft to have more lift and less drag coefficient [41]), Λ=30° leading edge sweep angle, 60.30m wingspan, 10.56m root chord, 2.51m tip chord, with aspect and tip ratios of 9.6 and 0.24 respectively as indicated in Figure 6 . To measure aerodynamic benefits of a variable winglet concept, values of twist (-10°< θ <10°, in steps of ±2.5°) and values of dihedral (-90°< θ <90°, in steps of ±15°) were designed and numerically analysed.

2.2 Aerodynamic Model and Numerical Method

To calculate the aerodynamic properties of the various wing configurations, Athena Vortex Lattice (AVL) software is used which was originally coded by Harold Younger and further developed by Mark Drela [42]. Athena Vortex Lattice is a mathematical simulation package that determines the solutions to a linear aerodynamic flow model. The flow is incompressible and inviscid (aerodynamic wing structure is shown in Figure 3 (a) and Figure 5). The variation in lift can be modelled as a step change from one panel to other. The control points are placed at

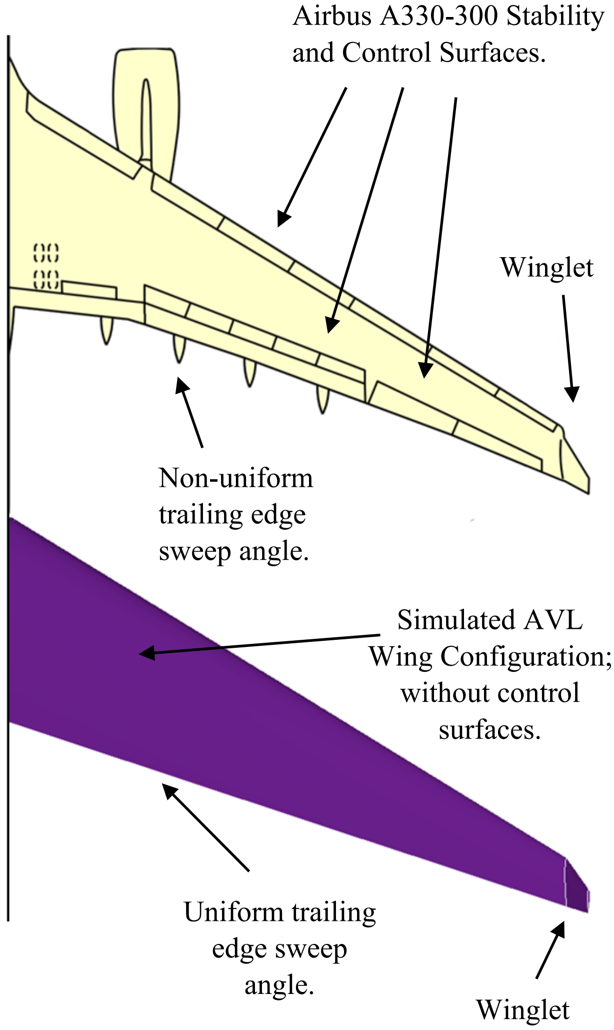


Figure 2. Airbus A330-300 Swept Wing Structure [40] and AVL Swept Wing Model.

3/4 chord for each panel at the midpoint position in the span-wise direction to achieve the required vortex strength by applying the flow tangency condition. Then, the Biot-Savart law was applied to solve the linear equations for the selected panel in three component vortex lines. One of the selected panel models is shown in Figure 4. For each panel, the same processes are followed to obtain the total vortex strength I_i.

The velocity at the control point of the panel is calculated by solving the formulas shown in Equation (1). R_1 and R_2 are the magnitude vectors

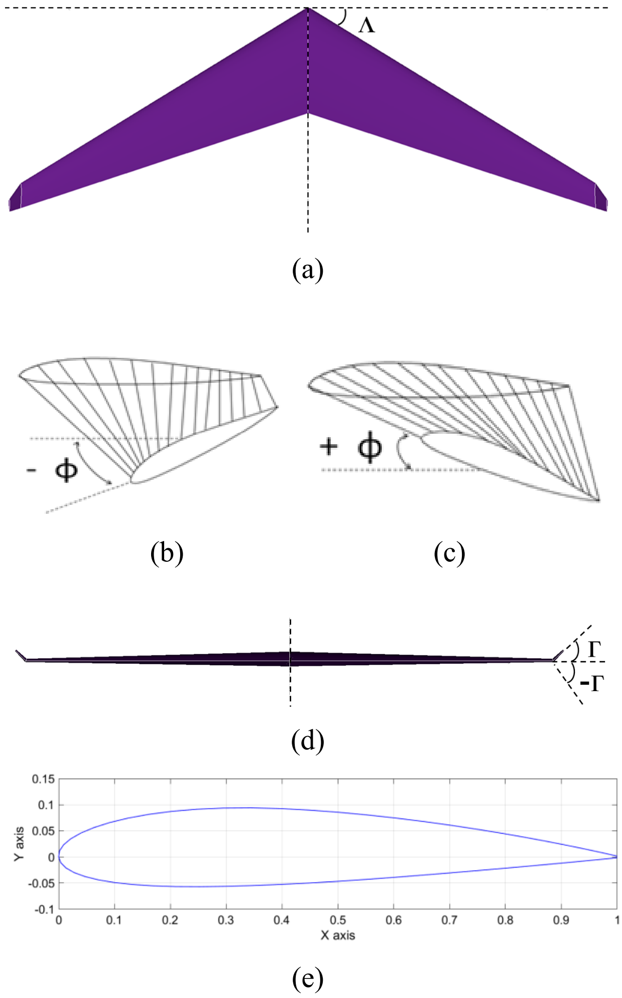


Figure 3. Computational Wing and Winglet Model: (a) AVL Aerodynamic Wing Structure, (b) Wash-in(positive twist) angle, (c) Wash-out(negative twist) angle, (d) Dihedral angle and (e) NACA 2415 Airfoil structure.

of r_1 and r_2 respectively (Equation (2)). The influenced matrix is created to solve the required vortex filament strength by multiplying the vortex strength vector and the free stream velocities as illustrated in Equation (3). (Where A is a non-linear function of a matrix depending on the wing shape, b is a vector that can be changed by varying the angle of attack and $U_\infty$is the given frestream velocity) [43].

$$w = \frac{I}{4\pi}\frac{r_1 \times r_2}{|r_1 \times r_2|}\left[r_0 \cdot \left(\frac{r_1}{r_1} - \frac{r_2}{r_2}\right)\right] \qquad (1)$$

$$R_1 = \sqrt{(x+h)^2 + (y+k)^2}$$
and
$$R_2 = \sqrt{(x-h)^2 + (y-k)^2} \qquad (2)$$

$$\mathrm{A\,I} = U_\infty\,\mathrm{b} \qquad (3)$$

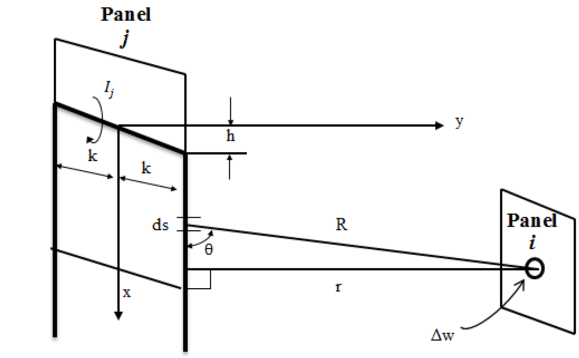


Figure 4. Selected panel in three component vortex lines for Vortex Filament Strength

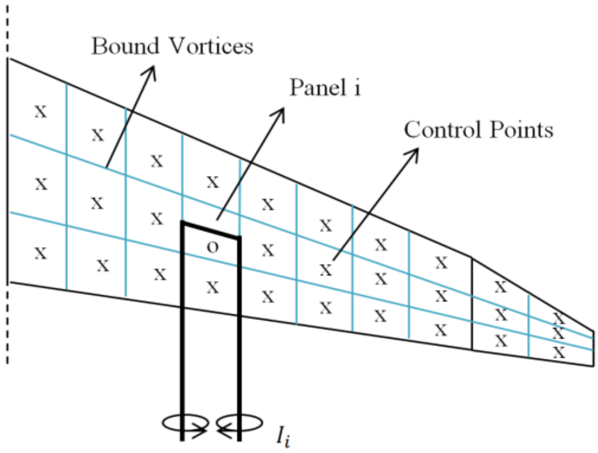


Figure 5. Computational Model of a Swept Wing Structure.

In order to compute the shape changing geometry such as the twist, sweep and dihedral angle, the relevant aerodynamic panel grids are deflected. This modelling method provides efficient and adequate solutions for the quick determination of the aerodynamic performance of the model being analysed. The vortex strength of the plane is determined by summing the multiplied vortex strength and rotation rates, as well as the velocities through following:

$$I = uI_u + vI_v + wI_w + pI_p + qI_q + rI_r + \delta_e I_{\delta_e} \qquad (4)$$

After solving the vortex strength of each panel, the Kutta-Joukowsky Law [44] is applied to obtain the force and moments on each panel over all of the bound vortex segments (Equation (5)).

$$dF = \rho U_\infty \times I\,dl \qquad (5)$$

The lift force is obtained thereafter by integrating the panel lift distribution. The lift coefficient for a wing can then be calculated using Equation (6).

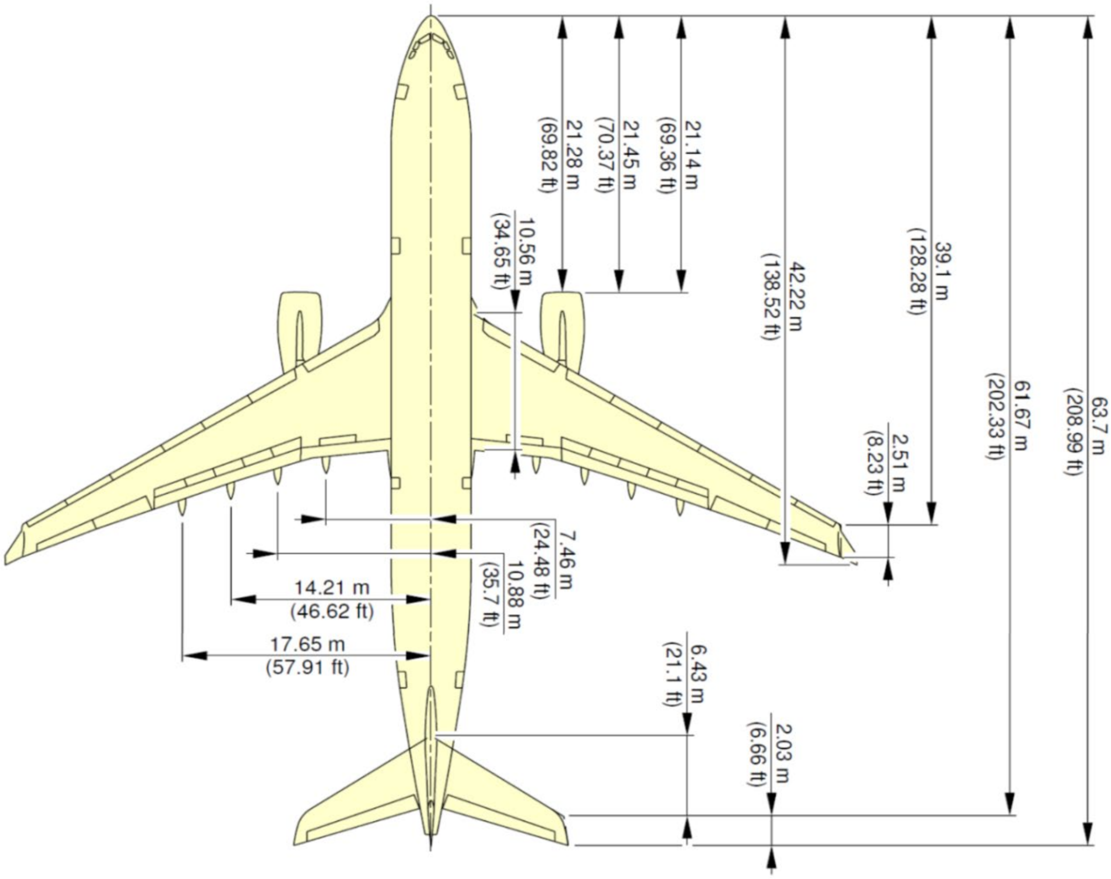


Figure 6. Airbus A330-300 Aircraft Structure [40].

$$C_L = \frac{L}{\frac{1}{2}\,\rho\,V^2\,S} \tag{6}$$

Once the wing loading of the structure had been calculated, the variation between the flow angle and freestream velocity for each panel can be obtained. To determine drag force, each panel's lift vector is rotated backwards relative to the freestream direction and integrated as follows:

$$dF = \rho U_\infty \times I\,dl\,sin(\alpha) \tag{7}$$

with the drag coefficient being calculated as;

$$C_D = \frac{D}{\frac{1}{2}\,\rho\,V^2\,S} \tag{8}$$

(Where dF is a force acting on an infinitesimal vortex segment, ρ is an air density, I is a displacement vector along an infinitesimal vortex segment, dl is a displacement vector along an infinitesimal vortex segment and U_∞ and V are the given freestream velocity, C_D is the drag coefficient and C_L is the lift coefficient).

The free-stream velocity chosen for this investigation was 30 m/s and all results were computed without the influence of compressibility. Panel sensitivity analyses were performed on the baseline configuration prior to the widespread use of the developed model. Generally, this study involved observing the force and/or coefficient values for numerous diverse panel densities. Following this activity, all calculations were thereafter based on 80 horseshoe vortices along the wing chord, and 140 along the semi-span of the baseline wing. Additionally, the wing was scaled down to 1/10 for ease of analysis.

3. Results and Discussion

3.1 Effects of Changing Winglet Twist and Dihedral angle on Lift and Drag Coefficients

The change in static coefficients obtained from winglet deflection between -10° ≤ ϕ ≥ +10° and -90°

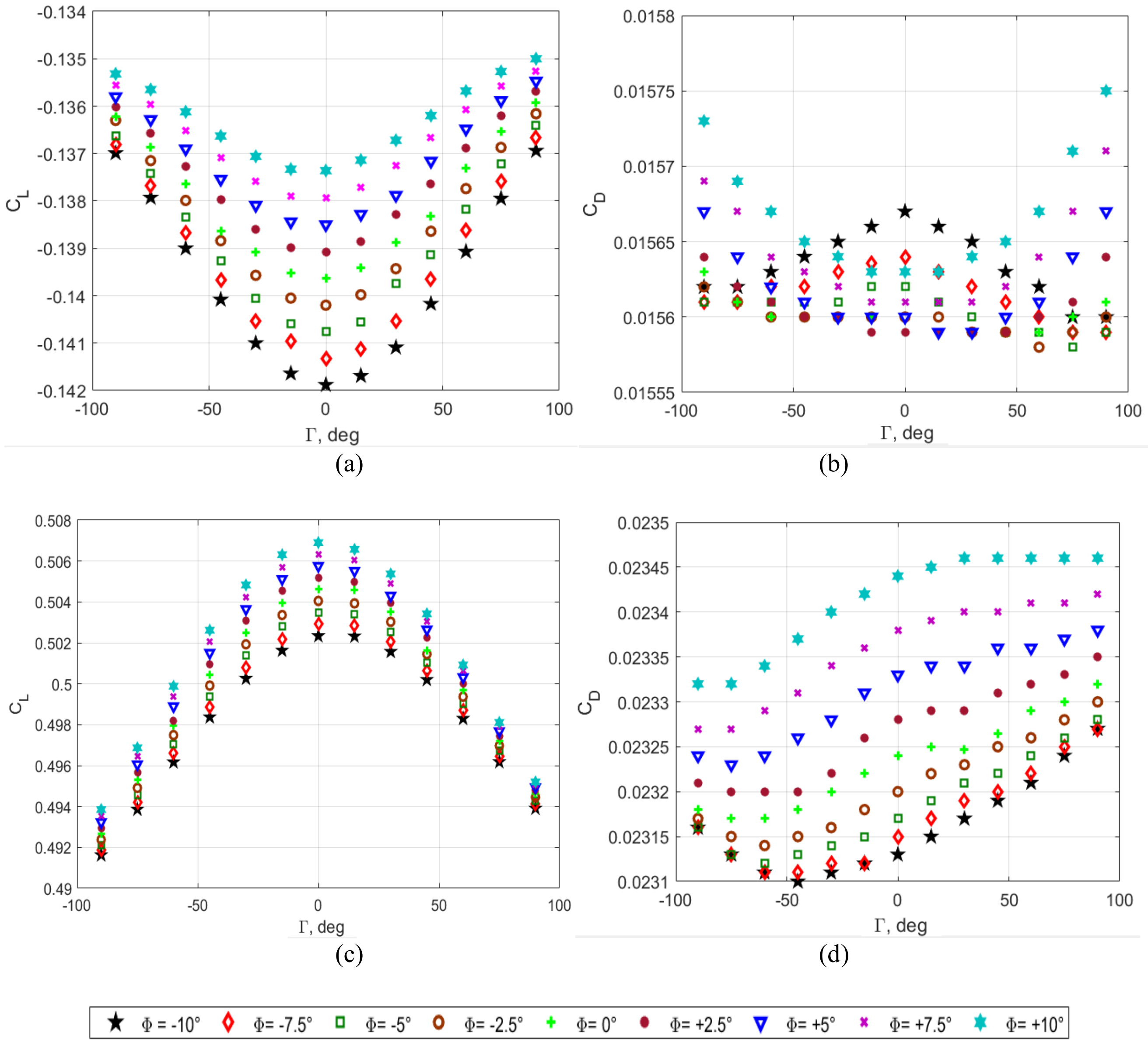


Figure 7. Effects of changing wing twist and dihedral angle: (a) Lift Coefficient (C_L) at α=-4° and (b) Drag Coefficient (C_D) at α=-4° (c) Lift Coefficient (C_L) at α=4° and (d) Drag Coefficient (C_D) at α=4°.

≤ Γ ≥ +90° are shown in Figure 7 and Figure 8. In order to dictate lift and drag coefficient results, both sides of the winglets were twisted and also winglets dihedral angles were changed. Figure 7 (a) and (c) illustrates the lift coefficient results at α=-4° and α=4° for different twisted and cant angled winglet configurations. It can be seen clearly that changing the twist angle of the winglet producing a corresponding increase and decrease in lift coefficient and maximum lift attained at ϕ= +10° and minimum lift value obtained at ϕ = -10°. As can be seen from Figure 7(b), at α = 4° where small incident angles are concerned, approximately 0.8% and 1.5% small improvement seen for ϕ = +10° compared to ϕ = 0° (Airbus A-330 winglet) and ϕ = -10° respectively. Increasing angle of attack to further, the lift capabilities of an aircraft constantly increases as expected. In Figure 8 (c), results seem to be enhanced further and comparing this pattern with other twist cases presented, similar results were obtained (at ϕ = +10°, 1.2% and 1.7% improvement compared to ϕ = 0° and ϕ = -10° respectively). This would be expected due to both net reductions in an effective angle of attack as the wingtip moves out of the wing plane and contribution to overall lift production reduces [45]. Similar results were also found in [46] [36] where experimental results present greater C_L for higher positive twist angles. control using winglet deflection as agreement with [36].

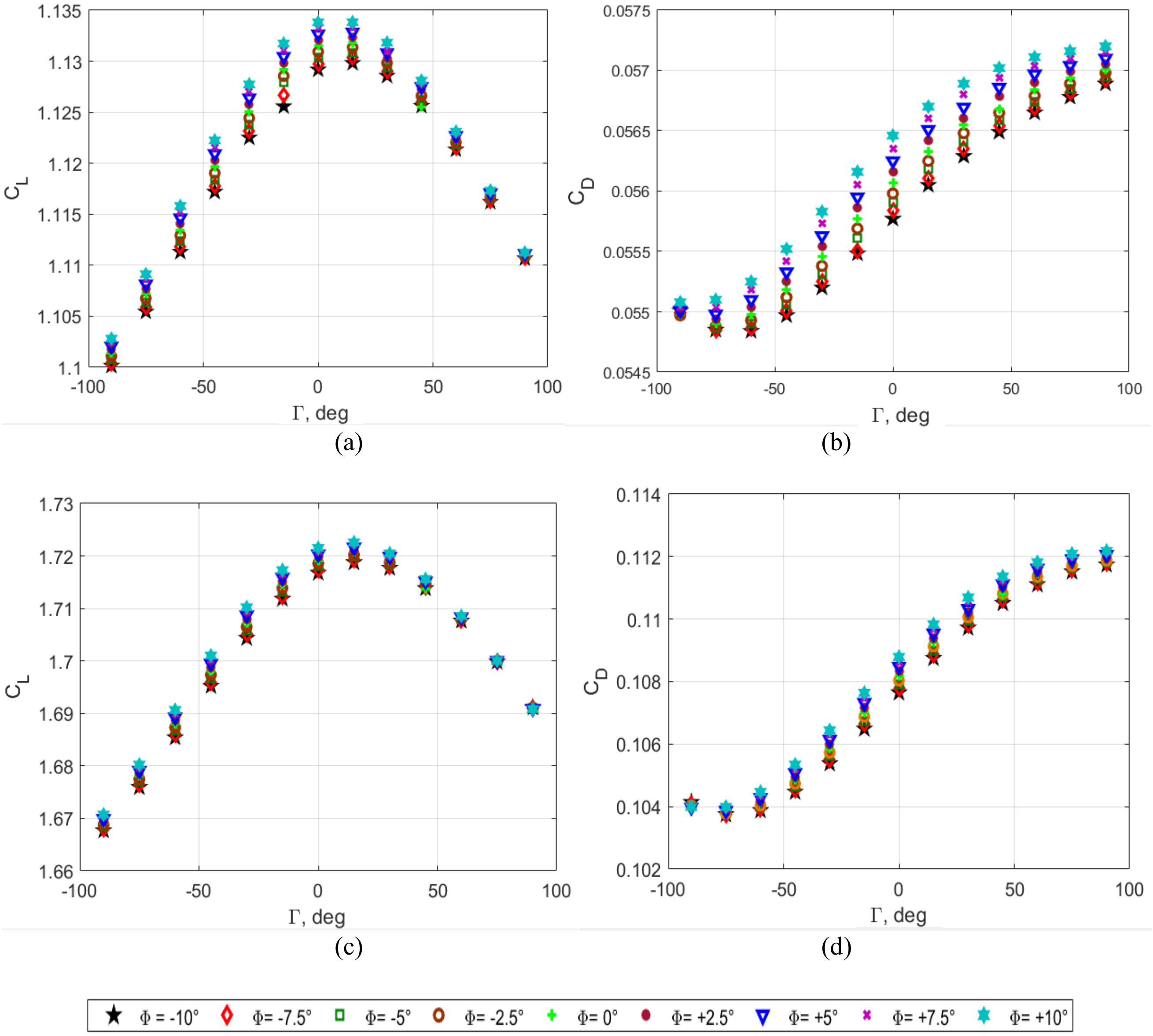


Figure 8. Effects of changing wing twist and dihedral angle: (a) Lift Coefficient (C_L) at α=12º and (b) Drag Coefficient (C_D) at α=12º (c) Lift Coefficient (C_L) at α=20º and (d) Drag Coefficient (C_D) at α=20º

Opposing that increasing the winglet dihedral angle does have a detrimental effect on lift production. It can be seen from Figure 7 (a) and (c) and Figure 8 (a) and (b), cant angle at 0° generates the highest lift coefficient compare to other dihedral angles are concerned. Comparing Γ=0° with Γ=-90° and Γ=90°, 4% and %3 improvement was achieved respectively. Similar results have also illustrated in [47] where increasing winglet dihedral angle reduces lift capabilities of an aircraft. This indication would be a good reference for aircraft

Combining both dihedral and twist configuration in together, aircraft lift curve was found to be substantial in some cases presented in Figure 7 and Figure 8. With ϕ =+10° and Γ= 0°-15°, the maximum lift value was obtained. Comparing this results with ϕ =-10°, Γ= -90° and ϕ =0° and Γ= 45° (original A330-300 winglet configuration) there are 4% and 1.5% improvement (as seen in Figure 8) respectively. Similar result patterns were also seen for other angles of attack. In overall, computational results showed that there is a greater improvement in lift coefficient when wings are positioned at ϕ =+10° and Γ= 0°, consequently this would be dihedral angles indicate the highest drag profile because increased winglet's angle of attack with a

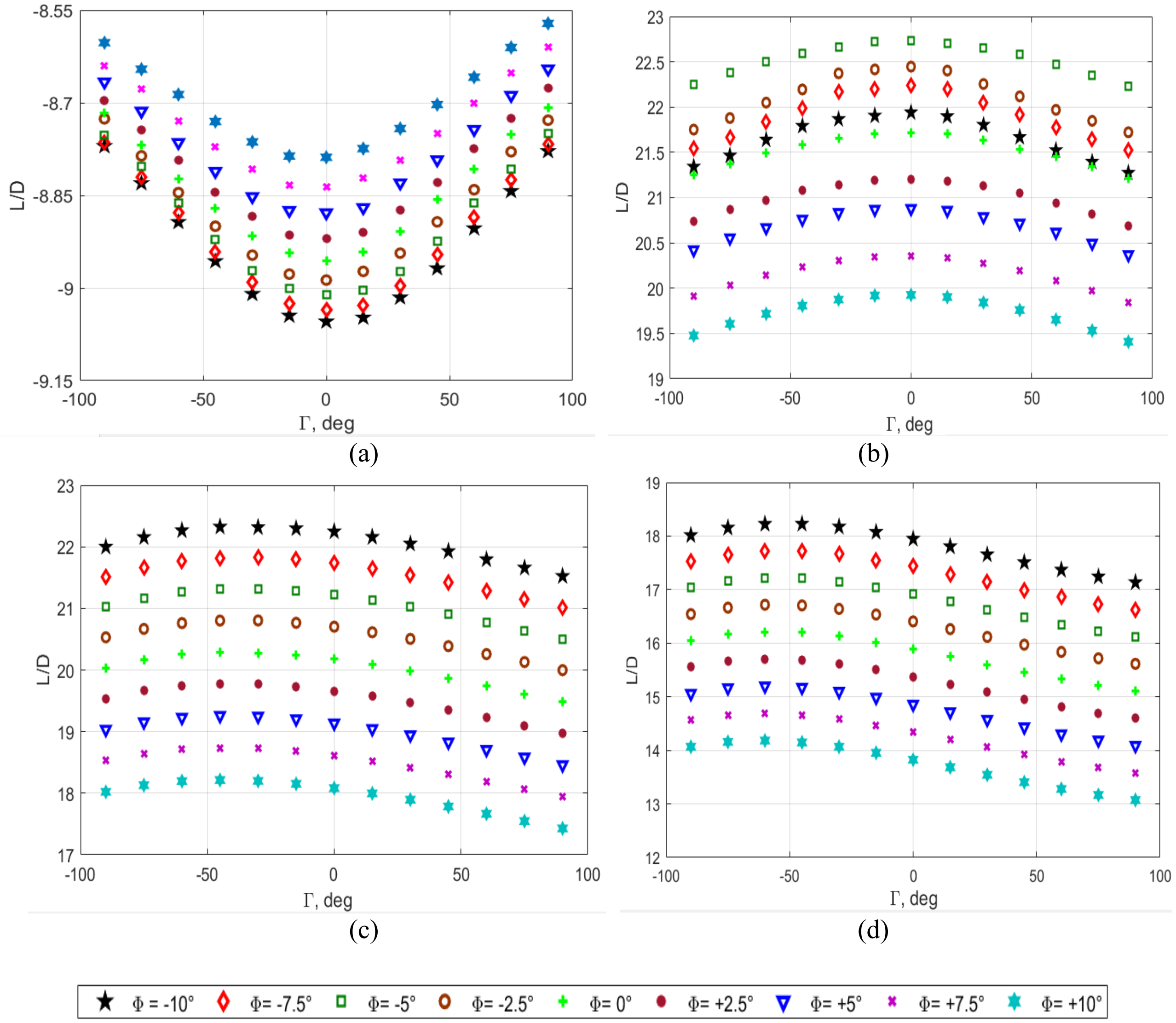


Figure 9. Effects of changing wing twist and dihedral angle: (a) Lift to Drag Ratio (L/D) at α=-4° and (b) Lift to Drag Ratio (L/D) at α=4° (c) Lift to Drag Ratio (L/D) at α=12° and (d) Lift to Drag Ratio (L/D) at α=20°.

assigned as an alternative lift production case while taking off and landing conditions of an air vehicle are considered. In addition, in agreement with [34], there is also a tendency of asymmetrical lift production between positive and negative both twist and dihedral angles due to the use of an unsymmetrical airfoil profile. This result seems to be more favour for winglet Γ > 0°.

Results for drag coefficients (see Figure 7(b) and (d) and Figure 8(b) and (d)) also illustrate significant changes with wing twist and dihedral angle change. As a whole, it can be seen that at positive winglet twist and greater winglet positive positive twist tends to increase the drag polar. The variation of drag coefficients C_D versus dissimilar twist and dihedral angles at α=4° are shown in Figure 7(d). As far as twist configurations are considered, it can be clearly seen that at ϕ =+10° the drag increase was found 1.3% and 2.4% comparing to ϕ =0° and ϕ =-10° respectively. At α=12°, for the curves of the morphing winglet indicates the value of C_D increased further, and the pattern seems to be very similar to other cases presented. However, drag variation between each twist configuration at the highest angle of attack(α=20°) was found to be reduced slightly but still shows similar drag curve (at ϕ =+10° the drag increase was found 1.2% and 1.9% comparing to ϕ =0° and ϕ =-10° respectively). Proof of this can be found in the significant number of studies available in the current literature showing increased downwash angle tends to raise drag coefficient results dramatically[34][35][26].

When dihedral features are also concerned minimum drag profile seems to exist for Γ= 60°. In general, there is a linear drag reduction from Γ= 60° to Γ= -45°. Minimum drag value obtained at Γ= -45° at α=4º for negative twist winglet (washout) configuration. As increasing angle of attack to further, this behaviours changed and it can be seen from Figure 8 (b) and (d), minimum drag result was shifted to Γ= -60° and Γ= -75°. When added twist movements are also considered, significant results experienced. Looking at ϕ =-10° and Γ= -45°, the drag reduction observed 1.4% and 2.1% comparing to ϕ=0° and Γ=45° (Airbus A330-300 winglet configuration) and ϕ =+10° and Γ= 90° (Airbus A330-300 winglet configuration) at α=4° respectively.

As can be seen from Figure 8 (b), drag curve shows increment with α growth to 12º and 20º. At ϕ =-10° and Γ= -60° the drag reduction was found 4.2% and 5.3% contrary to ϕ =0° and Γ= 45° (Airbus A330-300 winglet configuration) and ϕ =+10° and Γ= 90° respectively. This would later allow morphing winglets to improve an aerodynamic performance of an aircraft. As is well-known that drag reduction plays a noteworthy role to dictate how much fuel spent during the flight. According to NASA Dryden investigations, even a 1% reduction in drag would save the wide-body commercial aircraft $140 million/year, at a fuel cost of $0.70/gal[48].

3.2 Effects of Changing Winglet Twist and Dihedral angle on Aerodynamic Performance of an Aircraft

The lift to drag ratio is the ratio of the amount of lift to drag produced from an aerofoil and is a direct measure of aerodynamic efficiency. Figure 7 and Figure 8 illustrate lift and drag results for various winglet configurations. The information achieved from these two graphs permitted the construction of a graph measuring L/D ratio as shown in Figure 9. The graph depicts that winglets in some configuration have a positive impact on aerodynamic performance of an aircraft. This attribute makes the variable winglet technology suitable for an aircraft to perform multi-mission tasks in which the requirements on the flight speed and the range/endurance are diverse. At α=4°, the best aerodynamic efficiency (L/D) was obtained for ϕ= -5° and Γ=0° (see Figure 9 (b)). Comparing this configuration with original Airbus A330-300 winglet structure (ϕ =0° and Γ= 45°), ϕ =-2.5° Γ= 0°, and ϕ =+10° Γ= 90°, 1.4% 2% and 15% improvement was achieved respectively.

As increasing angle of attack to 12° (see Figure 9 (c)) results seem to be slightly changed. Overall, the magnitudes of L/D are decreased slightly for all configurations. This would be expected due to increasing angle of attack have a tendency to increase the drag coefficient results (as seen in Figure 8(b)) distinctly, hence it causes to diminish an aerodynamic performance of an aircraft. The maximum lift to drag ratio was observed for ϕ= -10° and Γ=-45°.Comparing this configuration with ϕ= -7.5° and Γ=-45°, ϕ= 0° and Γ=4° and ϕ= +10° and Γ=90°, 4%, 13% and 24% improvement was seen respectively which shows that when morphing winglets positioned to ϕ= -10° and Γ=-45° will have the optimum performance in climb. Figure 9 (d) shows L/D ratio for all configurations at α=20°. According to data, it can be seen that, in overall, values are marginally reduced and the highest performance was obtained at Γ=-45° and ϕ= 0°. Approximately 17% and 29% improvement was attained compare to ϕ= 0° and Γ=45° (A330-300 winglet configuration) and ϕ= +10° and Γ=90° respectively. Consequently, the use of the variable winglet concept enhances the aerodynamic performance of the Airbus A-330 by increasing its lift to drag ratio at low angles of attack, which is useful to increase the maximum range or endurance of an aircraft in cruise where the most of fuel is spending, in agreement with [49].

3.3 Morphing Winglet Adaptability for Flight Regimes

It is clear that various winglet configurations indicated different aerodynamic properties which were expressed in Section 3.1 and 3.2. Hereafter, figure 10 sufficiently demonstrates the morphing winglet applications for 6 different flight regimes. increasing winglet dihedral angle to maximum will increase the root bending

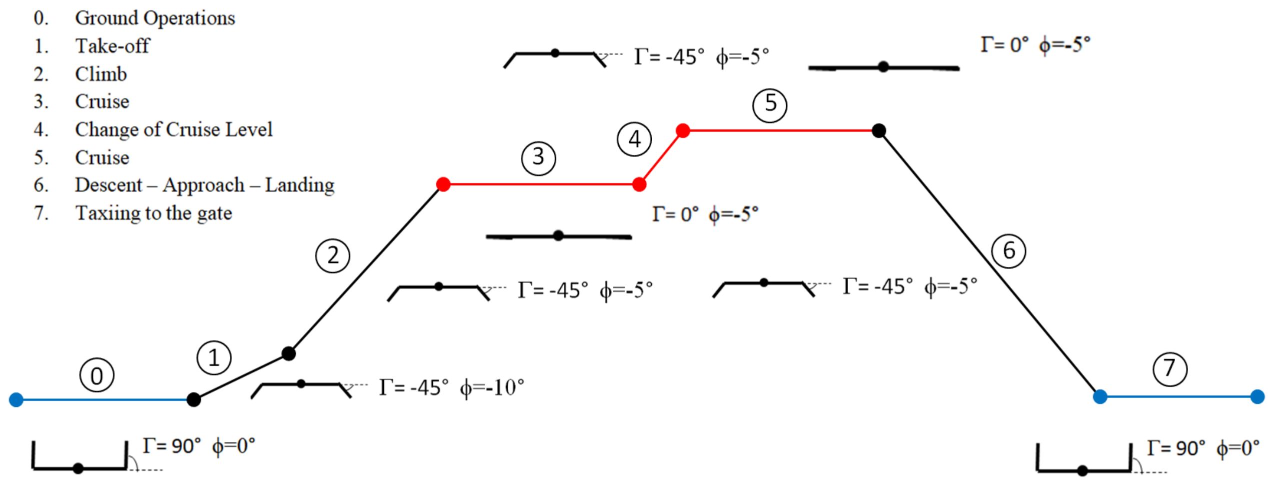


Figure 10. Morphing Winglet Adjustments for Various Flight Conditions.

The recommended winglet configurations were selected in a base of the enhancements in the aerodynamic performance of an aerial vehicle. Totally six flight profiles were suggested to utilize as agreement with [50] and according to results:

- During the movement of an aircraft on the ground, it is recommended to use winglet dihedral angle as high as possible to reduce wingspan of a wing, hence ϕ= 0° and Γ=90° winglet configuration can be used.
- When aircraft move to take-off stage, ϕ= -10° and Γ=-45° winglet configuration can be used. Furthermore, ϕ= -10° and Γ=-60° and/or ϕ= -7.5° and Γ=-60° winglet configurations are also be used which performs higher lift slope with low drag profile. In addition, at the beginning of the climb phase airplane can set the winglet position to ϕ= -5° and Γ=-45° or ϕ= -10° and Γ=-30°. This was taken due to the highest lift to drag ratio at high angle of attack.
- At cruise level where the most of fuel is spending, in agreement with [49], ϕ= -5° and Γ=0° winglets can be used. Alternatively, ϕ= -2.5° and Γ=0° can also be used due to low drag value. These configurations sometimes can be changed due to weather conditions, weights and other requirements. Furthermore, moments which can cause adverse effects for aircraft structure.
- At phase 4, when changing the cruise level ϕ= -5° and Γ=45° winglet settings can be adjusted due to high lift slope with less drag force. Moreover, ϕ= 0° and Γ=90° is also acceptable.
- Descents are an essential component of an approach to landing. At this stage (6), it is suggested to use ϕ= -5° and Γ=-45° winglet configuration.
- After landing, similar to phase 0, winglet with the highest degree of dihedral can be used (hence ϕ= 0° and Γ=90°). This allows aircraft to reduce wingspan (size) to fit regular gates.

4. Conclusion

Morphing winglet concept has been computationally examined in this paper. The concept consists of numerous twist (-10° ≤ ϕ ≥ +10°) and dihedral (-90° ≤ Γ ≥ +90°) winglet configurations. To illustrate performance benefits for all flight regimes, models are carefully analysed for each flight phase requirements. Besides that results are compared with A330-300 Wing and winglet configuration. According to the concept aforementioned (see Section 3), different dihedral and twist angles provide substantial improvements for an aircraft. Proposed concept appears to be a possible way to optimize flight performance for each flight conditions such as take-off, climb, cruise, descent and landing. Furthermore, the concepts also showed potential aerodynamic performance benefits at (the highest ratio (L/D) obtained when winglets positioned) ϕ= -5° and Γ=0° compare to Airbus A330-300 conventional wing configuration (ϕ=0° and Γ=45°).

Nomenclature

A = Non-linear function of a matrix
b = Variable vector
C_D = Drag coefficient
C_L = Lift coefficient
$^{L}/_{D}$ = Lift to Drag Ratio
c = Wing chord
i = Selected wing panel
I_i = Total vortex strength
L/D = Lift to Drag ratio
R_1 and R_2= Magnitude Vector
U_∞ = Freestream velocity
α = Angle of Attack
ϕ = Twist Angle
Λ = Sweep Angle
Γ = Dihedral or Can't Angle

References

[1] A. R. et al McGowan, "Recent Results from NASA's Morphing Project," in *9th International Symposium on Smart Structure and Materials*, 2002, p. SPIE PaperNo.4698-11.

[2] T. a. Weisshaar, "Morphing Aircraft Systems: Historical Perspectives and Future Challenges," *J. Aircr.*, vol. 50, no. 2, pp. 337–353, 2013.

[3] D. McRuer and D. Graham, "Flight Control Century: Triumphs of the Systems Approach," *J. Guid. Control. Dyn.*, vol. 27, no. 2, pp. 161–173, 2004.

[4] E. Wilson, "Nature photography," *Nature*, vol. 82, no. 2100, pp. 371–372, 1910.

[5] NASA, "21st Century Aerospace Vehicle, Morphing Airplane." .

[6] T. G. Ivanco, R. C. Scott, M. H. Love, S. Zink, and T. a. Weisshaar, "Validation of the Lockheed Martin morphing concept with wind tunnel testing," vol. 23, p. 26, 2007.

[7] S. Barbarino, O. Bilgen, R. M. Ajaj, M. I. Friswell, and D. J. Inman, "A Review of Morphing Aircraft," *J. Intell. Mater. Syst. Struct.*, vol. 22, no. 9, pp. 823–877, Aug. 2011.

[8] T. A. Weisshaar and T. H. E. M. Challenge, "Morphing Aircraft Technology – New Shapes for Aircraft Design," 2006.

[9] R. M. Ajaj, C. S. Beaverstock, and M. I. Friswell, "Morphing aircraft: The need for a new design philosophy," *Aerosp. Sci. Technol.*, vol. 49, no. December 2017, pp. 154–166, 2015.

[10] E. Kaygan and C. Ulusoy, "Effectiveness of Twist Morphing Wing on Aerodynamic Performance and Control of an Aircraft," vol. 2, no. 2, pp. 77–86, 2018.

[11] L. Prandtl, "Application of Modern Hydrodynamics to Aeronautics," *Naca*, vol. 116, no. 116. 1923.

[12] W. F. Phillips, N. R. Alley, and W. D. Goodrich, "Lifting-Line Analysis of Roll Control and Variable Twist," *J. Aircr.*, vol. 41, no. 5, pp. 1169–1176, 2004.

[13] W. F. Phillips, S. R. Fugal, and R. E. Spall, "Minimizing Induced Drag with Wing Twist, Computational-Fluid-Dynamics Validation," *J. Aircr.*, vol. 43, no. 2, pp. 437–444, 2006.

[14] D. Sahoo and C. Cesnik, "Roll maneuver control of UCAV wing using anisotropic piezoelectric actuators," *43rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf.*, no. April, pp. 1–11, 2002.

[15] D. A. N. Iii, D. J. Inman, and C. Woolsey, "Design , Development , and Analysis of a Morphing Aircraft Model for Wind Tunnel Experimentation by Design , Development , and Analysis of a Morphing Aircraft Model for Wind Tunnel Experimentation," 2006.

[16] H. Garcia, M. Abdulrahim, and R. Lind, "Roll Control for a Micro Air Vehicle Using Active Wing Morphing," in *AIAA Guidance, Navigation and Control Conference (Austin, TX)*, 2003, pp. 1–12.

[17] M. Majji, "Design of a Morphing Wing : Modeling and Experiments," *Am. Inst. Aeronaut. Astronaut.*, p. 9, 2008.

[18] R. Vos, Z. Gurdal, and M. Abdalla, "Mechanism for Warp-Controlled Twist of a Morphing Wing," *J. Aircr.*, vol. 47, no. 2, pp. 450–457, Mar. 2010.

[19] H. Lv, J. Leng, and S. Du, "A Survey of Adaptive Materials and Structures Research in China," in *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2009, no. May, pp. 1–8.

[20] Y. N. Sofla, D. M. Elzey, and H. N. G. Wadley, "Two-way Antagonistic Shape Actuation Based on the One-way Shape Memory Effect," *J. Intell. Mater. Syst. Struct.*, vol. 19, no. 9, pp. 1017–1027, 2008.

[21] D. M. Elzey, A. Y. N. Sofla, and H. N. G. Wadley, "A bio-inspired, high-authority actuator for shape morphing structures," *Proc. SPIE*, vol. 5053, pp. 92–100, 2003.

[22] B. K. Woods, O. Bilgen, and M. I. Friswell, "Wind tunnel testing of the fish bone active camber morphing concept," *J. Intell. Mater. Syst. Struct.*, vol. 25, no. 7, pp. 772–785, Feb. 2014.

[23] R. Eppler, "Induced drag and winglets," *Aerosp. Sci. Technol.*, vol. 1, no. 1, pp. 3–15, 1997.

[24] J. Guerrero, M. Sanguineti, and K. Wittkowski, "CFD Study of the Impact of Variable Cant Angle Winglets on Total Drag Reduction," 2018.

[25] N. M. Ursache, T. Melin, A. T. Isikveren, and M. I. Friswell, "Morphing Winglets for Aircraft Multi-phase Improvement," *7th AIAA Aviat. Technol. Integr. Oper. Conf. ATIO May*, no. September, pp. 18–20, 2007.

[26] D. D. Smith, M. H. Lowenberg, D. P. Jones, M. I. Friswell, and S. Park, "Computational and Experimental Analysis of The Active Morphing Wing Concept," 2012, pp. 1–9.

[27] M. J. Smith, N. Komerath, R. Ames, O. Wong, and J.Pearson, "Performance Analysis Of A Wing With Multiple Winglets," 2001.

[28] a Beechook and J. Wang, "Aerodynamic Analysis of Variable Cant Angle Winglets for Improved Aircraft Performance," no. September, pp. 13–14, 2013.

[29] R. T. Whitcomb, "Wind-Tunnel Subsonic Mounted Approach Results Speeds For And At Selected Wing-Tip Winglets National Aeronauticsand Space Administration," Washington D. C., 1976.

[30] R. Hallion, "NASA's Contributions to Aeronautics: Aerodynamics, Structures, Propulsion, and Controls," Washington, 2010.

[31] P. Bourdin, A. Gatto, and M. I. Friswell, "Aircraft Control via Variable Cant-Angle Winglets," *Journal of Aircraft*, vol. 45, no. 2. pp. 414–423, 2008.

[32] P. Bourdin, A. Gatto, and M. I. Friswell, "Potential of Articulated Split Wingtips for Morphing-Based Control of a Flying Wing," in *25th AIAA Applied Aerodynamics Conference*, 2007, no. June, pp. 1–16.

[33] A. Gatto, F. Mattioni, and M. I. Friswell, "Experimental Investigation of Bistable Winglets to Enhance Aircraft Wing Lift Takeoff Capability," *J. Aircr.*, vol. 46, no. 2, pp. 647–655, Mar. 2009.

[34] E. Kaygan and A. Gatto, "Investigation of Adaptable Winglets for Improved UAV Control and Performance," *Int. J. Mech. Aerospace, Ind. Mechatronics Eng.*, vol. 8, no. 7, pp. 1281–1286, 2014.

[35] E. Kaygan and A. Gatto, "Computational Analysis of Adaptable Winglets for Improved Morphing Aircraft Performance," *Int. J. Aerosp. Mech. Eng.*, vol. 9, no. 7, pp. 1127–1133, 2015.

[36] E. Kaygan and A. Gatto, "Development of an Active Morphing Wing With Adaptive Skin for Enhanced Aircraft Control and Performance," in *Greener Aviation 2016*, 2016, no. October.

[37] E. and Kaygan and A. Gatto, "Structural Analysis of an Active Morphing Wing for Enhancing UAV Performance," vol. 12, no. 10, pp. 948–955, 2018.

[38] A. Gatto and E. Kaygan, "BLADE OR WING," WO/2018/046936.

[39] C. Thill, J. Etches, I. Bond, K. Potter, and P. Weaver, "Morphing skins," no. 3216, pp. 1–23, 2008.

[40] Airbus S.A.S., "Aircraft Characteristics Airport and Maintenance Planning (A330-300/-800)," France, 2018.

[41] H. H. Açıkel, "An experimental study on aerodynamics of NACA2415 aerofoil at low Re numbers," *Exp. Therm. Fluid Sci.*, vol.

39, pp. 252–264, 2012.

[42] M. Drela and H. Youngren, “Project 4 – Aircraft Aerodynamic Characteristics,” pp. 1–7.

[43] C. E. Lan, “A quasi-vortex-lattice method in thin wing theory,” vol. 11, no. 9, 1974.

[44] P. G. Saffman, *Vortex Dynamics Cambridge*. England, U.K.: Cambridge Univ. Press, 1992.

[45] W. F. Phillips, “Lifting-Line Analysis for Twisted Wings and Washout-Optimized Wings,” *J. Aircr.*, vol. 41, no. 1, pp. 128–136, 2004.

[46] D. D. Smith, M. H. Lowenberg, D. P. Jones, and M. I. Friswell, “Computational and Experimental Validation of the Active Morphing Wing,” *J. Aircr.*, vol. 51, no. 3, pp. 925–937, May 2014.

[47] P. Bourdin, A. . Gatto, and M. Friswell, “The Application of Variable Cant Angle Winglets for Morphing Aircraft Control,” in *24th Applied Aerodynamics Conference*, 2006, no. June, pp. 1–13.

[48] A. Bolonkin and G. Gilyard, “Estimated Benefits of Variable-Geometry Wing Camber Control for Transport Aircraft,” *Tech. Memo. NASA Dryden Flight Res. Cent.*, no. October 1999, 2018.

[49] Q. Wang, Y. Chen, and H. Tang, “Mechanism Design for Aircraft Morphing Wing,” *53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf. AIAA/ASME/AHS Adapt. Struct. Conf. AIAA*, no. October, 2012.

[50] M. Sanguineti and K. Wittkowski, “V ariable cant angle winglets for improvement of aircraft flight performance,” no. July, 2019.