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Effects on Aircraft Peformance Due to Geometrical Twist of Wing

[1]Prajwal N, [2]Kushal Chatterjee
[1]Aerospace engineering student, R V College of engineering, Bengaluru
[2]Aerospace engineering student,R V College of engineering, Bengaluru

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ABSTRACT: This paper gives an overview about effects of Geometric Twist on Aircraft performance involved in an aircraft wing to create wash out condition. This creates effective Angle of Attack of tip of wing lesser than wing root's angle of attack. The variation of factors of an aircraft performance like lift, drag coefficients and aerodynamic efficiency with varying angle of attack with different Twist angles are calculated by CFD analysis, a plot of lift and drag coefficient with different Angle of attack has been obtained. These results of wing twist variation could help us understand its advantages, especially at higher angle of attack. One of the main advantages of Geometric Twist of wing tip Angle of Attack being lesser than the wing root is that the stall conditions first occur at the root which signals the pilot and control the aircraft before the stall reaches the wing tip and reduces the effectiveness of control surfaces which are present in wing trailing edge (Ailerons, Flaps, etc.). Comparison is done on the lift, drag coefficients and the aerodynamic efficiency of Twisted wing is done with that of untwisted wing with same parameters. Though the twisting of wing tip provides good results at higher Angle of Attack (AOA) compared to an untwisted wing, but at lower AOA aerodynamic efficiency of wings decreases making it less efficient at lower AOA. Applying the twist angle at high angles of attack, such as 10, 12.5, 15 and 20 degrees, increases the aerodynamic efficiency

Index terms: geometrical twist, Morphing wing,Aerodynamic efficiency

I. INTRODUCTION

Wing as one of the primary lift producing devices in an Aircraft plays important role while maneuvering, cruising, liftoff, and take-off. The pressure difference above and below the wing produces a net upward force. It is important to analyses and optimize the design of the wing to improve the 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 wing trailing edge forward sweep is provided[1]. One of the methods to increase the performance of Aircraft is WING TWISTING. Application of this wing twisting is morphing wing technology. This refers to changing the wing span area at different Angle of Attack (AOA). One of the most effectual morphing ideas is wing-warping or the ability to actively change the spanwise wing twist distribution[2]. Here we refer to the wing twisting at wing tip. The twisting of wing tip in a negative angle would make the chord line of wing root and wing tip oriented at different angles to fuselage reference line[3]. Due to this twisting the Effective Angle of attack (AOA) of wing tip is lesser than wing root.

At higher Angle of Attacks (AOA), due to increase in pitching Angle there is increase in lift coefficient initially. But as AOA crosses a particular Angle, the flow over wing separates, called Boundary layer separation which decreases the lift abruptly[4]. This condition is called Stall, after this $\alpha = \alpha_{stall}$ the lift decrease continuously. This is one of the major problems not in civil Aircrafts but in fighter Jets where the α need to go more than α_{stall} for maneuvering[5]. It is very important to solve this problem of the stall conditions, either by increases the Stall Angle or minimize the rate of decrease of lift after stall conditions.

This type of twisting of wing where there is physical twist in wing due to wing tip twist which need to be manufactured, this type of twisting of wing where wing is twisted to a particular Angle is called Geometrical twist[6]. Another type of twist of wing which include using of different airfoils at wing tip and wing root which is called as Aerodynamic twisting of wing[4].

Aerodynamic twist having two different Air foil without actual geometrical twisting provide ease of manufacturing compared to Geometrical twist of wing, there is also no large increase in drag as compared to other. The effective Angle of attack of horizontal tail is decided by the flow of wing trailing edge, due to twist the washout (ϵ) at 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 wing tip, twist is downwards with a negative angle with respect to fuselage reference line. This washout conditions occur when the Angle of Attack of tip is lower than the Angle of attack of wing root. Initially at lower angle of attacks Parasitic drag increases due to form of wing twist at tip. This throws a major problem that twisted wing configuration have a negative impact on lift, as lift is negative and drag increases.

This would make the wing root stall first rather than wing tip, since Ailerons are present at wing tip it is important to prevent the area from stalling which would decrease the effectiveness of ailerons [2]. Therefor the wing root is made to stall first, which would have no effect the control surfaces. Twisted wing throws a greater challenge in manufacturing, maintaining surface continuity before, during and after transition (to achieve best aerodynamic performance) further complicates this trade-of. This concept led to morphing wing, which changes the wing area (shape) in real time which would decrease the dependency on Ailerons, flaps, and other control surfaces. This allows us to change the wing area at for different mission requirements and different Angle 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 better choice than permanent twist[2]. Although the study done in this paper is focusses 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. 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 hinge line. In this paper solution is calculated by CFD analysis for different twist angles at wing tip for different angle of attack (AOA) and resulting plots for Lift coefficient, drag coefficient and Aerodynamic efficiency for different AOA. 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 the Aerodynamic center, which maintains the static equilibrium. For an Aircraft to be statically stable the pitching moment (C_m) slope must be negative, $\frac{dC_m}{dC_l} < 0$, which makes the Aircraft to initially return to its equilibrium position, thus maintaining static stability[7]. To trim the Aircraft at positive AOA, C_m must be positive for $\alpha = 0$. For to maintain stability in 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 static directional stability[8]. The wing configuration was theoretically designed from reference [1] and [2] and modelled in OPEN VSP. A cambered Air foil was chosen NACA 23012[9].

II. WING DESIGN

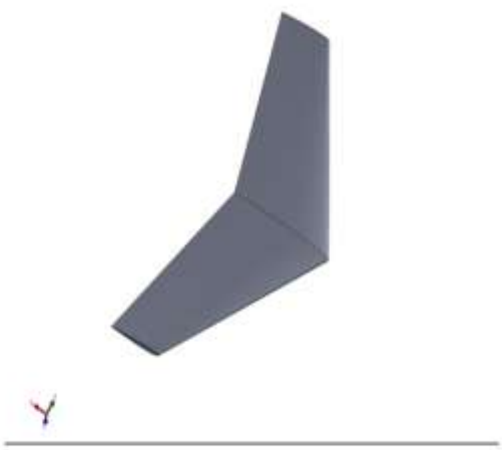

Figure 1 WING MODEL

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1.1. AIRFOIL AND WING DATA

NACA 23012 was used for both wing tip and root, having optimum $C_L = 0.3$, Camber location 15% of chord and maximum thickness is 12% of chord. Wing tip of chord is 0.8 ft and wing root chord is 1.6 ft, giving rise to Taper Ratio 0f 0.5. The twist angle was varied in the wing tip to create washout conditions, since AOA in wing tip is lesser than that of the wing root.

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)	$6\ ft^2$

Table 1 WING CONFIGURATIONS

III. GRID INDEPENDENT STUDY

Results like lift and drag coefficient were analyzed for different number of elements of mesh[10]. The obtained results were satisfactory for number of elements above 250000 since the results obtained were nearly same after this quantity of elements. The quality of mesh obtained was 0.839 with maximum quality of 0.999, with elements of 369857 for present CFD analysis.

Table 1 grid independent Study

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	
Average	0.83959
Standard Deviation	9.9919e-002
Inflation	
Advanced	
Statistics	
Nodes	67129
Elements	369857

Figure 3element quality

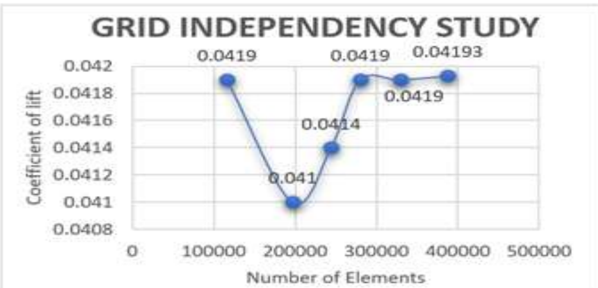

Figure 2 Mesh quality and Number of elements

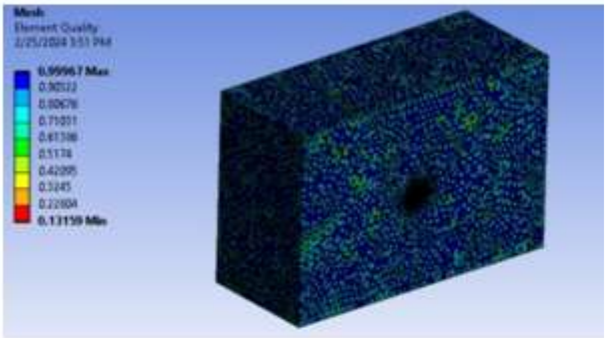

Figure 3Element quality

IV. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The model was analyzed using CFD with only half a wing since the wing is symmetrical, which would decrease the computational time and power. For the computational domain, the length of domain was 12 times the chord of the wing which is $14\,ft$ [10]. The boundary conditions were defined according to, the inlet velocity was $100\,m/s$ with pressure outlet. The model used is $viscous\ sst\ K\ omega$ with two report definitions of lift force and drag force. The simulation was run for 800 iterations. Though the solution was not converged, but a convincing constant lift, drag coefficients were obtained. The twist angles observed were $2°, 6°\ and\ 8°$ with AOA of $0°, 8°, 12°, 16°, 20°, 24°, 28°$ for analysis, then interpolation method was used to get a smooth and accurate curve, help us to analyze data more efficiently.The figure 6 shows the computational domain for CFD analysis with one side as velocity inlet for Air and other side is a pressure outlet, other faces are made as default walls[10].

MODEL	$viscous\ sst\ K\ omega$
VELOCITY OF THE AIR FLOW	$100\,m/s$
TWIST ANGLES ANALYSED	$2°, 6°\ and\ 8°$
ANGLE OF ATTACK OBSERVED	$0°, 8°, 12°, 16°, 20°, 24°, 28°$
NUMBER OF ITERATION FOR THE SOLUTION	$800\ iteration\ approx.$

Table 2 FLUENT INPUT FOR CFD ANALYSIS

Figure 4 computational domain

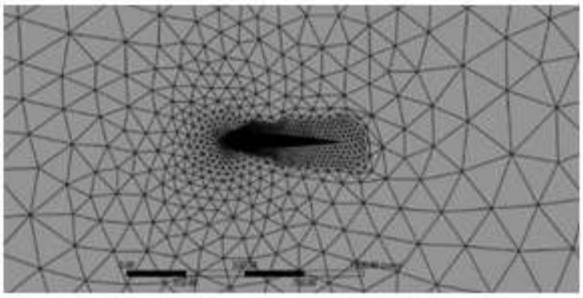

Figure 5 Meshed Model of Computational Domain

V. RESULTS AND DISCUSSIONS

The results obtained were for a twisted wing model at the wing tip for a washout conditions, which would result in a Angle of Attack (AOA) of tip to be lower than that of wing root[11]. The reason for choosing washout Condition for wing twist is that as mentioned, this would delay the stall and the Ailerons and other control surfaces would be unaffected, since the stall would first occur at wing root due to relatively higher AOA compared to wing tip. Although in present we focus only on wing and not on 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 like lift coefficient, drag coefficient and on Aerodynamic efficiency. But these significant changes were only observed at a higher Angle of Attack (AOA), at lower angle of attack untwisted wing showed a better result than the twisted one. Therefore, it is important to understand the effect of twist at lower AOA also as they might be not so advantageous at these conditions.

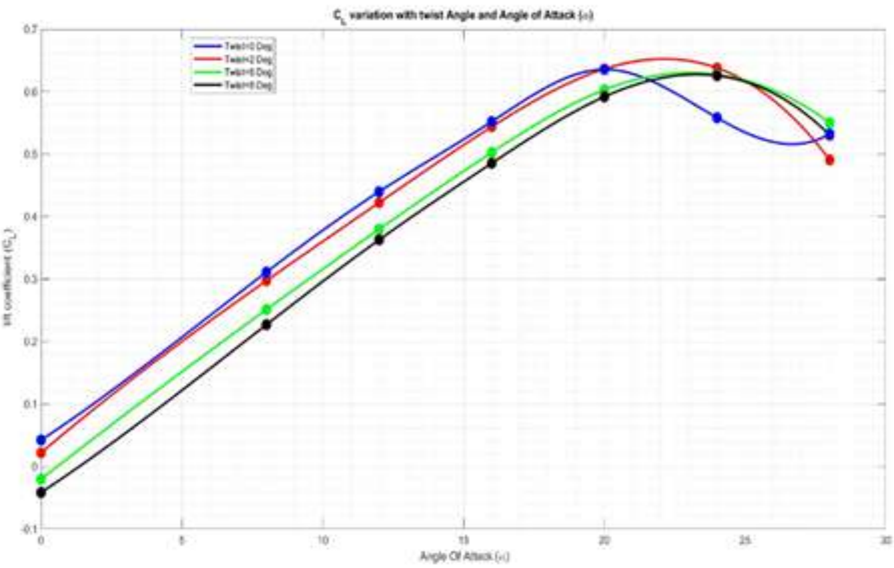

Figure 6 plot of lift coefficient and Angle of Attack for different twist Angles

The lift curve slope was obtained for different twist angles of wing tip with different angle of Attack as seen in the graph. As it can be observed that twist of wing for washout has a negative impact on lift at lower angle of attack($\alpha = 0°$) giving negative lift. The negative lift starts from the twist angle of $6°$, $twist = 8°$ have a negative lift of -0.0421 at $\alpha = 0°$. Twist provides no specific advantage at lower Angle of Attack, since all the lift coefficient values for twisted wing are lower than the untwisted one (refer lift coefficient graph). But at higher Angle of Attack such as $\alpha > 18°$ it is observed that twist produced considerably higher lift compared to untwisted wing. $\alpha = 20°$ becomes the Neutral Brink Angle for $twsit = 2°$, at this AOA there is no difference between the twisted and the untwisted wing,for all other twist Angles brink Angle is greater than $20°$.

It is also observed that the stall Angle increases (move forward) for twisted wing. The lift at 0° AOA $\left(C_{L_o}\right)$ is observed to be decreasing as the twist of tip(θ) of wing increases, higher the twist lower is the C_{L_o}. For $\theta = 0°\ and\ 2°$ have a positive C_{L_o} whereas, other twist Angles have negative lift coefficient or opposite lift in produced on the wing.

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°

Table 2 stall Angles at zero AOA and stall Angle

As observed in the above table Lift coefficient at Zero AOA decreases and becomes negative as twist angle increasing, but the stall Angle increases. Coming to drag coefficient,another important parameter which determine the overall Aircraft performance. As observed the graph of lift coefficient and AOA for different twist Angles, drag coefficient observed to be almost same at lower Angle of Attack, there was observed that at zero AOA the drag for twisted wing is slightly greater than untwisted but not much difference. As the AOA increases drag decreases for a twisted Wing and for that of an untwisted remains higher than others.

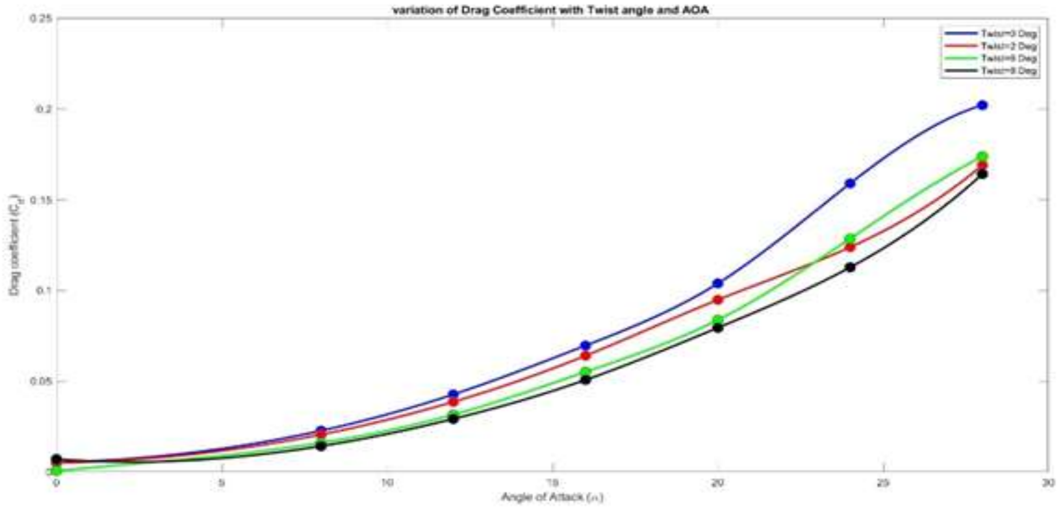

figure7 drag coefficient and AOA for different twist Angles

To analyze Aircraft performance easier parameters are to the range and endurance of an Aircraft, although these both depend on the fuel fraction of the Aircraft that is the amount of fuel present before the flight took off and at the end of a mission. They also depend on Aerodynamic efficiency of the Aircraft, that is the $\frac{L}{D}$ ratio[4], [13].

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

$$R = \left(\frac{v}{c}\right)\left(\frac{l}{D}\right)\ln\left(\frac{W_{i-1}}{W_i}\right) \quad \text{and} \quad E = \left(\frac{1}{c}\right)\left(\frac{l}{D}\right)\ln\left(\frac{W_{i-1}}{W_i}\right) \quad \text{for jet engine Aircrat} \ldots\ldots\ldots \text{Eq}(2)$$

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.

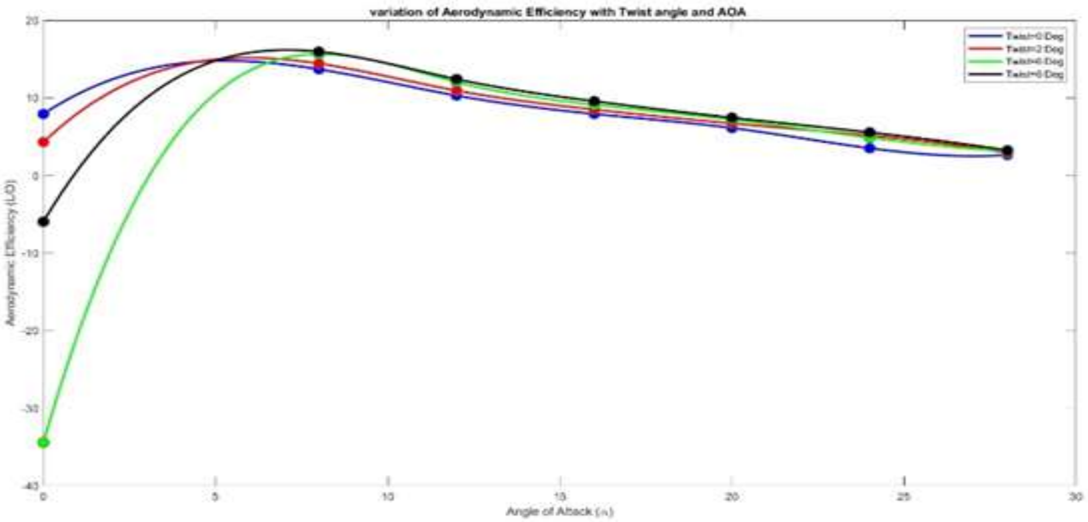

Figure 8 Variation of Aerodynamic Efficiency with AOA for different twist Angles

Thedrag coefficient acts differently and twist of wing provide a considerably reduction in the drag. As aircraft crosses the mark of $\alpha = 3$ the drag reduces for the twisted wing configuration for a given Angle of Attack, and even at the higher AOA as seen in the graph of drag coefficient. Lift and drag coefficient directly affect the Aerodynamic efficiency of the Aircraft. Since aerodynamic efficiency is $\frac{\mathbf{L}}{\mathbf{D}} = \frac{\mathbf{C_L}}{\mathbf{C_d}}$[15], the graph obtained would help analyze the performance of aircraft for it Range and Endurance, as range and endurance for both propeller driven and jet engine aircrafts depend on the Aerodynamic Efficiency of that Aircraft.as seen in the figure 5, initially at $\alpha = 0$ the aerodynamic efficiency for untwisted wing is higher than others, as the AOA increases $\frac{L}{D}$ ratio of untwisted wing decreases slightly and one with twist perform better though a small variation.

Figure 8 shows the variation of Aerodynamic Efficiency with different AOA and twist angles, initially the Aerodynamic efficiency for untwisted wing is better than the untwisted one. But as the AOA increases L/D ratio is slightly better for the twisted wing, it becomes better with increase of twist Angle, which improves the overall Range and Endurance for both propeller driven and jet engine aircraft. Airflow analysis of Airfoil 23012 is shown in figure 9.

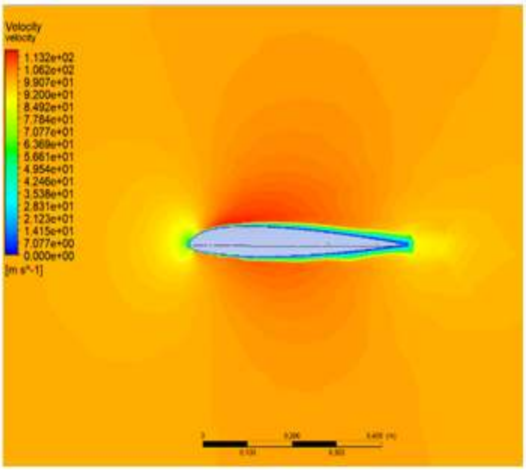

Figure 9 Airflow over 23012 Airfoil

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 the Ostwald's constant. The overall $C_L$is less in 3d case or for a case of a wing. Design lift coefficient in NACA 23012 is the design lift

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coefficient for a case of Airfoil or a wing with a Figure 9 shows the typical Airflow over the Airfoil. Airflow over the wing is displayed from figure 10 to figure 15. The boundary layer for a constant 16° for different Twist angles can be seen in the figures, the airflow separates near tip root and moves towards the wing root, this remains almost same with increase in the twist angles. But considering at higher angle of Attack and higher twist angles the boundary layer flow separation is slightly less compared to untwisted wings. This gives us an idea that untwisted wing are more efficient for higher angle of attacks as seen in graph of Aerodynamic efficiency.

It is clear from the above CFD results that the twisting of wing is not a suitable choice at lower angle of Attack, but more efficient at higher angle attacks. The Airliners and commercial Aircrafts does not exceed more than 15 to 20 degrees, and therefore the twist configuration is not more efficient. The main use of twisted wing would be in Fighter Aircrafts for maneuvering and during combats. But since twisted wing has a negative impact on lift coefficient, it is not practical using them. Secondly the manufacturability of twisted wing is more difficult and costlier than the untwisted one. Third important point is since the twist is at wing tip it becomes difficult for control surfaces such as Ailerons and flaps to manufacture and control them.

It is also important to note that due to twist of wing the stall conditions first occur at wing root rather than wing tip. The control surfaces are present in trailing edge of wing tip due to the stall it becomes difficult to control them. But if the same stall occurs at root first rather than tip it is easier to control the control surfaces and bring it back to the stable equilibrium position. This is due to the twist, which make the Effective angle of Attack of wing tip lesser than the effective Angle of Attack of wing root.

1.2. VELOCITY CONTOURS FOR DIFFERENT TWIST ANGLES

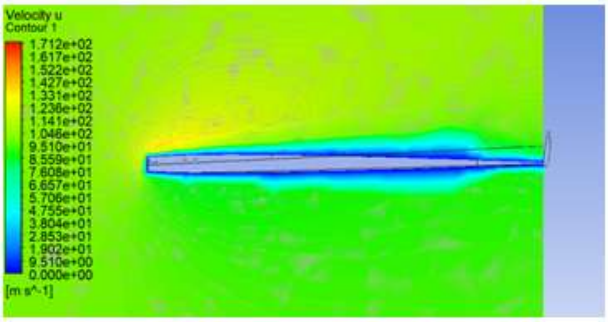


Figure 10 twist Angle 0 degree

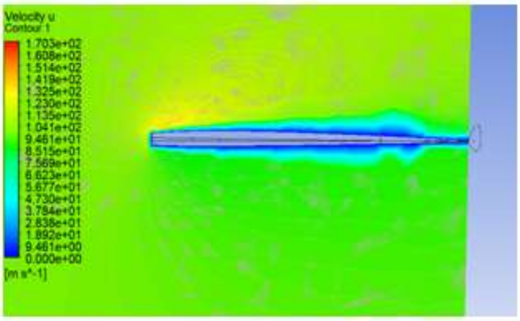


Figure 11 twist Angle 2 degree

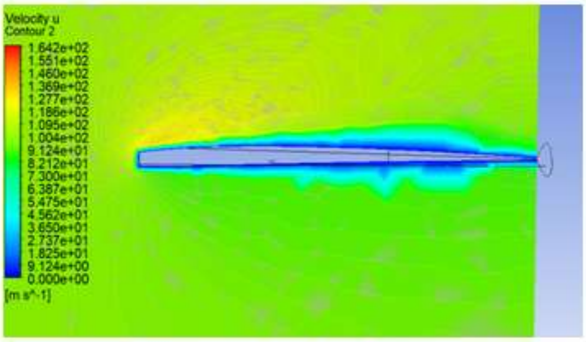


Figure 12 twist Angle 6 degree

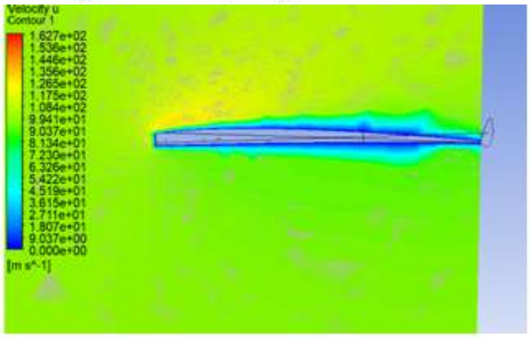


Figure 13 twist Angle 8 degree

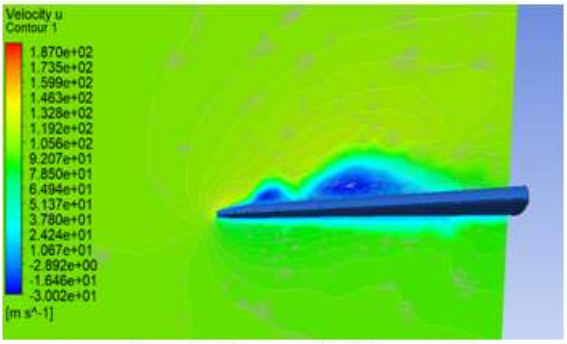


Figure 14: 6-degree twist at 24-degree AOA

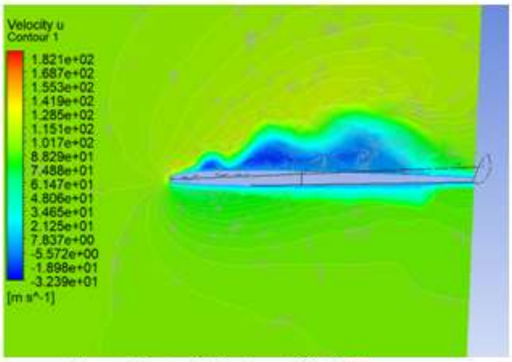
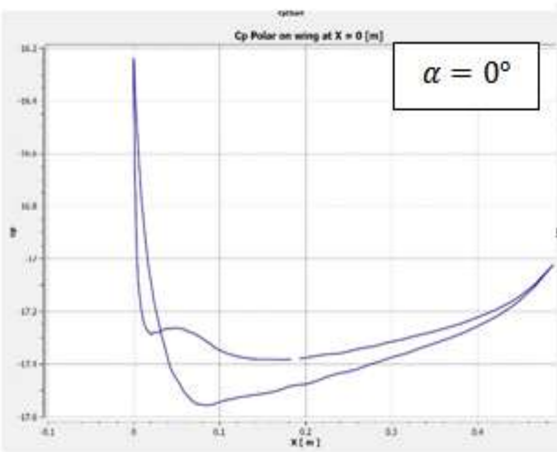


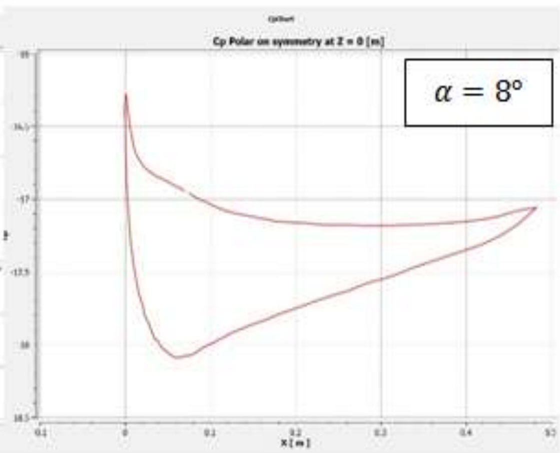
Figure 15:untwisted wing at 24 AOA

As observed the boundary layer separation for an untwisted is more than a 6° twist for a given same AOA (here is 24°). Although twist plays an efficient role at higher Angle of Attack, but have a negative impact on both lift and drag coefficient at lower Angle of Attack.

Solution for using Wing twist at higher angle of attack is by using Morphing wing technology.A morphing wing is more competitive compared to the conventional fixed-wing design as it allows an airplane to perform more tasks effectively. An airplane with a morphing wing can change the geometric shape of its wing during flight and optimize its performance based on mission requirements. Despite the ability to improve airplanesenergy efficiency, there are still many issues with the wing-morphing technology that need to be resolved before it can be fully implemented. Nevertheless, a morphing wing will certainly play an essential role in the future of aviation because of the exceptional benefits it has for airplanes.Most airplanes today have the conventional fixed-wing design that only allows airplanes to do one thing very well, but perform poorly in many other tasks [3]. For instance, an unmanned airplane often needs to switch between loiter and attack role in a mission. However, the two tasks contradict each other in terms of their design requirements, and the only way to optimize the airplane's efficiency is by changing the wing shape in flight through morphing technology.

1.3. PLOTS FOR COEFFICIENT OF PRESSURE





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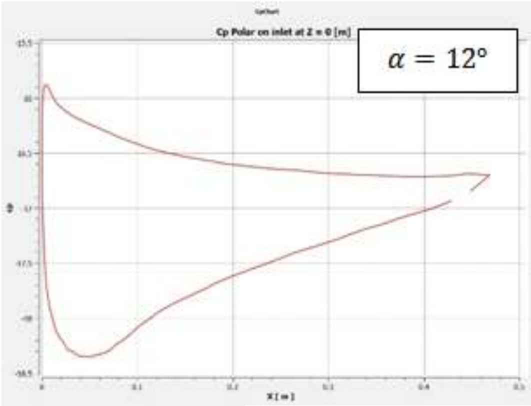

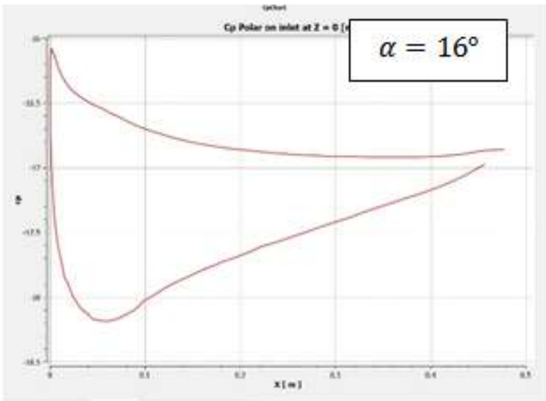

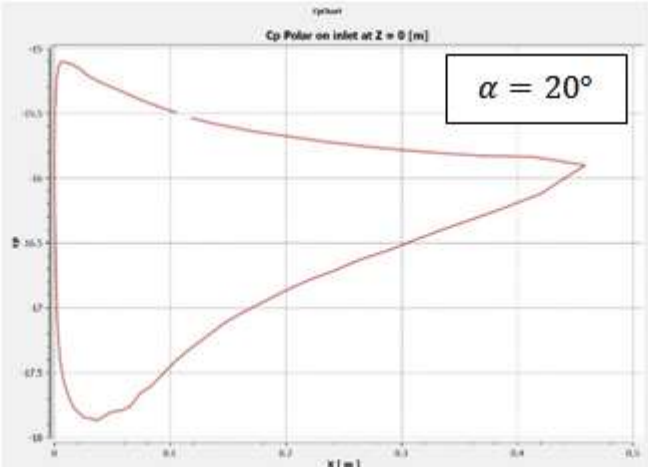

Above graph shows the Plots of pressure coefficient over the chord of wing for different AOA.These pressure coefficients are for an untwisted wing (twits = 0).

VI. CONCLUSION

Above discussion provides data to prove that wing twisting is more advantageous at higher angle of Attack, this paper gives a clear understanding about the effects of Aircraft performance due to wing twist. There are increases in Aerodynamic efficiency at higher AOA and negative lift coefficient during lower angle of attack. The boundary layer separation decreases at higher AOA with twist provided. This wing twist concept led to the development of Wing Morphing Technology, which primarily increases the Aircraft Performance during combat and maneuvering.It allows airplanes to operate efficiently under different flight conditions by changing the wing shape in flight, just like birds who change their wing positions to perform different tasks. The goal of morphing technology is to optimize airplanes' fuel efficiency and maneuverability. In future, wing morphing technology would be one of the leading Concept for better performance of Aircraft in terms of structural modification. The morphing technology also reduces the dependency on Ailerons, flaps, and other control surfaces for controlling the Aircraft.

As per the results obtained through CFD analysis it is observed that lift coefficient C_L at $\alpha = 0°$ is lower (negative) for twisted wing, it becomes more negative as the twist angle increases. At lower AOA twisted wing are observed to be disadvantageous since the lift is negative. Twisting of wing as no significance over drag at lower angle of attack for lower twist angles, but as the twist increases parasitic drag also increases. Though there is no positive effect of wing twist on Aerodynamic parameters at lower AOA, but at higher AOA both lift and Drag coefficient are on positive side for twisted wing configuration. That is lift increases for twisted wing at higher angle of attack (AOA) and drag decreases for a significant level. Overall Aerodynamic efficiency of wing also increases for a twisted wing.

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