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Analytical Study of Double Wedge Airfoil for Supersonic Applications and Shape Modification for Subsonic Applications

D Devasurya[1], Ashwanth P Nair[2] and Azim Zubair[3]

UG Students, Department of Aeronautical Engineering

MVJ College of Engineering, Bangalore, Karnataka, India

Corresponding Author: p.a08ashwanth@gmail.com[2]

Abstract: *A Double Wedge airfoil is an airfoil for supersonic blades and wings, with a wedge like tapered sharp leading and trailing edges. The shock waves and the expansion waves govern the supersonic characteristics of the double wedge airfoil. The present work is based on the design and aerodynamic analysis of double wedge airfoil at supersonic regime and shape modification of the airfoil for subsonic regime. The flow analysis is carried out using ANSYS Fluent, which is CFD based software. The supersonic analysis is performed for Mach number of 2.0. The airfoil was modified for subsonic applications and the analysis was performed for Mach number 0.7. Blowing technique was incorporated to further improve the aerodynamic performance of the modified double wedge airfoil. From the simulated results, it was found that the co-efficient of drag of double wedge airfoil at Mach number of 2.0 agreed with the manual calculations. The modified airfoil gave optimum performance with the addition of a blowing stream at subsonic speeds.*

Keywords: Double Wedge Airfoil (DWA), Computational Fluid Dynamics (CFD), Shock Wave, Mach Number, Co-efficient of Drag, Co-efficient of Lift

I. Introduction

An airfoil is the cross-section of any lift-generating surface such as wing, blades of a propeller or turbine. When an aircraft moves through the air, it produces an aerodynamic force. The component of this aerodynamic force perpendicular to the relative wind is called Lift and the component parallel to the relative wind is called Drag. The angle between the relative wind and the chord line is called the Angle of Attack of the airfoil.

An airfoil is a specially designed shape capable of producing more lift compared to drag. The shape of an airfoil differs based on the application. Subsonic airfoils generally have rounded leading edge whereas supersonic airfoils are thin with a sharp leading edge. An asymmetric or cambered airfoil can generate lift at zero angle of attack whereas a symmetric airfoil produces no lift at zero angle of attack.

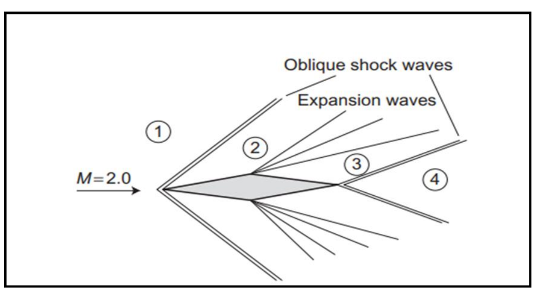


Figure 1: Typical Representation of Shock Waves on a Double Wedge Airfoil

The supersonic characteristics of a double Wedge airfoil (DWA) are associated with the shock waves and expansion waves produced. This however does add to the drag produced. The complex geometrical parameter variation of the DWA does limit the application of the airfoil. The two primary parameters to be considered for the design of any supersonic airfoil is the location of the shock waves and expansion waves along the wing surface. This location however depends on the speed and direction of the local flow over the airfoil as well as the geometry of the airfoil.

The double wedge shape of the airfoil tends to significantly reduce the negative impacts of the shock waves that are formed at the edges of the wing surface in a supersonic flow. Moreover, the thin leading edge of the airfoil often causes an oblique shock/connected shock to form instead of the detached/bow shock as the bow shock tends to produce more drag than the oblique shocks. Thus, double wedge airfoil gives good performance at supersonic speeds, however would lead to poor performance at subsonic speeds due to the sharp edges stall.

II. Methodology

Modelling and analysis have been done using the ANSYS software. The half Wedge angle for the airfoil is chosen as 10^0. The flow analysis over the airfoil is done for 0^o Angle of attack (AOA). The supersonic analysis was carried out for Mach number of 2.0. The objective is to study the flow variations, the position of the shock waves and expansion waves and also to carry out shape modification on the double wedge airfoil in order to study the airfoil performance in subsonic regime at a Mach number of 0.7 and to determine the improvement in performance of the modified airfoil with blowing flow control.

2.1 Airfoil Modelling

The airfoil was modelled using Ansys Design-Modeler. The chord length of the airfoil is 1000 mm and the half-wedge angle is 10^0. The airfoil is symmetric about the vertical axis.

For subsonic applications, the airfoil was modified by smoothening the sharp leading and apex edges by creating fillets of varying radii. For the leading edge, the fillet radius was chosen as 12mm and for the apex edges, the radius was chosen in the range of 500mm to 1000mm.

However, based on the analysis results, the fillet radii were decided as 12mm, 1000mm and 450mm for the leading edge, upper apex edge and lower apex edge, respectively.

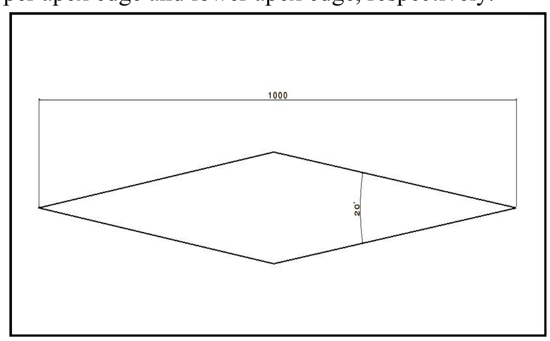


Fig. 2. Model of Double Wedge Airfoil

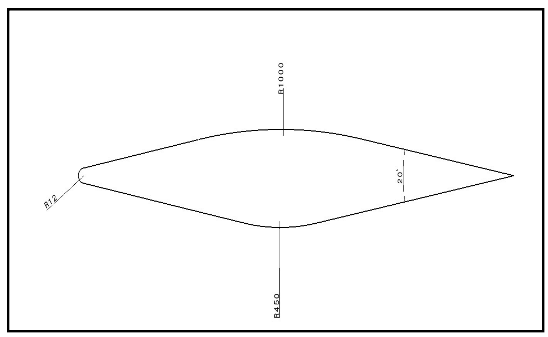
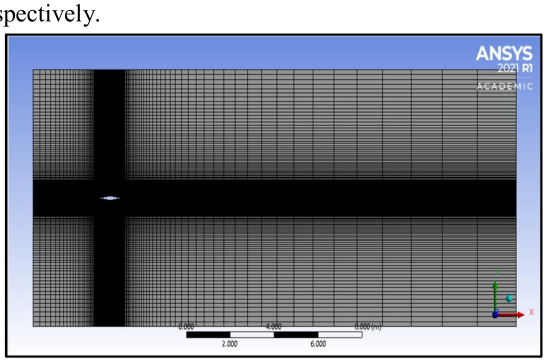


Fig. 3. Model of Modified DWA

2.2 Meshing of the Domain

Meshing was done using Ansys Mesh tool. CFD was chosen as the physics preference and the elements were chosen to be quadrilateral. The mesh quality was maintained by having a finer mesh around the surface of the airfoil. The boundaries were named as Inlet, Outlet and Airfoil for the left-end of the domain, right-end of the domain and the airfoil surface, respectively.



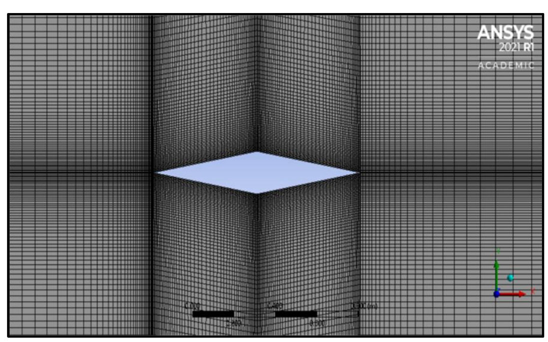


Fig. 4. Meshed Domain of Double Wedge Airfoil

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For the meshing of the modified airfoil, unstructured mesh using triangular elements was done for better body fitting around the curved surface of the modified airfoil. It was done making sure that the mesh quality was well within the permissible limits.

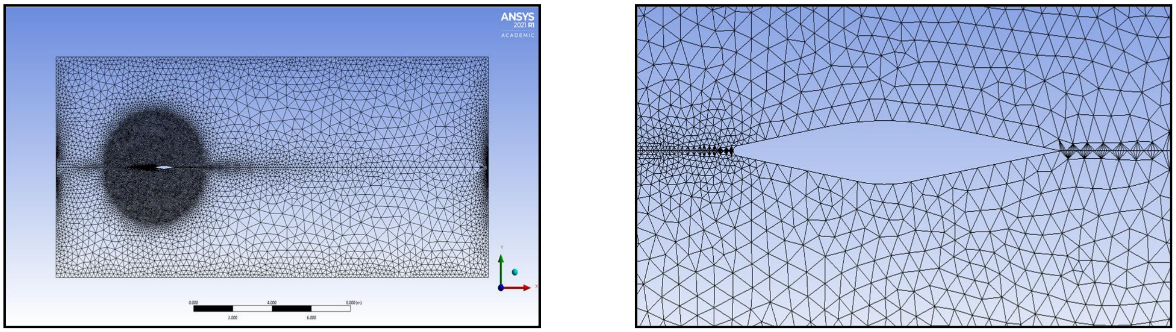

Fig. 5. Meshed Domain of Modified Double Wedge Airfoil

2.3 Improving Flow Characteristics using a Blowing Port

In an effort to further improve the flow over the airfoil surface and its performance, a Blowing port can be introduced at a location of about half the distance along the chord-wise length of the airfoil.

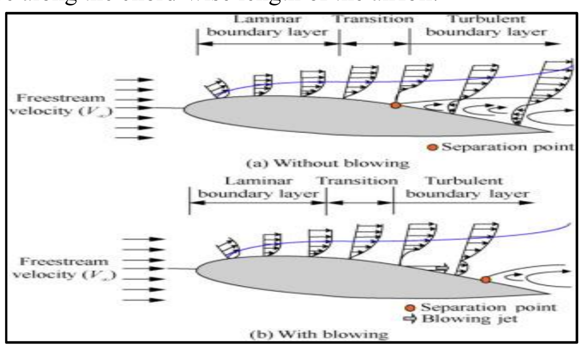

Fig. 6. Shift in flow separation point due to addition of blowing jet

Blowing is a technique used to delay the flow separation or boundary layer separation over a wing surface, by producing an additional flow at certain points over its chord length. Introduction of blowing stream does improve the flow over the airfoil and delays the point of flow separation and thereby giving us better performance.

Therefore, the same technique was introduced to improve the flow characteristics. In order to achieve it, the airfoil was further modified to accommodate the blowing port as the existing fillet radius would not yield the required results. The port was fixed at a chord wise position of X/C = 0.53, where it was found that the blowing stream would have a maximum effect.

A. Modelling and Meshing of Modified Double Wedge Airfoil with Blowing Port

The airfoil parameters considered are:
Leading Edge Fillet Radius: 12mm
Upper Apex Edge Fillet Radius: 800mm
Lower Apex Edge Fillet Radius: 450mm
Chord Length: 1 metre
Location of Blowing Notch: 0.53C (at about half the chord length of the airfoil)
Domain Size: 22 m X 10m

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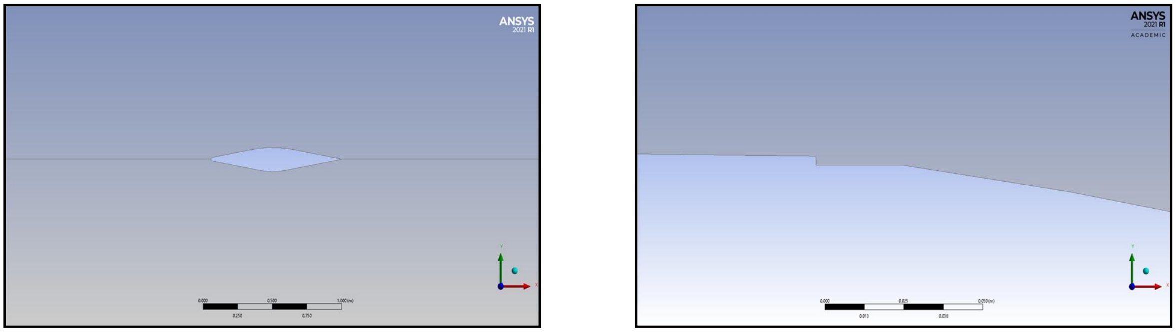

Fig. 7. Airfoil model with Blowing Port

The meshing done was an unstructured mesh where triangular elements were made use for better body fitting around the curved surfaces of the airfoil. It was done making sure that the mesh quality was well within the permissible limits.

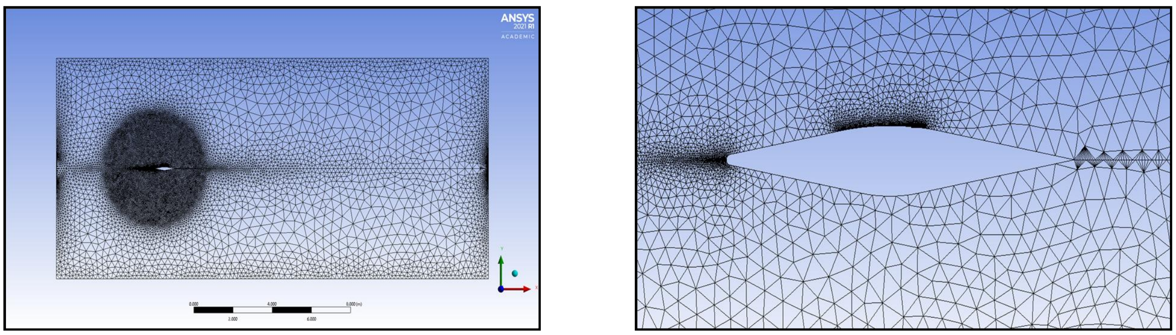

Fig. 8. Meshed Domain of airfoil with Blowing Port

2.4 Numerical Calculation of Co-Efficient of Drag

Referring Figures 1, 2 and 3, for the given airfoil, we have the following parameters:

Half-wedge angle, $\theta = 10°$

Length of each side of airfoil = $500mm = 0.5m$

Thickness $t = 176mm$; Angle of attack, $\alpha = 0°$

For the flow conditions we have,

Mach number, $M = 2.0$

Altitude of flight, $h = 18{,}000m$ or around 60,000 ft

The altitude and Mach number was chosen taking the cruising altitude and speed of the Concorde as a reference.

Using the oblique shock chart ($\theta - \beta - M\ relation$), we get

For $\theta = 10°, M = 2.0$, we have $\beta = 39.31°$

We know that, $M_x = M_1 \sin\beta$

$$= 2.0 \times \sin 39.31°$$

$$= 1.27$$

From normal shock table, we get

For $M_x = 1.27;\ M_y = 0.8016\ and\ \frac{P_y}{P_x} = 1.715$

We know that, $M_2 = \frac{My}{Sin\,(\beta-\theta)} = \frac{0.8016}{sin\,(39.31°-10°)} = 1.6375$

Therefore, in region 2, i.e., across the oblique shock the flow Mach number, $M_2 = 1.6375$

From isentropic tables, for $M_2 = 1.6375$

Mach angle, $\vartheta_2 = 16.043°$ and $\frac{P_2}{P_{02}} = 0.2217$

From region 2 to 3, the flow expands by $2\theta = 2 \times 10° = 20°$

Hence the Mach angle at region 3 is:

$$\vartheta_3 = \vartheta_2 + 2\theta = 16.043° + 20° = 36.043°$$

From isentropic tables, for $\vartheta_3 = 36.043°$

We have $\frac{P_3}{P_{03}} = 0.0716$

The drag per unit area is given by, $D = (P_2 - P_3) \times t$

$$= P_2 \times \left[1 - \frac{P_3}{P_2}\right] \times t$$

$$= P_2 \times \left[1 - \frac{\frac{P_3}{P_{03}}}{\frac{P_2}{P_{02}}}\right] \times t$$

$$= 1.715 P_1 \times \left[1 - \frac{0.0716}{0.2217}\right] \times t$$

$$= 1.715 \times 0.72 \times 10^4 \times 0.677 \times 0.176$$

$$= 1471.55N$$

Therefore, the drag force generated here is, $D = 1471.55N = 1.47KN$

To calculate for Co-efficient of drag, we have

$$C_D = \frac{D}{qS}$$

$$= \frac{D}{\left(\frac{\gamma P_1 M_1^2}{2} \times c\right)}$$

$$= \frac{1471.55}{\left(\frac{1.4 \times (0.72 \times 10^4) \times 2^2}{2} \times 1\right)}$$

$$= 0.073$$

Therefore, the Co-efficient of drag thus obtained is, $C_D = 0.073$

III. Analysis

Analysis of the model was done using ANSYS Fluent. Solver type was set to Density-based and the velocity formulation was set to Absolute. The solutions were obtained using the Energy Equation provided in the software. K-Epsilon Viscous model was used and the air properties were set based on density as Ideal Gas.

3.1 Analysis of Double Wedge Airfoil

The Mach number was set as 2.0 for the supersonic analysis of the Double Wedge Airfoil at 0º Angle of Attack.

3.2 Analysis of Modified Double Wedge Airfoil

The Mach number was set as 0.7 for subsonic analysis of the Modified Double Wedge Airfoils at 0º Angle of Attack. Fluent analysis was performed for various combinations of fillet radii for leading edge and apex edges. It was found that the flow characteristics improved with increasing radius of the fillet for the apex and leading edges. However, leading edge fillet radius of 12mm was chosen as it gave optimum flow characteristics.

For the apex edges, the co-efficient of lift did become positive at a fillet radius of 500mm, but the co-efficient of lift became negative again for a radius of 750mm and 1000mm. On studying the various pressure contours obtained, it was evident that the pressure distribution was similar over both the top and bottom surfaces of the airfoil. This meant that the airfoil wasn't generating sufficient amount of lift. To rectify this issue, a new model with different fillet radii of 1000mm and 450mm on the upper and lower apex edges, respectively was created.

3.3 Analysis of Modified Double Wedge Airfoil with Blowing Port

The airfoil with the blowing port was analysed at the same subsonic Mach number of 0.7, at 0º angle of attack. For the blowing stream, a velocity of 100m/s was provided. This stream of air for the port can be sourced from either the engine bleed air or even the inlet air into the aircraft engine.

IV. Results And Discussion

4.1 Double Wedge Airfoil

The following plots and contours are obtained after the analysis:

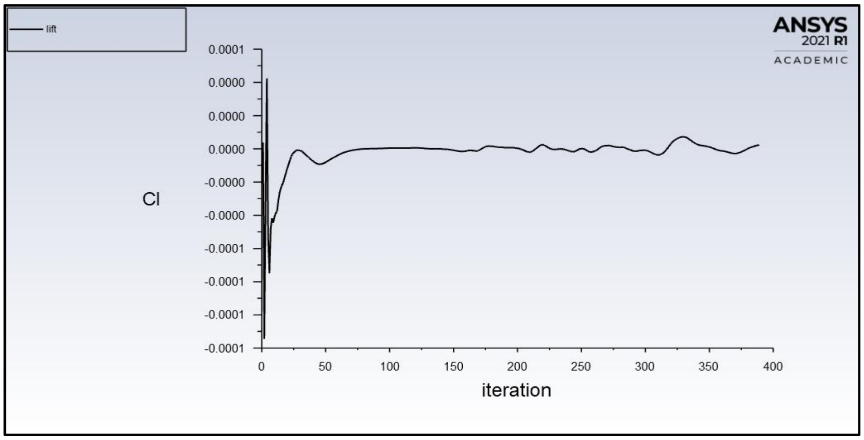

Fig. 9. Plot of Co-efficient of Lift v/s Iterations

The above plot gives the co-efficient of lift of the Double Wedge Airfoil at Mach No 2.0 and at 0^o Angle of Attack. From the plot, we find that the value of co-efficient of lift after 388 iterations converges to 0.0.

Since, the Double Wedge Airfoil chosen is symmetric, at 0^0 Angle of Attack, the pressure distribution over the top and bottom surface would remain identical. Hence, there's no differential pressure created which in turn results in Zero Lift and thereby, the value of co-efficient of lift is zero.

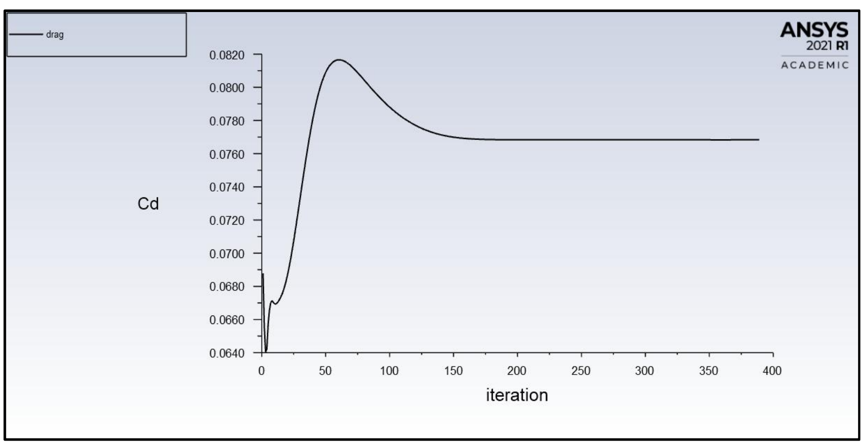

Fig. 10. Plot of Co-efficient of Drag v/s Iterations

The above plot gives the Co-efficient of drag of the Double Wedge Airfoil at Mach No 2.0 and at 0^o Angle of Attack. From the plot, we find that the value of co-efficient of drag after 388 iterations converges to 0.07684.

Drag is a mechanical force which is generated by the interaction and contact of a solid body with a fluid. Drag force, can be due to the skin friction between the surface of the airfoil and the molecules of the fluid, called Skin Friction Drag. The drag force can also be due to the shape of the airfoil, called the Form Drag. There is also Induced Drag which is due to the flow of air over an airfoil, which is inevitable.

Since the airfoil designed operates at supersonic speeds, there is an additional source of drag generated due to the formation of shock waves, called Wave Drag. As the aircraft approaches the speed of sound i.e., Mach Number= 1.0, shock waves are generated along the surface which produce a change in the static pressure and a loss of total pressure. The magnitude of the wave drag depends on the Mach Number of the flow.

Hence, irrespective of the lift force generated, a drag force will always be present when a body is passing through a fluid. Therefore, we obtain a non-zero value of Co-efficient of Drag which in this case, is equal to 0.07684.

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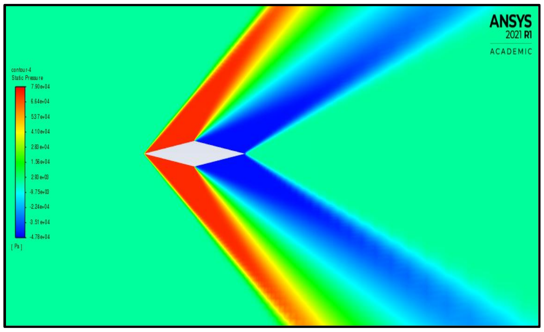

Fig. 11. Pressure Contour

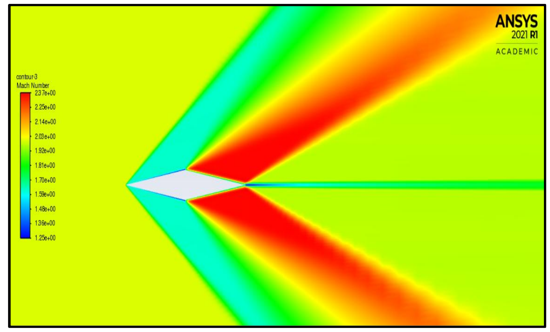

Fig. 12. Mach Number Contour

Due to the formation of oblique shock wave at the leading edge, the flow velocity decreases and there is a corresponding increase in pressure across the oblique shock. The formation of expansion waves at the apex edges causes the flow velocity to increase and a corresponding decrease in the pressure across the expansion wave, as shown in the contours above.

4.2 Modified Double Wedge Airfoil

Given below are the plots and contours obtained from the Fluent Analysis:

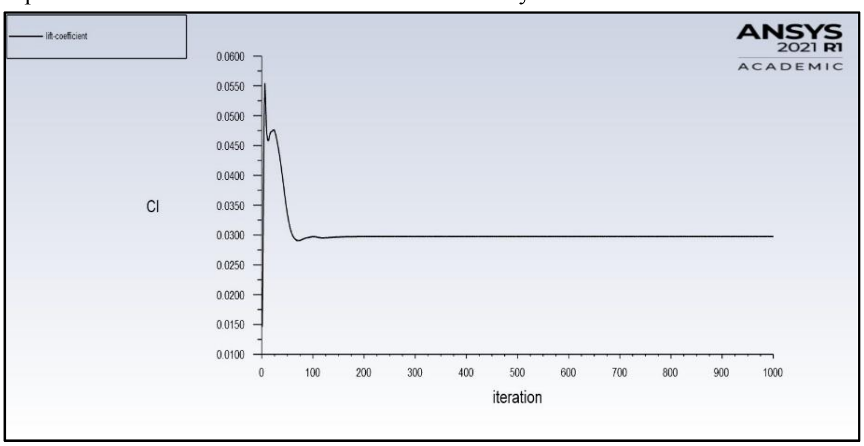

Fig. 13. Plot of Co-efficient of Lift v/s Iterations

For the airfoil, the Co-efficient of lift at Mach number 0.7 and 0^{o} angle of attack converges after 1000 iterations at a value of 0.0298. From the above plot it is evident that the positive value of co-efficient of lift even at 0^{o} Angle of Attack is due to the differential pressure created by providing variable fillet radii to the upper and lower apex edges.

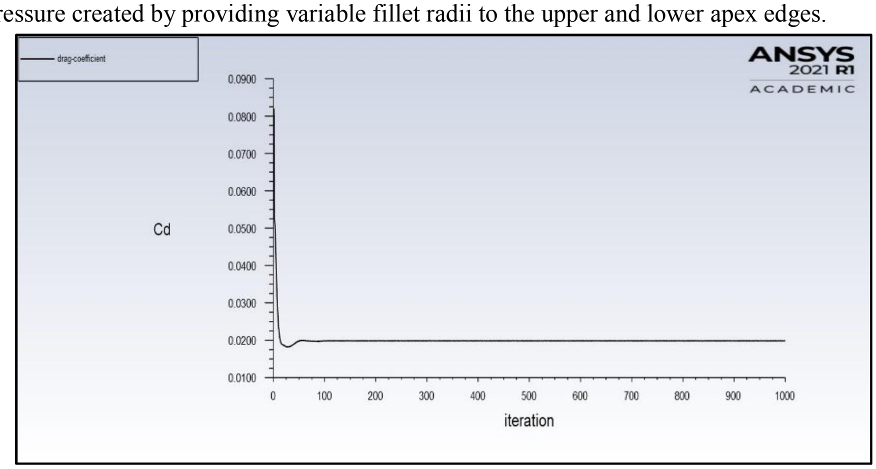

Fig. 14. Plot of Co-efficient of Drag v/s Iterations

For the airfoil, the Co-efficient of drag at Mach number 0.7 and 0º angle of attack converges after 1000 iteration at a value of 0.0199. The airfoil here produces significantly lower amount of co-efficient of drag. With a significant value of Co-efficient of lift and a lower Co-efficient of drag value, even at 0º Angle of Attack, the airfoil modification is applicable for use in the subsonic regime.

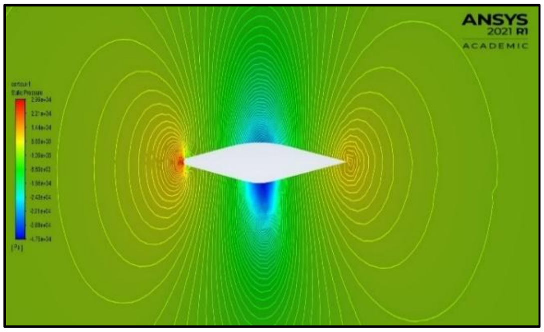

Fig. 15. Pressure Contour

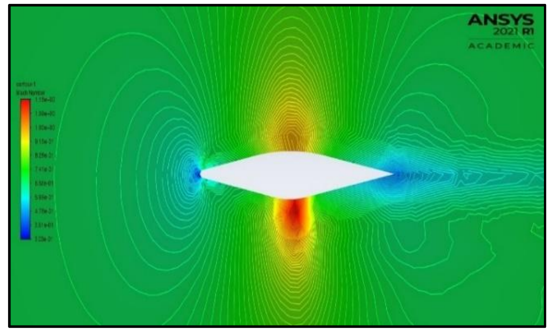

Fig. 16. Mach Number Contour

From the pressure contour, we can see that the pressure distribution is more concentrated towards the apex edges rather than being spread over the entire top and bottom surfaces. Such a distribution helps create a differential pressure between the top and bottom surface and thereby producing sufficient lift force.

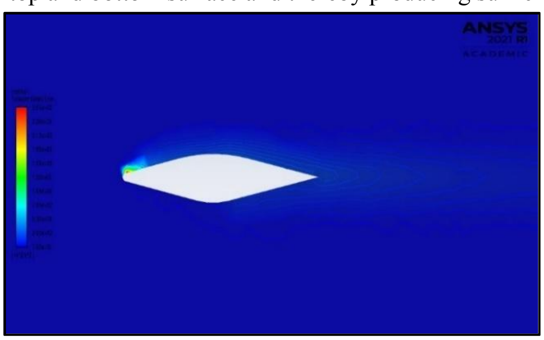

Fig. 17. Turbulent Kinetic Energy Contour

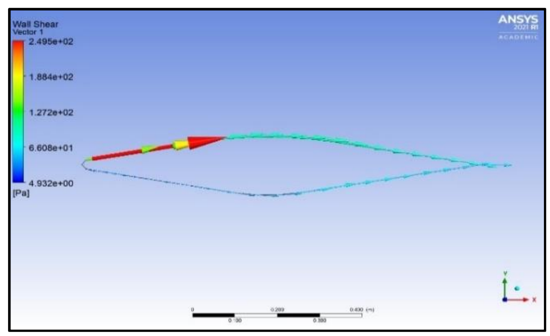

Fig. 18. Wall Shear

From the turbulent kinetic energy contour, we see that only a small amount of turbulence is produced at the leading edge of the airfoil and of negligible amount over the rest of the airfoil surface, which indicates better flow properties. The turbulence over the airfoil surface is supported by the wall shear diagram, which indicates considerable shear forces at the leading edge.

We now have an airfoil that has been derived from the standard Double Wedge Airfoil that gives good performance at subsonic speeds, which is evident from the above obtained results. Since the Double Wedge Airfoil is capable of giving good performance at supersonic speeds, we can have a wing structure that can effectively and efficiently perform at both subsonic and supersonic speeds. With several advancements in material technologies and the development of structures and materials that are capable of shape changing as per requirement, a transition between the two different airfoil shapes can be obtained.

4.3 Modified Double Wedge Airfoil with Blowing Port

Given below are the plots and contours obtained from the Fluent Analysis:

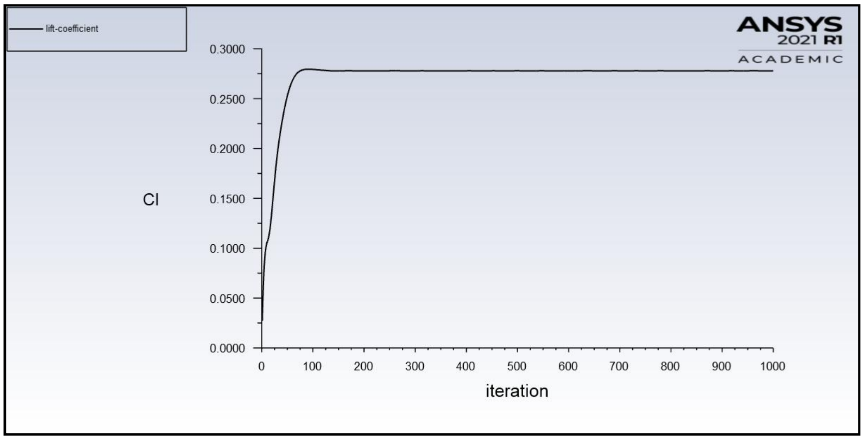

Fig. 19. Plot of Co-efficient of Lift v/s Iterations

For the airfoil, the co-efficient of lift at Mach number 0.7 and 0^o angle of attack converges after 1000 iterations at a value of 0.278. From the above plot it is evident that for the modified airfoil with the blowing notch, we are getting a positive value for the co-efficient of lift. Also, the co-efficient of lift is of a significant magnitude compared to the airfoil without the blowing stream, which shows that the blowing stream has delayed the point of flow separation and thus improved the flow over the airfoil and thereby its performance.

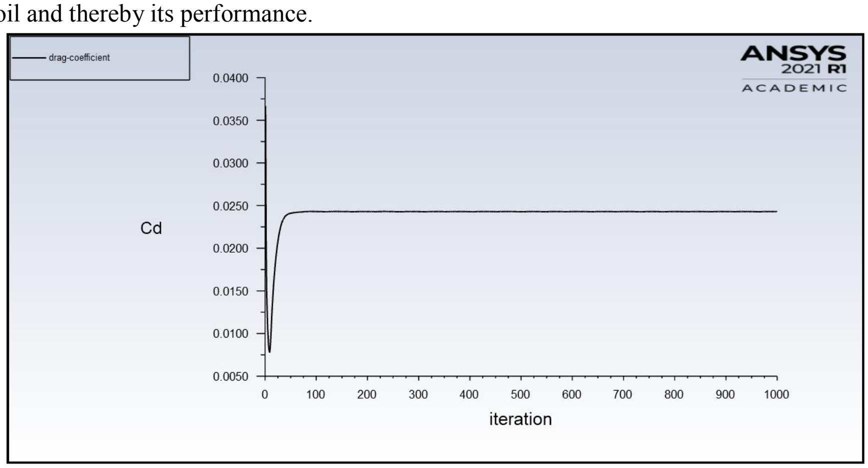

Fig. 20. Plot of Co-efficient of Drag v/s Iterations

For the airfoil, the Co-efficient of drag at Mach number 0.7 and 0^o angle of attack converges after 1000 iteration at a value of 0.0237. Similar to the modified airfoils, the airfoil with the blowing stream also generates comparatively lower values of Co-efficient of drag.

With a significant value of Co-efficient of lift and a lower Co-efficient of drag value, the airfoil with the blowing stream is suitable at subsonic speeds.

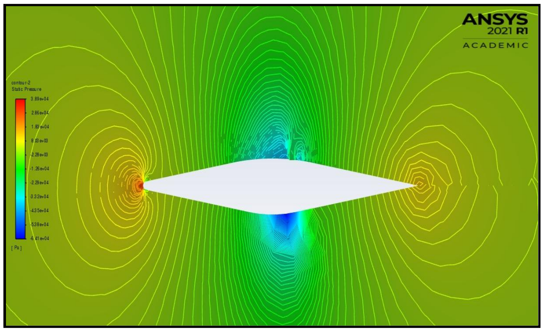

Fig. 21. Pressure Contour

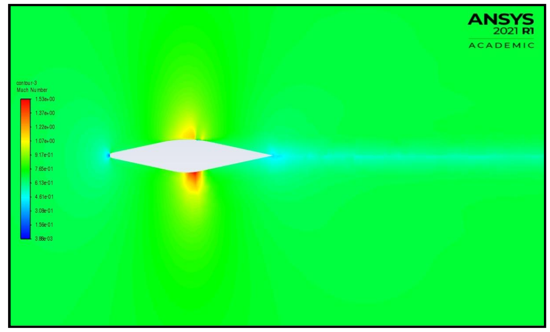

Fig. 22. Mach Number Contour

From the pressure contour we can see that the pressure distribution over the upper and lower surface of the airfoil is such that it is capable of producing sufficient amount of differential pressure to produce the required amount of lift force.

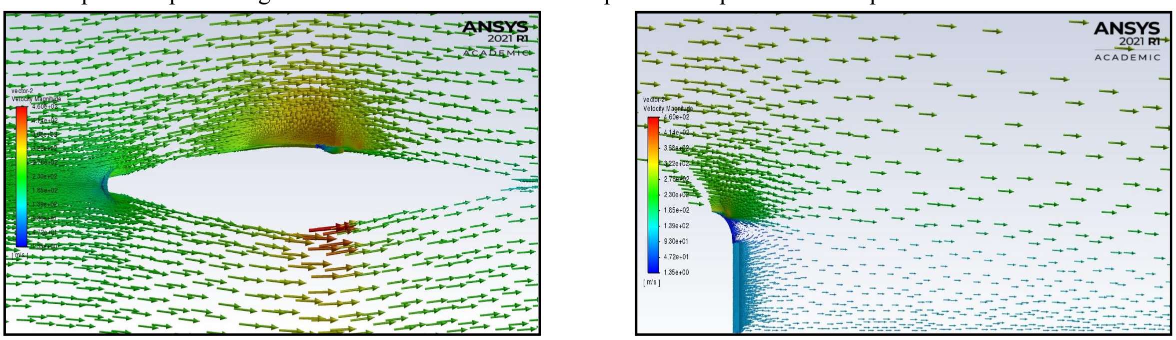

Fig. 23. Flow Velocity Vector around the Airfoil Surface and Blowing Port

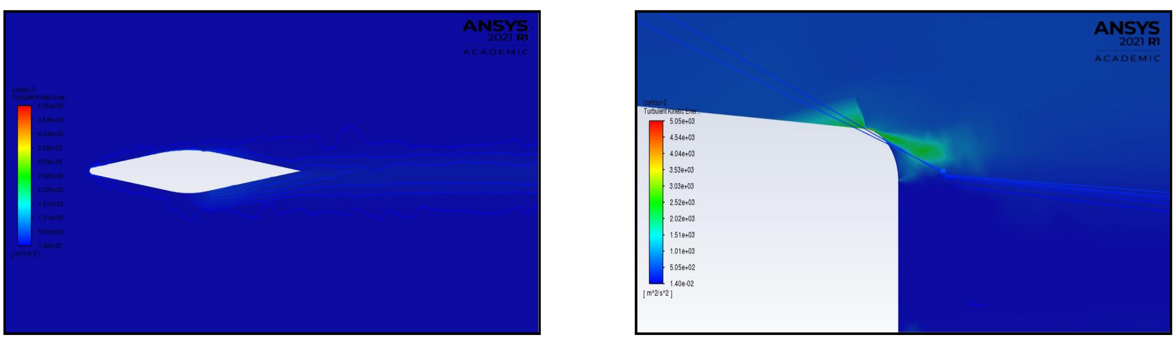

Fig. 24. Turbulent Kinetic Energy Contour

Here we see that only a small amount of turbulence is produced near the blowing notch and of negligible amount over the rest of the airfoil surface, which indicates better flow properties

V. Conclusion

At 0o angle of attack and Mach number 2.0, the results obtained from the Fluent analysis, very well agreed with the manual calculations. The co-efficient of lift was obtained as 0.0, which is true for symmetric airfoils at 0o angle of attack. The co-efficient of drag was found to be very negligible i.e., 0.07684. Hence the Double Wedge Airfoil is an efficiently performing airfoil at supersonic speeds.

The modified Double Wedge Airfoil with the fillet radii for the leading edge, Upper apex edge and Lower apex edge of 12mm, 1000mm and 450mm respectively was found to be effective at Mach number 0.7. The co-efficient of lift was found to be 0.0298 and the drag co-efficient 0.0199.

The modified airfoil gave us a better performance with an addition of a blowing stream of 100m/s through a notch provided at the upper apex edge. To accommodate the notch, the fillet radius for the upper apex edge was reduced to 800mm. The co-efficient of lift was found to be 0.278 and the drag co-efficient 0.0237. The better performance of the airfoil is attributed to the delayed flow separation over the airfoil surface due to the presence of a blowing stream. Since the aircraft engine is more often attached to the wing of the aircraft, the stream of air for the port can be sourced from either the engine bleed air or even the inlet air into the aircraft engine.

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