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Effectiveness of Twist Morphing Wing on Aerodynamic Performance and Control of an Aircraft

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Abstract

In this paper, effectiveness of twist varied wing configurations for aircraft control and performance is described. The primary variables investigated involved changing the wing twist angle of a comparable Airbus A320 wing structure by identifying the ideal angle of twist. The aerodynamic performance and control of the morphing wing is characterised in AVL (Athena Vortex Lattice Method). In order to better understand the aerodynamic performance and control of twist morphing wing for diverse flight regimes, predetermined values of twist ($-8° < \phi < 8°$, in steps of ±2°) were examined. The results from this work indicate that if morphing wings were employed on aircraft, performance benefits could be achieved.

Keywords: Aerodynamics, Aircraft, Control, Morphing, Twist

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1. Introduction

Current interest in morphing vehicle is accelerating with the development of advanced materials, sensors, and actuators. Although this area is fairly new, the applications were developed many years ago. Wing warping techniques were practically applied by the Wright Brothers to control the first powered, heavier than air, aircraft through wing twist via subtended cables [1]. However in today's aviation world, this technique is no longer available and replaced by compliant based techniques which are widely accepted techniques of strategically placed, small deflection, discrete control surfaces (aileron for roll, elevator for pitch and rudder for yaw control). Alas, fixed positioned, conventional wings with these traditional control surfaces do not provide the optimum solution for aircraft performance in all flight regimes as the lift requirements for aircraft can vary within a typical flight due to fuel burn. In consequence of these reasons, many designers lean towards the search for variable morphing concepts.

The idea of variable wings, 'morphing', comes from the observation of flying birds where they tend to change wings geometry during the flight to adapt various flight conditions such as take-off, landing, gliding, soaring, and so on. In this regard, a detailed

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description of past and current morphing aircraft concepts are well summarized by Barbarino et al.[2], and Weissahaar et al. [3]. According to their survey, numerous morphing designs were discussed and the benefits, as well as the difficulties, were clearly expressed. Similarly, Ajaj et al. [4] succinctly mapped out the morphing applications by highlighting the latest research as well as presenting the historical connections of adaptive aerial vehicles. Moreover, several adaptive wing concepts of varying complexity were investigated and categorized by Jha et al. [5]. According to the investigation, the most significant challenges tend to be in the structural design of the concepts, morphing the skin, and the mechanisms employed.

A study of early designs and approximation techniques made the assumption that changing the twist in the outboard sections of the wings can improve the desired control forces needed for maneuvering flight. Prandtl’s Lifting Line Theory was the initial numerical technique to assess the performance of a wing’s lift capabilities for an aerial vehicle [6]; being thereafter modified by Philips [7,8] to estimate the effects of wing twist on lift distribution. Following this seminal work, more studies have taken cognizance of morphing wing twist structure both theoretically and experimentally, to examine influences on the aerodynamic performance of an aircraft. Recent work have detailed of wing twist systems using piezoelectric and pneumatic actuators [9-11], torque rods [12-14], adaptive stiffness structures[15], threaded rods [16], and shape memory alloys[17-19]. Similar to wing twist concepts, winglet and/or wingtip twist can also provide performance increases. Proof of this can be found in the significant number of studies available in the current literature. Bourdin et al.[20,21] and Alvin et al. [22] 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. Studies using novel design concepts of twisted and cant angled C wingtip configurations were also investigated by Smith et al. [23] and results indicating that the high twist angles tended to increase the lift coefficient with winglet twist angles of up to ϕ=-3° providing good aerodynamic efficiency. The fishbone active camber wing concepts were introduced by Woods et al. [24]. 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. Recently, active wing twist concepts investigated by Kaygan et al. [25,26]. Novel design concepts with multiple morphing elements were utilised and the results show the concept is superior to more traditional methods under selected 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. In addition to all, the aerodynamic and structural performance of a morphing wing concept, based on fully compliant structures and actuated by closed-loop controlled solid state piezoelectric actuators, is investigated numerically and experimentally by Molinari et al. [27]. The concept was tested in the wind tunnel and also deployed to model aircraft to demonstrate the roll capability of an aircraft. The results showed the concept would be one of the promising morphing wing designs by achieving significant efficiency improvements as well as illustrating similar controllability with traditional aileron systems.

Although the variety of morphing mechanisms for both fixed and rotating wing applications concepts were explored and huge possible advantages have been discussed over the last several decades, the majority of concepts have been limited due to problems such as excess weight, cost, structural integrity, skin configuration, and smooth surface design [28,29]. An efficient widely accepted mechanism with a corresponding to realistic skin still eludes development and widespread application. Smart materials aim to meet these needs; nonetheless, the skin problem remains unsolved. The morphing skin remains one of the significant challenges in this area.

The purpose of the current study is to investigate the aerodynamic characteristics of a variable twist morphing wing to enhance aerodynamic performance and control of an aerial vehicle. The primary variables investigated involved changing the wing twist angle of a comparable Airbus A320 wing structure by identifying the ideal angle of twist. To that end, the remaining sections of this paper will describe the computational methodologies and aerodynamic analysis of selected twist cases.

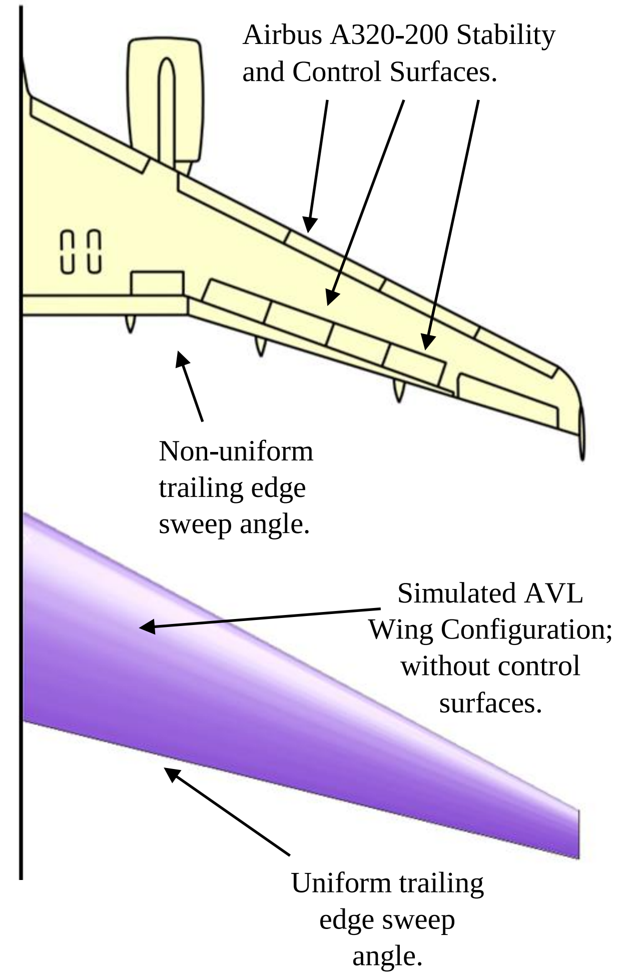


Figure 1. Airbus A320 Swept Wing structure [30] and AVL Swept Wing Model.

2. Design and Methodology

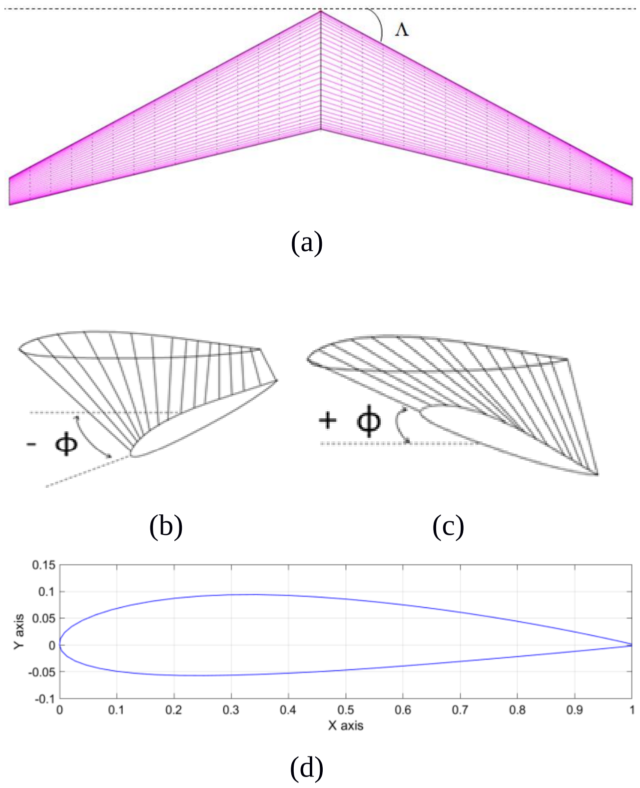
2.1 Wing Geometry

The model chosen for this study is shown in Figure 1 and Figure 2. It can be seen that sweep wing configuration has been investigated which is comparable wing structure with Airbus A320. It should be noted that the wing was modeled without having non-uniform trailing edge angles whereas A320 wing structure has [30]. The wing configuration comprised of NACA 2415 airfoil section(as shown in Figure 2 (d), which is an asymmetrical airfoil that allows the plane to generate more lift and less drag force [31]), Λ=25° leading edge sweep angle, 34m wingspan, 6.5m root chord, 1.5m tip chord, with aspect and tip ratios of 8.5 and 0.23 respectively. In order to better understand the aerodynamic performance and control of twist morphing wing for diverse flight regimes, predetermined values of twist ($-8° < \theta < 8°$, in steps of ±2°) were examined. An initial expiratory investigation was conducted on a baseline configuration (without having a twist angle) and then for each twist cases, new geometry structure was generated.

2.2 Aerodynamic Model and Computational Method

Aerodynamic modeling and numerical analysis were carried out using Athena Vortex Lattice (AVL) software, which was originally coded by Harold Younger and further developed by Mark Drela [32]. Athena Vortex Lattice is a numerical simulation package that determines the solutions to a linear aerodynamic flow model. For all simulations, modeling was performed from a set of wing panels along the wing span and chord axes (computational model of wing structure is shown in Figure 2(a) and Figure 3).

The variation in lift can be modeled as a step change from one panel to other. The control points are placed at 3/4 chord for each panel at the midpoint position in the spanwise direction to achieve the required vortex strength by applying the flow tangency condition. Using the “Biot-Savart law”, for each surface panel, an equation can be set up which is a linear combination of the effects of the strengths of all panels. A solution for



(a)

(b) (c)

(d)

Figure 2. AVL Wing Model: (a) AVL Aerodynamic Wing Structure, (b) Wash-in(positive twist) angle, (c) Wash-out(negative twist) angle and (d) NACA 2415 Airfoil structure.

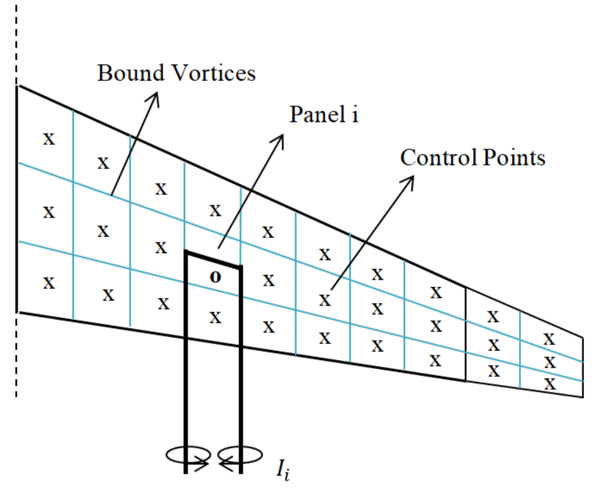


Figure 3. Computational Model of a Swept Wing Structure.

(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_∞ is the given freestream velocity).

The free-stream velocity chosen for this investigation was 30 m/s and all results were computed 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. Grid refinement analysis is a method of defining the best panel size in order to reduce the complexity and increase speed of analysis. The findings from the grid refinement study were also used as a guide to define the best structural models of the configuration. Overall, this involved monitoring the coefficient values for several different panel densities. Subsequent to this activity all computations were thereafter based on 30 horseshoe vortices along the wing chord, and 60 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 Wing Twist on Lift and Drag Characteristics of an Aircraft

The static force results produced on the morphing wing at twist angles between -8° < ϕ > +8° are shown in Figures 4 (a) and (b). To achieve lift and drag coefficient results, both sides of the wings were twisted. Fig. 4(a) illustrates the lift coefficient results for different twist angles. It can be seen clearly that altering the twist angle of the morphing wing producing a corresponding increase and decrease in lift coefficient. It would be expected that the lift capabilities of an aircraft constantly increases with increasing the angle of attack of an aircraft. Comparing this pattern with other twist cases presented, similar results were obtained.

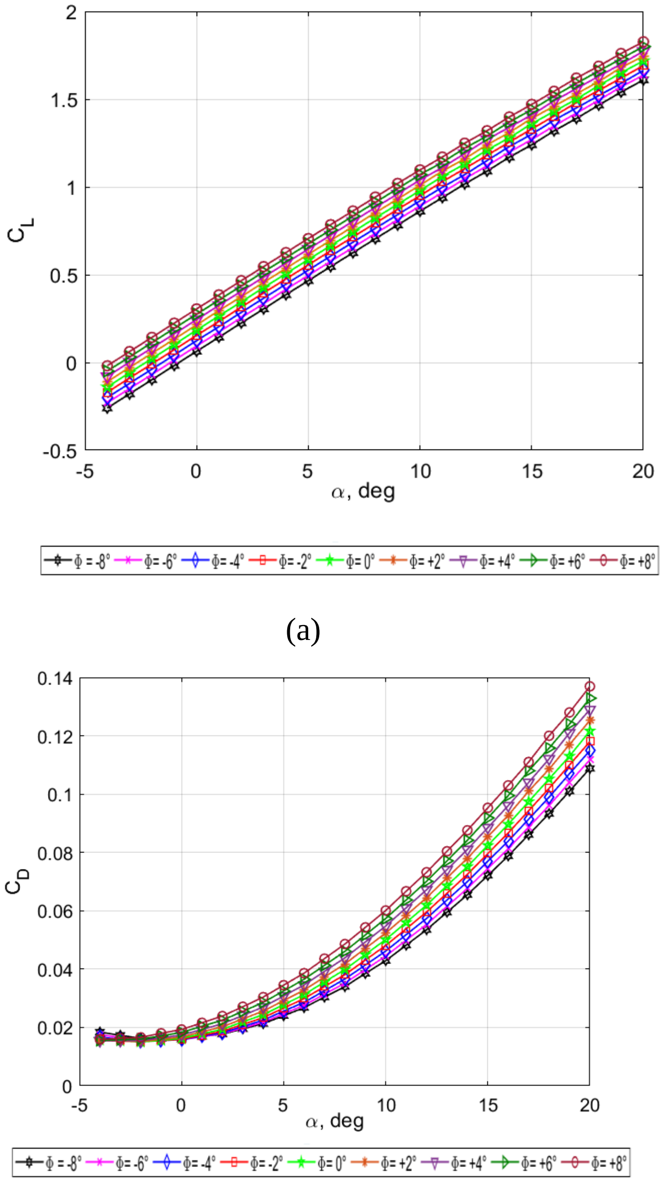
On the other hand, results for wing twist of ϕ =-8°, at α=20°, the lift coefficient in this study were found to produce lift reductions of approximately 11% and 20% compare to ϕ =0° and ϕ =+8° respectively. This would be also expected due to both net reductions in effective angle of attack as the wingtip moves out of the wing plane and contribution to overall lift production reduces [7]. Similar results were also found in [23] where experimental results present greater C_L for higher positive twist angles. Considering other twist cases (-6° < ϕ > +6°) presented in here, general trend as seen for ϕ =±8° was also observed, in overall, numerical results showed that there is a greater improvement in lift coefficient when wings are positioned at ϕ =+8°, therefore this would be assigned as an alternative lift production case while taking off and landing conditions of an aircraft are considered.

Results for drag coefficient (Figure 4(b)) also show significant changes with wing twist angle change. With twist movement, overall drag, as would be expected, was found to increase with the positive twist (downwash) and decrease with the negative twist. These results showed marked increases at the extremities of twist angles and angles of attack tested as the wing tip becomes more aerodynamically loaded [36]. 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[34-36].

Looking at ϕ =+8°, the drag increase was found 12.5% comparing to ϕ =0° at a high angle of attack (α=20°), thus the aerodynamic performance of a morphing wing will be diminished due to added positive twist angle. Conversely, from ϕ =0° to ϕ =-6°, drag reduction was observed at almost 8% and results for ϕ =-8° shows this reduction further exacerbated with 10% in contrast to ϕ =0°. Moreover, comparing this feature with ϕ =+8°, it seems there is 25% of total drag reductions. This would allow aircraft to boost its aerodynamic performance. As is well-known principles in aviation, drag reduction plays a significant role to assess fuel consumption. According to NASA Dryden studies, even a 1% reduction in drag would save the US fleet of wide-body transport aircraft $140 million/year, at a fuel cost of $0.70/gal [37].

3.2 Effects of Wing Twist on Aerodynamic Performance of an Aircraft

To show the effectiveness of the twist morphing wing on the overall aerodynamic performance of the wing, the L/D is computed by simple division, hence the information gained from Figure 4 (a) and (b) allowed to plot of a graph assessing L/D ratio as shown in Figure 5(a). Overall, this active wing technology generates a slight influence on the C_L and C_D which result in relatively substantial deviations in the L/D.

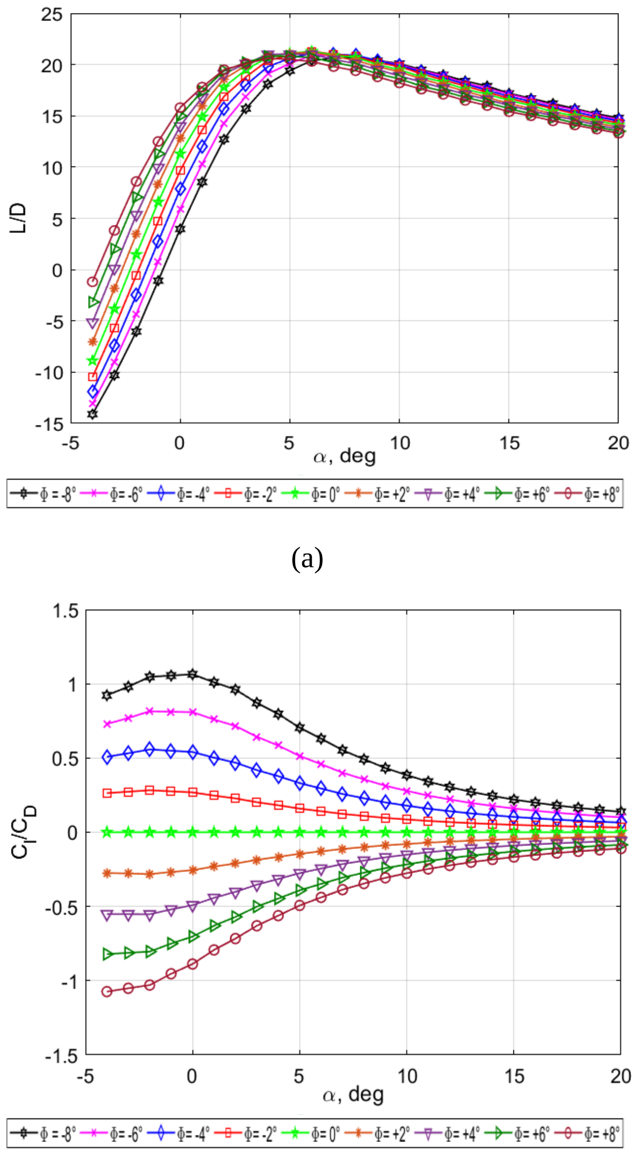


(a)

(b)

Figure 4. Effects of changing wing twist angle: (a) Lift Coefficient (C_L) and (b) Drag Coefficient (C_D) versus angle of attack.

This feature makes the morphing technology convenient for an air vehicle to perform multi-mission tasks in which the requirements on the flight speed and the range/endurance are different. It can be seen from Figure 5(a), the morphing wing places a significant influence on the L/D particularly at low angles of attack, for α <7°. In this region (α < 7°), twisting wing here provides an increase in L/D and the maximum lift to drag ratio is approximately 21.5 for ϕ =-2°, and this is achieved at an angle of attack of 6°. Comparing ϕ =-2° with nearest highest ratio wing configuration which is ϕ =0°, it was found approximately 2% less efficient.



(a)

(b)

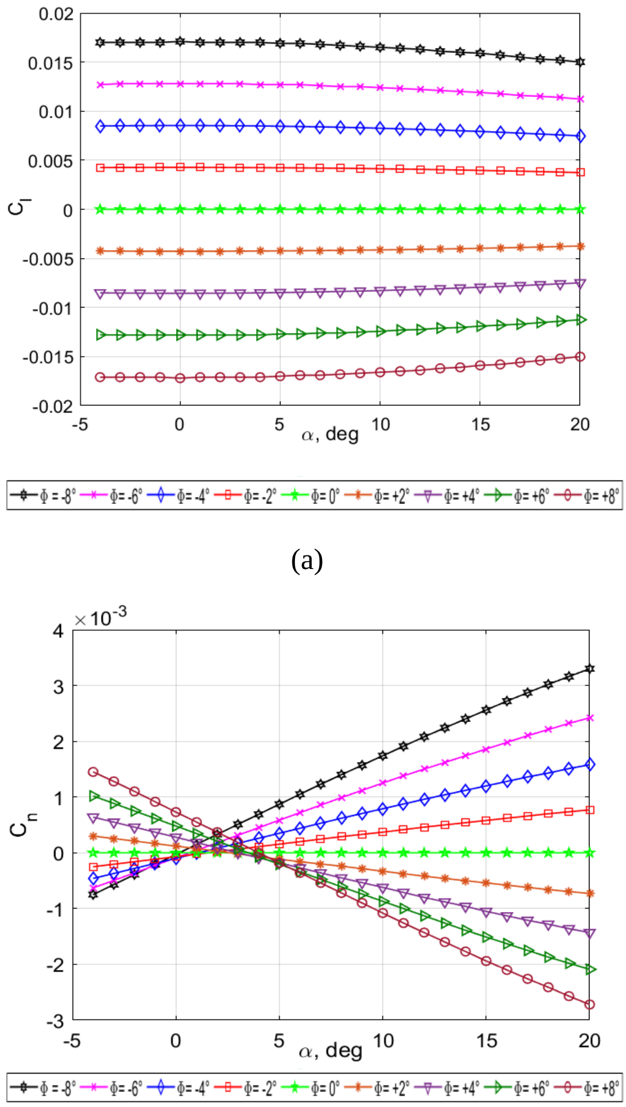
Figure 5. Effects of Active Morphing on the Wing Efficiency: (a) Aerodynamic Efficiency (lift to drag ratio) and (b) Roll to drag ratio for different twist cases.

At angles of attack greater than 7°, the L/D values and their changes drop slightly with the increase of the angle of attack. At twist case of +8°, L/D ratio reduced radically after α =6° and became less effective wing configuration compare to other twist cases while it was fully effective model up to the angle of attack range of -4 to 7 deg. This would be expected due to increased angle of incident tend to increase the drag coefficient results (as seen in Figure 4(a)) markedly, thus it causes to reduce aerodynamic performance of an aerial vehicle. Consequently, the use of the morphing twist wing system improves the aerodynamic performance of the aircraft by increasing its lift to drag ratio at low angles of attack, which is useful to increase the maximum range or endurance of an air vehicle in cruise where the most of fuel is spending, in agreement with [38].

Figure 5 illustrates the roll to drag coefficient ratio that evaluates the overall effectiveness of the concepts at producing roll moment with an inclusion of the aerodynamic cost. From Figure 5, it can be clearly seen that both the +8° and -8° wing twist configurations are superior to any of the corresponding twisted cases over the entirety of the angle of attack range tested.

3.3 Effects of Wing Twist on Aerodynamic Control of an Aircraft

The graphs of Figure 6 and Figure 7 represent the graphical interpretation of the numerical results of the variation of the aerodynamic moment coefficients (C_l,C_n, and C_m) as a function of the angle of attacks. Moments attainable by twisting the right wing while the left one remains planar. As is well known, Prandtl's classical lifting-line theory and the Fourier coefficients have shown previously that increases in wing twist away from the planar configuration can provide substantial roll authority suitable for aircraft roll control [8]. Figure 6(a) highlights the roll moment coefficient results for the various twist wing configurations. As is shown that the concept demonstrates an ability to produce control moments in roll at various levels depending on the degree of twist. Predominantly, developed roll moment was found to increase slightly with an angle of attack, and increase or decrease distinctly with an increase or decrease in applied wing twist angle. This would be expected due to the variation of the lift distribution over the wing structure (as shown in Figure 4(a)) and it can be seen from Figure 6(a) that maximum roll moment coefficient obtained at maximum degree of twist (ϕ =+8°) with almost -0.017. It is clearly perceived that negative moment data was achieved which dictates the direction of the roll (aircraft will roll to left.) Comparing this result with a negative twist configuration (ϕ =-8°), similar results were seen with C_l=0.015; nevertheless, a positive roll moment is produced in $\phi < 0°$ that is the wing will roll in the right direction. Overall, results using this control methodology do show adequate roll control moment ($\Delta C_l/\Delta\phi$ =0.11) and comparable roll control moments obtained relative to traditional aileron systems ($\Delta C_l/\Delta\xi$ = 0.08−0.25 rad−1) [39] hereby this would be an alternative control technique to substitute for a traditional aileron control system.



(a)

(b)

Figure 6. Effects of changing wing twist angle: (a) Rolling Moment Coefficient (C_l) and (b) Yawing Moment Coefficient (C_n) versus angle of attack for different twist cases.

Considering the same operational conditions discussed for the results of roll moment coefficient above, results indicate noticeable influences on yaw moment coefficient as shown in Figure 6(b). It can be seen that there is a linear trend with an angle of attack with the degree of yaw moment measured increasing significantly at higher angles of attack. Similar to roll moment coefficient, the negative results indicates the aircraft will yaw to left (due to drag increase for ϕ>0°) and positive results show the aircraft yaw directions are right. Proverse yaw is also being observed that is the same direction with roll moment coefficient. Overall, at ϕ =-8°, yaw moment coefficient measured C_n=3.3×10^{-3} and it is reducing to C_n=0.85×10^{-3} at ϕ =-2°. As far as positive twist cases are considered, similar to ϕ>0°, added twist on morphing wing was found to increase yaw moment coefficient (C_n=2.8×10^{-3} at ϕ =+8°)

Figure 7 depicts the pitching moment coefficients for different twist angles within the angle of attack range from -4° to 20°. Results for C_m illustrate that the airfoil chosen for the wing model is producing negative moments which indicates the wing configurations at all twist cases are inherently stable. Added more positive twist cases seem to reduce more negative moments. This would be expected that increasing positive twist angle tends to increase the trim angle (lower the angle of attack); hence more pitch down moment occurred. Overall, the C_m show predominantly linear relationships with applied wing twist and/or angle of attack and maximum pitching moment observed at ϕ = +8° (C_m=-0.41).

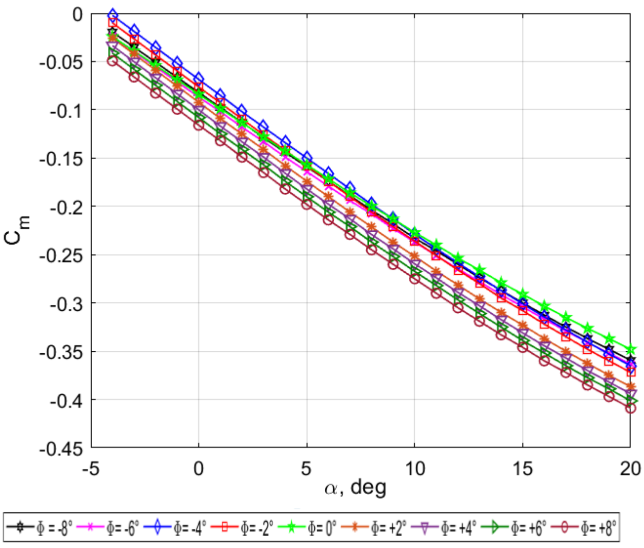


Figure 7. Effects of changing wing twist angle: Pitching moment coefficient versus angle of attack for different twist cases.

4. Conclusion

Variable wing twist concept has been numerically investigated in this paper. The concept consists of several twist wing configurations (-8° ≤ ϕ ≥ +8°). As discussed earlier in section 3.3, maximum twist angles provide substantial aerodynamic moments and overall, the investigated concept appears to be a possible alternative to traditional control surfaces such as ailerons, elevators, and rudders as far as basic maneuvers are concerned. Moreover, the concepts also showed potential aerodynamic performance benefits at ϕ=-2° compare to Airbus A320 conventional and/or fixed wing configuration (ϕ=0°). These results are all particularly encouraging and provide an incentive for further investigation of wing twist morphing technology, principally with regard to its practical implementation.

Nomenclature

A = Wing Area
b = Wing Span
C_D = Roll moment coefficient
C_L = Yaw moment coefficient
C_l = Roll moment coefficient
C_l/C_D = Roll to Drag Ratio
C_m = Pitching moment coefficient
C_n = Yaw moment coefficient
c = Wing chord
i = Selected wing panel
I_i = Total vortex strength
L/D = Lift to Drag ratio
U_∞ = Freestream velocity
α = Angle of Attack
ϕ = Twist Angle
Λ = Sweep Angle
ξ = Standard aileron angle

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