ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 9, Issue, 06, pp.52513-52521, June, 2017

INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

RESEARCH ARTICLE

SWEPT WING AERODYNAMICS AT TRANSONIC SPEEDS AND AT DIFFERENT TURBULENCE LEVELS

[*,1]Balaji, R. and [2]Dr. P. K. Dash

[1]Research Scholar, JNTUH, Hyderabad
[2]Professor Institute of Aeronautical Engineering, Hyderabad

ARTICLE INFO

Article History:
Received 23rd March, 2017
Received in revised form
08th April, 2017
Accepted 14th May, 2017
Published online 30th June, 2017

Key words:

Swept wing,
Angle of Attack (AOA),
0.7Mach,
0.9Mach,
3D wing,
K-ω SST Turbulence model,
Lift,
Drag.

ABSTRACT

Swept wings are widely used in commercial Aircraft's to cruise at transonic speeds with drag comparatively less than straight wings at transonic speed conditions. On the other hand trainer aircrafts both for commercial and defence trainings are preferred with swept wings to attain higher critical Mach speeds which is very less in straight wing trainer Aircraft's. Swept wings are preferred for its high lift to drag ratio low speed takeoff conditions and for near sonic flight operating conditions. Much research work on swept wings were done in past and many more are being carried out by different research centres around the globe and aircraft manufacturer's, but still the performance and aerodynamics of swept wings at transonic speeds and under different Turbulence levels and conditions is a grey area which needs to be addressed. In this paper two different configuration of swept wing (30^0 and 40^0 sweep) is analyzed and presented for two different Transonic speeds of 0.7 Mach and 0.9 Mach. The 3D wing model analyzed and presented in this paper is of NACA2412 profile. The lift and drag coefficient of this 3d wing at 0^0AOA and at 4^0AOA is tabulated in this paper for two of sweep angles 30^0 and 40^0. K-ω SST Turbulence model is used with Ansys Fluent as CFD software. The wing model is analyzed at four different Turbulence intensity levels of 2%, 5%, 10% and 15% and the results are tabulated. Pressure plot and Mach number plot of wing at symmetric section is shown at 0^0 and 4^0AOA and at different operating speeds of 0.7 and 0.9Mach. High altitude environment conditions are considered for this analysis since the commercial aircraft and defence trainer aircrafts are meant to operate at high altitudes. Also an overview of the Swept wing flow instabilities and flow transitions are briefed in this paper.

Citation: Balaji, R. and Dr. P. K. Dash, 2017. "Swept wing aerodynamics at transonic speeds and at different turbulence levels", *International Journal of Current Research*, 9, (06), 52513-52521.

INTRODUCTION

The use of wing sweep to increase the efficiency of aircraft intended for flight at supersonic speed was first suggested by Busemann in 1935. Before that for many years, reducing the airfoil thickness ratio was the only known method of increasing the wing critical Mach number. Many investigators have studied the influence of turbulence in turbines blade aerodynamics and aerofoil performance. Hiller and Cherry (Hillie and Cherry, 1981) have studied the effects of the stream turbulence on two-dimensional, separated and reattached flows. They found that the mean flow-field responds strongly to the turbulence intensity but with little effect on integral scale and fluctuating pressures depend strongly upon both intensity and scale. Mueller and Pohlen (1983) described in their paper the influenc of turbulence intensity on Lissaman 7769 airfoil. They published the results for the nominal turbulent intensity level from 0.08% to 0.30%, and at the Reynolds numbers below $3.0 *10^5$. It is concluded by them that the increase in free stream turbulence and acoustic excitation also caused the laminar shear layer transformed into the transition region much earlier, thus allowing the flow to reattach. Hoffmann (1991) in his paper concluded that increasing the turbulent intensity from 0.25% to 9% has resulted 30% increased in maximum lift coefficient on the NACA 0015 airfoil at Reynolds number of $2.5x10^5$. The results also show that the increase in turbulent intensity increased the drag coefficient, however, the rate of change is negligible. Huang and Lee (1999) investigated NACA 0012 and found that the lift coefficient increased with the increase in turbulence intensity up to 0.45% and however for the turbulence intensity higher than 0.45%, the lift coefficient decreased with the turbulence. They also concluded that the drag coefficient increases and the ratio of lift and drag coefficient decreases with the increase in turbulence intensity. T.I. Saeed and others (2014) in their paper described about their initial findings on the effects of surface roughness on a swept wing in a moderate-disturbance facility through flow

***Corresponding author: Balaji, R.**
Research Scholar, JNTUH, Hyderabad

visualisation and boundary-layer hot-wire measurements at higher flow speeds. They have done linear stability calculations using experimentally determined pressure distributions at two chord Reynolds numbers of Re = $1.3*10^6$ and Re = $1.6*10^6$. Flow visualisation measurements by them revealed that for the baseline, clean leading-edge case, impressions were made by the stationary crossflow vortex on the surface of the wing, with a wavelength of approximately 6 mm. For Re=$1.3*10^6$ transition was seen to arise in the region of adverse-pressure gradient toward the trailing edge of the wing, suggesting that the growth of the crossflow instability is weak and that T-S instabilities lead to transition. Rec = 1:6_106, a saw-tooth transition front was seen to arise between 55 – 60% chord, indicative of stationary crossflow dominated transition. The experimental observations by them confirmed that turbulence intensity alone is not the only receptivity parameter that determines which crossflow mode will ultimately be prevalent, and that roughness is an important parameter for the growth of travelling waves as well as stationary cross flows.

Despite there being no shortage of publications on the topic of swept-wing aerodynamics the effect of different levels of turbulence intensities on the performance of swept wing(especially of commercial and trainer aircraft applications which will be of NACA2412 aerofoil profile) at transonic speed conditions is still unclear. In this paper a 3d wing of two different sweep angles of 30^0 and 40^0 is analyzed at two different transonic speed of 0.7Mach and 0.9 Mach and at different turbulence intensity levels of 2%, 5%, 10% and 15% and the lift and drag coefficient results are tabulated. The pressure and Mach number plots near to wing surface at symmetric plane is shown for few of analysis cases The wing is modelled as 3d and the aerofoil profile is NACA2412 which is commonly used for high speed Transport aircrafts. Symmetric conditions are applied considering the flow and aircraft structure is symmetric. Fluent is the CFD software used and k-ω SST Turbulence model is used as it was the well proven and widely accepted model for most of external and adverse Turbulence dominated flows. In this CFD simulation only the Turbulence intensity levels are varied considering the Turbulence length scale and wing surface roughness as constant. Since the swept wings are used especially in transonic speed aircrafts the properties of air at high altitude condition is applied for all the iterations presented in this paper. In addition to this an overview of swept wing aerodynamics and the utilized Turbulence model governing equation is described in this paper.

Swept wing theory and boundary layer transitions

Straight wing Aircrafts do not cruise at Mach numbers much beyond the critical value. At supersonic speeds, the aircraft must have sufficient power to overcome the high drag in the transonic speed range and be capable of controlled flight through this transonic and supersonic Mach number ranges. Until 1935 reducing the airfoil thickness ratio was the only known method of increasing the wing critical Mach number. Busemann in 1935 found that wing sweep increase the efficiency of aircraft intended for supersonic flight. In swept wing as shown in Fig 1 the free stream velocity is resolved in to two components the normal flow which is normal to leading edge and the one that is parallel to leading edge. If the swept wing is of infinite aspect ratio, the critical Mach number of the swept wing is related to the corresponding unswept wing as follows

$$\frac{M_{cr}\,\Delta}{M_{cr}\Delta_{=0}} = \frac{1}{Cos\,\Delta} \qquad \text{- - - - - - -- (1)}$$

where Δ is the wing sweep angle, $M_{cr}\Delta_{=0}$ is the critical Mach number of the unswept wing, $M_{cr}\Delta$ is

the critical Mach number of the swept wing, and the airfoil thickness ratio normal to the leading edge remains constant as the wing is rotated to different angles of sweep. This relationship is based on the assumption that the critical Mach number of the wing is controlled only by the flow normal to the leading edge and is independent of the Mach number parallel to the leading edge. The flight Mach number of the aircraft, is resolved into two components the normal component which is normal to leading edge and the parallel component which is parallel to leading edge of wing. The assumption of independence of the two components of the stream Mach number is strictly true only for inviscid flow, but this assumption works reasonably well in predicting the critical Mach number of swept wings in real flows with viscosity.

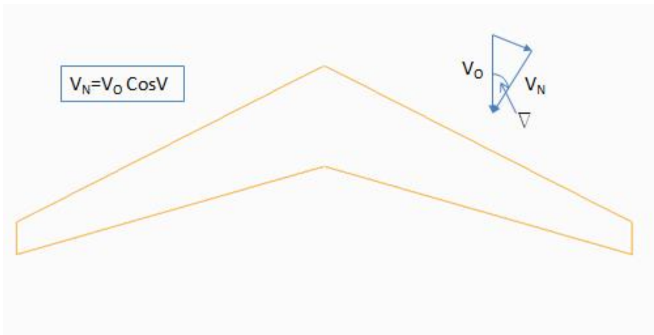

Fig.1. Normal and parallel component of free stream velocity in Swept wing

Wings and their attachments are among the top contributors to total friction drag of an Aircraft. Evidently reducing this drag will reduce the fuel consumption. Optimisation of the aircraft wing design to delay transition and using laminar flow controls to prevent the onset of turbulence completely can achieve a decrease in drag. Being relevant to Aerospace technology the flow transition mechanism in boundary flows is not fully understood yet and one of the reasons is difficulty inherent in the mathematical problem of transition. The transition involves several intermediate stages between laminar and turbulent flow. Where laminar flow is highly ordered spatially and temporally, but turbulent flow is irregular, nonlinear and three-dimensional and is characterised by the presence of numerous instability modes with different length-scales and frequencies. Various receptivity studies are done earlier and being done to determine the role of disturbances acting on the boundary layer, namely, free stream turbulence, surface roughness, and acoustic waves. Such perturbations can occur in the far field or on the wing surface, however once they penetrate the boundary layer their characteristics change. Morkovin (1969) in his book described about different stages of transition and defined the term Receptivity as shown in Fig 2. Receptivity is the process in which the external disturbances penetrate into the boundary layer altering in scales, amplitude and other characteristics. In this process the boundary layer acts as a filter. Such disturbances can then seize different paths to transition or die out depending on the mean flow. Goldstein (1983 & 1985), categorized the receptivity process into two. The first category includes the receptivity near a body leading edge, due to the boundary layer thickness which is small, and subject to a large pressure gradient. The second part, covers a region further downstream where for instance, surface imperfections can generate initial perturbations and called as localised receptivity. Boundary layers associated with the receptivity to surface roughness with different levels of free stream turbulence is the commonly reported observations by many researchers.

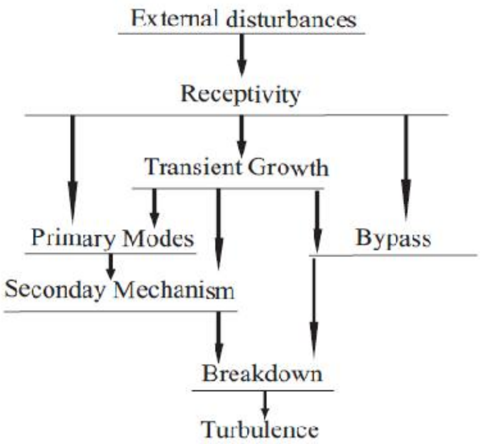

Fig.2. Transition process at boundary layer due to external disturbances

Saric *et al*. (2003) in their paper explain the process in which disturbances of different sorts, penetrate a boundary layer and set the initial condition and the process is shown in Fig 2. Saric *et al*. (2003) also noted that stationary crossflow disturbances are prone to dominance in low levels of free stream turbulence. Tempelmann *et al*. (2012b) numerically investigated worst case scenarios in the receptivity of a boundary layer to surface roughness and free stream vorticity. They concluded that the optimal surface roughness led to a wavy shape in the stream wise direction, while the optimal free stream disturbance takes a localized streak-type structure.

Transition instabilities

The different region's on a wing where the flow faces different local features, such as curvature, and pressure gradient is shown in Fig 3. One region can act as stabilising for one type of instability while destabilising the other type simultaneously.

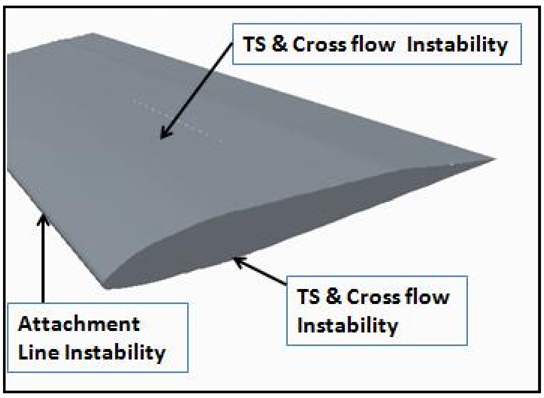

Fig.3. Flow Instabilities on a Swept Wing

The different types of instabilities over a swept wing are explained below.

TS-Waves are viscous type of instability that was first theoretically described by Tollmien (1929) and Schlichting (1933). They did research and explained the travelling waves within the boundary layer. Inherently negative pressure gradients stabilises such travelling waves, whereas the positive pressure gradient destabilises the waves.

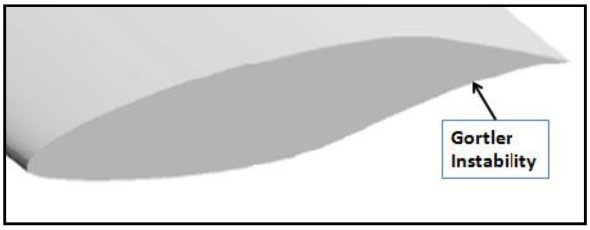

Fig.4. Region of Gortler Vortices in Swept Wing

Gortler Vortices are created due to flow over a concave surface as shown in Fig 4. This flow over concave surface gives way to destabilising centrifugal forces which can create instabilities in the form of counter rotating vortices called Gortler Vortices. Another kind of instability is Cross Flow Instability. In Swept wings the wing sweep causes the boundary layer to acquire an inflection point. This inflection point boosts the centrifugal forces, which are in turn balanced by pressure adjustment of the flow outside the boundary layer. On the other hand, inside the boundary layer the pressure remains constant while, velocity reaches zero on the wall. The imbalanced forces are then transpired in the form of vortices, termed as crossflow vortices. A negative pressure gradient is a destabilising factor leading to their dominance on the upper side of the wing at a negative angles of attack. Attachment Line Instability is also known as Leading Edge Contamination. This instability is normally brought about by the propagation of waves along the attachment line of the wing as shown in Fig 3. Such waves can be generated from the wing root. This was first observed in the experiments by Gray (1952). He noticed that by increasing the sweep angle the transition location moves towards the attachment line. Poll (1979) in his research paper distinguished between transitions induced by crossflow instability and leading edge instability.

Swept wing model and domain

The Swept wing which is of 30^0sweep is shown in Fig 5.

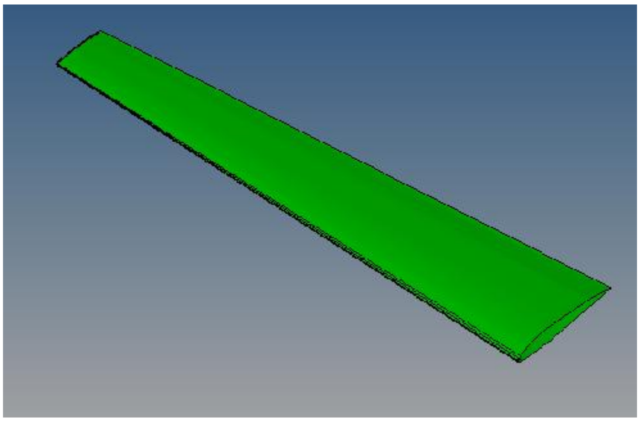

Fig.5. 30^0 Swept wing model

The 3D wing is of NACA2412 and the Aspect Ratio of the wing is 5.3. The fluid domain is meshed with hybrid elements which comprise of both Tet and Prismelements.

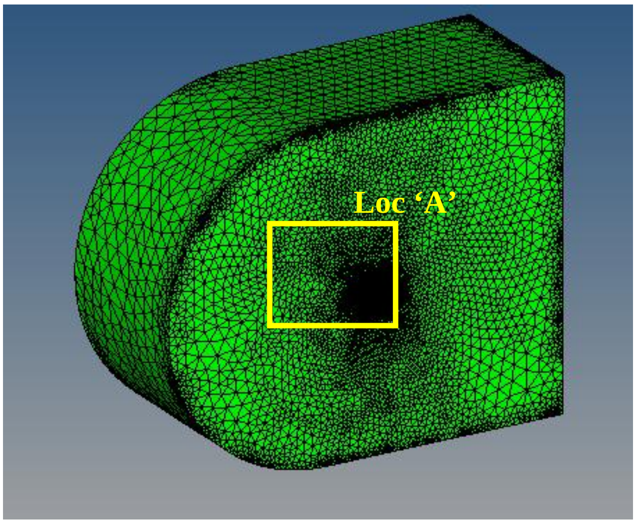

Fig.6. Fluid Domain with 3d wing

The domain size is selected accordingly to simulate the flow similar to a wind tunnel test. The domain walls are far enough from the wing surface to consider and apply the "Pressure far field" boundary condition. The mesh is made fine near to wing surface to simulate the flow separations, boundary layer transitions and flow instabilities accurately. To arrive at optimum number of elements and refinement the convergence study is done on 30^0 swept wing for the lift coefficient and the mesh size which resulted in 1757578 elements is identified as the optimum size at which the solution converged. Meshed domain of 30^0 sweep wing is shown in Fig 6.

As shown in Fig 7 at Loc 'A' the mesh is kept fine near to the wing surface to get accurate results. Considering the computation time and to avoid the high end machine computing, the mesh is not refined further once the lift coefficient convergence is achieved. This meshed domain comprising of 1757578 elements of 30^0 sweep wing is used to do CFD analysis at different Mach speed of 0.7 & 0.9Mach and at two different angles of attacks of 0^0 and 4^0 AOA in this study.

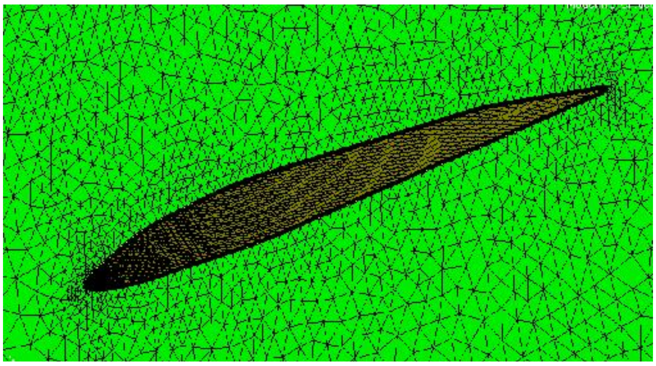

Fig.7. Fine mesh near to wing surface in domain

Similar to 30^0 sweep wing model for 40^0 swept wing model the mesh size is kept fine near to wing surface in the domain. With mesh refinement near to wing surface the mesh convergence study is done for lift coefficient and mesh size with 1961250 elements is identified as the optimum mesh size. CFD analysis of this 40^0 sweep wing model for 0.7 Mach and 0.9 Mach at 0^0 and 4^0 AOA is done with the converged mesh size of 1961250 elements.

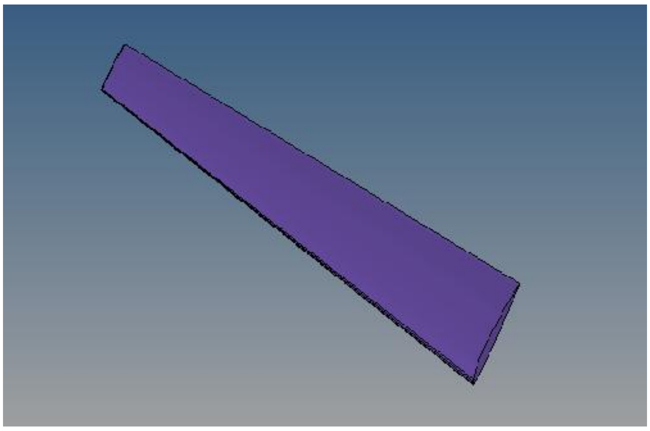

Fig.8. 40^0 Swept wing model

Turbulence model, properties and boundary conditions

For the swept analysis discussed and presented in this paper SST K-ω model is used as the Turbulence model as it is recommended by many of researchers who have done similar external fluid flow simulation in the past. LES and Reynolds stress model are not widely used due to the complexity and high end computation requirements. Moderate computation time and generic software and hardware requirements makes the SST K-ω model handy and widely accepted by research establishments and aerospace industries as the best suitable turbulence model for transonic flow simulations. As in k-ε model, it was assumed while deriving the transport equation that the flow is fully turbulent, and the effects of molecular viscosity are negligible and hence k-ε model is valid only for fully turbulent flows. In SST K-ω model as compared to standard K-ω model, the turbulent viscosity is modified to account for the transport of the principal turbulent shear stress. This feature gives the SST k − ω model an advantage in terms of performance over both the standard k − ω model and the standard k − ε model.

The transport equation of SST k − ω model is given by

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \quad --- (1)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad ----- (2)$$

Where Γ_k and Γ_ω are the effective diffusivity of k and ω respectively. Y_k and Y_ω represent the dissipation of k and ω due to turbulence and D_ω represents the cross diffusion term. S_k and S_ω are user defined source terms. G_k represents the generation of turbulence kinetic energy due to mean velocity gradients and G_ω represents the generation of ω.

For Transonic flow conditions compressibility of fluid has to be considered and hence Air which is the fluid medium of the domain is considered compressible. As this research work is focussed on the performance evaluation of swept wing which are more widely used in commercial aircraft and defence trainers, the properties of air (Airbus, 2000) at high altitude of approximate 35000ft is considered in all the CFD simulation which are done as part of this work. CFD code Ansys Fluent is used for the flow Analysis over the wing. The domain inlet temperature is as per International standard atmosphere applicable at high altitude of approximate 35000ft. "Pressure Far Field" boundary condition is applied at both inlet and outlet faces which are shown in figure 9. Wall boundary condition is applied to faces except for the face to which wing is attached. Symmetric boundary condition is applied to the face to which the wing is attached, this is because the flow is considered to be symmetric about this face as the fuselage is not modelled and this study is only related to performance of wing and not the complete aircraft. "No Slip Wall" boundary condition is applied to the 3D wing model on all its wing surfaces to include the effects of boundary layer, surface roughness, separation and shocks.

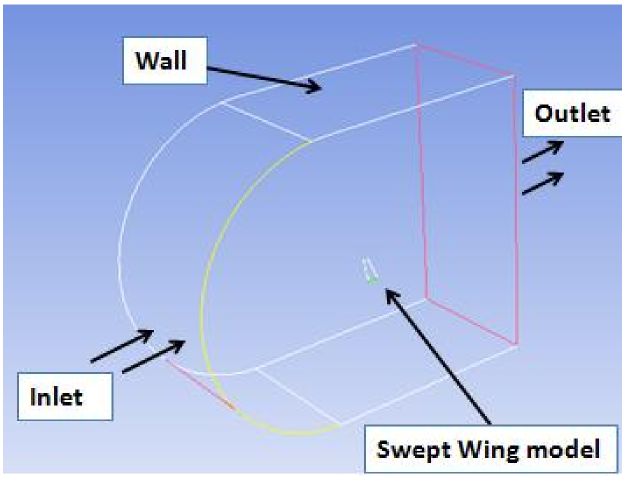

Fig.9. Analysis Domain and Boundary conditions

Compressible effects are included as the flow is simulated at transonic condition of 0.7Mach and 0.9Mach. Flow over the 3D wing is simulated for two sweep angles of 30^0 and 40^0. Analysis is carried out for four different Turbulent intensity conditions of 2%, 5%, 10% and 15% for each of Transonic flow speed 0.7Mach and 0.9 Mach. For each of sweep angle of 30^0 and 40^0 the flow is simulated for two of wing angle of attacks of 0^0 and 4^0 and results are discussed and tabulated in next section.

RESULTS AND DISCUSSION

Swept wing model of NACA 2412 profile and of two different sweep angles of 30^0 and 40^0 is analyzed at transonic speeds of 0.7Mach and 0.9Mach and the performance of wing is tabulated in this paper. The lift and drag coefficient of both the wings at two different angle of attack of 0^0 and 4^0 is calculated using CFD code Ansys Fluent and presented in this paper. SST k-ω Turbulence model is used considering accuracy and computation time and based on past research done in the similar flow simulations. For each of Transonic speed condition four different Turbulence intensity levels of 2%, 5%, 10% and 15% is considered and the lift and drag coefficient is evaluated for each of this Turbulence percentage level and tabulated in this paper.

Results of 30^0 Swept Wing at 0^0 AOA: In the Table1 Lift and Drag coefficient of the 30^0 Swept wing at 0^0 AOA is listed for two different Transonic speeds of 0.7Mach and 0.9 Mach. Turbulence intensity levels of 2%, 5%, 10% and 15% is considered and the respective lift and drag coefficients are tabulated in Table I below.

Table I. Lift and Drag coefficient of 30^0 Sweep wing at 0^0 AOA and at different Turbulence Intensity level

S.No	Mach	Turbulence Intensity %	Lift Coefficient (Cl)	Drag Coefficient (Cd)
1	0.7	2	0.124	0.007
2	0.7	5	0.111	0.011
3	0.7	10	0.101	0.015
4	0.7	15	0.095	0.021
1	0.9	2	0.107	0.023
2	0.9	5	0.100	0.025
3	0.9	10	0.094	0.028
4	0.9	15	0.091	0.031

From figure10 we see that for both speeds of 0.7 Mach and 0.9 Mach the lift coefficient of 30^0 Sweep wing decreases with increase in Turbulence Intensity level from 2% to 15%. It is also seen that with increase of speed of Aircraft from 0.7Mach to 0.9Mach the lift coefficient decreases this is because of the instabilities which grows as speed nears sonic condition and due to isentropic deceleration and compression waves. At higher turbulence levels the delta difference in lift coefficient between 0.7 Mach and 0.9 Mach is very small which implicates that losses are more at higher transonic speeds.

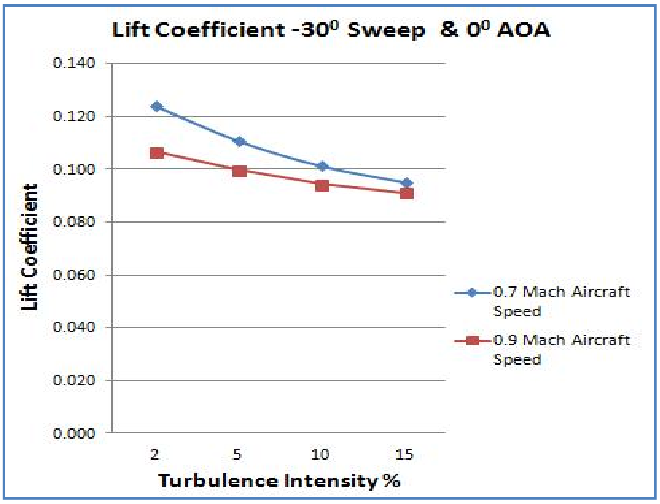

Fig.10. Lift coefficient of 30^0 Sweep wing at 0^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

Figure 11 shows the drag coefficient of 30^0 Swept wing at 0^0 AOA for different Turbulence intensity levels. It is clearly evident that with increase of Turbulence intensity level from 2% to 15% drag coefficient increases, also it is seen that with increase of speed of Aircraft from 0.7Mach to 0.9Mach for a particular Turbulence intensity level the drag coefficient will be higher at 0.9Mach speed when compared to 0.7Mach speed.

The Static Pressure plot of the 30^0 Swept wing near to wing surface at symmetric plane is shown in Figure 12 for 0.7Mach flow speed and at 15%Turbulence intensity level. The Mach number of flow over the swept wing at symmetric plane and at 0.7Mach flow speed and at 15% Turbulence intensity level is shown in Figure 13. From the figure it is seen that the max velocity over wing surface has not reached sonic speed.

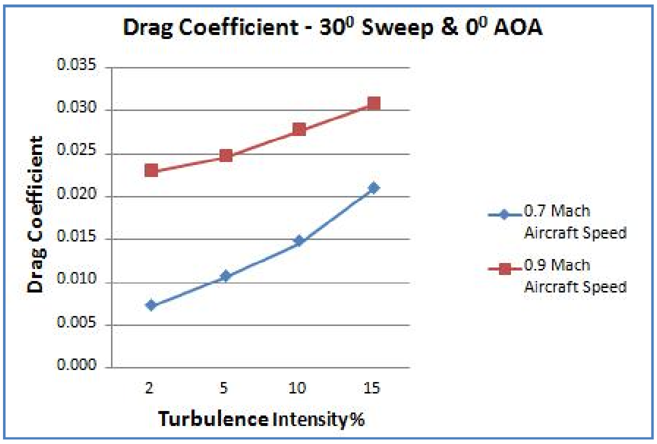

Fig.11. Drag coefficient of 30^0 Sweep wing at 0^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

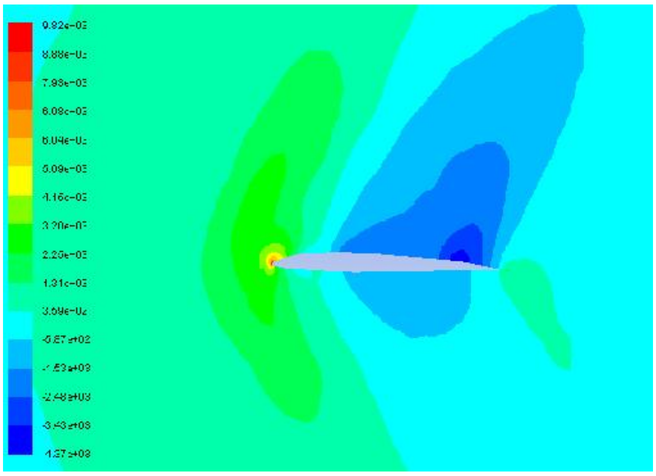

Fig.12. Static Pressure plot at symmetric plane of 30^0 sweep wing and at 0^0 AOA, Turbulence intensity of 15% and at 0.7 Mach

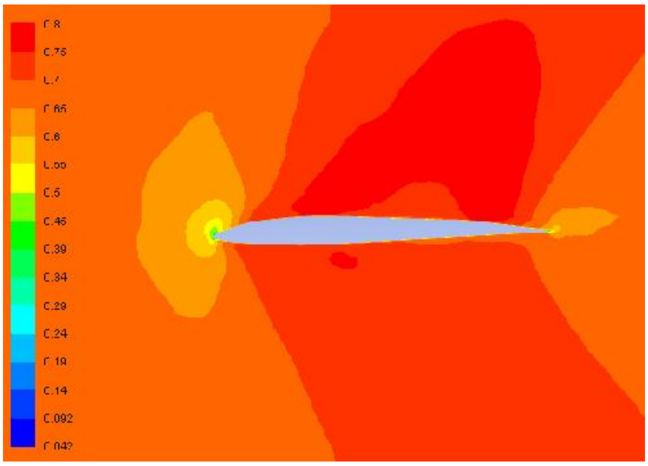

Fig.13. Flow Mach number of 30^0 Swept wing at 0^0 AOA, 0.7Mach inlet condition and at 15% Turbulence intensity

For 30^0 swept wing the Static Pressure plot at 0.9 Mach and at 15% Turbulence intensity level and at 0^0 AOA is shown in Figure 14. It is seen that at top surface of wing the pressure becomes highly negative near to trailing edge due to separation, deceleration and recompression effects of shock waves.

The Mach number of flow over the 30^0 swept wing and at 0^0 AOA and for a speed of 0.9 Mach and at 15% Turbulence intensity is shown in Figure 15. It is seen that at 0.9 Mach speed the flow attains sonic speed at approximate 35 % of chord length.

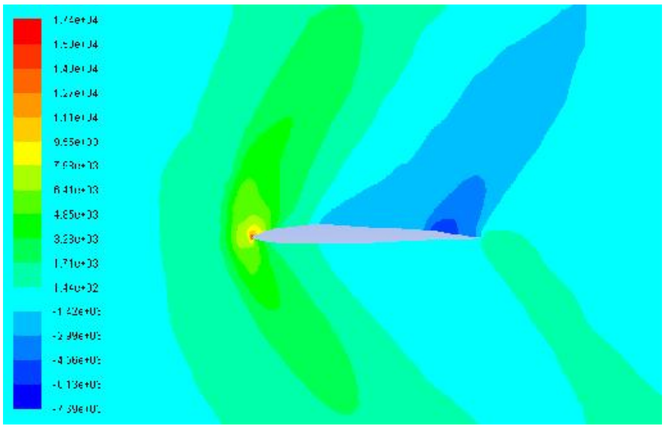

Fig.14. Static Pressure plot of 30^0 Sweep wing at 0^0 AOA, Turbulence intensity of 15% and at 0.9 Mach

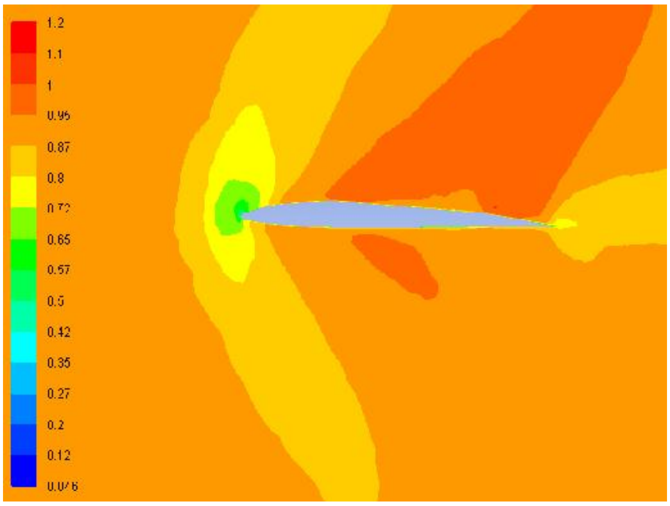

Fig.15. Flow Mach number of 30^0 swept wing at 0^0 AOA, 0.9Mach inlet condition and at 15% Turbulence intensity

Results of 30^0 Swept wing at 4^0 AOA

For 4^0 AOA the lift and drag coefficient of the 30^0 Swept wing at 0.7 Mach and 0.9 Mach is tabulated below at different Turbulence intensity levels of 2%, 5%, 10% and 15%.

Table II. Lift and Drag coefficient of the 30^0 Swept wing at 4^0 AOA and at different Turbulence Intensity level

S.No	Mach	Turbulence Intensity %	Lift Coefficient (Cl)	Drag Coefficient (Cd)
1	0.7	2	0.455	0.034
2	0.7	5	0.441	0.036
3	0.7	10	0.437	0.044
4	0.7	15	0.433	0.054
1	0.9	2	0.480	0.055
2	0.9	5	0.469	0.056
3	0.9	10	0.462	0.058
4	0.9	15	0.450	0.060

By comparing the lift coefficient of 30^0 Swept wing at 0^0 AOA and 4^0 AOA in Table I and Table II we see lift coefficient at 4^0 AOA is higher than 0^0 AOA for the same Aircraft speed and Turbulence intensity level.

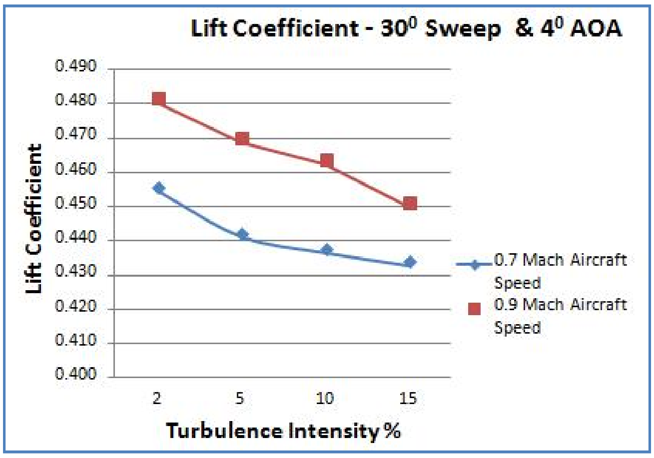

Fig 16. Lift coefficient of 30^0 Sweep wing at 4^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

From Figure 16 it is evident that at 4^0 degree AOA as compared to 0^0 AOA the lift coefficient of wing at 0.9 Mach number is higher than 0.7 Mach number at all the Turbulence intensity level. This is different from the results observed at 0^0 degree AOA where Cl of 0.7 Mach is higher than 0.9Mach. This difference in performance is observed at 4^0 AOA because the lift coefficient is high enough at higher AOA and the delta decrease in lift coefficient due to shock and recompression effects is not a large fraction of Cl and hence lift coefficient of wing at 0.9 Mach is higher than lift coefficient of wing at 0.7 Mach at 4^0 AOA.

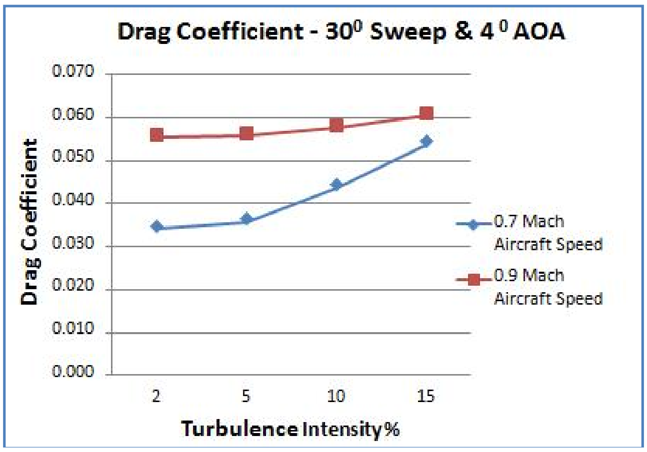

Fig.17. Drag coefficient of 30^0 Swept wing at 4^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

The drag coefficient of 30^0 Swept wing at 4^0 degree AOA and at Aircraft speed of 0.7 Mach and 0.9 Mach is shown in figure 17 for different Turbulence intensity levels. For 30^0 Swept wing at 4^0 AOA the Static Pressure plot of the domain near to wing surface is shown in Figure 18 for 0.7Mach flow speed and at 2%Turbulence intensity level. In this paper only few of plots at 0.7 Mach is shown at 4^0 AOA.

The flow Mach number of 30^0 Swept wing at 4^0 AOA and at 2% Turbulence intensity level and at 0.7 Mach flow speed is shown in Figure 19.

The flow Mach number plot of 30^0 Swept wing at 4^0 AOA and at 0.9 Mach inlet condition and at 15% Turbulence intensity level is shown in figure 21. It is seen that the flow reaches sonic velocity at approximately 20% of chord length.

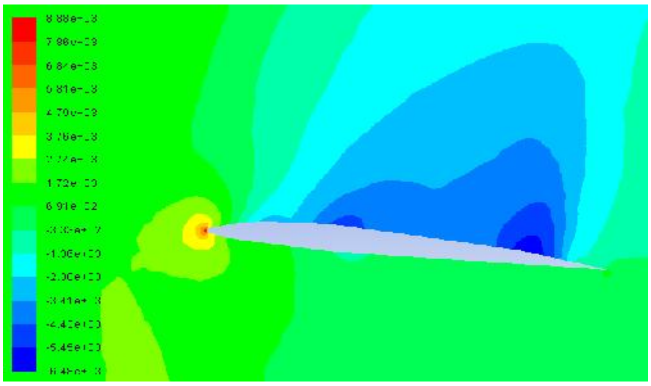

Fig.18. Static Pressure plot of 30^0 Swept wing at 4^0 AOA, Turbulence intensity of 2% and at 0.7 Mach

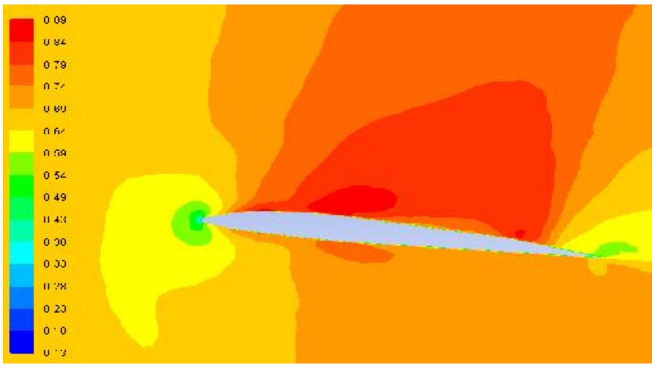

Fig.19. Flow Mach number plot of 30^0 Swept wing at 4^0 AOA, 0.7 Mach inlet condition and at 2% Turbulence intensity. For 4^0 AOA of 30^0 Swept wing the static pressure plot is shown in figure 20 for 0.9 Mach flow speed and at 15% Turbulence intensity level

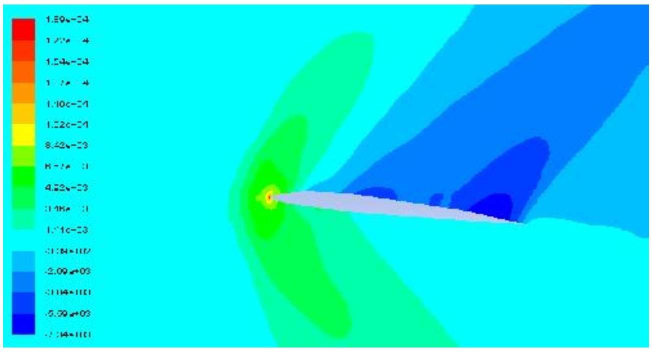

Fig.20. Static Pressure plot of 30^0 Swept wing at 4^0 AOA, Turbulence intensity of 15% and at 0.9Mach

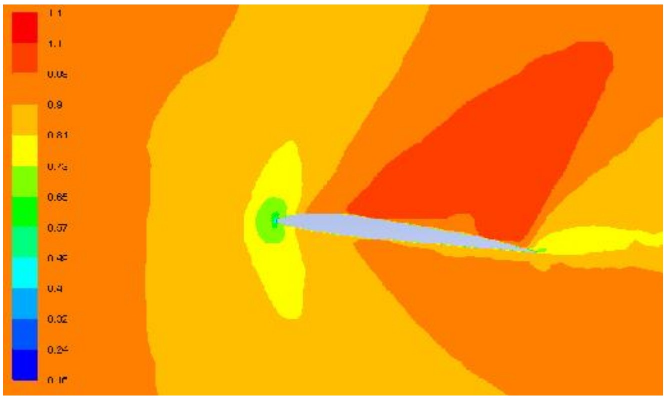

Fig.21. Flow Mach number of 30^0 Swept wing at 4^0 AOA, 0.9Mach inlet condition and at 15% Turbulence intensity

Results of 40^0 Swept Wing at 0^0 AOA

The lift and drag coefficient 0f 40^0 Swept wing at 0^0 AOA and at two different flow speeds of 0.7 and 0.9 Mach is shown in below Table III.

Table III. Lift and Drag coefficient of the 40^0 Swept wing at 0^0 AOA and at different Turbulence Intensity level

S.No.	Mach	Turbulence Intensity %	Lift Coefficient (Cl)	Drag Coefficient (Cd)
1	0.7	2	0.105	0.011
2	0.7	5	0.102	0.012
3	0.7	10	0.098	0.014
4	0.7	15	0.095	0.015
1	0.9	2	0.120	0.012
2	0.9	5	0.114	0.013
3	0.9	10	0.111	0.014
4	0.9	15	0.109	0.016

In figure 22 we see for the 40^0 Swept wing at 0^0 AOA the lift coefficient decreases with increase of Turbulence intensity level from 2% to 15%. Also we see the lift coefficient at 0.9 Mach is higher than the lift coefficient at 0.7 Mach which is not similar to behaviour of 30^0 swept wing. This is due to the reduction of drag to a great extent in 40^0 Swept wing as compared to 30^0 Swept wing

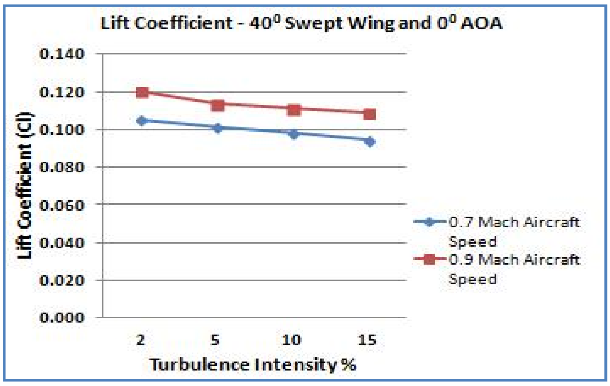

Fig.22. Lift coefficient of 40^0 Sweep wing at 0^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

The drag coefficient of 40^0 Swept wing at 0^0 AOA and at different Turbulence intensity levels is shown in figure 23 for two different flow speeds of 0.7 Mach and 0.9 Mach. It is observed that the drag increases with increase in Turbulence intensity level and with increase of flow speed from 0.7 Mach to 0.9 Mach.

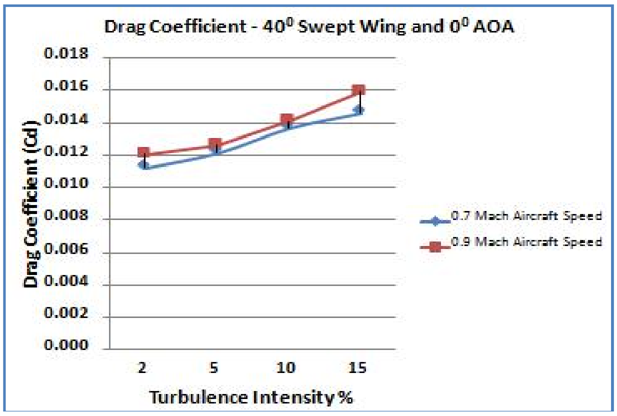

Fig.23. Drag coefficient of 40^0 Swept wing at 0^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

Results of 40^0 Swept Wing at 4^0 AOA

The lift and drag coefficient 0f 40^0 Swept wing at 4^0 AOA and at two different flow speeds of 0.7 and 0.9 Mach is shown in below Table IV.

Table IV. Lift and Drag coefficient of the 40^0 Swept wing at 4^0 AOA and at different Turbulence Intensity level

S.No.	Mach	Turbulence Intensity %	Lift Coefficient (Cl)	Drag Coefficient (Cd)
1	0.7	2	0.390	0.026
2	0.7	5	0.400	0.026
3	0.7	10	0.412	0.026
4	0.7	15	0.415	0.028
1	0.9	2	0.447	0.034
2	0.9	5	0.448	0.036
3	0.9	10	0.450	0.040
4	0.9	15	0.454	0.051

In figure 24 we see for the 40^0 Swept wing at 4^0 AOA the lift coefficient increases with increase of Turbulence intensity level from 2% to 15%. This is because the Turbulence aids in the lift at higher swept angles. This behaviour is seen in both the aircraft speed (flow speeds) of 0.7 Mach and 0.9 Mach.

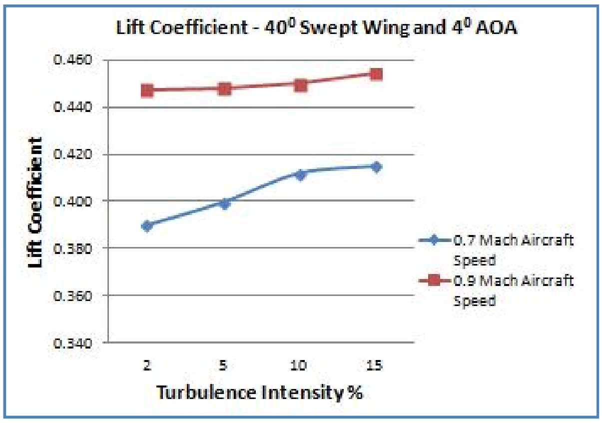

Fig.24. Lift coefficient of 40^0 Sweep wing at 4^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

The drag coefficient of 40^0 Swept wing at 4^0 AOA and at different Turbulence intensity levels is shown in figure 25 for two different flow speeds of 0.7 Mach and 0.9 Mach. It is observed that the drag increases with increase in Turbulence intensity level and with increase of flow speed from 0.7 Mach to 0.9 Mach

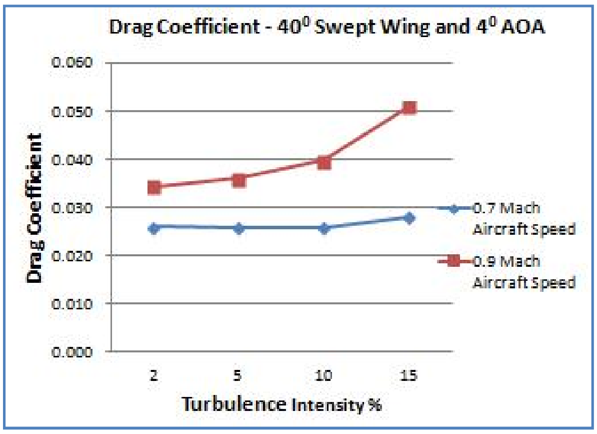

Fig.25. Drag coefficient of 40^0 Swept wing at 4^0 AOA and at Transonic speed of 0.7 Mach and 0.9 Mach

The Static Pressure at symmetric plane of the 40^0 Swept wing and at 4^0 AOA is shown in Figure 26 for 0.9 Mach flow speed and at 15%Turbulence intensity level.

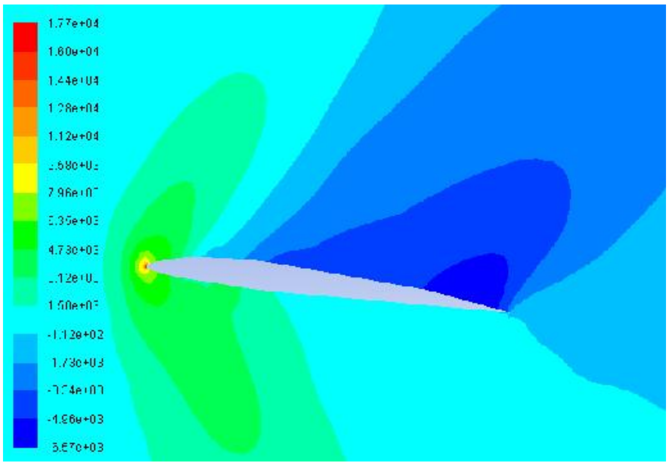

Fig.26. Static Pressure plot of 40^0 Swept wing at 4^0 AOA, Turbulence intensity of 15% and at 0.9Mach

The flow Mach number plot of 40^0 Swept wing at 4^0 AOA and at 0.9 Mach inlet condition and at 15% Turbulence intensity level is shown in Figure 27.

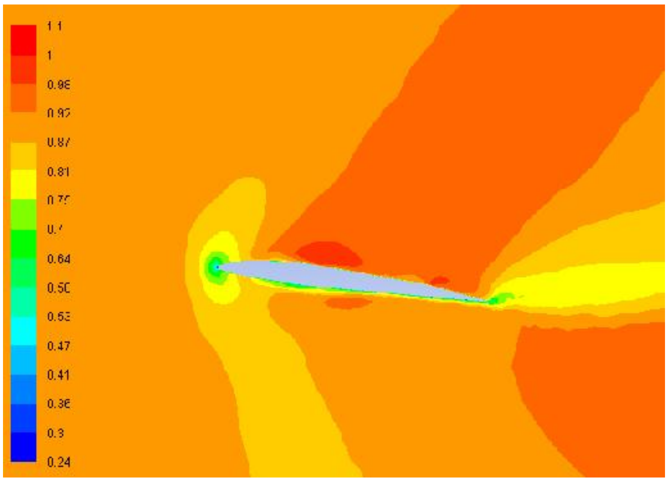

Fig.27. Flow Mach number of 40^0 Swept wing for 4^0 AOA, 0.9 Mach inlet condition and at 15% Turbulence intensity

Conclusion

In this paper the aerodynamic performance of 30^0 and 40^0 Swept wing at two different angle of attack of 0^0 and 4^0 and at aircraft cruise speed of 0.7Mach and 0.9 Mach is discussed and presented. The lift and drag coefficient of Swept wing which is of Aspect ratio 5.3 and of NACA 2412 profile is tabulated in table I, II, III & IV for different Turbulence intensity levels of 2%, 5%, 10% and 15%. By comparing the table of 30^0 swept wing with 40^0 swept wing we see in 40^0 Swept wing at 0^0 AOA the lift coefficient at 0.9 Mach is higher than the one at 0.7 Mach speed, where as in 30^0 Swept wing this behaviour is entirely opposite. At 4^0 AOA if we compare the lift coefficient of 30^0 Swept wing and 40^0 Swept wing we see that the lift coefficient of 40^0 Swept wing increases with increase of Turbulence intensity level whereas in 30^0 Swept wing it decreases with increase of Turbulence at 4^0 AOA. The trend of drag coefficient variation in both 30^0 and 4^0 Swept are same. The static pressure plot and flow Mach number plot is shown for few of Turbulence intensity level and flow speeds. The results of Swept wing which was analyzed and tabulated in this paper for two of wing configuration of 30^0 and 40^0 and at transonic speed conditions and at different Turbulence intensity levels can be used in future research work to compare its performance with other transonic and supersonic wings and to explore the possibility of using similar wing configuration to mitigate the risk of impact of higher atmospheric turbulence levels on the wings performance.

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