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Effects on Aircraft Performance Due to Geometrical Twist of Wing

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Abstract: This paper provides an overview of the effects of Geometric Twist on Aircraft performance by introducing a washout condition in an aircraft wing. This condition results in an effective Angle of Attack at the wingtip that is lower than the Angle of Attack at the wing root. Using CFD analysis, the variation of aircraft performance factors such as lift, drag coefficients, and aerodynamic efficiency is calculated for different Twist angles. A plot of lift and drag coefficients at varying Angle of Attack angles has been generated based on these analyses. These results illustrate the advantages of wing twist variation, particularly at higher angles of attack. One significant advantage of Geometric Twist is that it causes stall conditions to first occur at the wing root, providing a signal to the pilot to control the aircraft before the stall reaches the wingtip. This ensures the effectiveness of control surfaces, such as Ailerons and Flaps, located at the wing trailing edge. A comparison is made between the lift, drag coefficients, and aerodynamic efficiency of twisted wings and untwisted wings with identical parameters. While twisting the wingtip yields favourable results at higher Angles of Attack (AOA) compared to an untwisted wing, the aerodynamic efficiency of the wings decreases at lower AOA. However, applying the twist angle at high angles of attack, such as 10, 12.5, 15, and 20 degrees, leads to an increase in aerodynamic efficiency.

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1. Introduction

Wing, as one of the primary lift-producing devices in an aircraft, plays an important role in maneuvering, cruising, lift-off, and take-off. The pressure difference above and below the wing produces a net upward force. It is important to analyze and optimize the design of the wing to improve aircraft performance according to different mission requirements. For example, to increase the Critical Mach number for an aircraft, generally sweep is provided. To maintain better performance of control surfaces and high lift devices at the wing trailing edge, forward sweep is provided [1]. One of the methods to increase aircraft performance is wing twisting. The application of this wing twisting is morphing wing technology. This refers to changing the wing span area at different angles of attack (AOA). One of the most effective morphing ideas is wing-warping or the ability to actively change the span wise wing twist distribution [2]. Here, we refer to the wing twisting at the wingtip. The twisting of the wingtip at a negative angle would make the chord line of the wing root and wingtip oriented at different angles to the fuselage reference line [3]. Due to this twisting, the Effective Angle of Attack (AOA) of the wingtip is lesser than the wing root.

At higher Angles of Attack (AOA), due to an increase in pitching angle, there is an initial increase in lift coefficient. But as AOA crosses a particular angle, the flow over the wing separates, called Boundary layer separation, which decreases the lift abruptly [4]. This condition is called Stall. After this $\alpha = \alpha_{stall}$, the lift

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decreases continuously. This is one of the major problems not in civil aircraft but in fighter jets where the α needs to go more than α_{stall} for maneuvering [5]. It is very important to solve this problem of the stall conditions, either by increasing the Stall Angle or minimizing the rate of decrease of lift after stall conditions.

This type of twisting of the wing, where there is physical twist in the wing due to wingtip twist, which needs to be manufactured, is called Geometrical twist [6]. Another type of twist of the wing which includes using different airfoils at the wingtip and wing root is called Aerodynamic twisting of the wing [4]. Aerodynamic twist having two different airfoils without actual geometrical twisting provides ease of manufacturing compared to Geometrical twist of the wing, there is also no large increase in drag as compared to others. The effective Angle of Attack of the horizontal tail is decided by the flow of the wing trailing edge, due to twist the washout (ϵ)at the horizontal tail changes according to different twist Angles. Since we require a positive pitching moment (C_{m_o}) at $\alpha = 0$ to have a positive trim Angle (Angle at which the net moment of Aircraft is 0), it is also important for us to analyze the pitching moment of twisted wing to understand the longitudinal stability of Aircraft [7].

Washout conditions appearing near the trailing edge are generally due to the twist of the wingtip; the twist is downwards with a negative angle with respect to the fuselage reference line. These washout conditions occur when the Angle of Attack of the tip is lower than the Angle of Attack of the wing root. Initially, at lower angles of attack, Parasitic drag increases due to the form of wing twist at the tip. This poses a major problem that twisted wing configurations have a negative impact on lift, as lift is negative and drag increases.

This would make the wing root stall first rather than the wingtip, since Ailerons are present at the wingtip it is important to prevent the area from stalling, which would decrease the effectiveness of ailerons [2]. Therefore, the wing root is made to stall first, which would have no effect on the control surfaces. Twisted wing poses a greater challenge in manufacturing, maintaining surface continuity before, during, and after transition (to achieve the best aerodynamic performance) further complicates this trade-off. This concept led to morphing wing, which changes the wing area (shape) in real time, decreasing the dependency on Ailerons, flaps, and other control surfaces. This allows us to change the wing area for different mission requirements and different Angles of Attack. Twisted wing without real-time twisting (active twist control) would be a problem since these wings have a negative impact on the lift and overall aerodynamic efficiency of the Aircraft [6]. Therefore, Wing morphing or Active twist control (ATC) would be a better choice than permanent twist [2]. Although the study done in this paper focuses only on twist and not on ATC.

Deflection of control surfaces during flight often promotes premature flow separation (at the hinge line through strong adverse pressure gradient development), reducing overall effectiveness and efficiency. The wing trailing edge can act as control surfaces with Active twist control or morphing wing in real time, solving the problem of adverse pressure gradient at the hinge line. In this paper, the solution is calculated by CFD analysis for different twist angles at the wingtip for different angles of attack (AOA) and resulting plots for Lift coefficient, drag coefficient, and aerodynamic efficiency for different AOAs. If there is an increase in aerodynamic efficiency, it would increase the range and endurance for both propeller-driven and jet engine aircraft [4].

The wing model designed in OPEN-VSP and modified in SolidWorks, CFD analysis was performed in Ansys Fluent. The wing model for CFD analysis was designed for a wing-alone configuration. Keeping in mind the stability perspective and making the CG of the wing ahead of the Aerodynamic center, which maintains static equilibrium. For an Aircraft to be statically stable, the pitching moment (C_m) slope must be negative, $\frac{dC_m}{dC_l} < \mathbf{0}$, which makes the Aircraft initially return to its equilibrium position, thus maintaining static stability[7]. To trim the Aircraft at a positive AOA, (C_m) must be positive for α=0. To maintain stability in a wing-alone configuration, we provide sweep to the wing of 30° to 40° for the Center of pressure to move behind the center of Gravity (COG). This might not create a positive initial moment, and there is a negative trim Angle of Attack (AOA), but since we do not have a horizontal tail, we must provide sweep to make the structure statically directional stable[8]. The wing configuration was theoretically designed and modeled in OPEN VSP. A cambered Airfoil was chosen NACA 23012[1-2, 9].

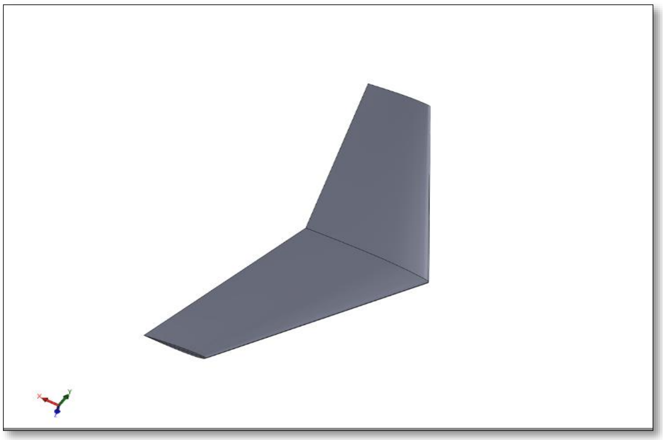


Figure-1 Wing Model

2. Wing Design

2.1. Airfoil and Wingdata

NACA 23012 was used for both the wing tip and root, with an optimum $C_L = 0.3$,, camber location at 15% of chord, and maximum thickness of 12% of chord. The wing tip chord is 0.8 ft, and the wing root chord is 1.6 ft, resulting in a Taper Ratio of 0.5. The twist angle was varied at the wing tip to create washout conditions, as the angle of attack at the wing tip is lower than that at the wing root.

Table-1Wing Configurations

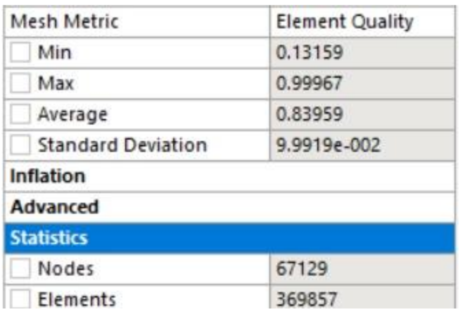
Wing span (b)	**5 ft**
Mean aerodynamic chord ($\bar{c}$)	1.2 ft
Taper ratio ((λ)	0.5
Sweep angle	30°
Airfoil	$NACA$ 23012
Wing Area (S)	6 ft^2

2.2. Grid Independent Study

Results such as lift and drag coefficients were analyzed for different numbers of mesh elements **[10]**. The results were found to be satisfactory for numbers of elements above 250,000, as the results remained nearly the same beyond this quantity of elements. The quality of the mesh obtained was 0.839, with a maximum quality of 0.999, utilizing 369,857 elements for the present CFD analysis.

Table-2 Grid Independent Study - Parameters

No. of Elements	C_l	C_D
116314	0.0419	0.00529
196929	0.0410	0.0054
244239	0.0414	0.0055
354640	0.0419	0.0054



Mesh Metric	Element Quality
Min	0.13159
Max	0.99967
Average	0.83959
Standard Deviation	9.9919e-002
Inflation	
Advanced	
Statistics	
Nodes	67129
Elements	369857

Figure-2 Details of Mesh Quality and Number of Elements

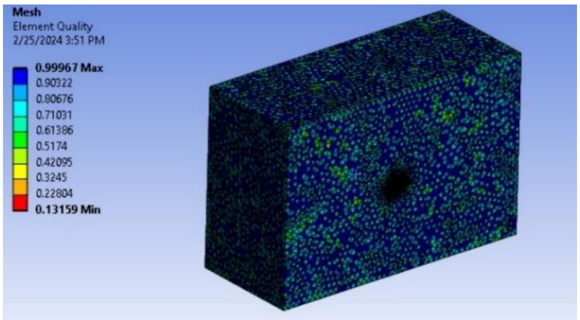


Figure-3 Element Quality

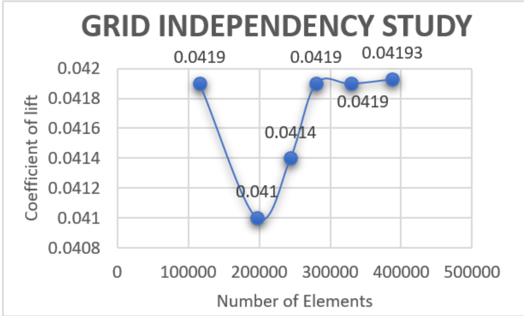


Figure-4 Number of Elements

2.3. Computational Domain and Boundary Condition

The model was analyzed using CFD with only half a wing, as the wing is symmetrical, which reduced computational time and power. For the computational domain, the length was set to 12 times the chord of the wing, which is 14 ft **[10]**. Boundary conditions were defined accordingly: the inlet velocity was set to 100 m/s with a pressure outlet. The model utilized the $viscous\ sst\ K\ omega$ method with two report definitions for lift force and drag force. The simulation ran for 800 iterations. Although the solution did not converge, consistent lift and drag coefficients were obtained convincingly. Twist angles of 2°, 6°, and 8° were observed with angles of attack (AOA) at 0°, 8°, 12°, 16°, 20°, 24°, and 28° for analysis. An interpolation method was then employed to generate a smooth and accurate curve, aiding in more efficient data analysis. Figure 5 depicts the computational domain for CFD analysis, with one side designated as a velocity inlet for air and the other side as a pressure outlet, while the remaining faces are set as default walls **[10]**.

Table-3 Models and their parameters observed

Model	$viscous\ sst\ K\ omega$
Velocity of the air flow	100 m/s
Twist angles analyzed	2°,6° and 8°
Angle of Attach Observed	0°,8°,12°,16°,20°,24°,28°
Number of Iteration for the result	800 iteration approx.

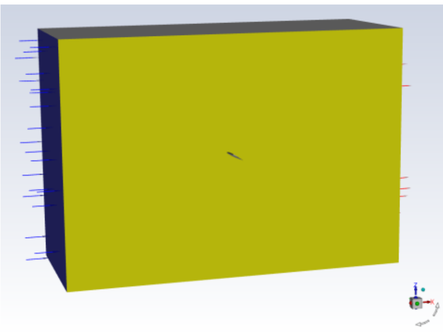


Figure-5 Computation Domain

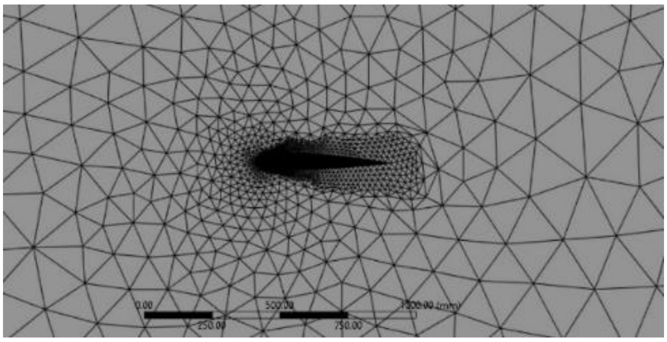


Figure-6 Mesh Model of Computational Domain

3. Results and Discussion

The results obtained were for a twisted wing model at the wing tip, simulating washout conditions, where the angle of attack (AOA) at the tip is lower than that at the wing root **[11]**. The rationale for choosing washout conditions for wing twist is that, as mentioned, it would delay the stall, and the ailerons and other control surfaces would be unaffected, since the stall would first occur at the wing root due to a relatively higher AOA compared to the wing tip. Although our focus is solely on the wing at present, and not on the vertical or horizontal tail where other important control surfaces are present **[12]**.

Results obtained after CFD analysis were recorded and analyzed. It was observed that the twist had a significant effect on wing performance parameters such as lift coefficient, drag coefficient, and aerodynamic efficiency. However, these significant changes were only observed at higher angles of attack (AOA); at lower angles of attack, the untwisted wing showed better results than the twisted one. Therefore, it is important to understand the effect of twist at lower AOAs as well, as they might not be as advantageous under these conditions.

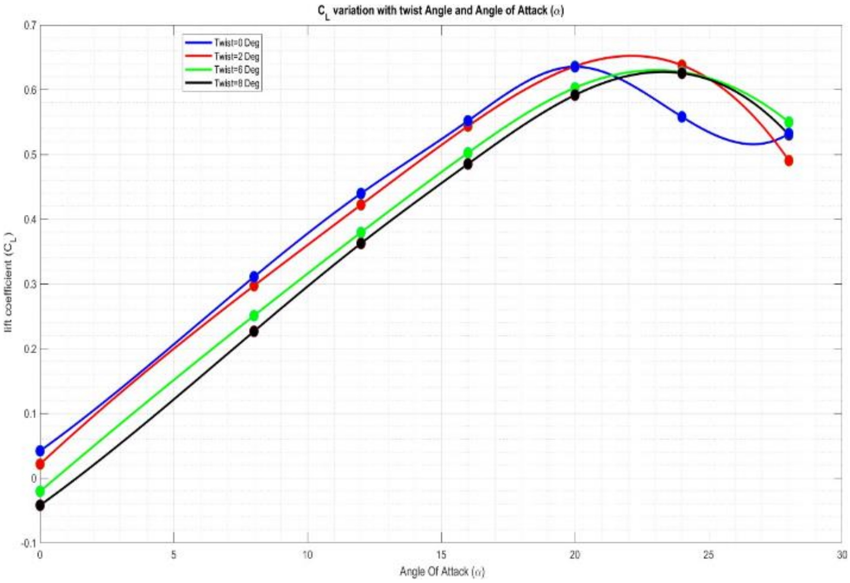


Figure-7 Plot of Lift Coefficient and Angle of Attack for Different Twist Angles

The lift curve slope was obtained for different twist angles of the wing tip at various angles of attack, as depicted in the graph. It is evident that wing twist for washout has a negative impact on lift at lower angles of attack (α=0°), resulting in negative lift. The occurrence of negative lift begins at a twist angle of 6°, with twist=8° yielding a negative lift of -0.0421 at α=0°. Twist offers no specific advantage at lower angles of attack, as all the lift coefficient values for the twisted wing are lower than those for the untwisted wing (refer to the lift coefficient graph). However, at higher angles of attack such as α >18°, it is observed that twist generates significantly higher lift compared to the untwisted wing. At α = 20°, twist = 2° becomes the Neutral Brink Angle; at this angle of attack, there is no difference between the twisted and untwisted wings, while for all other twist angles, the brink angle is greater than 20°. Additionally, it is observed that the stall angle increases (moves forward) for the twisted wing. The lift at 0° angle of attack (C_{L_o}) is observed to decrease as the twist of the wing tip (θ) increases; the higher the twist, the lower the (C_{L_o}). Twist angles of 0° and 2° yield a positive (C_{L_o}), whereas other twist angles result in negative lift coefficients or opposite lift produced on the wing.

Table-4 Stall Angles at Zero AOA and Stall Angle

Twist Angles	Lift at 0° AOA (C_{L_o}),	Stall Angle
0°	0.0419	20°
2°	0.02146	22°
6°	-0.02065	24°
8°	-0.0421	25°

As observed in the above table, the lift coefficient at zero angle of attack decreases and becomes negative as the twist angle increases, while the stall angle increases. Turning to the drag coefficient, another important parameter that determines the overall aircraft performance, it was observed that, in the graph of lift coefficient and angle of attack for different twist angles, the drag coefficient remained almost the same at lower angles of attack. It was noted that at zero angle of attack, the drag for the twisted wing is slightly greater than that for the untwisted wing, but the difference is not significant. As the angle of attack increases, the drag decreases for a twisted wing, while for an untwisted wing, it remains higher than the others.

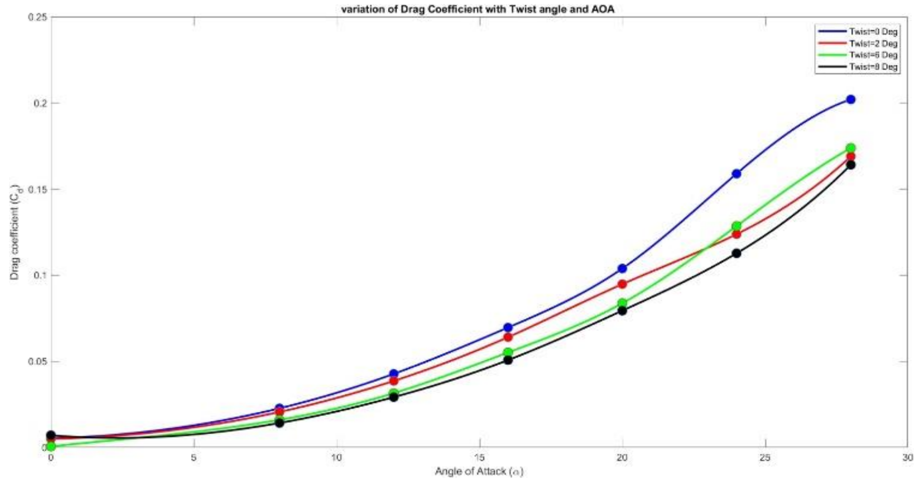


Figure-8 Drag Coefficient and AOA for different Twist Angles

To analyze aircraft performance more easily, parameters such as range and endurance are crucial. Both of these factors depend on the fuel fraction of the aircraft, which is the amount of fuel present before the flight takes off and at the end of a mission. They also rely on the aerodynamic efficiency of the aircraft, represented by the lift-to-drag (L/D) ratio **[4, 13]**.

$$R = \left(\frac{\eta}{c}\right)\left(\frac{l}{D}\right)\ln\left(\frac{w_{i-1}}{w_i}\right) \quad and \quad E = \left(\frac{\eta}{c}\right)\left(\frac{1}{v}\right)\left(\frac{l}{D}\right)\ln\left(\frac{w_{i-1}}{w_i}\right) \quad \text{For propeller driven aircraft……Eq (1)}$$

$$R = \left(\frac{v}{c}\right)\left(\frac{l}{D}\right)\ln\left(\frac{w_{i-1}}{w_i}\right) \quad and \quad E = \left(\frac{1}{c}\right)\left(\frac{l}{D}\right)\ln\left(\frac{w_{i-1}}{w_i}\right) \quad \text{For jet engine Aircrat…………………Eq(2)}$$

As seen in the Range and Endurance equations both contain $\frac{L}{D}$ terms, which effect the range of aircrafts directly. On case of propeller driven aircraft for range to be maximum $\left(\frac{C_L}{C_D}\right)_{max} = \left(\frac{L}{D}\right)_{\max}$ **[14]**, for Endurance to be maximum $\left(\frac{C_L^{\frac{3}{2}}}{C_D}\right)_{max}$ is condition. As $\frac{l}{D}$ increases Range and Endurance associated with it also increases.

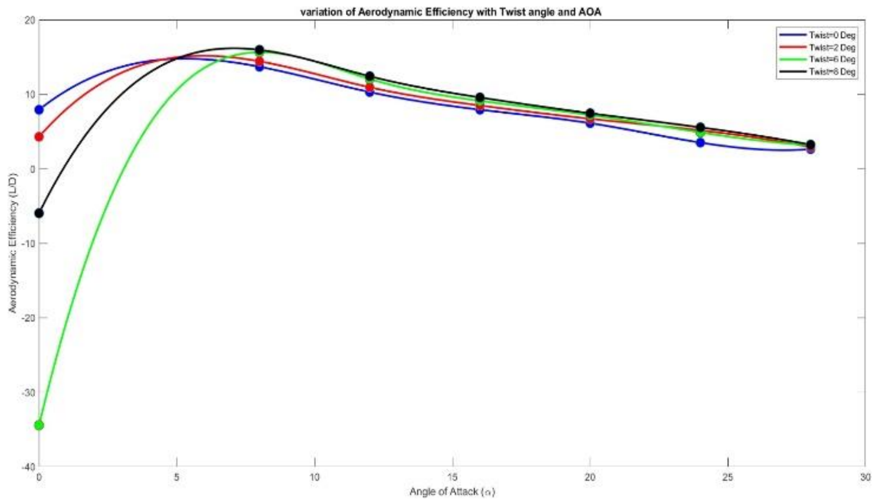


Figure-9 Variation of Aerodynamic Efficiency with AOA for Different Twist Angles.

The drag coefficient behaves differently with wing twist, leading to a considerable reduction in drag. As the aircraft surpasses an angle of attack of α=3, the drag decreases for the twisted wing configuration at a given angle of attack, even at higher angles of attack as depicted in the drag coefficient graph. Both lift and drag coefficients directly impact the aerodynamic efficiency of the aircraft. Since aerodynamic efficiency is represented by the lift-to-drag ratio $\frac{L}{D} = \frac{C_L}{C_d}$ **[15]**, the obtained graph would aid in analyzing the aircraft's performance in terms of range and endurance. It's known that both propeller-driven and jet engine aircraft rely on the aerodynamic efficiency of the aircraft for their range and endurance. As shown in figure 6, initially at α=0, the aerodynamic efficiency for the untwisted wing is higher than for others. However, as the angle of attack increases, the L/D ratio of the untwisted wing decreases slightly, while the one with twist performs better, albeit with a small variation. Figure 8 illustrates the variation of aerodynamic efficiency with different angles of attack and twist angles. Initially, the aerodynamic efficiency for the untwisted wing is better than for the twisted one. However, as the angle of attack increases, the L/D ratio slightly favors the twisted wing, improving with an increase in twist angle, thus enhancing the overall range and endurance for both propeller-driven and jet engine aircraft. Figure 10 displays the airflow analysis of Airfoil 23012.

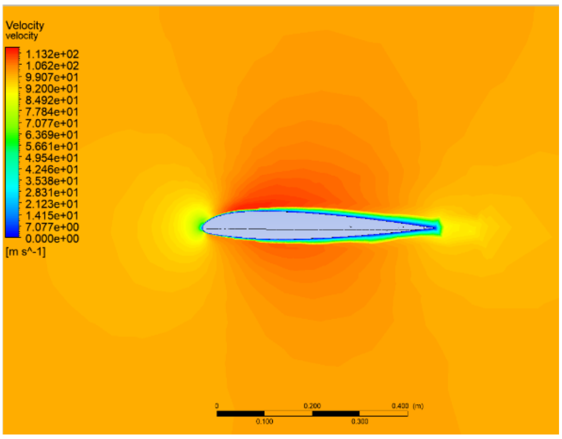


Figure-10 Airflow over 23012 Airfoil

The data of lift and drag coefficients were calculated from CFD for some values of α , then interpolation method was used to get a smoother curve. The airfoil 23012 with 0.3 as design lift coefficient but for case of 2d, whereas 3D airfoil as altogether different C_L **[15]**.

$$C_{L3d} = \frac{C_{L2d}}{1 + \left(\frac{C_{L2d}}{\pi e AR}\right)}$$

Where AR refers to the wing aspect ratio and e is Ostwald's constant. The overall lift coefficient is lower in a 3D case or for a case involving a wing. The design lift coefficient in NACA 23012 is specific to either an airfoil or a wing. Figure 10 illustrates the typical airflow over the airfoil, while airflow over the wing is depicted in figures 10 through 15. The boundary layer remains constant at 16° for different twist angles, as shown in the figures. The airflow separates near the wing root and moves towards the wing root, a phenomenon that remains consistent with increasing twist angles. However, at higher angles of attack and twist angles, the boundary layer flow separation is slightly less compared to untwisted wings. This suggests that untwisted wings are more efficient for higher angles of attack, as observed in the graph of aerodynamic efficiency.

It is evident from the CFD results above that twisting the wing is not a suitable choice at lower angles of attack but is more efficient at higher angles of attack. Airliners and commercial aircraft typically do not exceed more than 15 to 20 degrees, making the twist configuration less efficient. The main utility of twisted wings would be in fighter aircraft for maneuvering and during combat. However, since twisted wings negatively impact the lift coefficient, their practical use is limited. Additionally, the manufacturability of twisted wings is more difficult and costlier than that of untwisted ones. Another important point is that since the twist is at the wingtip, it becomes challenging to manufacture and control control surfaces such as ailerons and flaps.

It's also crucial to note that due to the twist of the wing, stall conditions first occur at the wing root rather than the wingtip. Control surfaces located at the trailing edge of the wingtip become difficult to control during stall conditions. However, if the stall occurs at the root first rather than the tip, it is easier to control the control surfaces and bring them back to a stable equilibrium position. This is due to the twist, which reduces the effective angle of attack of the wingtip compared to the effective angle of attack of the wing root.

4. Velocity Contours for Different Twist Angles

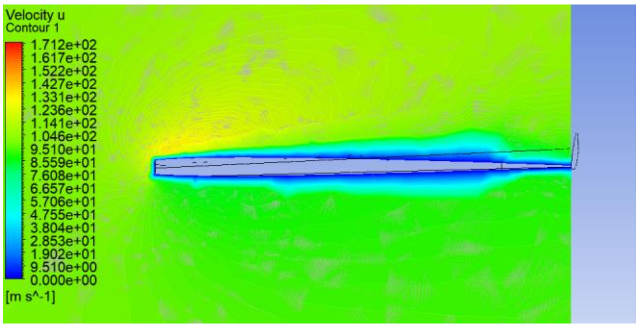


Figure-11 Twist Angle 0 Degree

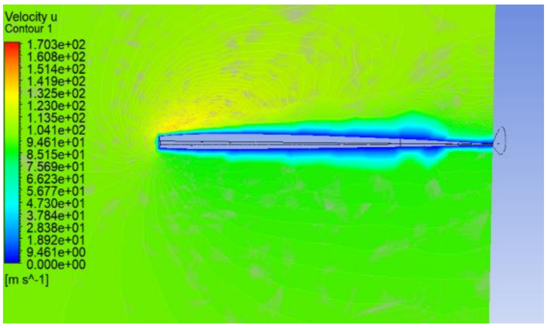


Figure-12 Twist Angle 2 Degree

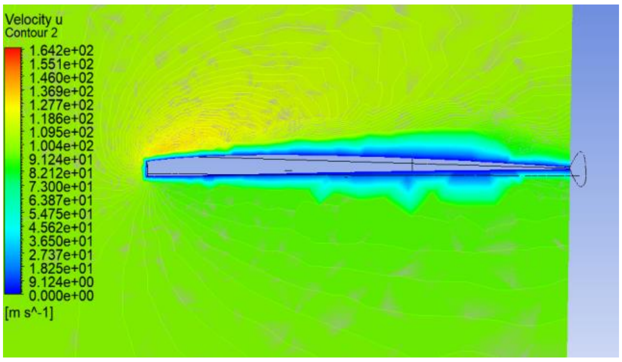


Figure-13 Twist Angle 6 Degree

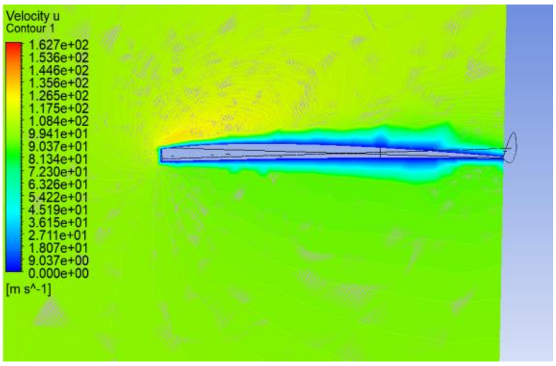


Figure-14 Twist Angle 8 Degree

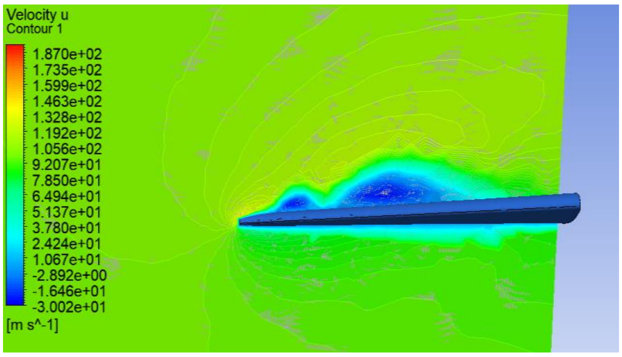


Figure-15 6-Degree Twist at 24-degree AOA

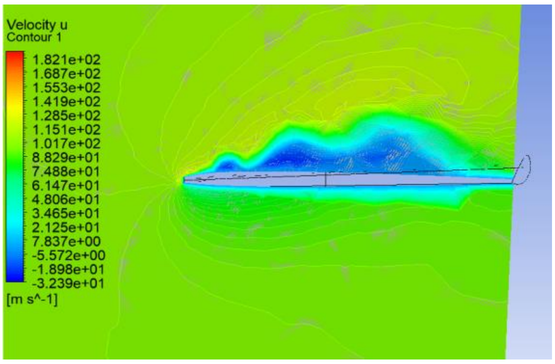


Figure-16 Untwisted Wing at 24 AOA

As observed, the boundary layer separation for an untwisted wing is greater than that for a wing with a 6° twist at the same angle of attack (here, 24°). Although twist plays an efficient role at higher angles of attack, it has a negative impact on both lift and drag coefficients at lower angles of attack.

One solution for using wing twist at higher angles of attack is by employing morphing wing technology. A morphing wing offers greater competitiveness compared to conventional fixed-wing designs, as it enables an airplane to perform multiple tasks effectively. An airplane equipped with a morphing wing can alter the geometric shape of its wing during flight, optimizing its performance according to mission requirements. Despite the potential to enhance energy efficiency in airplanes, there are still several issues with wing-morphing technology that need resolution before full implementation can be achieved. Nonetheless, morphing wings will undoubtedly play an essential role in the future of aviation due to their exceptional benefits for airplanes.

Most airplanes today feature conventional fixed-wing designs, which excel at specific tasks but perform poorly in others. For example, an unmanned airplane often needs to switch between loitering and attacking roles within a mission. However, these tasks have conflicting design requirements, and the most efficient way to optimize the airplane's performance is by adjusting the wing shape during flight using morphing technology **[3]**.

5. Plots for Coefficient of Pressure

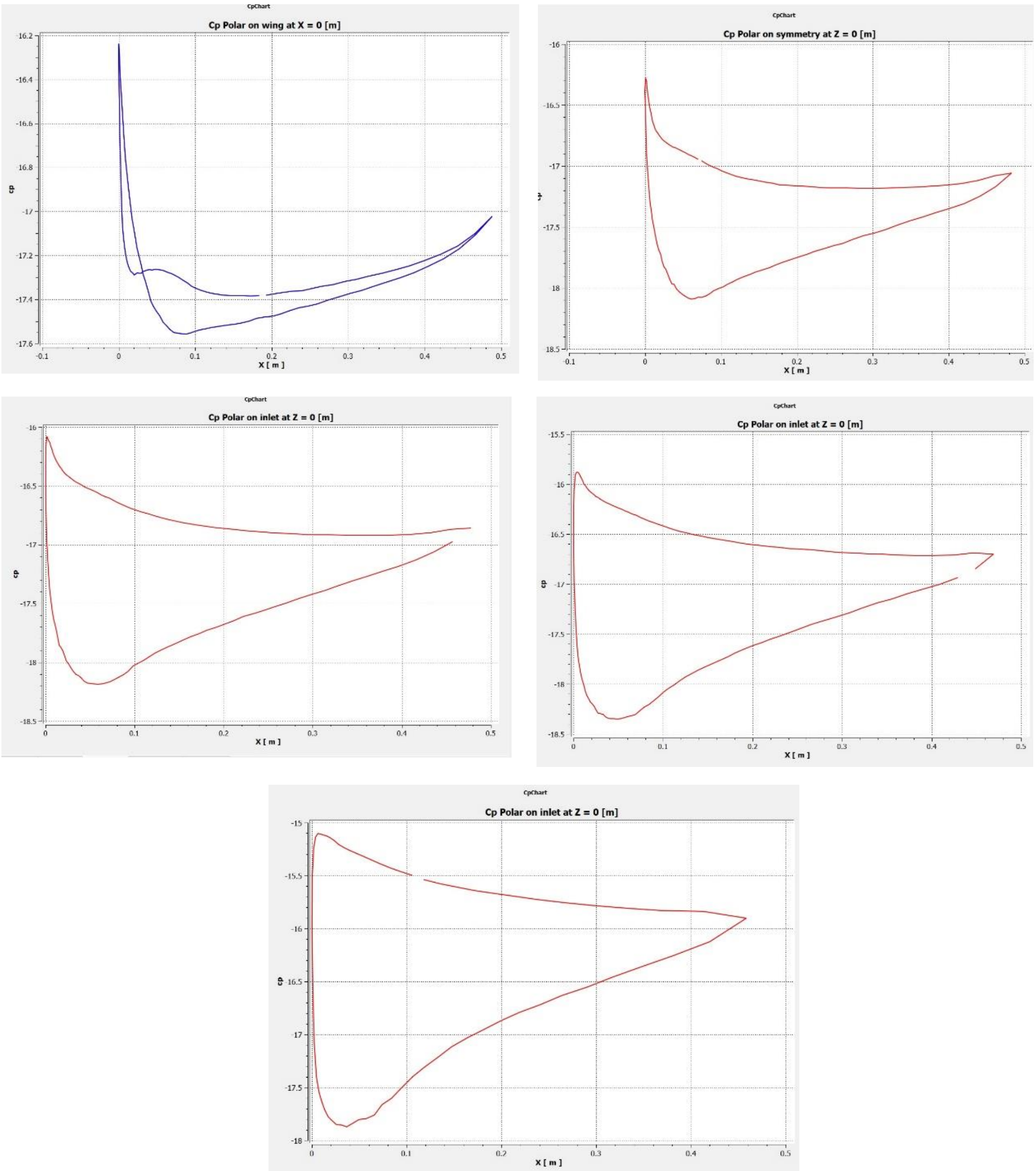


Figure-17 Plots of pressure coefficient over the chord of wing for different AOA. These pressure coefficients are for an untwisted wing (twits = 0).

6. Conclusion

In conclusion, the discussion above provides compelling evidence to support the notion that wing twisting yields greater advantages at higher angles of attack. This paper offers a comprehensive understanding of the impact of wing twist on aircraft performance. The findings reveal improvements in aerodynamic efficiency at higher angles of attack, alongside negative lift coefficients during lower angles of attack. Moreover, the presence of wing twist diminishes boundary layer separation at higher angles of attack. This concept of wing twist has spurred the development of Wing Morphing Technology, which enhances aircraft performance during combat and maneuvering scenarios. By allowing airplanes to adjust their wing shape mid-flight, akin to birds altering their wing positions for various tasks, morphing technology aims to optimize fuel efficiency and maneuverability. In the future, wing morphing technology is poised to become a leading concept for enhancing aircraft performance through structural modification. Furthermore, it reduces reliance on ailerons, flaps, and other control surfaces for aircraft control.

Through CFD analysis, it is evident that the lift coefficient C_L at α=0° is lower (and even negative) for twisted wings, with further decreases as the twist angle increases. Twisted wings exhibit disadvantages at lower angles of attack, where the lift is negative. While wing twisting shows minimal impact on drag at lower angles of attack for lower twist angles, an increase in twist leads to a rise in parasitic drag. Despite the lack of positive effects on aerodynamic parameters at lower angles of attack, twisted wing configurations demonstrate positive lift and drag coefficients at higher angles of attack. This translates to increased lift and decreased drag for twisted wings at higher angles of attack, ultimately enhancing overall aerodynamic efficiency.

7. References

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8. Biography

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10. Conflict of Interest

The authors declare no competing conflict of interest.

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