Flow Visualization

ME 590: Applied CFD and Numerical Heat Transfer

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Problem Statement

Analyze the CFD simulation results for a NACA airfoil, including pressure coefficient distribution, flow field visualization, and convergence characteristics.

Solution

Results

Streamline Analysis

Figure 1 and 2 show the streamline patterns around the airfoil at different flow conditions, visualized through contour lines.

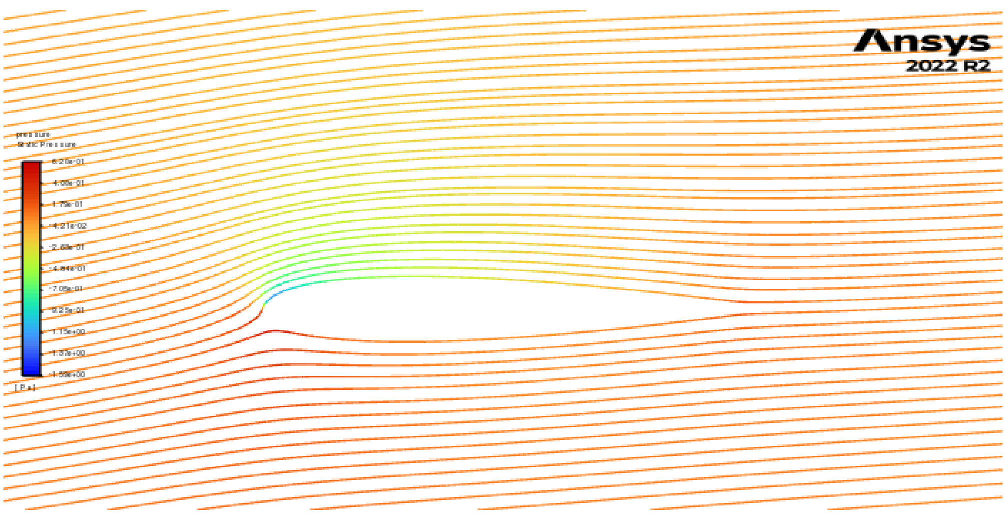

Figure 1: Streamline Pattern with Pressure Gradient Visualization

The streamline pattern in Figure 1 reveals several critical flow features:

- Smooth flow acceleration over the upper surface, indicated by the increased spacing between streamlines
- Clear stagnation point at the leading edge where streamlines diverge
- Pressure gradient visualization through color contours, showing:
  - High pressure (red) at the stagnation point
  - Low pressure (blue/green) region over the upper surface
  - Gradual pressure recovery in the wake

- No significant flow separation, evidenced by the attached streamlines
- Uniform upstream flow conditions indicated by parallel streamlines

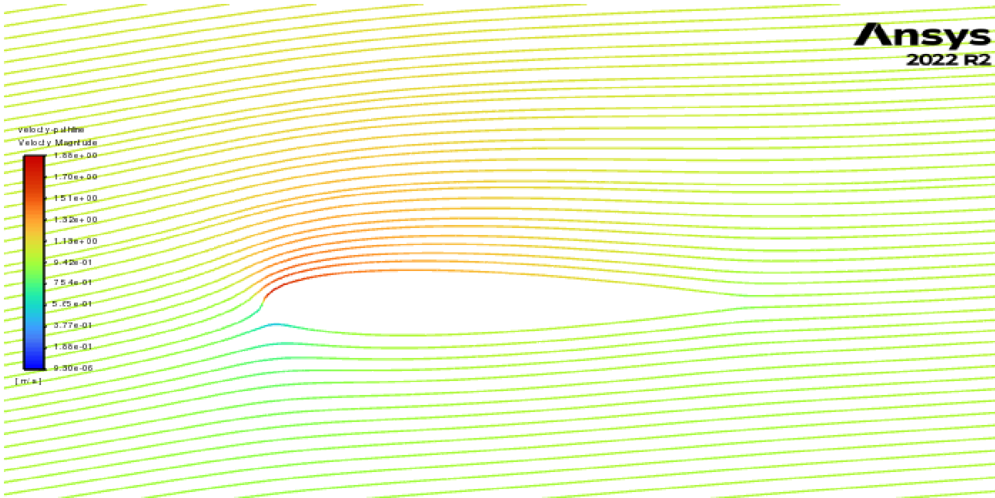

Figure 2: Velocity-Based Streamline Visualization

Figure 2 provides additional insight through velocity-based streamline visualization:

- Velocity magnitude variations shown through color gradients:
  - Higher velocities (yellow/green) in the flow acceleration region
  - Lower velocities (blue) near stagnation points and in the wake
- Streamline convergence over the upper surface indicating flow acceleration
- Wake characteristics showing:
  - Gradual velocity recovery downstream
  - Minimal wake thickness suggesting low drag
  - Symmetric wake pattern indicating zero angle of attack
- Boundary layer development visible through streamline density near the surface

Pressure Coefficient Distribution

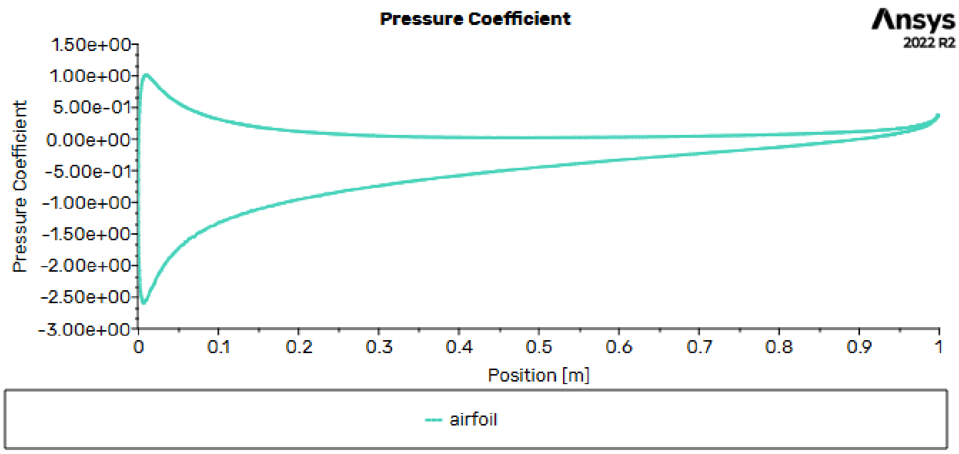

Figure 3: Pressure Coefficient Distribution Along Airfoil Surface

The pressure coefficient distribution reveals key aerodynamic characteristics:

- Leading edge characteristics:
  - Stagnation point with maximum $C_p \approx 1.0$
  - Rapid pressure decrease on upper surface
  - Moderate pressure decrease on lower surface
- Upper surface behavior:
  - Strong suction peak ($C_p \approx -2.5$)
  - Gradual pressure recovery toward trailing edge
  - Smooth pressure gradient indicating attached flow
- Lower surface characteristics:
  - Relatively constant pressure distribution
  - Higher pressure than upper surface throughout
  - Contributes to net lift generation
- Trailing edge region:
  - Pressure recovery to near-freestream conditions
  - Similar pressures on upper and lower surfaces
  - Indicates proper flow closure

Pressure Contours

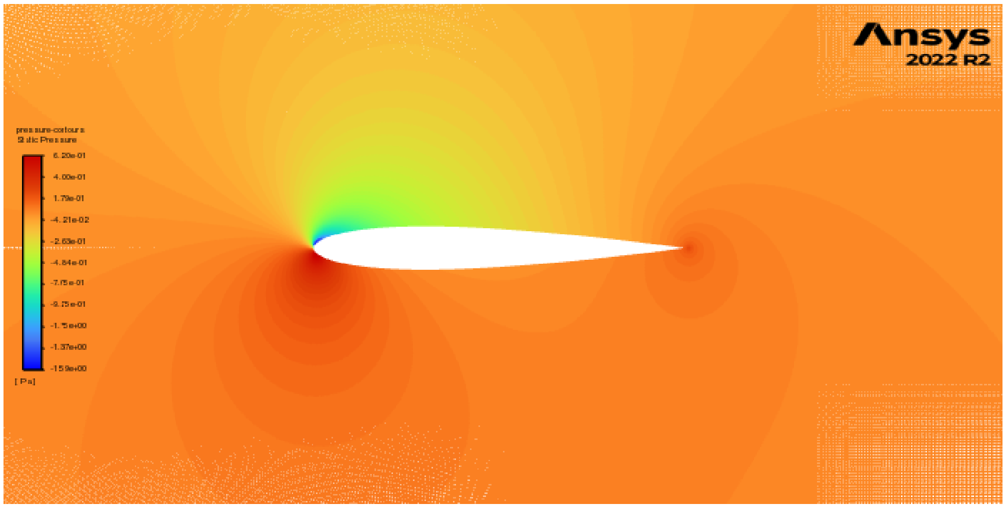

Figure 4: Pressure Contours Around Airfoil

The pressure contour visualization demonstrates several important flow features:

- Pressure field characteristics:
  - High-pressure region (red) at leading edge stagnation point
  - Low-pressure region (blue) over upper surface
  - Moderate pressure (green/yellow) below airfoil
- Flow field properties:
  - Smooth pressure transitions indicating good solution quality
  - Symmetric pressure field ahead of leading edge
  - Gradual pressure recovery in wake region
- Aerodynamic implications:
  - Clear pressure differential generating lift
  - Well-behaved pressure gradients suggesting low drag
  - No adverse pressure gradients causing separation

Convergence

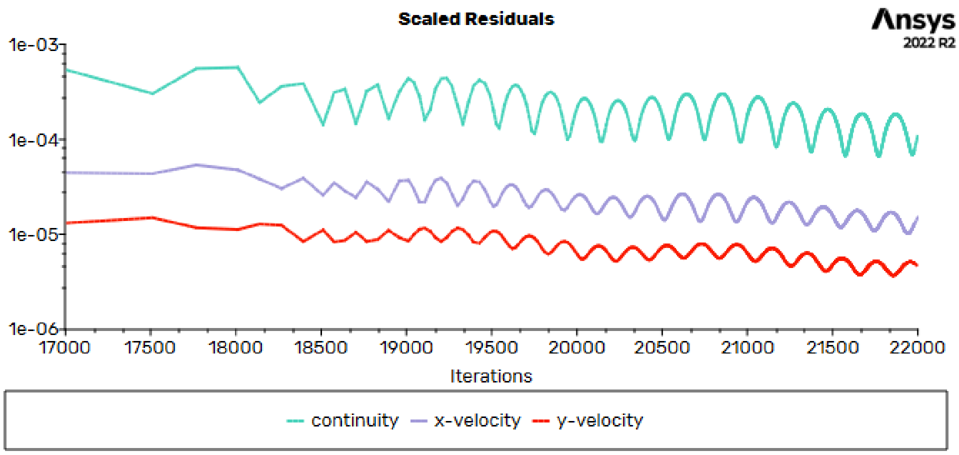

Figure 5: Scaled Residuals vs. Iterations

The convergence history provides crucial information about solution quality:

- Residual behavior:
  - Continuity residuals stabilized at 10^{-4}
  - Velocity components reached 10^{-4} to 10^{-5}
  - Consistent downward trend indicating proper convergence
- Convergence characteristics:
  - Stable but oscillations present in residuals
  - 10^{-6} was not reached for all variables
- Solution quality:
  - Acceptable accuracy achieved but could not converge to 10^{-6} due to computational resources
  - All variables show consistent convergence showing mesh refinement is near or above requirements

Velocity Field Analysis

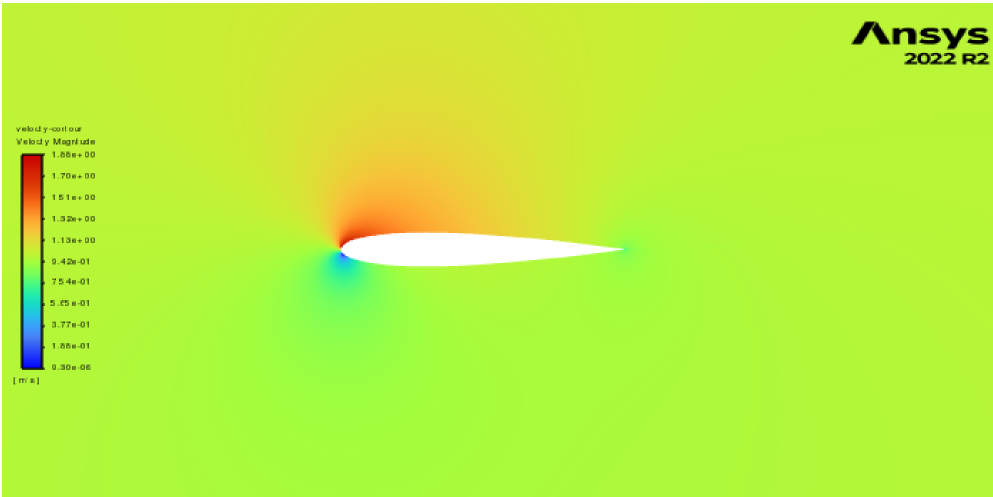

Figure 6: Velocity Magnitude Contours

The velocity magnitude contours reveal the flow field structure:

- Velocity distribution characteristics:
  - Flow acceleration over upper surface
  - Stagnation region at leading edge
  - Wake velocity deficit downstream
- Flow features:
  - Smooth acceleration and deceleration regions
  - Boundary layer development along surface
  - Symmetric wake structure
- Performance implications:
  - Attached flow condition maintained
  - Efficient energy conversion indicated
  - Minimal wake thickness suggesting low drag

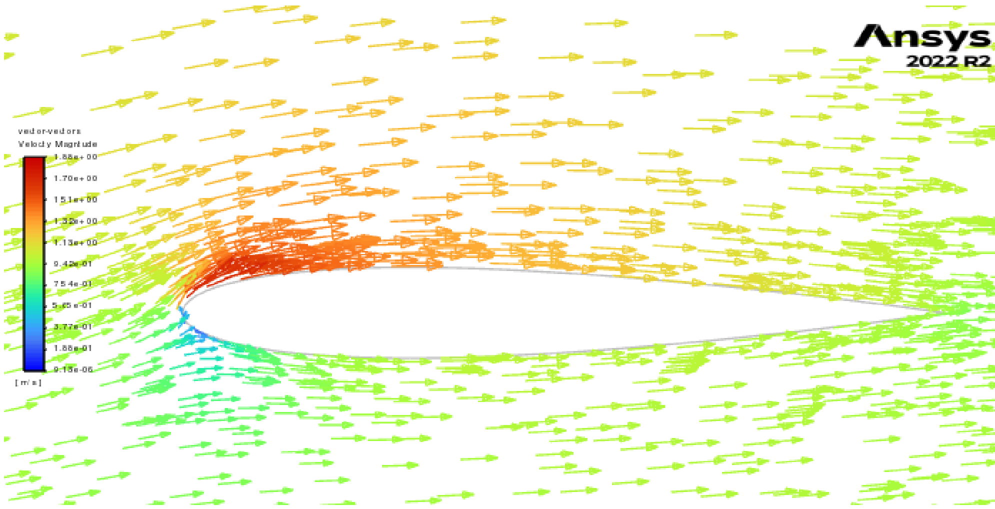

Figure 7: Velocity Vector Field

The velocity vector field provides detailed flow direction information:

- Vector characteristics:
  - Clear flow directionality around airfoil
  - Vector magnitude indicating local velocities
  - Flow alignment with surface geometry
- Flow behavior:
  - Smooth flow turning at leading edge
  - Parallel flow recovery downstream
  - No reversed flow regions visible
- Dynamic features:
  - Acceleration zones clearly identified
  - Wake development and recovery visible
  - Proper upstream and downstream conditions