Numerical Investigation of Aerodynamic Characteristics of a Diamond Airfoil

Introduction

This report presents a computational fluid dynamics (CFD) analysis of a symmetrical double-wedge airfoil (DIAMOND AIRFOIL) in a supersonic flow regime at zero degrees angle of attack. The objective of this study is to visually and quantitatively understand the fundamental aerodynamic phenomena associated with supersonic flow, including the formation of oblique shock waves and Prandtl-Meyer expansion fans, and their effect on key fluid properties such as pressure, velocity, and Mach number.

The analysis was performed using ANSYS FLUENT software, which numerically solves the Navier-Stokes equations for fluid flow. The double-wedge airfoil is an ideal model for this study due to its sharp geometric features, which simplify the interpretation of supersonic wave interactions. The freestream conditions for this simulation were set to a Mach number (M_∞) of 3.0.

Theoretical Background

In supersonic flow (Mach number $M>1$), small disturbances in the flow field, such as those caused by an airfoil's leading edge, cannot propagate upstream. Instead, they form shock waves that are inclined at a specific angle to the flow.

1. **Oblique Shock Waves:** When the supersonic flow encounters the leading edge of the double-wedge airfoil, it must turn to follow the airfoil's surface. This compression causes an oblique shock wave to form. Across this shock wave, the fluid properties change abruptly:
   - **Pressure:** Increases significantly.
   - **Velocity:** Decreases.
   - **Mach Number:** Decreases, but remains supersonic.
   - **Density:** Increases.

2. **Prandtl-Meyer Expansion Fans:** As the flow moves past the maximumthickness of the airfoil and turns back towards the trailing edge, it undergoes an expansion. This expansion is not a single shock wave, but a continuous series of Mach waves known as a Prandtl-Meyer expansion fan. Across an expansion fan, the fluid properties change in the opposite manner to a shock wave:
   - **Pressure:** Decreases.
   - **Velocity:** Increases.
   - **Mach Number:** Increases.
   - **Density:** Decreases.

Analysis of CFD Results

The CFD simulations provide a clear visualization of these phenomena. The following sections describe the key observations from the pressure, velocity, and Mach number contour plots.

1. Velocity Contour

The velocity contour image shows the flow field in terms of velocity magnitude. The freestream is characterized by a high, uniform velocity. As the flow approaches the leading edge of the airfoil, two distinct regions of reduced velocity (indicated by the change from yellow to green) are observed. These correspond to the regions immediately behind the oblique shock waves. The flow then accelerates again (indicated by the shift from green back to yellow and then into purple) as it passes over the rear half of the airfoil, a direct result of the Prandtl-Meyer expansion fan.

2. Mach Number Contour

The Mach number contour provides an excellent visualization of the shock and expansion waves.

- **Leading Edge:** At the leading edge, two oblique shock waves are clearly visible. The Mach number drops from the freestream value of $M_\infty=3.0$ (yellow region) to a lower, but still supersonic, value (green region) behind the shock. This confirms the compression of the flow and the formation of a shock wave.

- **Trailing Edge:** At the point of maximum thickness, the flow turns again, creating an expansion fan. The Mach number increases in this region (from green to purple), as the flow expands and accelerates towards the trailing edge. This is a classic characteristic of supersonic expansion fans.
- **Wake Region:** A complex interaction of waves occurs behind the airfoil as the expansion fans from the top and bottom surfaces reflect and interact with each other, creating a distinct wake pattern.

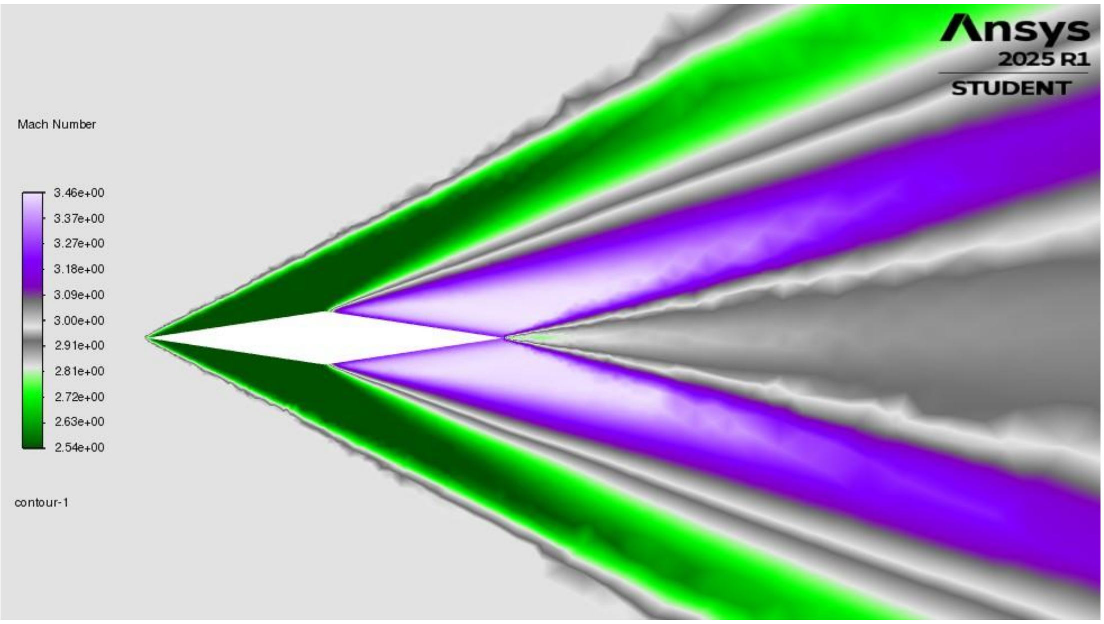
3. Pressure Contour

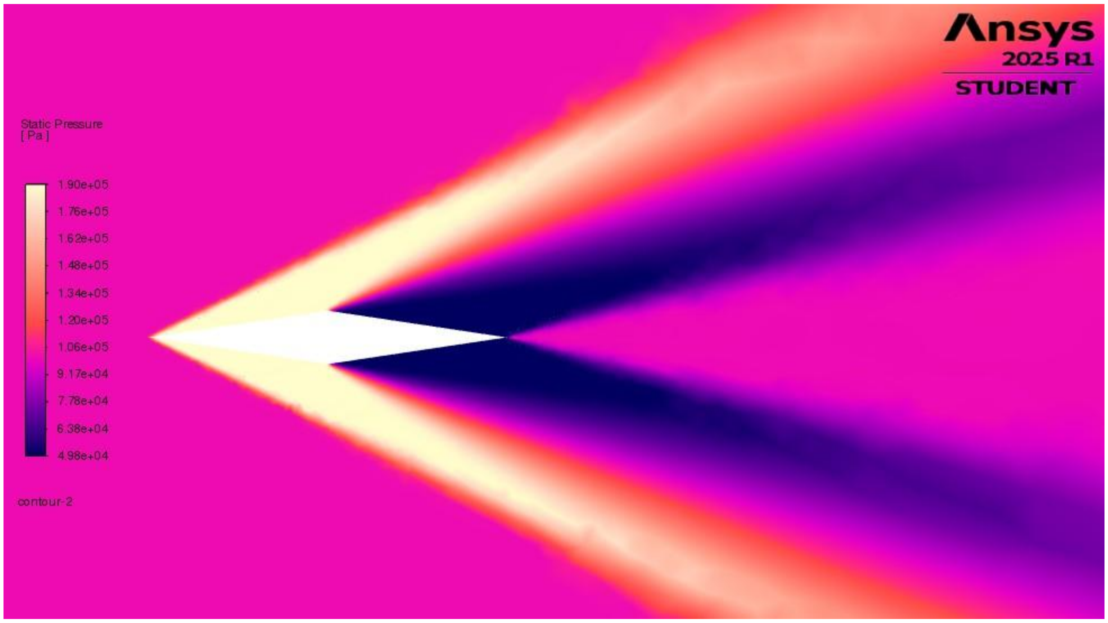
The pressure contour image is perhaps the most direct way to observe the effect of the shock and expansion waves.

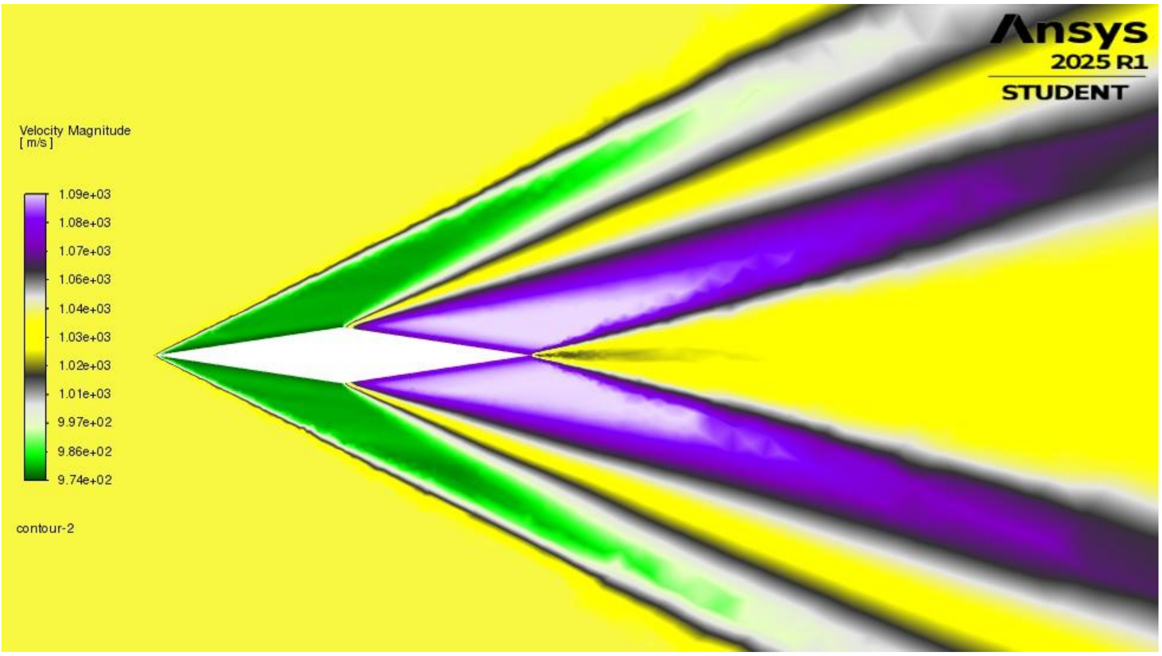
- **Leading Edge:** The pressure contour shows a sharp increase in static pressure immediately behind the oblique shock waves at the leading edge. The freestream pressure (represented by the light yellow) jumps to a higher-pressure region (dark red/orange) on the surface of the airfoil.
- **Trailing Edge:** Over the rear half of the airfoil, the pressure drops significantly (indicated by the dark blue/purple region) due to the expansion fan. The pressure on the surface of the airfoil in this region is actually lower than the freestream pressure, which is a key factor in generating lift and drag.
- **Overall:** The analysis clearly shows a region of high pressure behind the leading-edge shock and a region of low pressure behind the expansion fan. The pressure distribution across the airfoil's surface is responsible for the overall aerodynamic forces (lift and drag) acting on it.

Conclusion

The CFD analysis successfully captures the fundamental characteristics of supersonic flow over a double-wedge airfoil at a freestream Mach number of 3.0. The contour plots for velocity, Mach number, and pressure clearly demonstrate the formation of oblique shock waves at the leading edge and Prandtl-Meyer expansion fans at the point of maximum thickness. These phenomena are directly responsible for the sudden changes in fluid properties and the resulting pressure distribution on the airfoil's surface. This study provides a strong foundation for understanding the complex nature of compressible flow and its interaction with simple geometric shapes.






Velocity Magnitude
[m/s]
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1.08e+03
1.07e+03
1.06e+03
1.04e+03
1.03e+03
1.02e+03
1.01e+03
9.97e+02
9.86e+02
9.74e+02
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