Wing Aerodynamic Design & Pipeline Development for STOL Aircraft High Lift

Tools: Python (AeroSandbox), OpenVSP, Ansys Fluent

1. Aim & Objective

The objective of this project was to design and validate a clean-sheet wing geometry for a regional Short Take-Off and Landing (STOL) aircraft. The design requirements targeted high-lift performance for short-field operations and high aerodynamic efficiency (L/D > 15) during cruise.

A multi-fidelity analysis pipeline was developed to accelerate the design process, integrating Python-based automation for rapid airfoil sizing, OpenVSP for 3D spanwise optimization, and Ansys Fluent (RANS CFD) for high-fidelity physics validation. The final design achieved a cruise Lift-to-Drag ratio of **18.4**, validating the wing's efficiency for regional mobility missions.

2. Design Methodology: The "Digital Pipeline"

2.1 Automated Parametric Sweep (Low-Fidelity)

To bypass manual iterative testing, a Python automated pipeline was developed using the **AeroSandbox** library to interface with XFOIL. [Refer to Figure 1.1 & 1.2]

- **Automation:** A script was written to parametrically generate flap geometries by applying rotation matrices to the airfoil coordinates at the 70% chord line.
- **Sweep:** The script automated 80+ simulations across flap deflection angles (0° to 30°) and Angles of Attack (α = -5° to 15°).
- **Result:** The **NACA 4412** profile was selected for its superior camber characteristics. The automation identified that a 30° simple flap deflection increased the 2D Maximum Lift Coefficient (C_{Lmax}) from **1.2 to 1.98** (+65%), confirming STOL capability.

2.2 3D Sizing & Induced Drag Analysis (Mid-Fidelity)

The optimized 2D section was extruded into a finite wing geometry (b=12m, c=1.5m) in **OpenVSP**.

- **Physics Modeling:** A Vortex Lattice Method (VLM) simulation was performed to capture 3D finite wing effects, specifically **wingtip vortices** and **induced drag**.
- **Optimization:** A straight-wing planform was chosen over a swept configuration to maximize low-speed lift distribution and ensure favorable stall characteristics (root-to-tip stall progression) for pilot controllability during slow approaches.
- **Outcome:** The VLM analysis quantified a ~ 45% reduction in realized lift compared to 2D theory due to 3D downwash, informing the necessary wing sizing area (S_{ref} = 18 m^2). [Refer to Figure 2]

2.3 High-Fidelity RANS Validation (CFD)

To validate the VLM predictions and capture viscous boundary layer effects, a Reynolds-Averaged Navier-Stokes (RANS) simulation was performed in **Ansys Fluent**.

- **Domain:** A 20c length fluid domain was constructed to eliminate blockage effects.
- **Mesh:** A hybrid mesh with **inflation layers** (prism cells) was generated on the wing surface to resolve the boundary layer gradient.
- **Physics:** The (**SST k - ω) turbulence model** was utilized for its industry-standard accuracy in predicting flow separation and adverse pressure gradients.
- **Conditions:** Cruise velocity of 40 m/s (Re $\approx$ 4.1 x 10^6).

3. Results & Discussion

3.1 Aerodynamic Performance

The high-fidelity CFD analysis confirmed that the design meets the efficiency targets for a regional transport aircraft.

Parameter	Value	Unit	Notes
Lift Force (L)	**4,027**	N	At 0° AOA (Cruise)
Drag Force (D)	**218.5**	N	Total Viscous + Pressure Drag
Lift Coefficient (C_L)	**0.228**	-	Validated 3D Cruise Lift
Aerodynamic Efficiency (L/D)	**18.43**	-	**Exceeds Target (>15)**

3.2 Flow Physics Visualization

The CFD post-processing provided critical insights into the flow regime:

- **Pressure Distribution:** [Refer to Figure 3.1] The pressure contour reveals a distinct suction peak (low pressure) at the leading edge of the upper surface, driving lift generation. The pressure recovery towards the trailing edge is smooth, indicating no premature flow separation at cruise.

- **Velocity Acceleration:** [Refer to Figure 3.2] Velocity contours confirm the acceleration of flow over the cambered surface, consistent with Bernoulli's principle. The stagnation point is clearly defined at the nose.

- **Streamlines:** [Refer to Figure 3.3] Analysis of pathlines confirmed the formation of wingtip vortices, matching the induced drag predictions from the OpenVSP VLM stage.

4. Conclusion

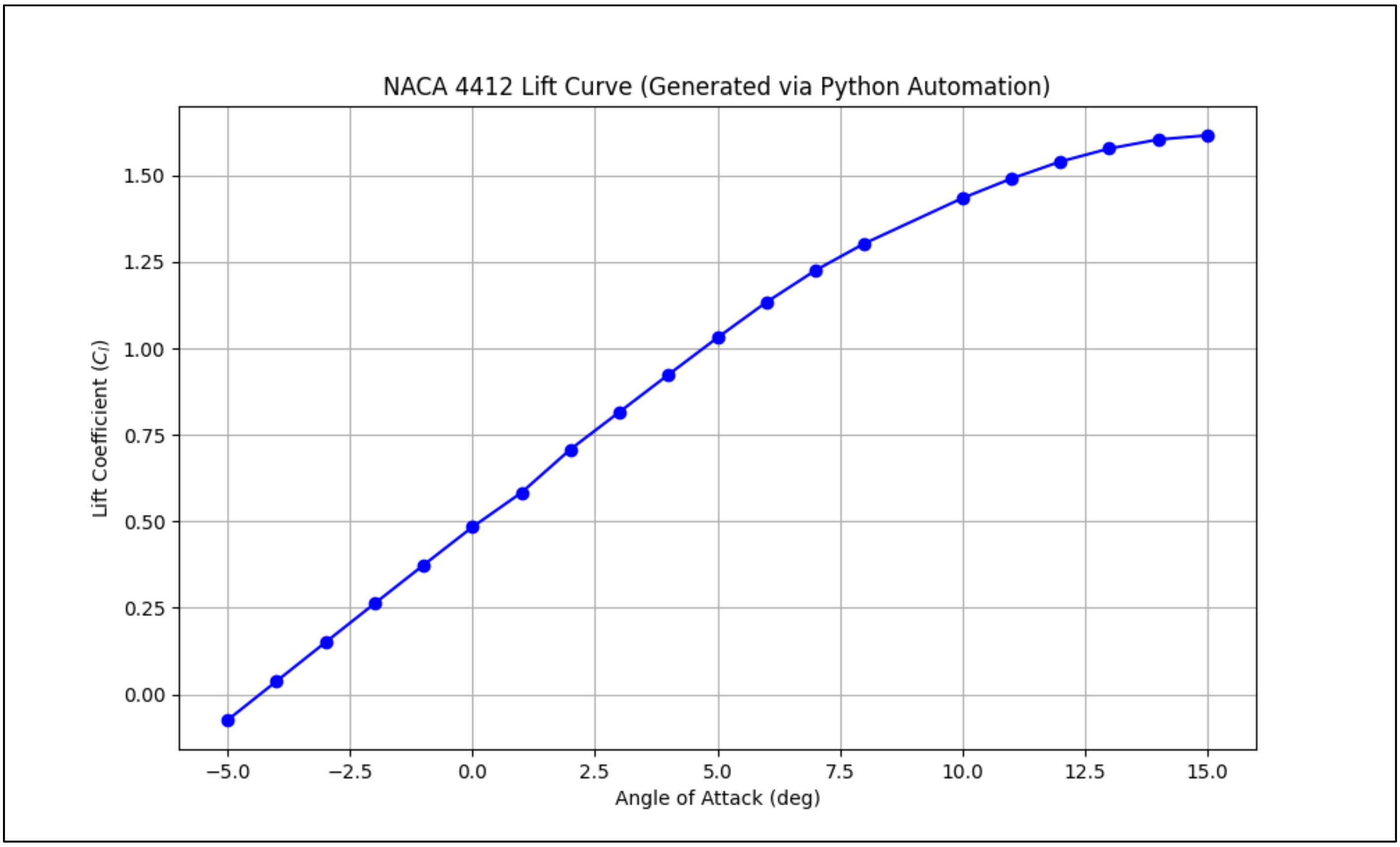
This project successfully established a scalable aerodynamic design pipeline, linking code-based optimization with industrial physics solvers.

1. **Automation:** The Python pipeline reduced the time required for flap configuration trade studies by approximately **90%** compared to manual GUI interaction.
2. **Performance:** The NACA 4412 straight-wing configuration achieved a high cruise efficiency (L/D = 18.4) while offering significant high-lift potential via flaps.
3. **Correlation:** The progression from 2D theoretical lift ($C_L \approx 0.4$) to 3D realized lift ($C_L \approx 0.23$) highlighted the critical importance of high-fidelity 3D modeling in the preliminary design phase.

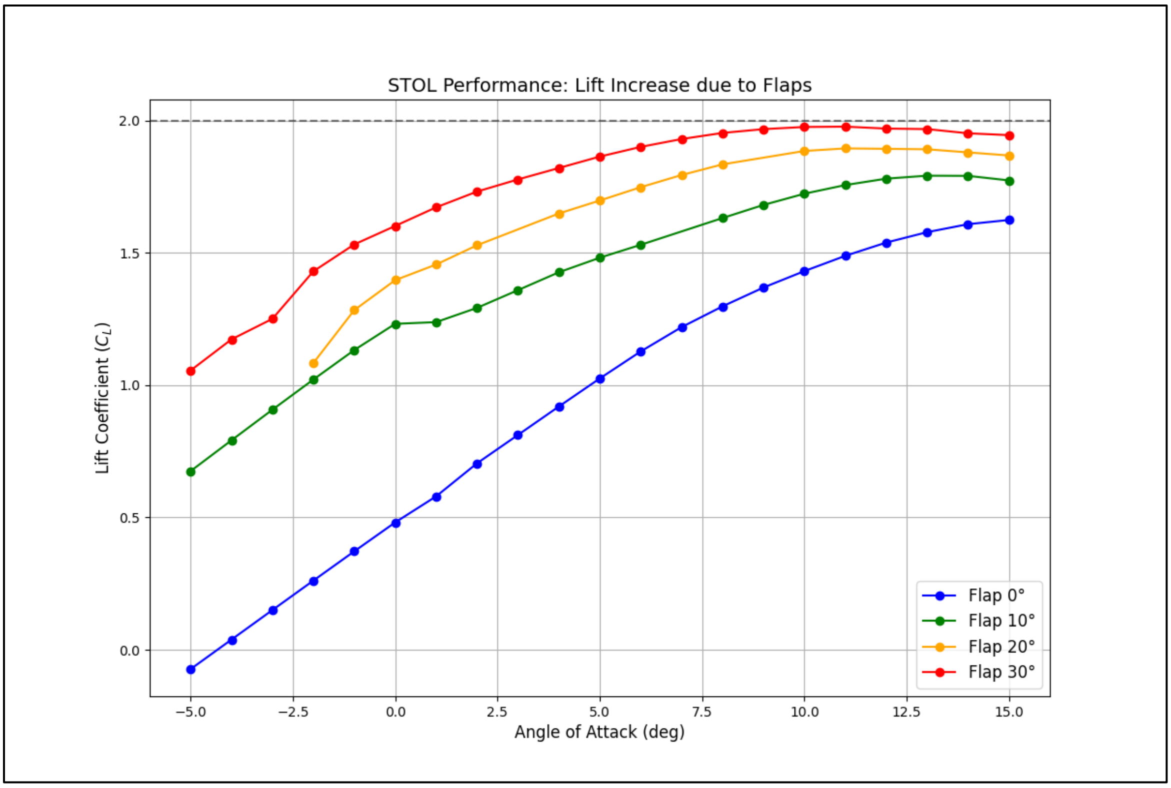
This workflow is directly applicable to the rapid conceptual design of future STOL variants and regional air mobility platforms.

[Appendices]

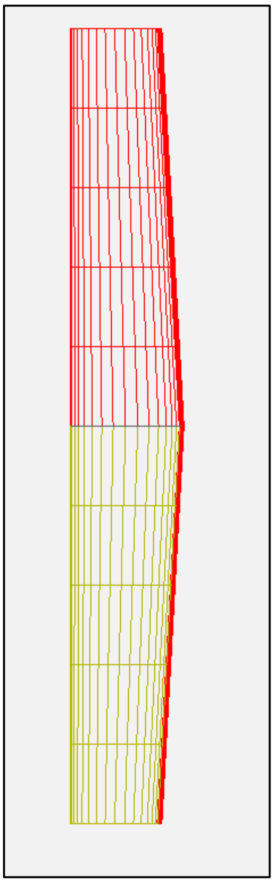
1.1 NACA 4412 Lift Curve (C_L VS Angle of Attack)

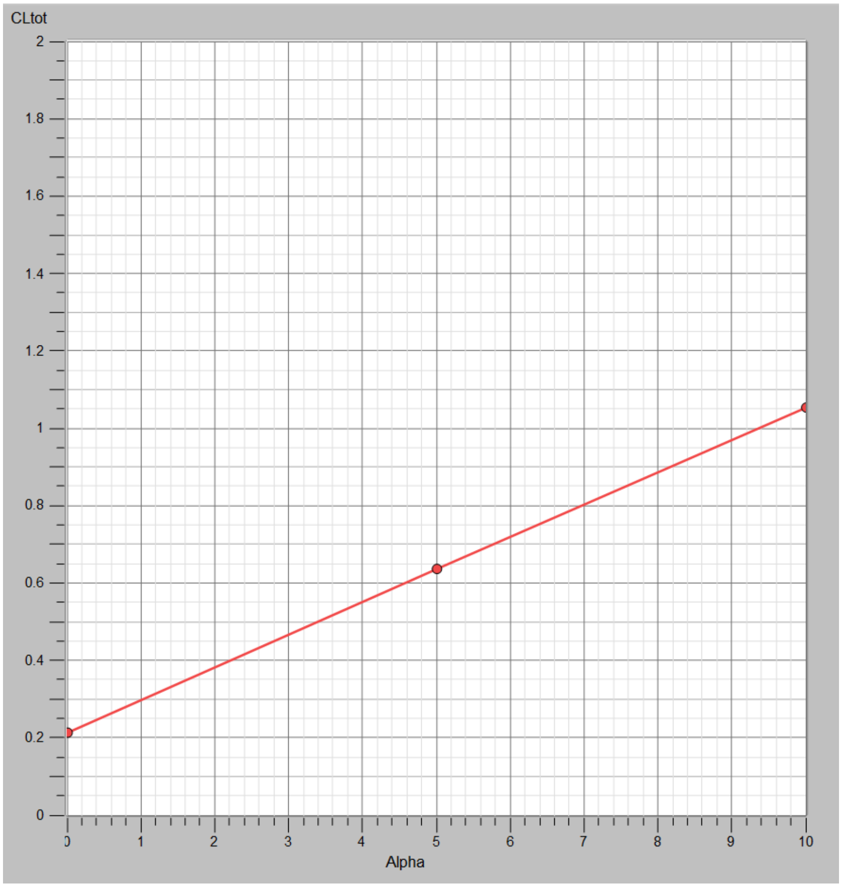


1.2 Effect of Flaps on Lift

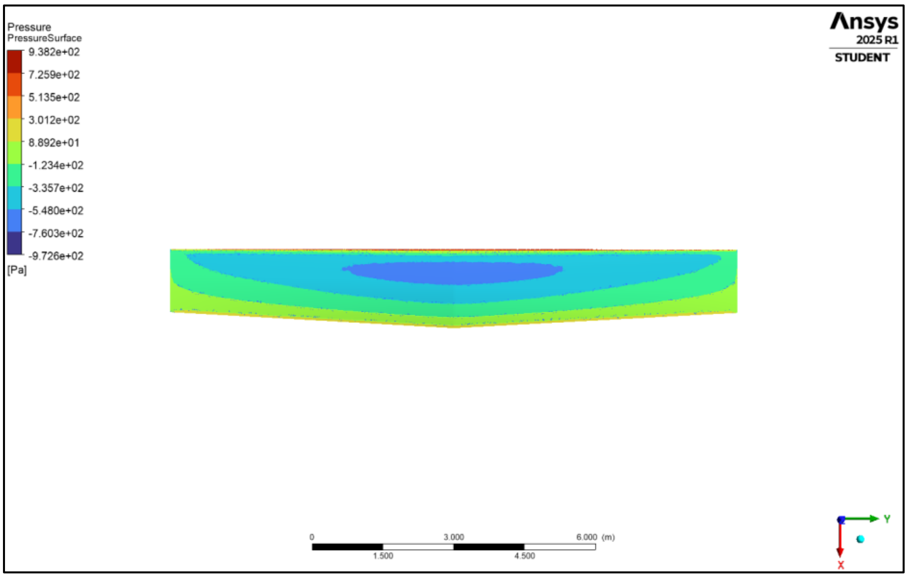


2 Studying the C_{L_TOT} curve generated by NACA 4412 3D Wing





3. High Fidelity [3.1] Pressure [3.2] Velocity [3.3] Wing Vortex Distributuions using Ansys Fluent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-5.480e+02
-7.603e+02
-9.726e+02
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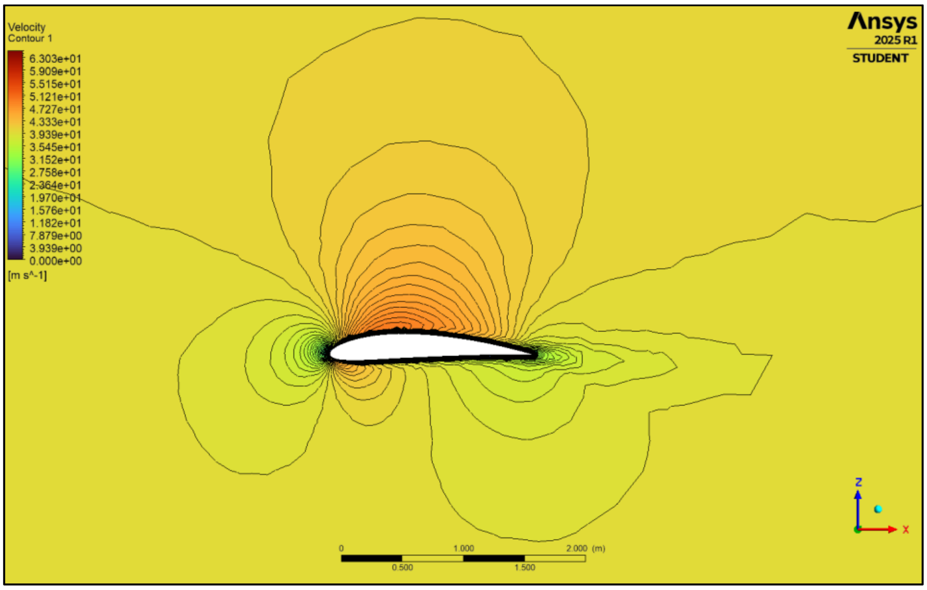
Ansys
2025 R1
STUDENT
0
3.000
6.000 (m)
1.500
4.500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Ansys
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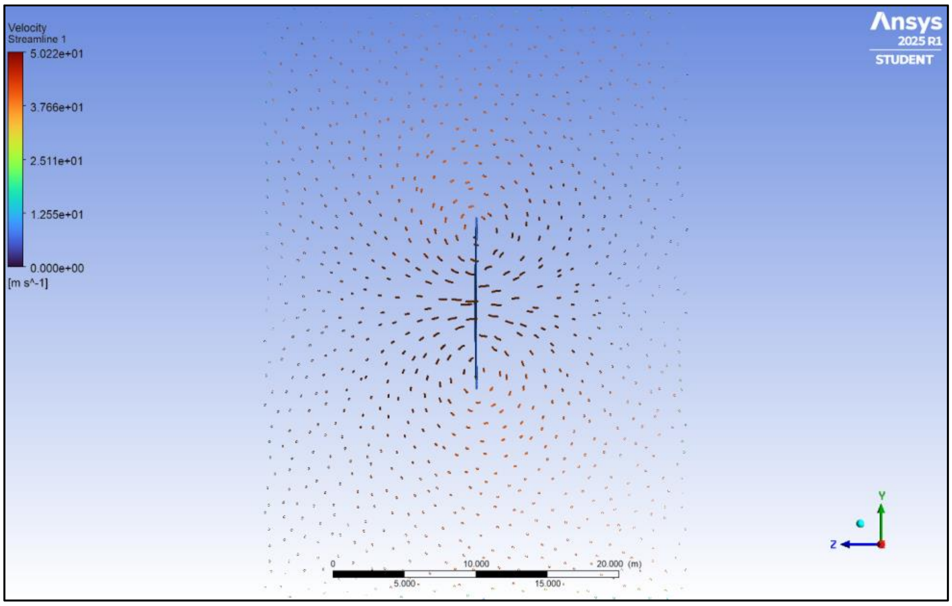
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