DESIGN OPTIMIZATION OF HIGH-LIFT CONFIGURATIONS USING A VISCOUS ADJOINT-BASED METHOD

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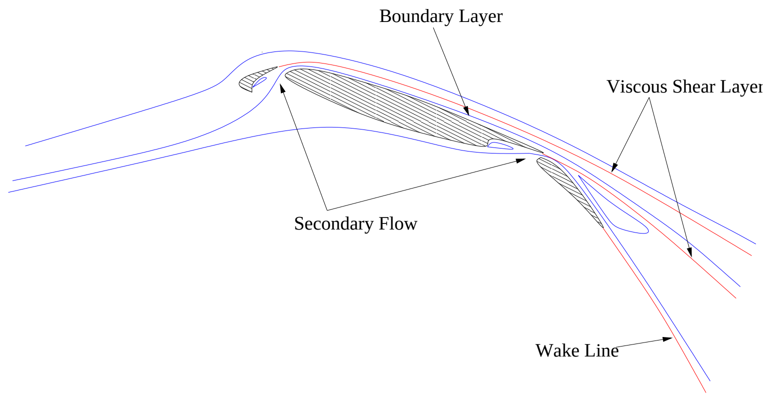
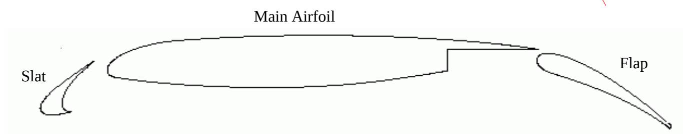
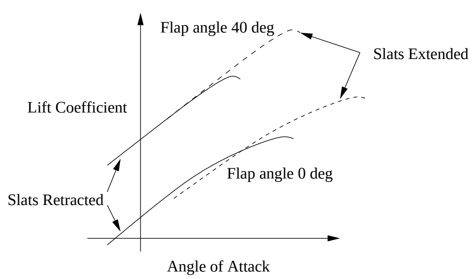
Outline

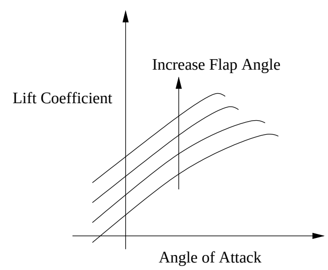
- Introduction
- Objectives
- Description of Continuous Adjoint Method
- Viscous Aerodynamic Sensitivity Accuracy Study
- High-Lift System Design
- Conclusions and Future Work

High–Lift System Configuration









Introduction

- **High-Lift System Configuration Design**
  - Wind tunnel testing
  - **CFD** as an **Analysis Tool**
  - **Difficulties** in **Decision Making**
- **CFD** as a **Design Tool**
  - **Automatic Design Procedure** : **CFD** + **Gradient Based Optimization**
  - **Gradient Based Optimization**
    * **Cost function** to be Min/Maximized (Drag, L/D).
    * **Control function** to be Optimized (Airfoil Shape).
    * **Design Variables** (Mesh points, Sine Bump function)
    * **Constraint** (Euler eq. NS eq)
    * **Gradients** (Finite Difference, Complex, Adjoint)
    * **Optimization Algorithm** (Steepest Descent)
  - **Control Theory Approach** or **Adjoint Method** by Jameson 1988.
- **Continuous Adjoint Design Method** using the **Navier-Stokes** equations as a flow model and the **Gradient Accuracy** study.
- **Application to High-Lift System Design.**

Objectives

1. **Viscous Aerodynamic Sensitivity Accuracy Study**
   - 2D Implementation of a **Continuous Adjoint Design Method** that uses the **Navier-Stokes** equations as a flow model.
   - Verification of the **Accuracy** and **Efficiency** of the present **Continuous Adjoint Method** by comparison with **Gradients** from **Finite Difference Method**.
   - Demonstration with **Preliminary Examples**.
2. **High-Lift System Design**
   - Develop numerical optimization tools for design and development of high-lift system configurations.
   - Improve take-off and landing performance of high-lift systems using a **Continuous Adjoint Design Method**.

     $-Cl$, Cd, L/D and Cl_{max}.

Symbolic Description of Continuous Adjoint Method

Let I be the **cost** (or **objective**) function

$$I = I(w, \mathcal{F})$$

where

$$\begin{aligned} w &= \text{flow field variables} \\ \mathcal{F} &= \text{design variables} \end{aligned}$$

The **first variation** of the cost function is

$$\delta I = \frac{\partial I}{\partial w}^T \delta w + \frac{\partial I}{\partial \mathcal{F}}^T \delta \mathcal{F}$$

The **flow field equation** and its **first variation** are

$$R(w, \mathcal{F}) = 0$$

$$\delta R = 0 = \left[\frac{\partial R}{\partial w}\right] \delta w + \left[\frac{\partial R}{\partial \mathcal{F}}\right] \delta \mathcal{F}$$

Introducing a **Lagrange Multiplier**, ψ, and using the **flow field equation** as a **constraint**

$$\begin{aligned}\delta I &= \frac{\partial I}{\partial w}^T \delta w + \frac{\partial I}{\partial \mathcal{F}}^T \delta \mathcal{F} - \psi^T \left\{ \left[\frac{\partial R}{\partial w}\right] \delta w + \left[\frac{\partial R}{\partial \mathcal{F}}\right] \delta \mathcal{F} \right\} \\ &= \left\{ \frac{\partial I}{\partial w}^T - \psi^T \left[\frac{\partial R}{\partial w}\right] \right\} \delta w + \left\{ \frac{\partial I}{\partial \mathcal{F}}^T - \psi^T \left[\frac{\partial R}{\partial \mathcal{F}}\right] \right\} \delta \mathcal{F}\end{aligned}$$

By choosing ψ such that it satisfies the **adjoint equation**

$$\left[\frac{\partial R}{\partial w}\right]^T \psi = \frac{\partial I}{\partial w},$$

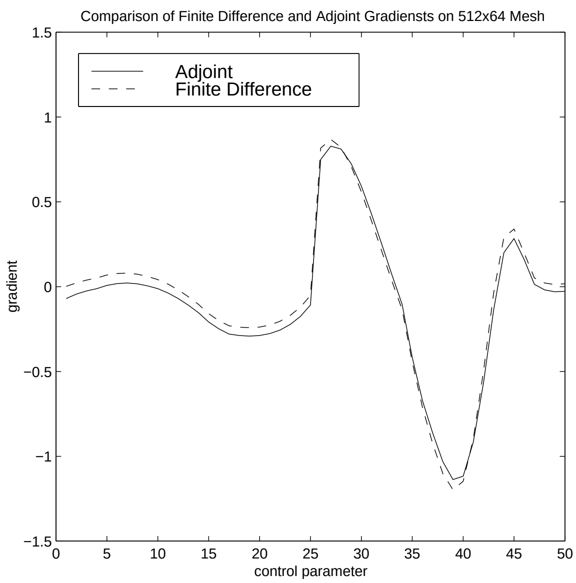
we have

$$\begin{aligned}\delta I &= \left\{ \frac{\partial I}{\partial \mathcal{F}}^T - \psi^T \left[\frac{\partial R}{\partial \mathcal{F}}\right] \right\} \delta \mathcal{F} \\ &= \mathcal{G}^T \delta \mathcal{F}\end{aligned}$$

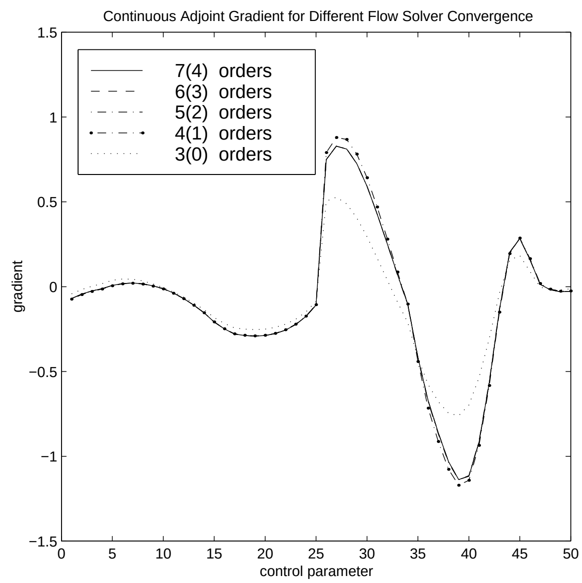
This reduces the **gradient**($\mathcal{G}$) calculation for an **arbitrarily large number of design variables** at a **single design point** to

One Flow Solution
\+ **One Adjoint Solution**

Navier–Stokes Inverse : Adjoint Gradient

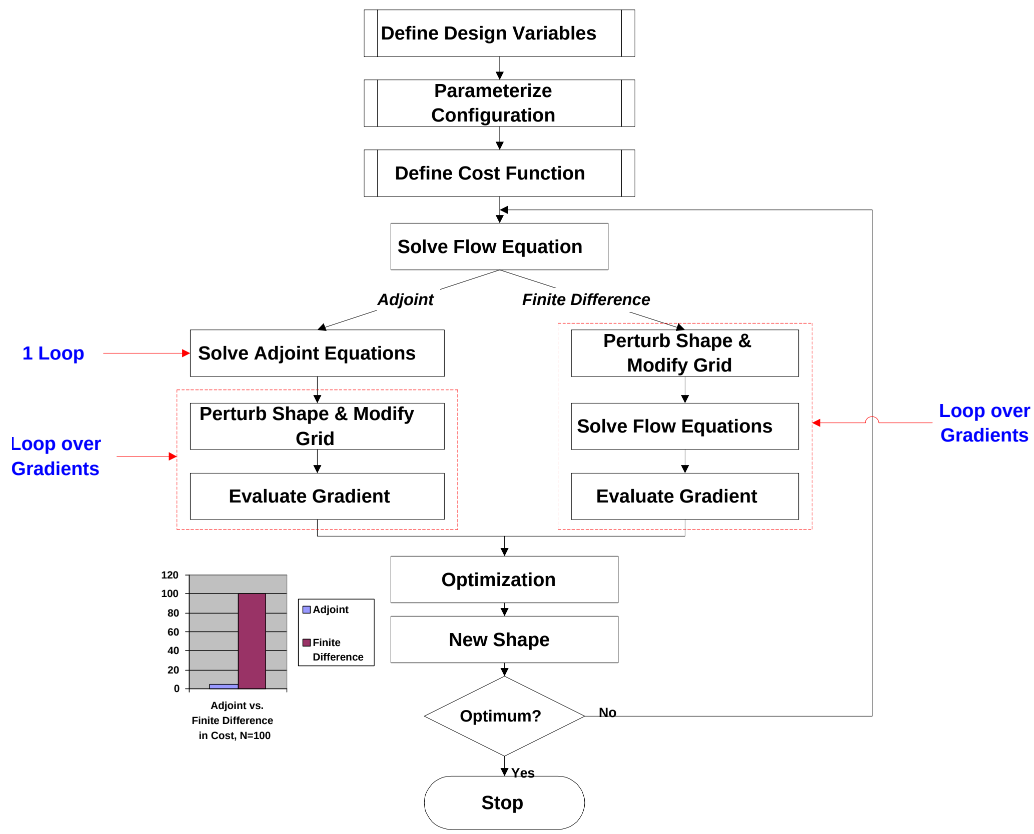


1a: Finite Difference vs. Adjoint Gradient

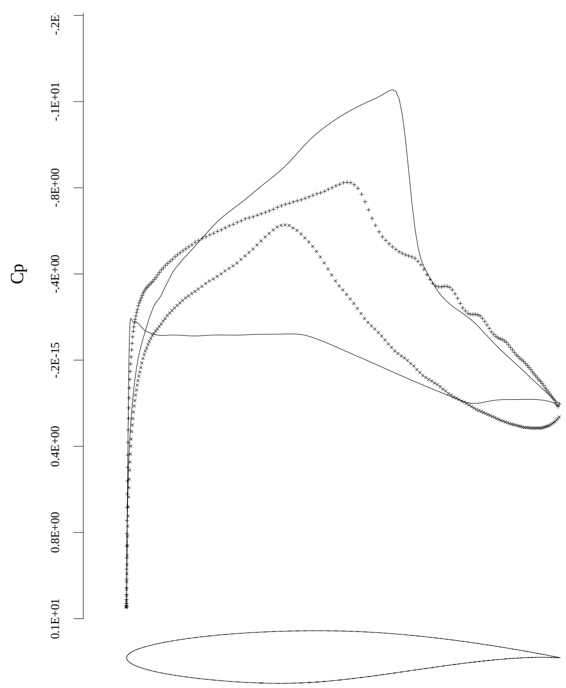


1b: Continuous Adjoint on Flow Convergence Levels

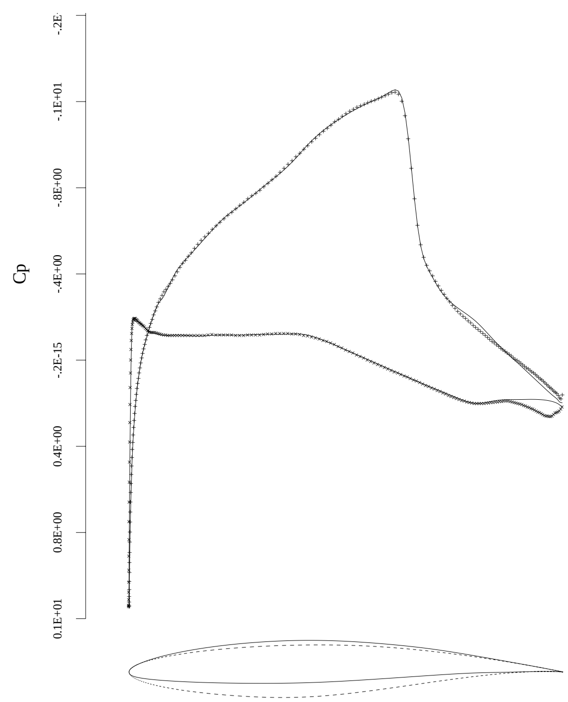
Flowchart of the Design Process



Navier–Stokes Inverse : RAE2822 → NACA64A410

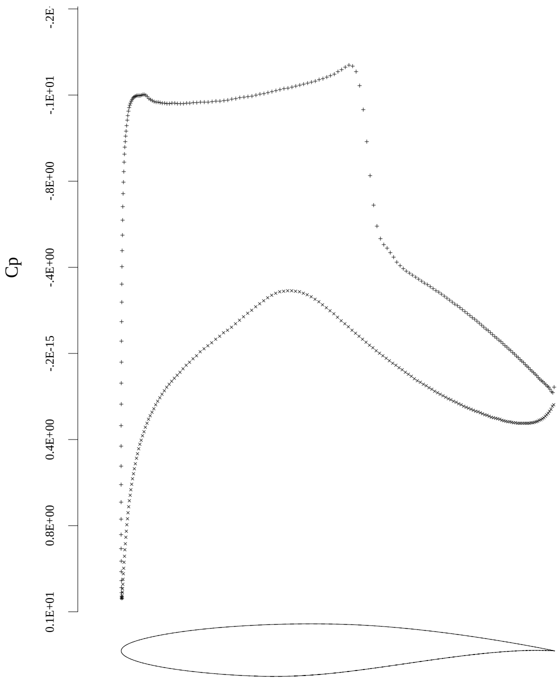


2a: Initial, $P_{error} = 0.0504$

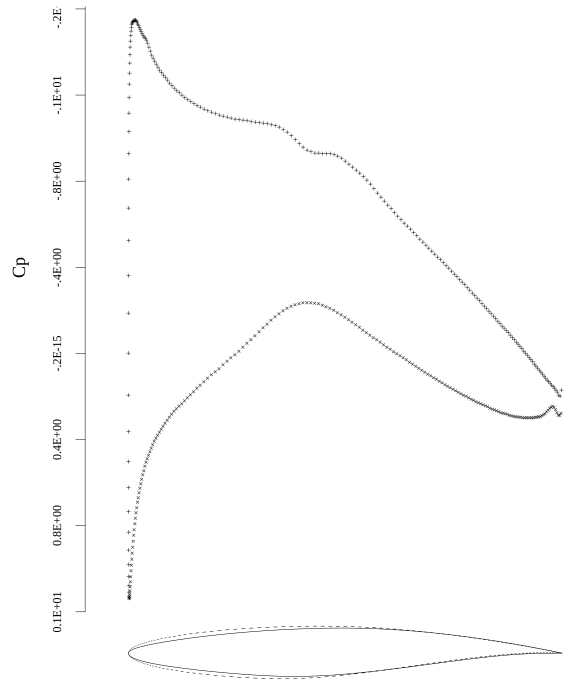


2b: 100 Design Iterations, $P_{error} = 0.0029$

Navier–Stokes C_d Min. : RAE2822 at Fixed $C_l = .84$



3a: Initial, CD_t=0.0169
$M = 0.73$, $\alpha = 2.739$, $C_l = 0.8411$



3b: 40 Design Iterations, C_d=0.0097
$M = 0.73$, $\alpha = 2.949$, $C_l = 0.8406$

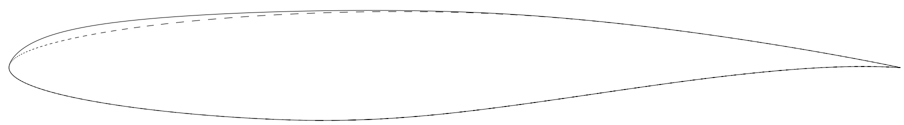
Advantages of Viscous Adjoint Method Over Finite Differencing

- Computational Cost was Drastically Reduced.
- Required Level of Flow Solver Convergence is Lower than for Finite Differencing.
- Step Insensitive. (In Adjoint Method, Step is only used for Geometry Perturbation.)
- Required Level of Convergence of Adjoint is Minimal.

$\Longrightarrow$ More Efficient, More Robust Method for Sensitivity Analysis in Viscous Flows.

High-Lift System Design : **SYN103MB**

- **Design Variables**
  - **Sine Bumps** : Shape design for each element.



  - **Rigging Variables** : Gaps, Overlaps and Deflections

  - **Angle of Attack (α)** : Cl_{max} maximization

- **Grid Topology** : Multi-block structured, Overall C- and O- mesh topologies.

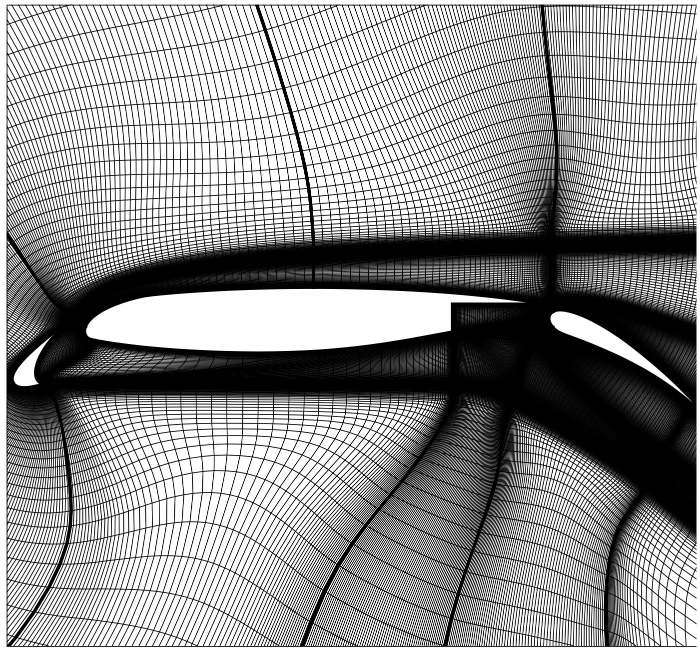
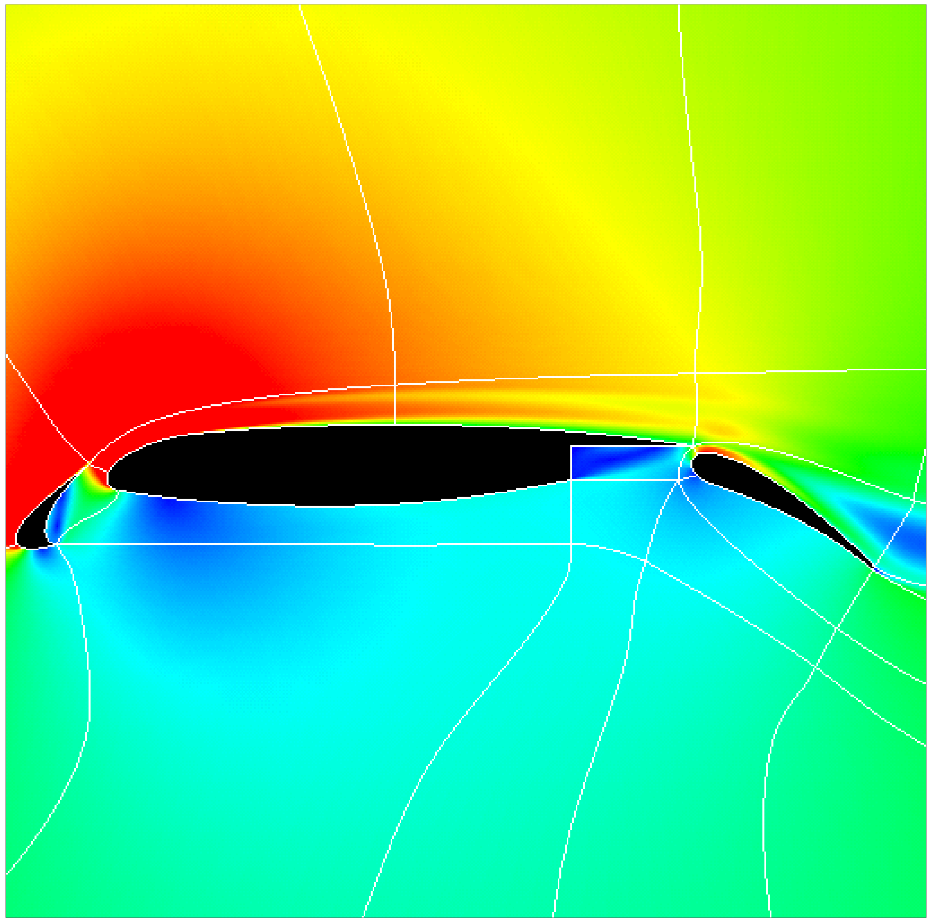


Figure 4: Viscous Mesh for 30P30N Multielement Airfoil

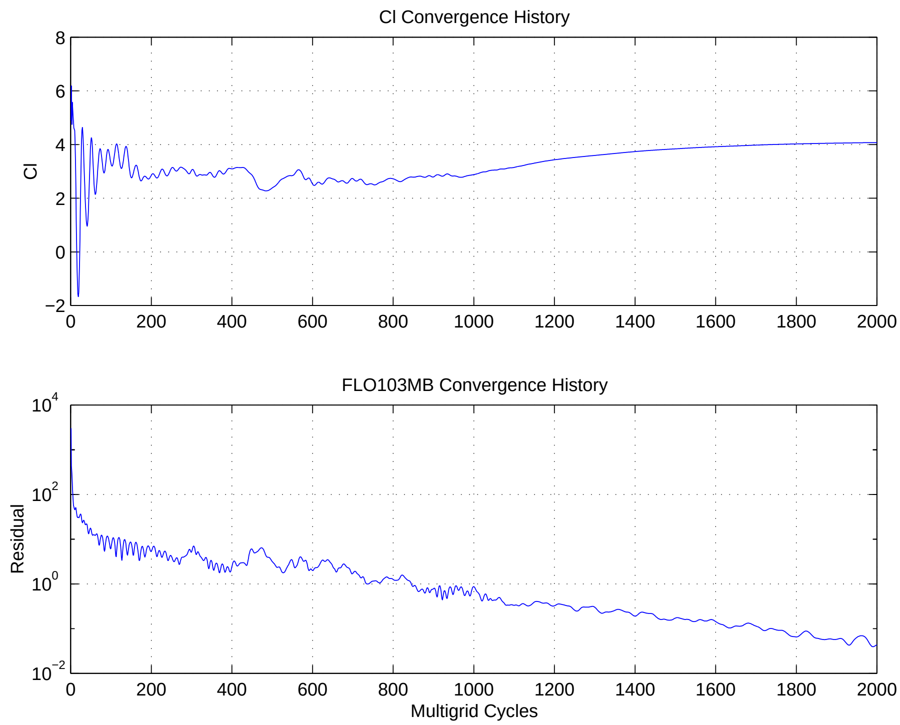
- **Mesh Perturbation**
  New grids are generated by shifting the grid points along the radial coordinate lines depending on the shape boundary modification.



High-Lift System Design : **SYN103MB** (cont.)

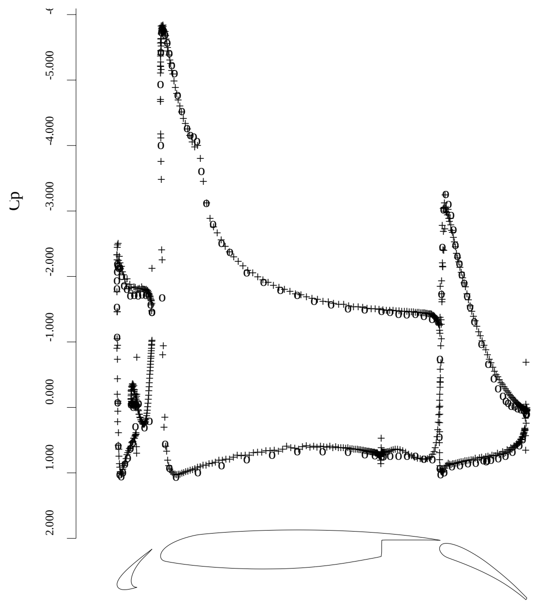
- **FLO103-MB Methodology**
  - **Runge-Kutta Explicit Time Stepping**
  - **Cell Centered Spatial Discretization**
  - **Jameson-Schmidt-Turkel(JST) Scheme**
  - **Local Time Stepping**
  - **Implicit Residual Smoothing**
  - **Multigridding**
- **Turbulence**
  - **Spalart-Allmaras** One Equation Model solved by **ADI** Scheme for Multi-Element Airfoil Designs. (Dr. Creigh McNeil)
- **ADJ103-MB** : The same methodology.
- **MPI** (Message Passing Interface) parallel solution methodology.

FLO103-MB CONVERGENCE HISTORY (SA Model)



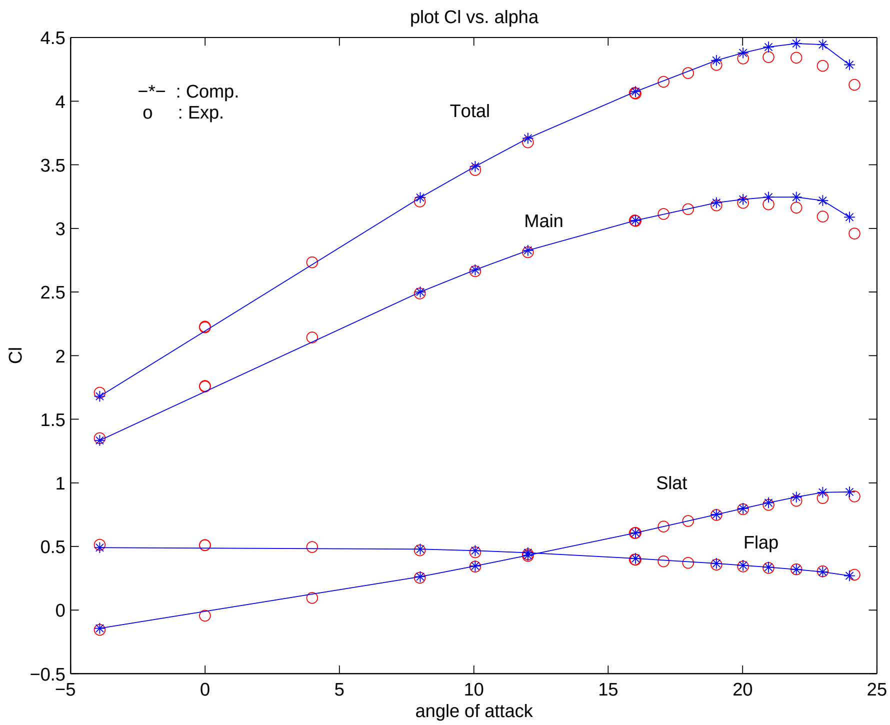
4a: Convergence history for the Spalart-Allmaras model

Cp Comparison : M=0.2, $\alpha = 8°$, $Re = 9 \times 10^6$, 30P30N



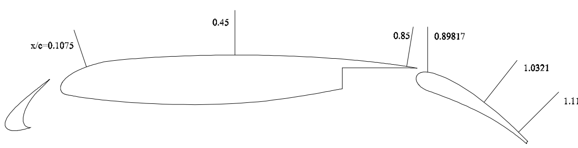
4b: Experimental and computational Cp : o - Exp. $+$,x - Comp.

Stall Prediction : $M = 0.2$, $Re = 9 \times 10^6$

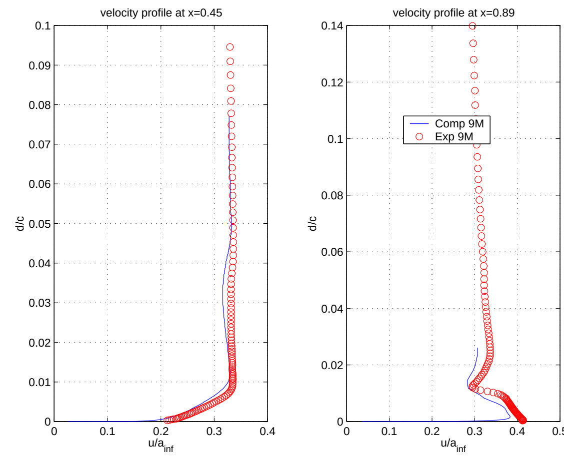


4c: Experimental and computational Cl vs. α

Velocity Profiles : $M = 0.2\ \alpha = 8^\circ\ Re = 9 \times 10^6$



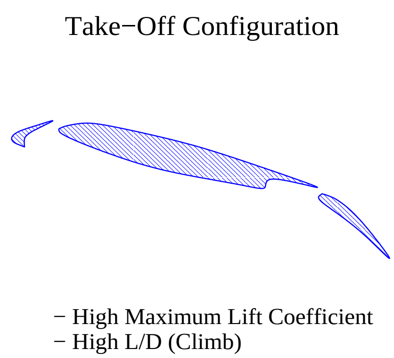
4d: High-Lift Configuration

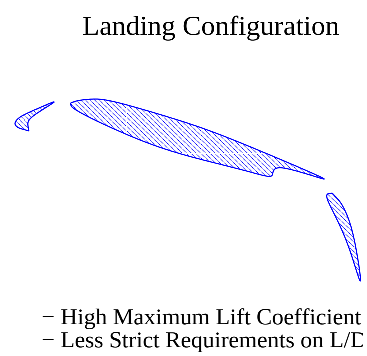


4e: Comparison of velocity profiles

High–Lift System Design Philosophy

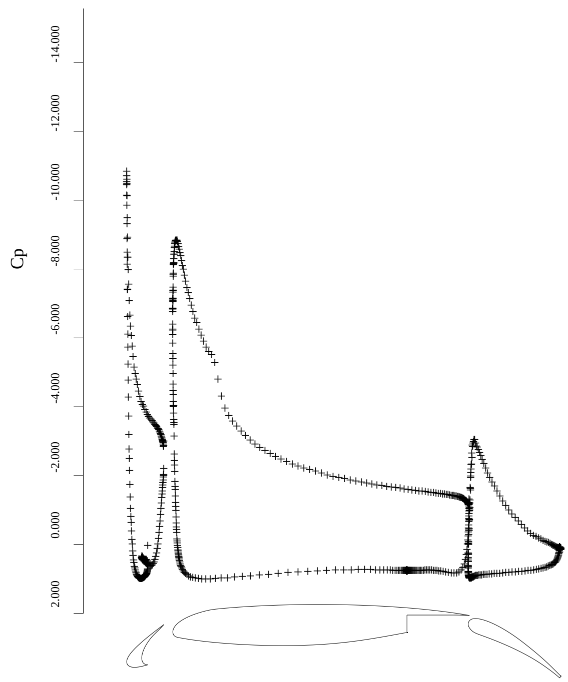
- Neccessary in take-off and landing conditions
  - Minimize runway length and Maximize payload.
- Typical Configurations



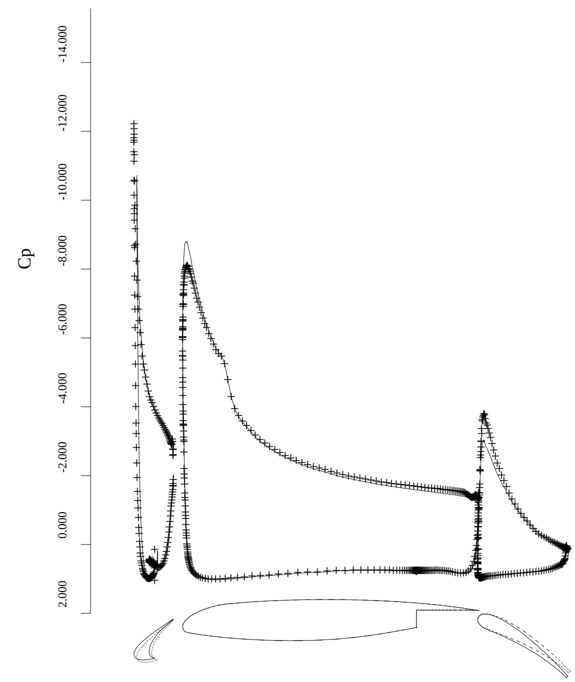


- Approaches
  - Take–off : Maximize Cl while maintaining high L/D.
    - ∗ Fix Cd and Maximize Cl (shape and α)
    - ∗ Fix Cl and Minimize Cd (shape and α)
  - Landing : Maximize Cl without worrying about Cd or L/D.
    - ∗ Cl_{max} maximization.

Multi-Element Cl Max. : 30P30N with Fixed Cd=0.065

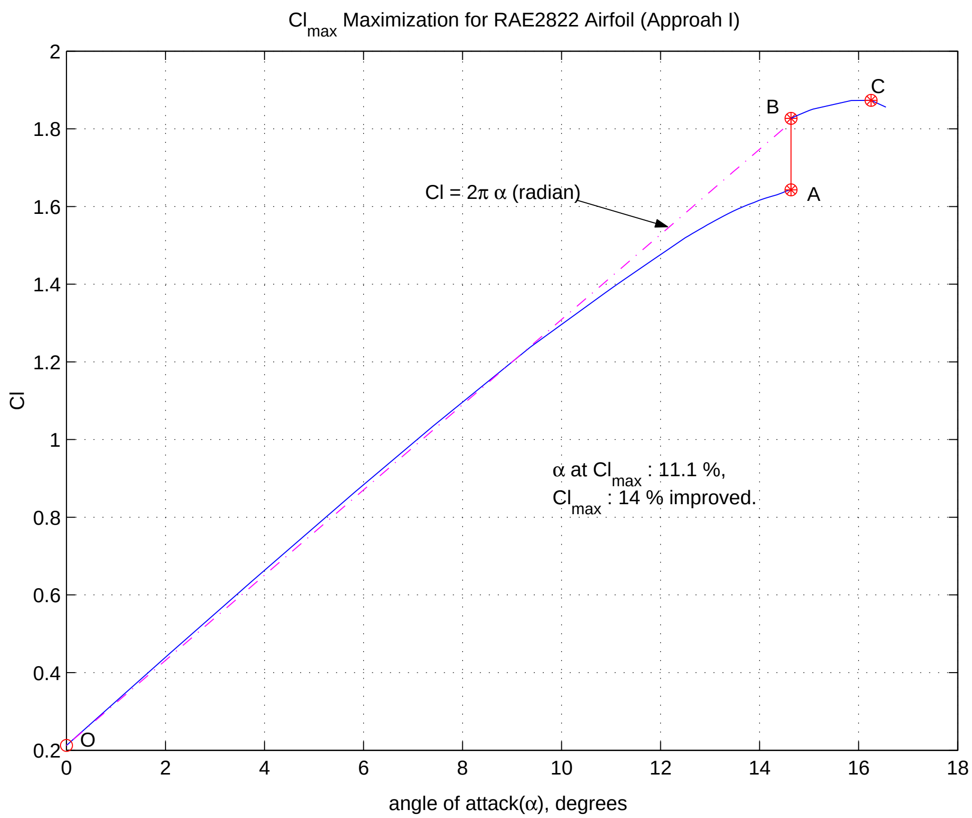


5a: Initial, Cl=4.0412
$M = 0.2$, $\alpha = 16.02°$, $Re = 9 \times 10^6$,
$Cd = 0.0650$

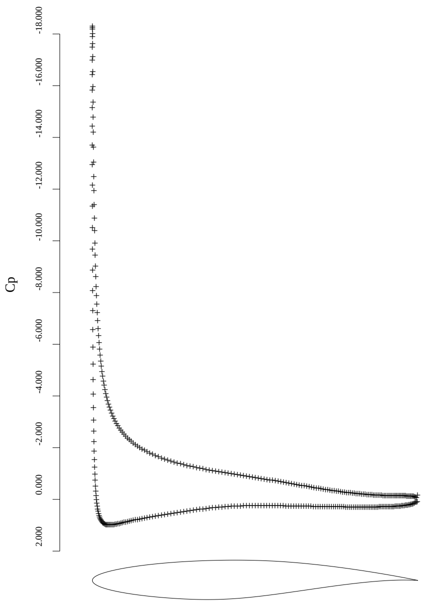


5b: 10 Design Iteration, Cl=4.1227
$M = 0.2$, $\alpha = 15.127°$, $Re = 9 \times 10^6$,
$Cd = 0.0661$

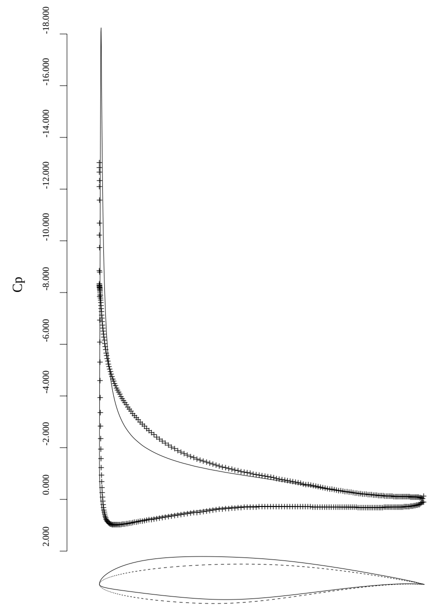
RAE2822 Cl_{max} Maximization.



RAE2822 Cl_{max} Maximization.

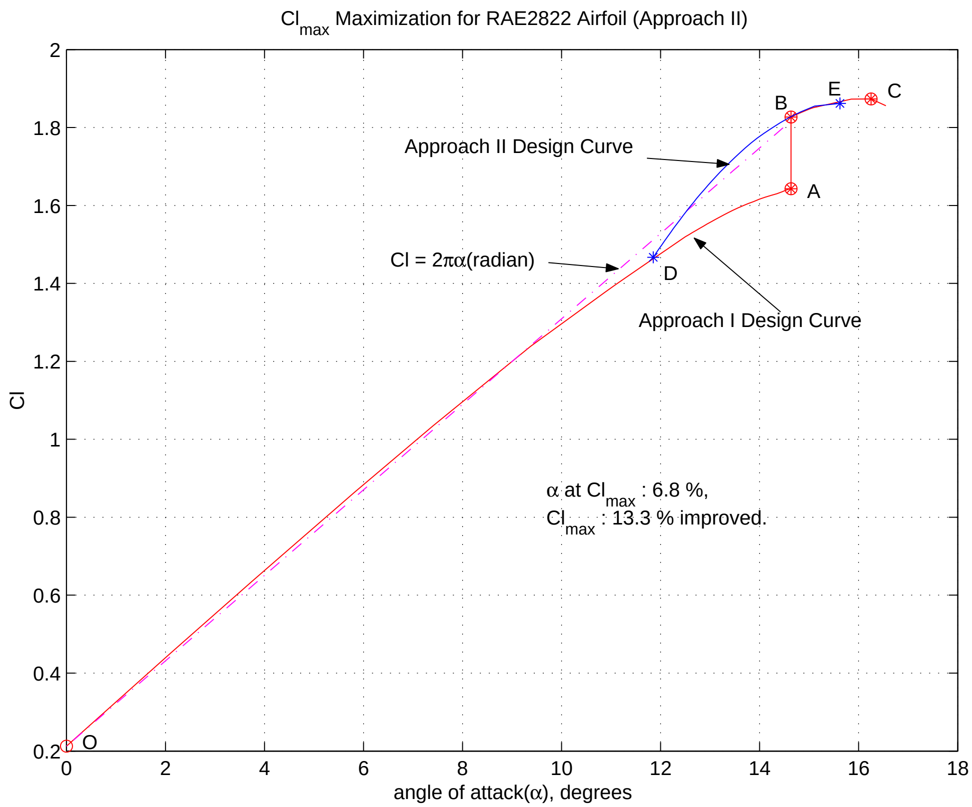


5c: Initial, Cl=1.6430
$M = 0.2$, $\alpha = 14.633°$, $Re = 6.5M$,
$Cd = 0.0359$

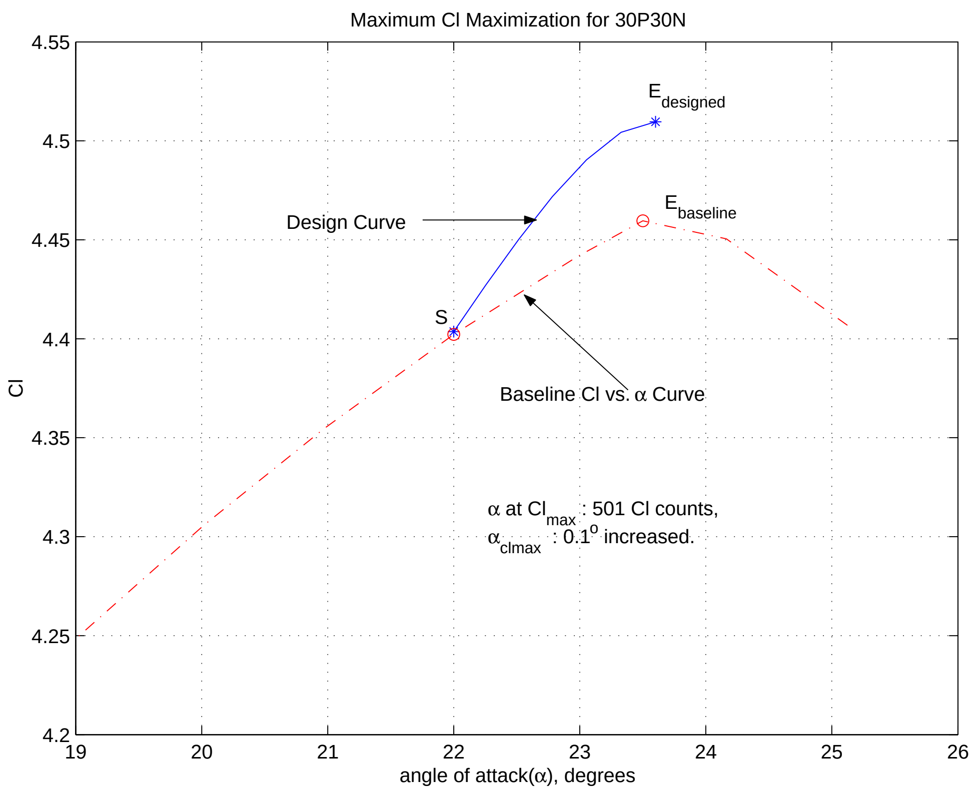


5d: 31 Design Iterations, $Cl = 1.8270$
$M = 0.2$, $\alpha = 14.633°$, $Re = 9 \times 10^6$,
$Cd = 0.0326$.

RAE2822 Cl_{max} Maximization Using α and Bump.



30P30N Cl_{max} Maximization.



Conclusions and Future Work

- Making use of the **Large Computational Savings** provided by the **Adjoint Method**, a **Numerical Optimization Procedure** for Designs of **High-Dimensional Design Space** has been developed.
- **High-Lift System Configuration Design Examples** have been performed in order to validate the **Sensitivity Calculation Procedure** using our **Continuous Viscous Adjoint Method**.
- Further Study of **Adjoint Solver** and **Adjoint Boundary Conditions**.
- Enhancement of Design Methods by Survey of **Optimization Algorithm** and **Design Parameterization**.
- Extension to More Realistic Problems inculding **3D Design Problems** and **Multi Point Designs**