

# INVESTIGATION OF THE EFFECTS OF TWIST ANGLE ON WING PERFORMANCE AND STALL CHARACTERISTICS IN LOW-SPEED WINGS

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## ABSTRACT

One of the most notable features expected from the wings used in airplanes is that they allow an economical flight. In addition, wings must contribute to the provision of a safe flight in terms of their structural features. Therefore, studies on improving the performance of wings are increasing day by day. In these studies, performance analysis is carried out by changing the incidence angle from the root to the tip without changing the airfoil structure of the wing. However, it has been observed that the effect of the twist angle on the performance and flow separations of the wings used in low-speed aircraft has not been sufficiently examined or the research have not been compiled in a regular format. It is known that changing the angle of incidence along the wing, that is, twist of the wing, increases the lift stability along the wing and improves the stall characteristics of the wing. In this review, for the reasons, it is aimed to investigate the effects of twist angle on wing performance, flow separation and stall characteristics of wings used in low-speed aircraft.

**Keywords:** Flow Separation, Low Reynolds, Low-Speed, Twist Angle,

## INTRODUCTION

Unmanned aerial vehicles (UAVs) are used for many missions, both military and scientific, such as surveillance, tracking and scientific investigation. Aircrafts are designed to operate at low and high flight speeds, and at low and high flight altitudes, according to the assigned mission. Depending on the task assigned on the aircraft, it may be desirable to increase the payload to be carried. As in other aircraft, how long you can stay in flight without refuelling is an important design variable in UAVs. At this point, it is important to choose the airfoil to be used in the wing design of the aircraft.

Airfoil structure is one of the fundamental issues in the field of fluid mechanics. It is a key factor in many design fields, from the flight behaviour of animals to the design of the propellers of a submarine. The airfoil structure was first designed in the form of a teardrop at the end of the 19th century and this structure attracted a lot of attention. It was not long before some fluid mechanics researchers at the time discovered that there could be no single ideal profile. They discovered that the airfoil structure had to be

modified according to the size and speed of the wing. They defined this relationship between the airfoil structure and the size and speed of the wing as the *scale effect* (Lissaman, 1983).

In the 1930s, when studies in the field of aircraft design increased considerably; the definition of scale effect has become widespread. It has been the subject of research that this definition, which expresses the relationship between the wing sizes and the airfoil structures of birds or insects, can also describe the ones in large airplane wings. As a result of the studies, scale effect was classified by discovering the Reynolds number (Lissaman, 1983).

A low Reynolds number airfoil is mostly preferred for UAVs, including low-speed UAVs operating at an altitude of more than 30 km above sea level. Considering the compressibility of air,  $Re = 10^5$  is accepted as a threshold value. Flight regimes below  $Re = 10^6$  are considered low Reynolds number flight regimes. Figure 1 gives a visual about this classification (Lissaman, 1983).

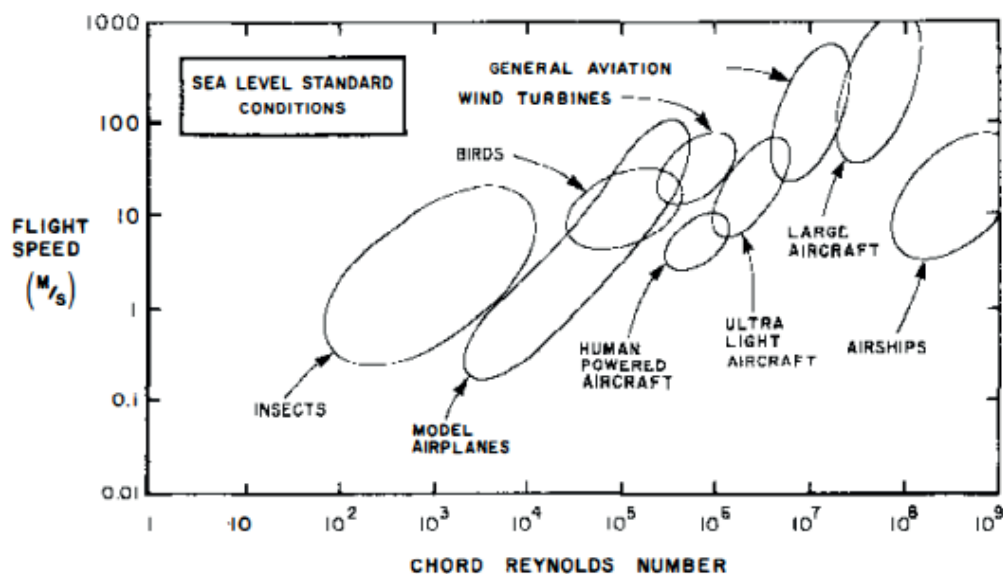
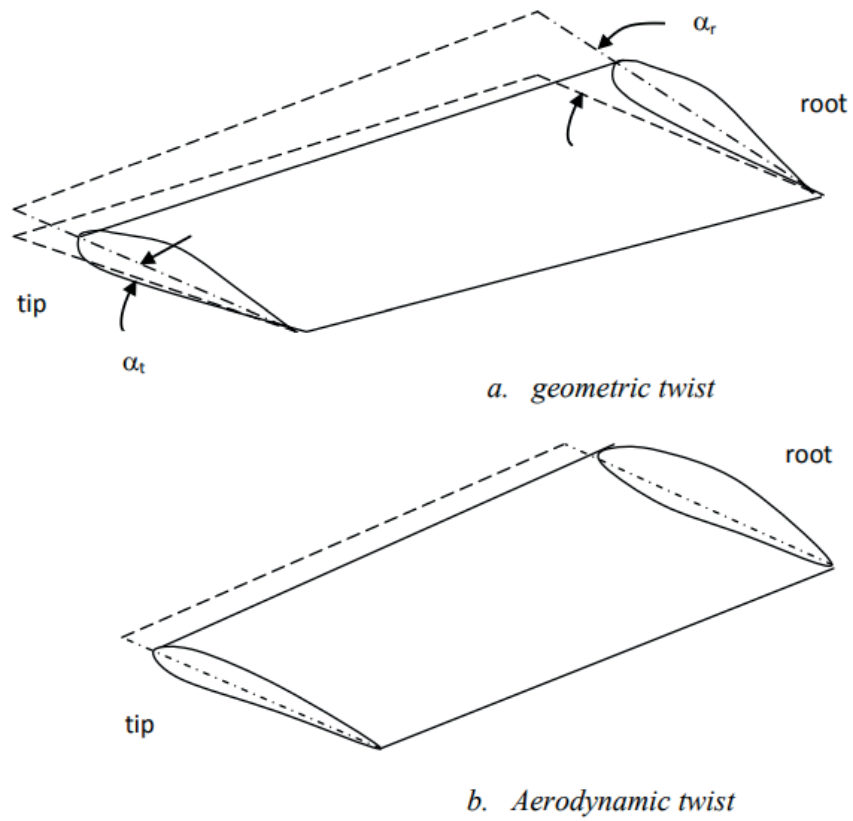


Figure 1. Classification of aircraft according to the Reynolds number (Lissaman, 1983)

The choice of appropriate airfoil structure in aircraft design is not sufficient for the best performance. Better performance can be achieved by improving the wing structure. Sadraey (2012) defined the wing design requirements in his studies. Wing design procedure is shown in Figure 3.

Wing twisting is one of the methods using to optimise wing performance. The angle of incidence of the wing tip section is lower than the wing root section is called negative twist or wash-out. The fact that the wing tip section has a higher angle of incidence is called positive twist or wash-in. The difference between the wing root airfoil section and the wing tip airfoil section is called *aerodynamic twist*. The wing tip airfoil section of wings with aerodynamic twist is generally thinner than the root airfoil section. Twist in which the airfoil section does not change along the wing, and the zero-lift angles of attack of the wing root airfoil section and the wing tip airfoil section are different, is called geometric twist. Geometric and aerodynamic twist are shown in Figure 2 (Sadraey, 2012).



**Figure 2.** Wing twist (Sadraey, 2012)

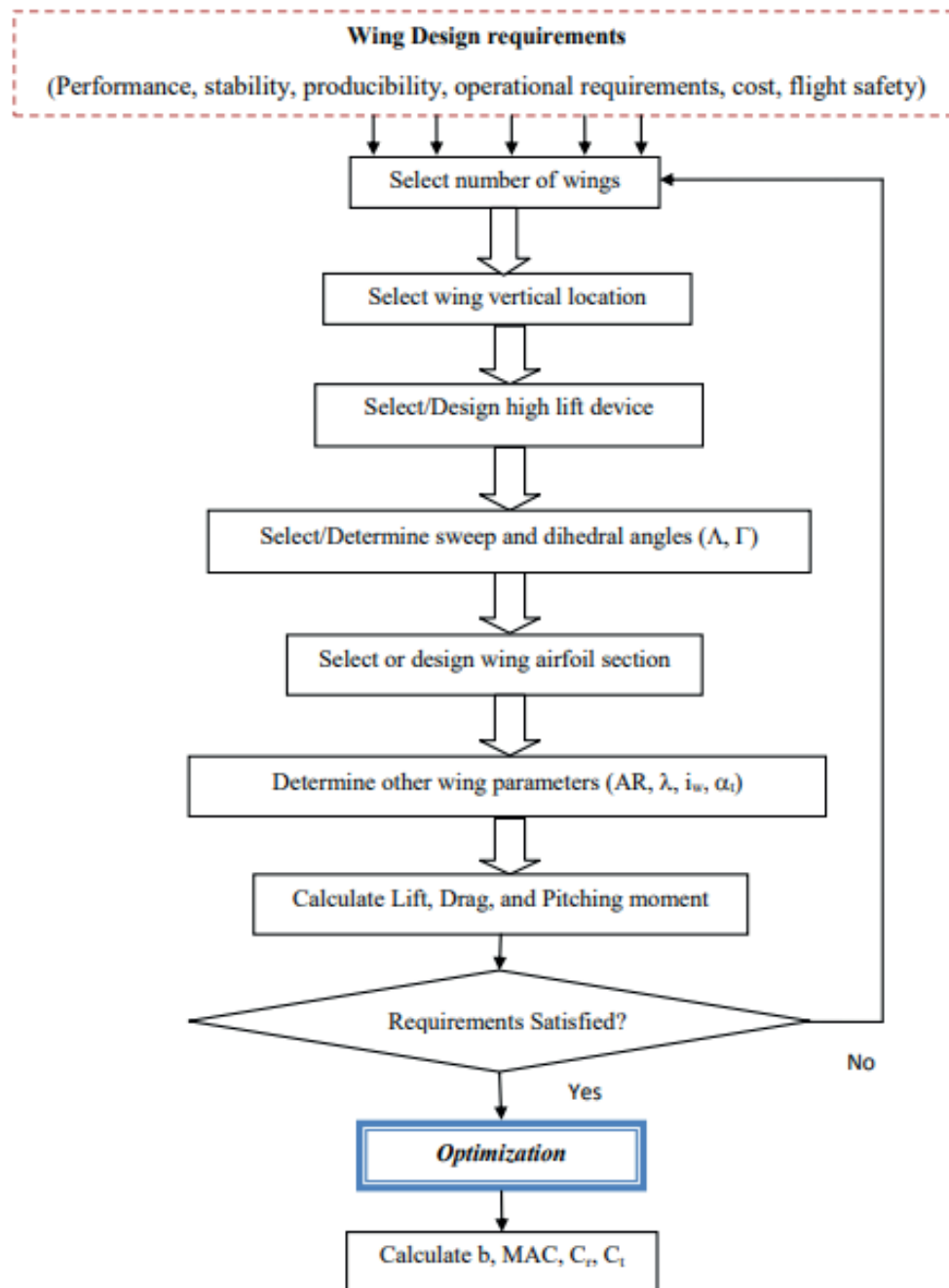


Figure 3. Wing design procedure (Sadraey, 2012)

## EFFECTS OF TWIST ANGLE

With the widespread use of UAVs, the reduction of power consumption, the extension of the duty time and the desire to increase the payloads that it have brought along with scientific research. Research and development of wing performance characteristics is one of these fields of research. Many experimental and numerical studies have been carried out to optimise the wing structure. In recent years, researches conducted to analyse the effect of twist angle on the performance of the wing in this field have taken a wide place. The twisted design of the wing and its effects on performance have been analysed both numerically and experimentally in wings be used many different airfoils. Prandtl's Lifting Line Theory

was the first numerical technique used to estimate the lift capacity of an aircraft's wing (Prandtl, 1925). Phillips (2004) used this technique to analyse the effect of wing twist on the lift distribution.

Applying wash-out along the wing reduces the wing's outer cross-sectional area, thereby delaying boundary layer separation, ultimately improving the wing's aerodynamic efficiency, and even improving the performance of control surfaces at high angles of attack (Roskam, 1985). According to the study of Lyu et al (2014), wash-out also increases the flight stability of the aircraft by reducing induced drag. It has been found in studies that induced drag and specific fuel consumption can be reduced by applying the wash-out to a wide variety of wing structures (Philips et al, 2005). However, it is seen in studies that wash-in angle does not show the same effects. Rodrigue et al (2016) observed in their study that the application of wash-in at low angles of attack increases the lift. However, it has been determined that if the angle of attack is selected higher than  $8^\circ$ , the lift coefficient decreases considerably and when the angle of attack is more than  $6^\circ$ , the drag coefficient directly increases (Rodrigue et al, 2016).

Truong et al (2013) investigated the effect of negative wing twist on performance in an insect-like flapping wing system. The efficiency of the design in terms of lift and power consumption is discussed both experimentally and computationally. The lift obtained by the wing with twist angle and without twist angle was estimated using the unsteady blade-element-theory model. As a result, it has been seen that the flapping wing system with wing twist provides 37% more energy savings and produces 9.5% more lift than the flapping wing system without wing twist (Truong et al, 2013).

In their study on butterflies, Zheng et al (2013) investigated computationally and experimentally how deformations of the wing shapes of butterflies, both along the chord and along the wingspan, effect performance during flapping. While performing their experimental analysis, they recorded the wing kinematics of a butterfly in free flight using high-speed video-grammetry. These experimental results were then computationally analysed using a high-fidelity, three-dimensional, unsteady Navier Stroke flow solver. A series of plates placed along the wing like to simulate the wing of a butterfly over time, but whose length does not change along the chord, were used to perform these numerical studies. As a result, it was seen that the wing performance of the butterfly was much higher than the numerical analysis, but the twisted wing was the closest one to this performance (Zheng et al, 2013).

Fazelzadeh et al (2020) computationally investigated the effect of wing twist on sudden changes in air velocity in the boundary layer on tapered and swept wing designs with different airfoil structures. Wash-in has been applied on the wing, increasing linearly along the wing. Obtained results were compared with previous experimental studies. Images of the wash-in are shown in Figure 4 (Fazelzadeh et al, 2020).

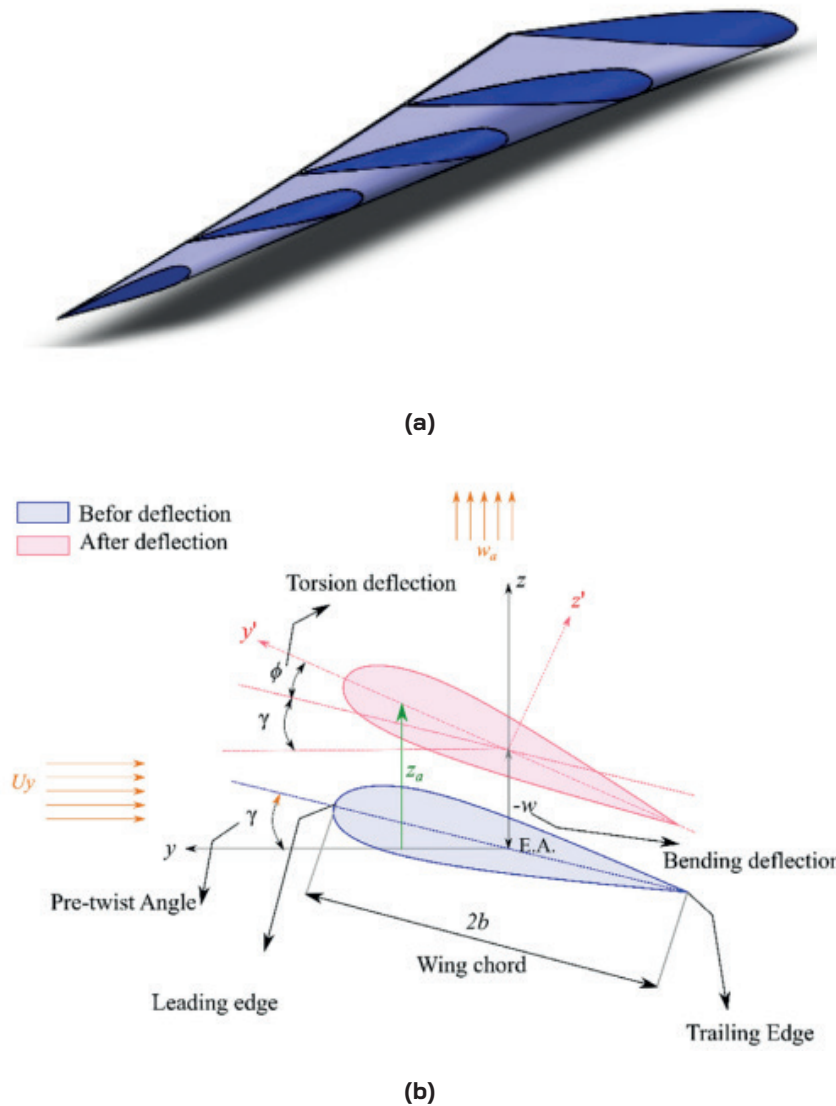
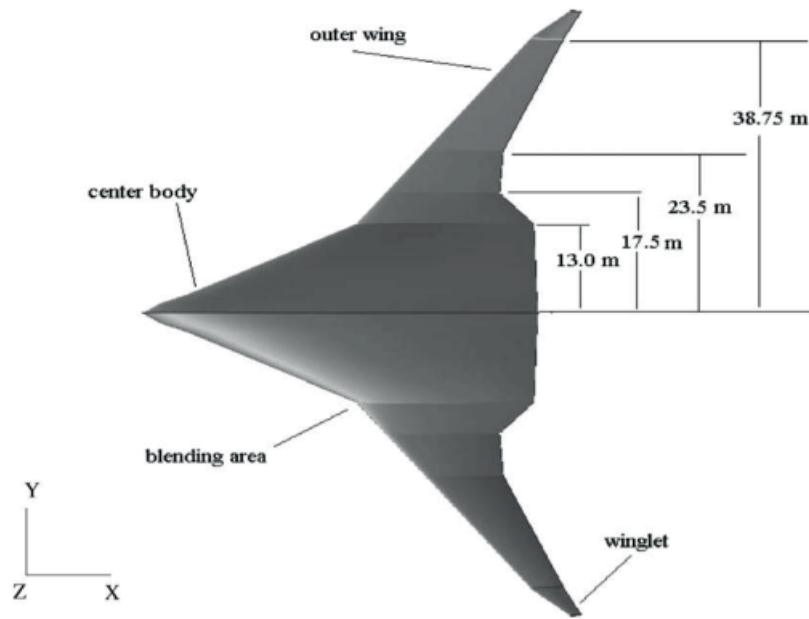


Figure 4. a) Twisting on tapered and swept wing b) Root and tip airfoil (Fazelzadeh et al,2020)

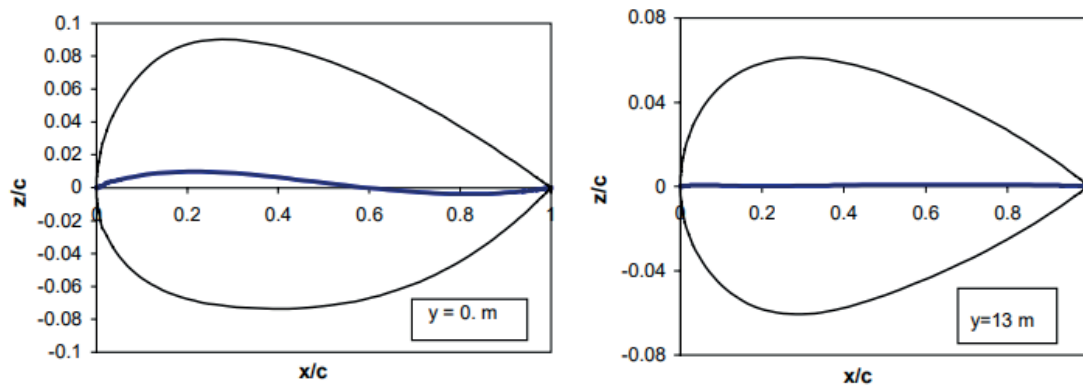
Fazelzadeh et al (2020) used the governing equations derived based on the Hamilton Principle in their numerical analysis. Peters' Finite State Aerodynamic Model, which explains the effects of wing finite span, wing sweep angle and wing pre-twist angle, was used to simulate the aerodynamic loads on the wing by adapting it to the designed aircraft. As a result, it was determined that the application of wash-in on the wing increased the vibration along the wing with the effect of the torsion moment.

Qin et al (2004) investigated the wing performance characteristics from multiple perspectives by designing a fixed wing body in their project. Lift distribution along the wing was analysed using both the low-fidelity panel method and the high-fidelity Reynolds-Averaged Navier-Stokes (RANS) equations and observed in viscous flow simulations. A delta wing-like aircraft was designed with the fixed wing body. The designed aircraft and its structure are shown in Figure 5. The effects of different thickness of the wing along the span, sweep wing and twist were tested together at different angles of attack (Qin et al, 2004).



**Figure 5.** Fixed wing baseline configuration platform (Qin et al, 2004)

NACA 0012 airfoil structure was preferred on the wing of the designed aircraft. The wing structure is tapered from root to tip, swept from front to back, wing thickness varying along the wing and twisted along the spanwise. Non-linear, varying twist angles along the wing are used in the design. The root and tip sections of the central part of the wing are shown in Figure 6. The twist distribution of the wing is shown in Figure 7 (Qin et al, 2004).



**Figure 6.** Wing Center body root and tip section (Qin et al, 2004)

The lift and drag values along the wing, and the changes in the drag coefficient along the wing at different angles of attack were noted. It has been determined that the fixed wing structure increases the performance in general. However, while wing twist increases the lift stability, a sudden drop in lift was observed at high angles of attack near the middle of the wing along the spanwise. This effect occurred because of increasing the twist angle up to a point along the wing and then decreasing (Qin et al, 2004).

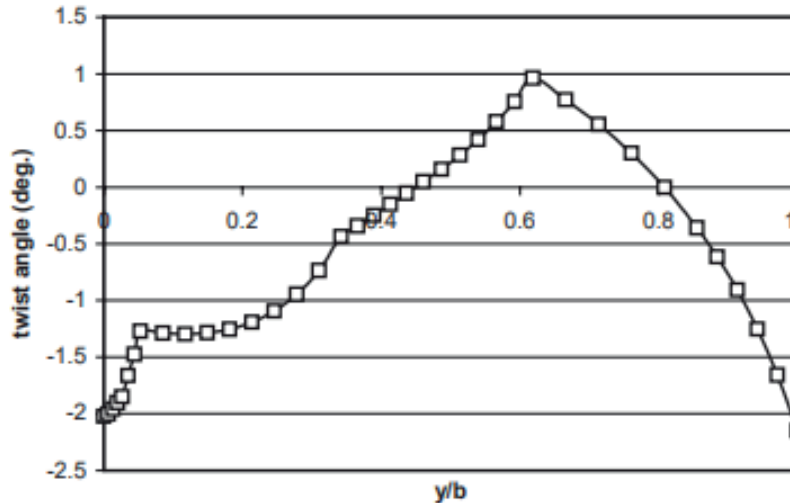


Figure 7. Twist distribution along the spanwise (Qin et al, 2004)

As a result, it has been observed that the positive twist angles numerically reduce the optimal performing range based on the angle of attack, and on the contrary, increase it. It has been found that a negative twist angle allows to delay the wing stall, thus improving stall characteristics (Qin et al, 2004).

Kelayeh et al (2021) investigated the effects of twist angle on wing performance computationally and experimentally. Numerical analyses were performed using incompressible RANS equations based on the two-equation of the  $k-\omega$  Shear Stress Transport (STS) turbulence model. The flow velocity is 30 m/s, and the Reynolds number 69000 is defined. A lambda-shaped tailless aircraft with  $56^\circ$  sweep angle is designed such that the twist angle decreases linearly (wash-out) along the wing. Experimental analyses were completed in a low-speed wind tunnel. NACA 66009 symmetrical airfoil is used in the designed aircraft. The designed aircraft model is shown in Figure 8 with different perspectives (Kelayeh et al, 2021).

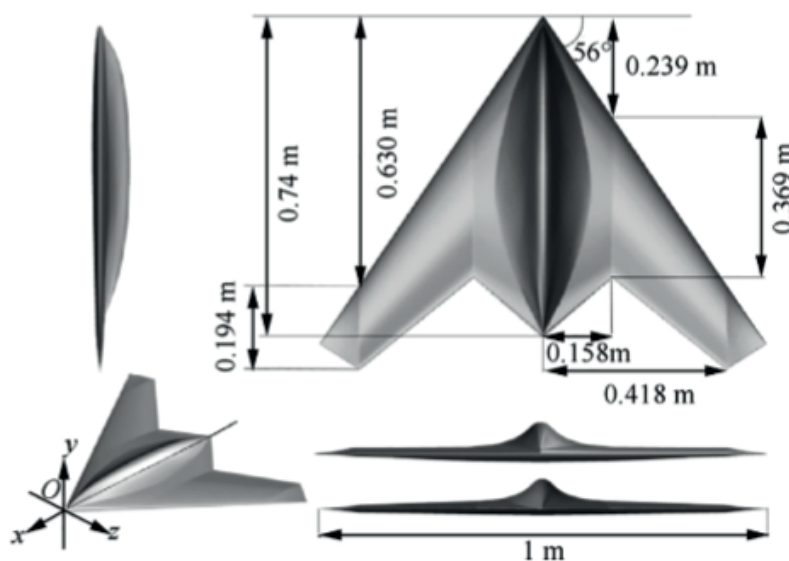


Figure 8. Planform of the model (Kelayeh et al, 2021)

Kelayeh et al (2021) used 3 different models with  $0^\circ$ ,  $3^\circ$  and  $6^\circ$  twist angles to examine the effect of twist on aerodynamic performance and tested these models in  $-5^\circ$ ,  $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$  and  $20^\circ$  angle of attack. The distribution of the twist angle along the wingspan is shown in Figure 9. The image of the designed aircraft in the wind tunnel is shown in Figure 10. The computational domain and boundary conditions for the computational analysis are shown in Figure 11 (Kelayeh et al, 2021).

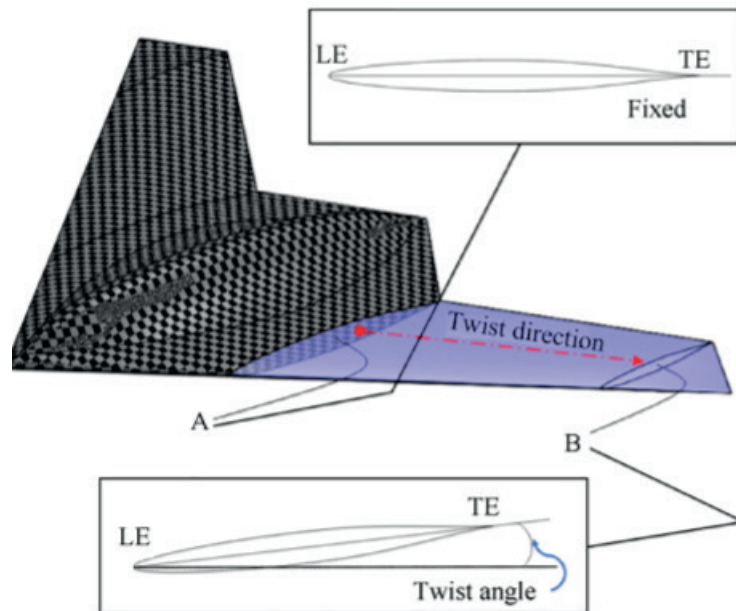
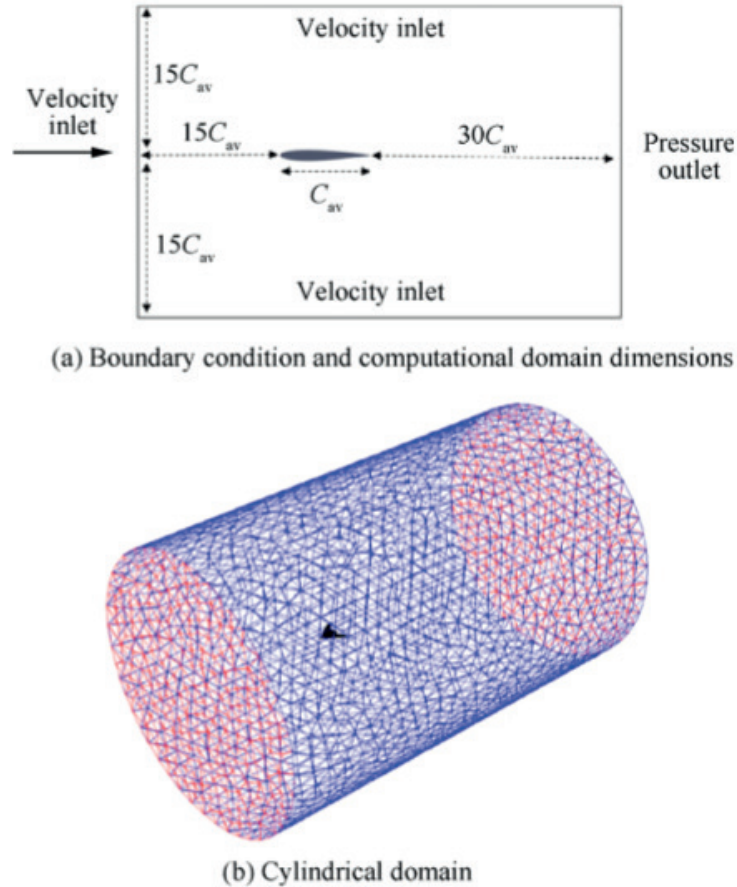


Figure 9. Twist angle distribution along wingspan (Kelayeh et al, 2021)



Figure 10. Designed model in wind tunnel (Kelayeh et al, 2021)



**Figure 11.** Boundary condition and computational domain (Kelayeh et al, 2021)

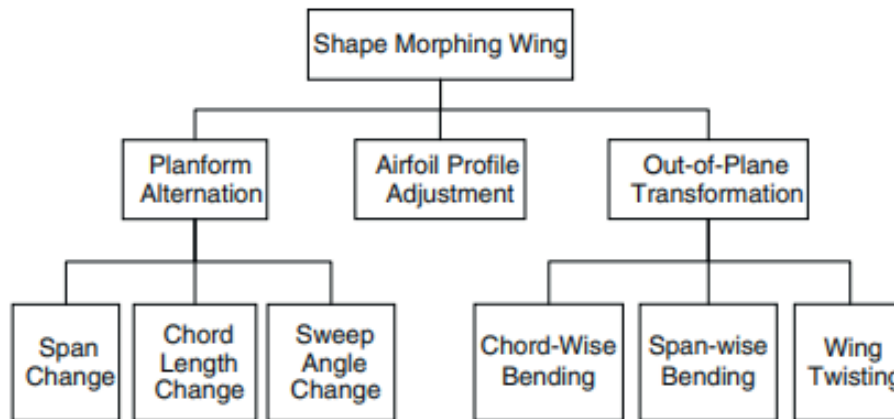
The data from the computational analysis was validated with the data from the experimental analysis. It has been observed that the increase in the twist angle reduces the lift coefficient at all angles of attack. However, it has been determined that the decrease in the lift coefficient at high angles of attack is negligible and at the same time, the significant decrease in the drag coefficient increases the aerodynamic performance by increasing the lift/drag ratio. After a certain value at high angles of attack, it was observed that the lift/drag ratio suddenly decreased considerably, and this angle of attack value was accepted as a threshold value. The threshold value of a twisted wing is higher than the angle of attack threshold value of a wing without twist angle. It was concluded that the stall characteristics of a wing with a twist angle are more satisfactory (Kelayeh et al, 2021).

### Shape Morphing

Geometric changes made in aircraft to fulfil the expected tasks in the most appropriate way are called shape morphing. There is no specific definition of shape morphing accepted among researchers. High lift devices such as flaps and slots are not included in the geometric changes made on the wing under the name of shape morphing (Sofla et al, 2010). Reich et al (2007) defined shape morphing requirements. These are:

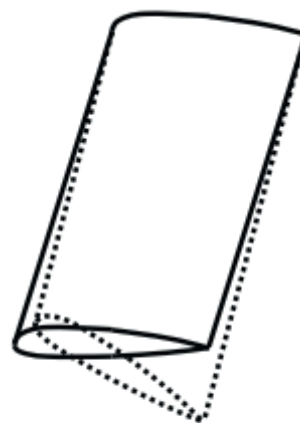
- a) High power for actuation distribution along spanwise,
- b) Structural mechanical parts,
- c) Control and processing systems.

Sofla et al (2010) analysed the effects of the use of smart materials in the wing structure on the performance from many aspects. These smart materials have been specified as shape memory alloys (SMA), piezoelectric actuators (PZT), and shape memory polymers (SMP). They have shown in their studies that the shape morphing of aircraft wing can be made during flight and this is a performance-enhancing technology that can be developed. Wing twisting has been specified as one of the shape morphing methods. Figure 12 shows the shape morphing methods (Sofla et al, 2010).



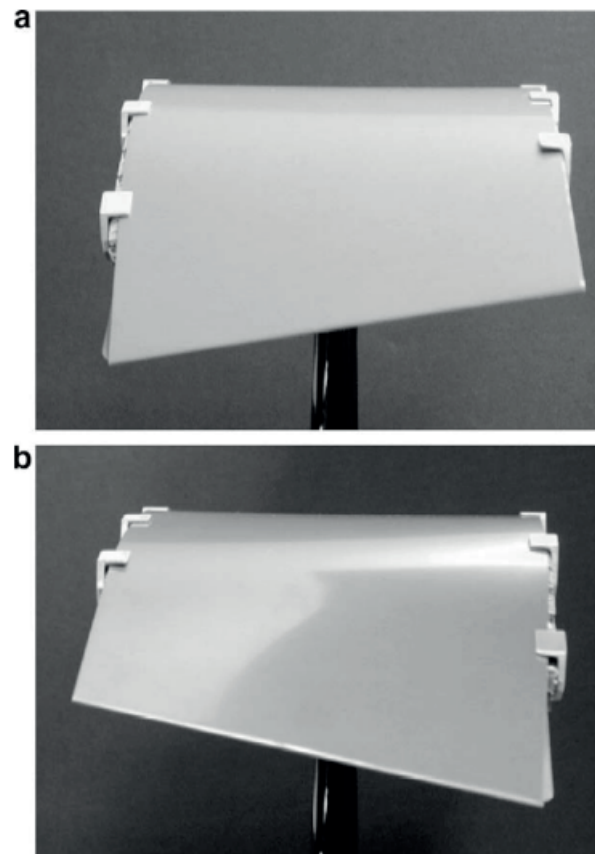
**Figure 12.** Methods of shape morphing (Sofla et al, 2010)

In the experiments, actuators were added to the surface of the wing or to the inner structure of the wing to twist the wing. In shape memory alloys, wing twist is achieved by heating SMA actuators, and by energizing PZT actuators in piezoelectric materials. Wing twisting is shown in Figure 13 and Figure 14.



Twisting: airfoil profile remains unchanged

**Figure 13.** Wing twisting (Sofla et al, 2010)



**Figure 14.** (a) The left rib is flexed downward and right rib upward. (b) The left rib is actuated upward and the right one downward (Sofla et al, 2010)

Sofla et al (2010) concluded that the only disadvantage of wing performance optimisation with shape morphing wing is the extra weight of the system parts to be used. Although a lot of research has been done on shape morphing wing, there is almost not application on aircraft. Except for the use in supersonic military aircraft, prototypes have been produced only for use in flight tests. Its use in low-speed aircraft remained in the conceptual design and testing phase (Sofla et al, 2010).

In another study, Jo et al (2023) conducted flight range optimisation studies with shape morphing wing on the RQ-7a Shadow UAV model in use. A wing whose thickness can vary along the wing has been designed with the shape morphing wing. Practical tests were carried out by using the aerodynamic twist on UAV model and were compared with the conventional fixed wing. NACA 4410, NACA 6410, and NACA 8410 airfoil structures are used along the wingspan. The UAV used in practical experiments is shown in figure 15. The results show that morphing the basic airfoil thickness by 2% along the wing (from NACA 2410 to NACA 4410) does not improve the performance of the aircraft. Conventional wing performs better. However, the morphing 4% and 6% of the basic airfoil thickness, the use of NACA 6410 and NACA 8410 airfoils, has been shown to considerably increase the flight range compared to conventional ones. Wing morphing with the NACA 6410 airfoil increased the flight range by 17%, and the wing morphing with the NACA 8410 airfoil increased the flight range by 60%. With the use of shape morphing wing, the drag coefficient on the wing has decreased considerably, thus reducing the specific fuel consumption. This was the main reason for the change in flight range (Jo et al, 2023).

UAV Model	RQ-7 Shadow
Wing chord	0.54 m
Wingspan	3.89 m
Cruising speeds	24.7 m/s
Operating altitude	2000 m
Density	1.007 kg/m <sup>3</sup>
Dynamic viscosity	1.726 × 10 <sup>-5</sup> Ns/m
Re	778,179
Baseline airfoil	NACA 2410



Figure 15. UAV model and specifications (Jo et al, 2023)

## CONCLUSION

As a result, twist angle,

1. Reduces induced drag by delaying boundary layer separations.
2. Provides steady lift distribution by reducing the angle of incidence from the root to the tip of the wing,
3. Allows the wing to operate at higher angles of attack so improving stall characteristics,
4. Increases the flight time of the aircraft by reducing the specific fuel consumption,

According to these results, it is inevitable to apply wing twist in UAVs using low-speed airfoils. The importance of wing twist to optimise the wing performance of UAVs has been understood. However, although there are many low-speed airfoils, research on wing twist has been insufficient. The effects of twist angle on wing performance offers a wide field of study for researchers. The effects of twist angle can be investigated numerically and experimentally using different low Reynolds number airfoils.

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