53rd AIAA Aerospace Sciences Meeting

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# Aerodynamic Shape Optimization Benchmarks with Error Control and Automatic Parameterization

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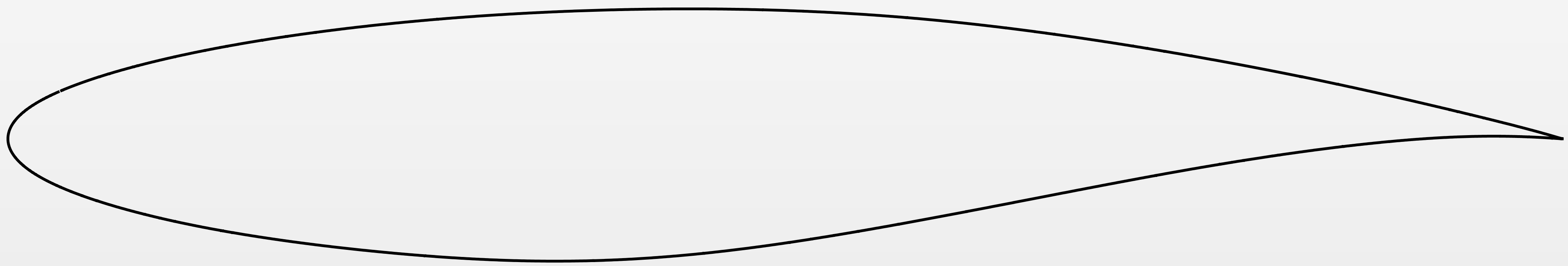
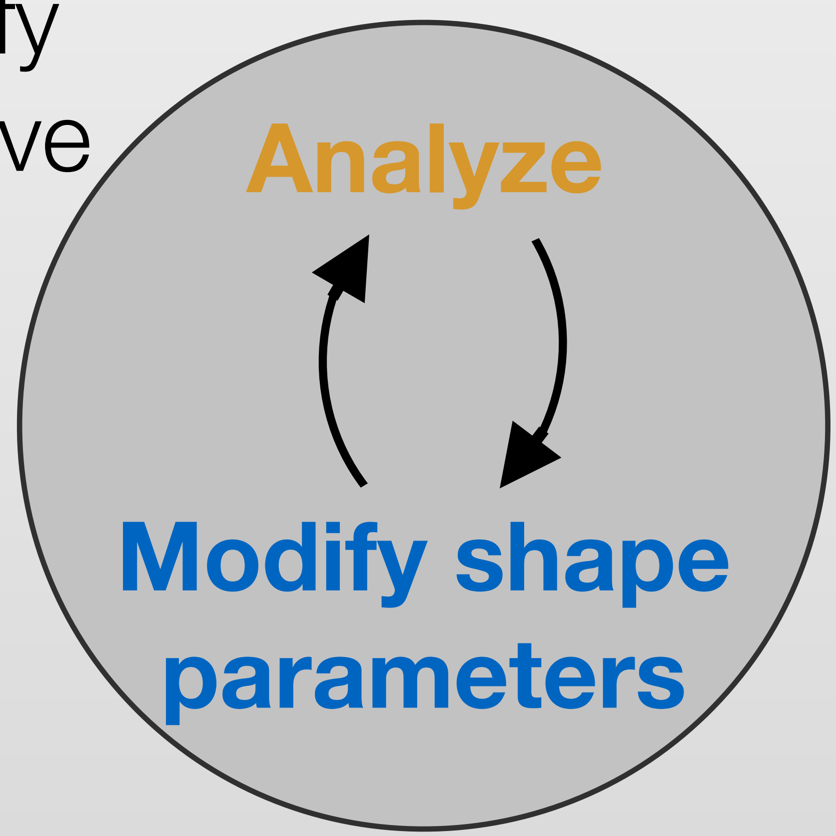
# Parametric Shape Optimization

Start with baseline aerodynamic shape



Iteratively modify shape to improve performance



# Parametric Shape Optimization

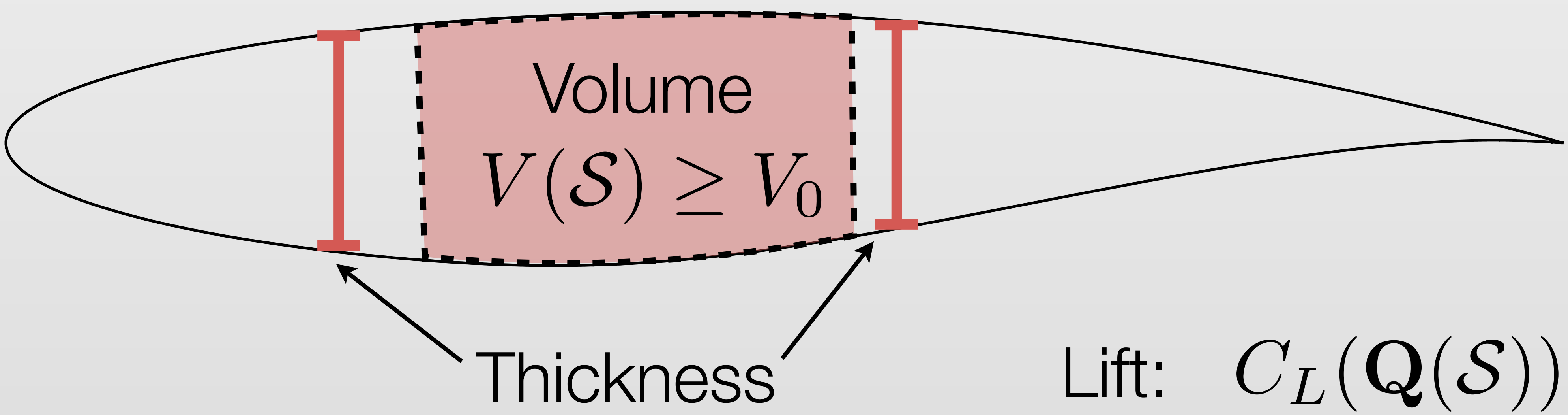
Minimize **objective:**

Flow variables

$$\min C_D(\mathbf{Q}(\mathcal{S}))$$

Surface

Subject to **constraints:**




Lift: $C_L(\mathbf{Q}(\mathcal{S})) = C_L^*$

# Motivation

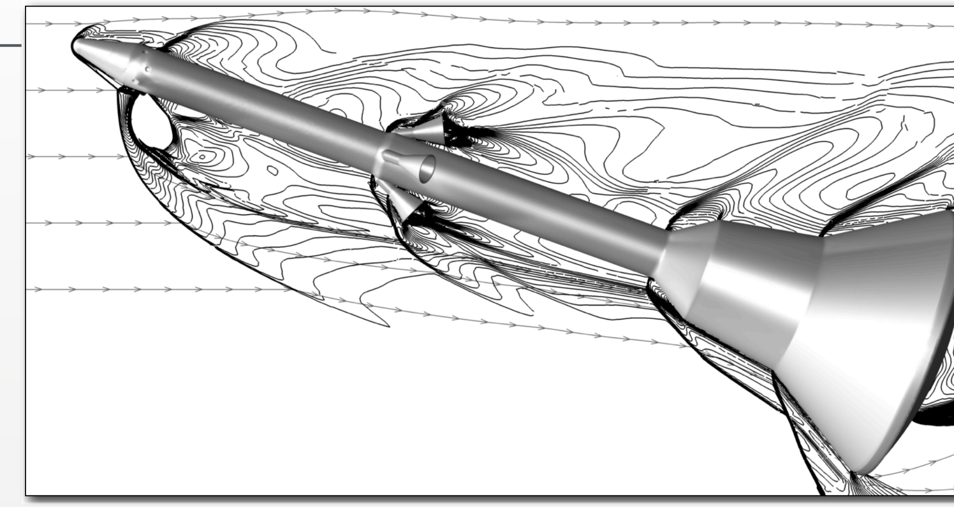
- AIAA *Aerodynamic Design Optimization Discussion Group* (ADODG)
  - Encourage cross-comparisons and communication among research groups.
  - Demonstrate **accuracy** of flow solutions.
  - Explore **adequacy** of shape parameters.
- Posed four optimization **benchmark problems**:
  - Airfoil and wing design
  - Inviscid/viscous, subsonic/transonic conditions
  - Lift, pitching moment, volume constraints

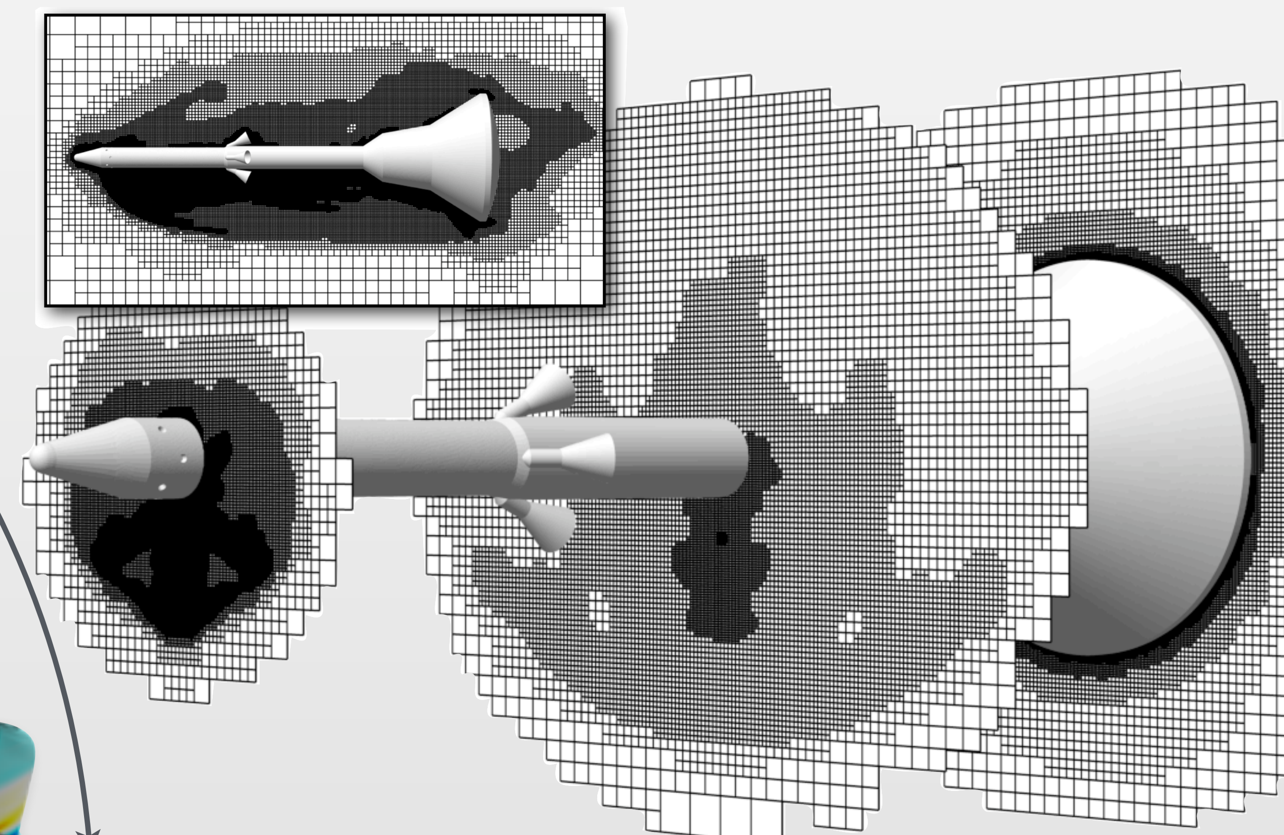
# Objectives

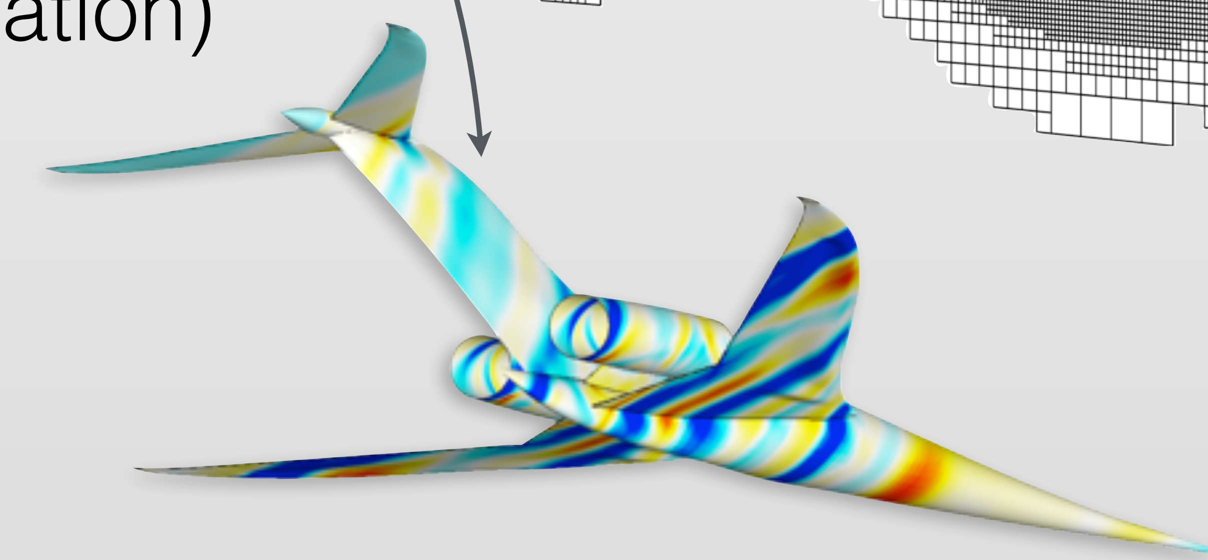
- Demonstrate use of **Cart3D inviscid design framework** to solve the benchmarks.
- Automated approach:
  1. **Adaptive mesh refinement** to control discretization error.
  2. **Progressive shape parameterization** to efficiently approach the continuous optimal design.

# Cart3D Design Framework

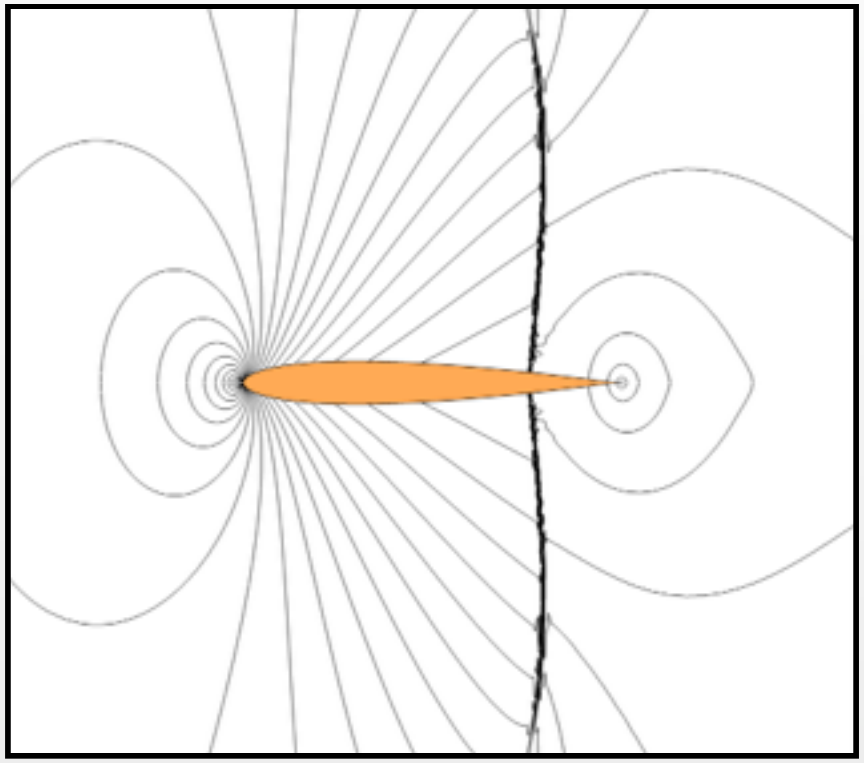
- Cartesian cut-cell method
- **Inviscid** flow solver:
  - Adjoint-driven flow meshing
  - Adjoint-derived objective and constraint gradients
- SNOPT — SQP optimizer for general constrained problems
- **2D RANS** flow solver used for verification (not optimization)







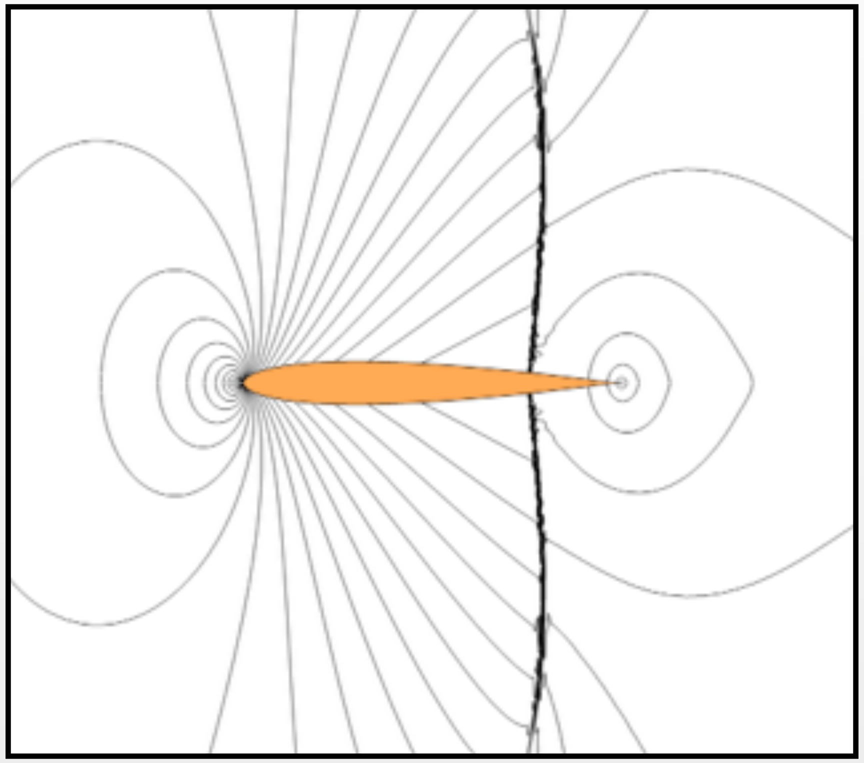
# Inviscid Benchmarks



**1** Optimize **symmetric airfoil** for minimum drag.
**(M0.85, inviscid)**

- Simple geometry
- Highly sensitive optimum

# Inviscid Benchmarks



**1** Optimize **symmetric airfoil** for minimum drag.
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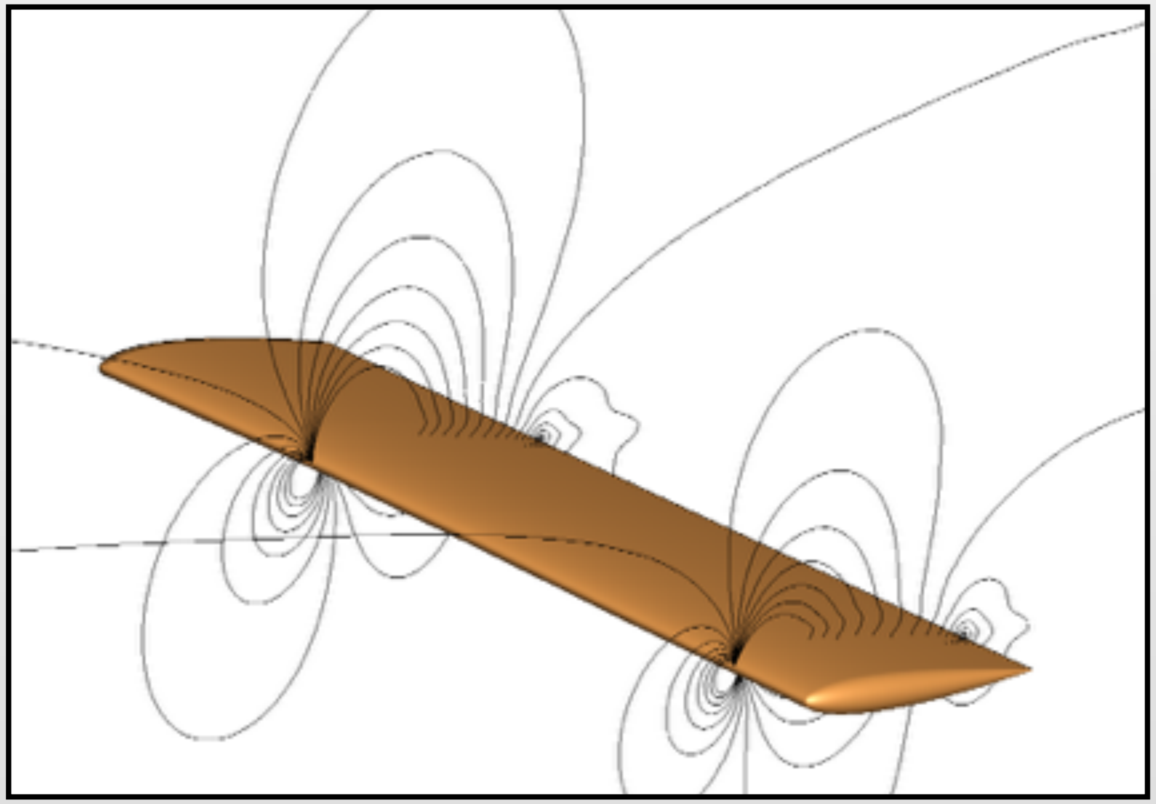
- Simple geometry
- Highly sensitive optimum

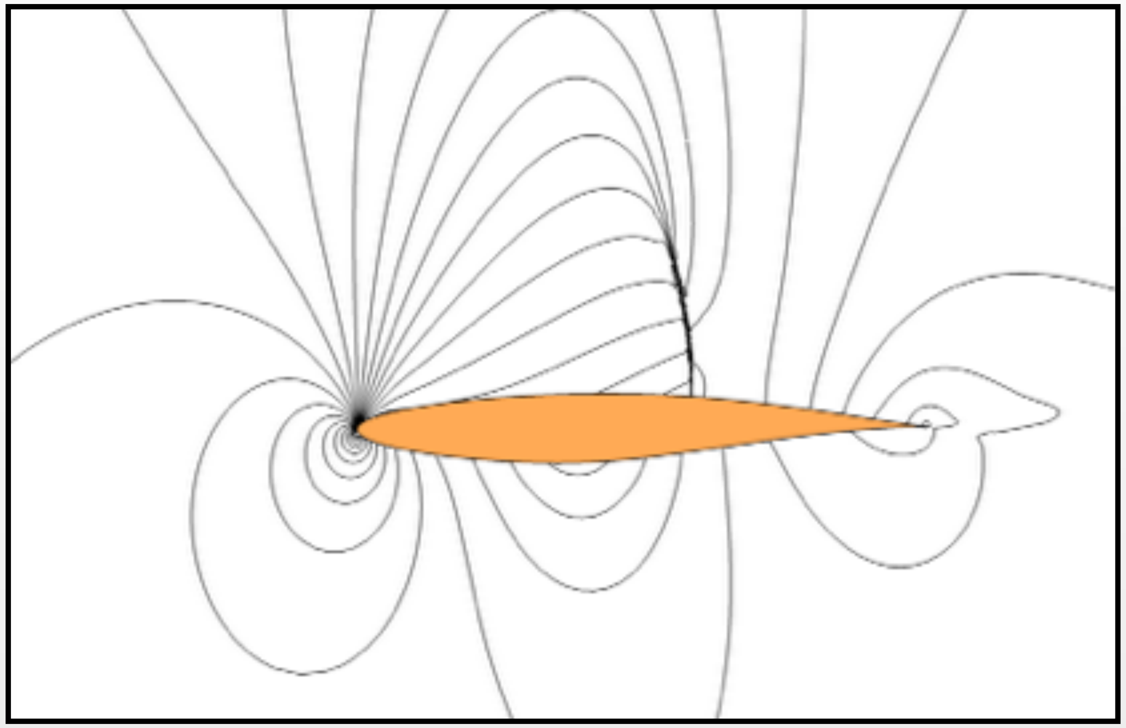


**3** Optimize **wing twist** for minimum induced drag at fixed lift.
**(M0.5, inviscid)**

- Subsonic, induced drag
- Already close to optimum
- High meshing requirements

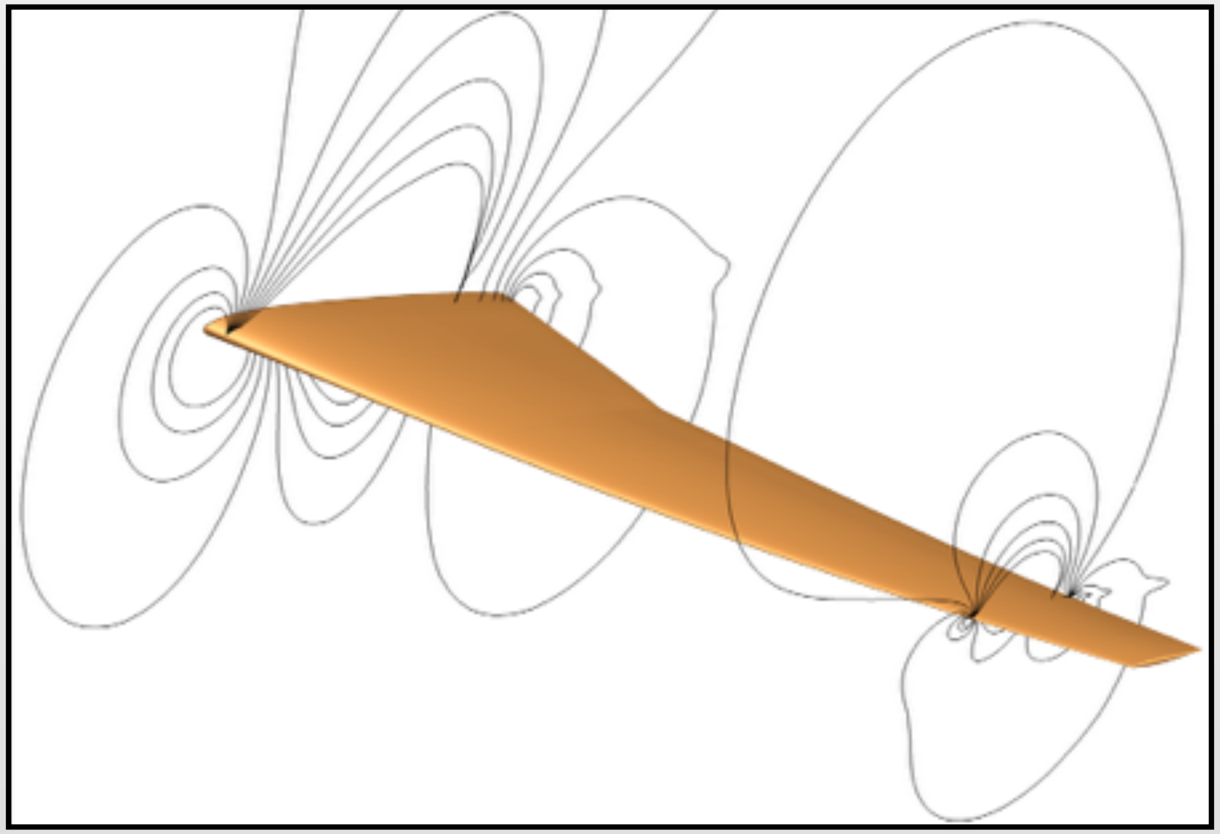
# Inviscid Approach to Viscous Benchmarks

**2** Optimize **transonic airfoil** for minimum drag at fixed lift, pitching moment and area. **(M0.724, viscous)**



- Use inviscid solver to improve viscous performance

**4** Optimize **transonic wing** for minimum drag at fixed lift, pitching moment and volume. **(M0.85, viscous)**



- Demonstrate automated wing design.

# Outline

## Approach

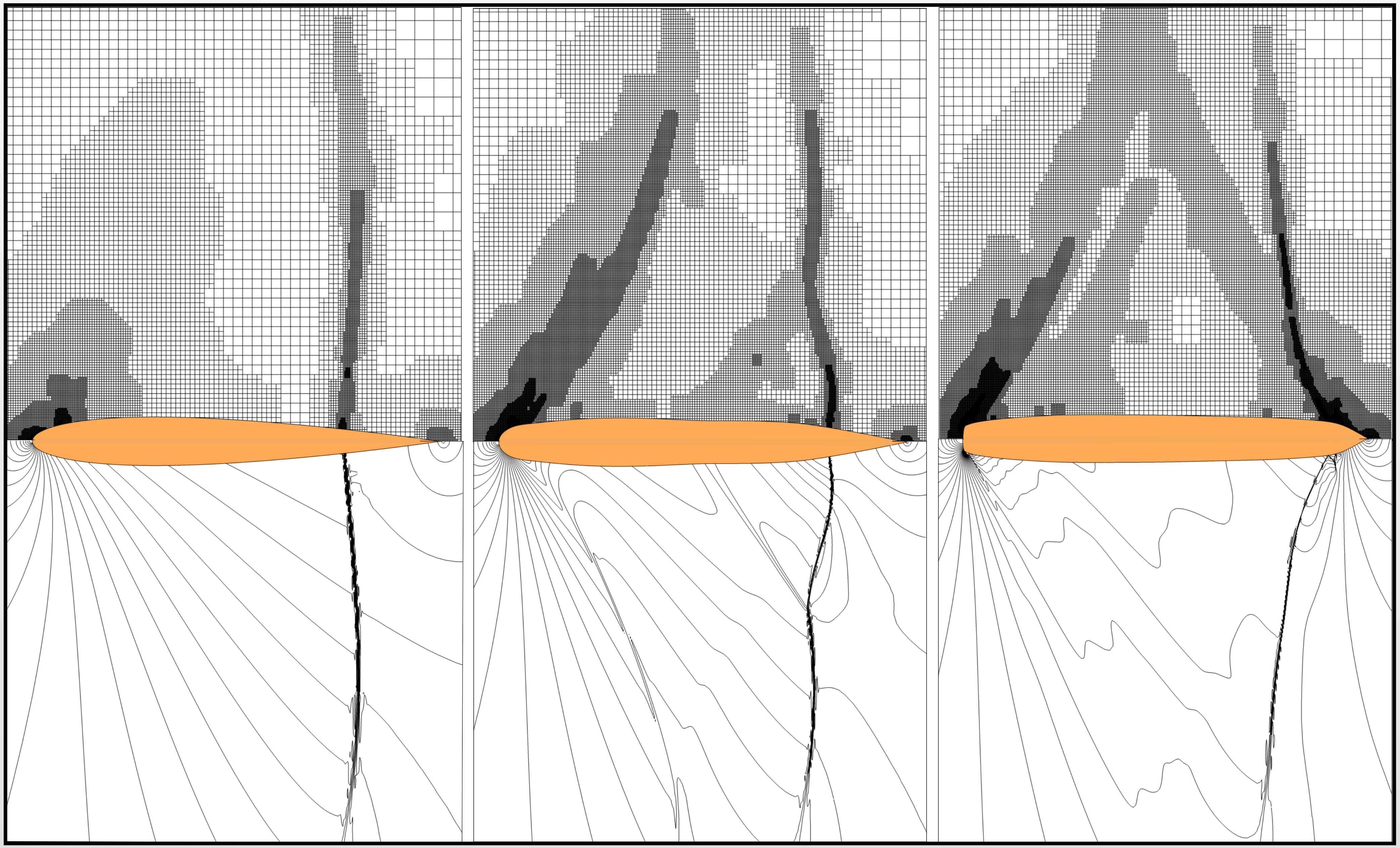
- Adaptive mesh refinement
- Progressive shape parameterization

## Optimization results:

- **Case 1** - Symmetric transonic airfoil design
- **Case 3** - Twist for minimal induced drag
- **Case 2** - Transonic airfoil
- **Case 4** - Transonic wing

# Discretization Error Control

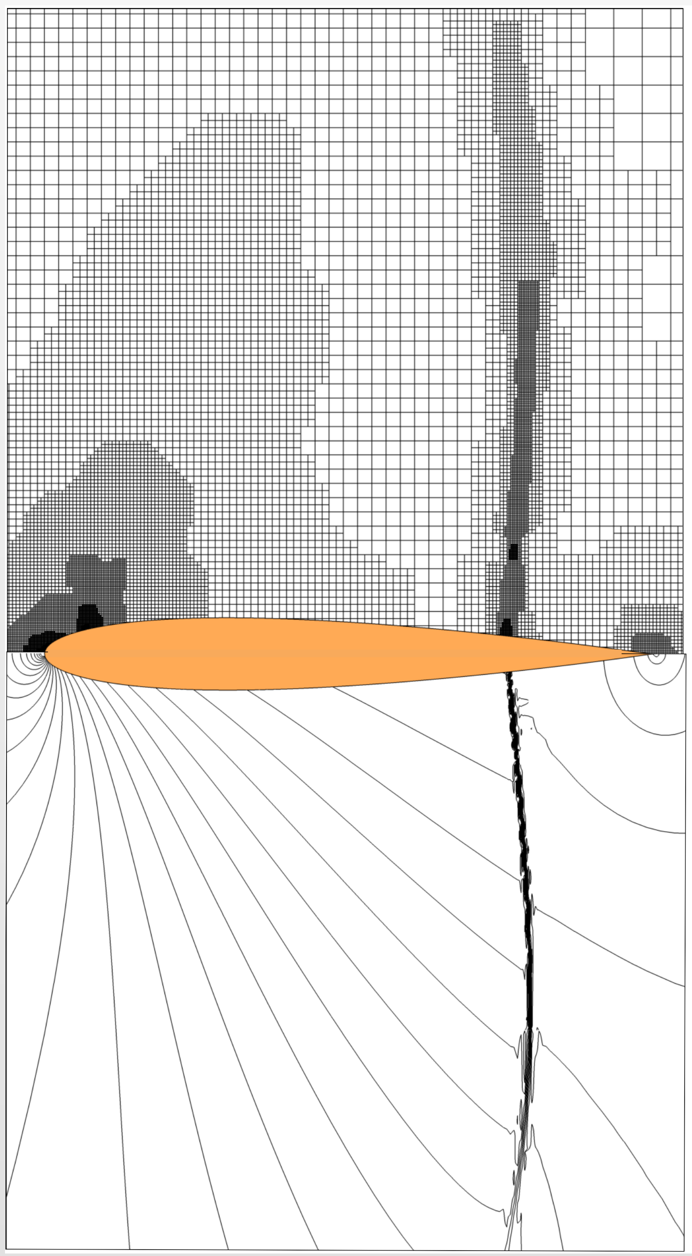
Mesh is adapted to compute drag accurately
**at each design iteration**.†

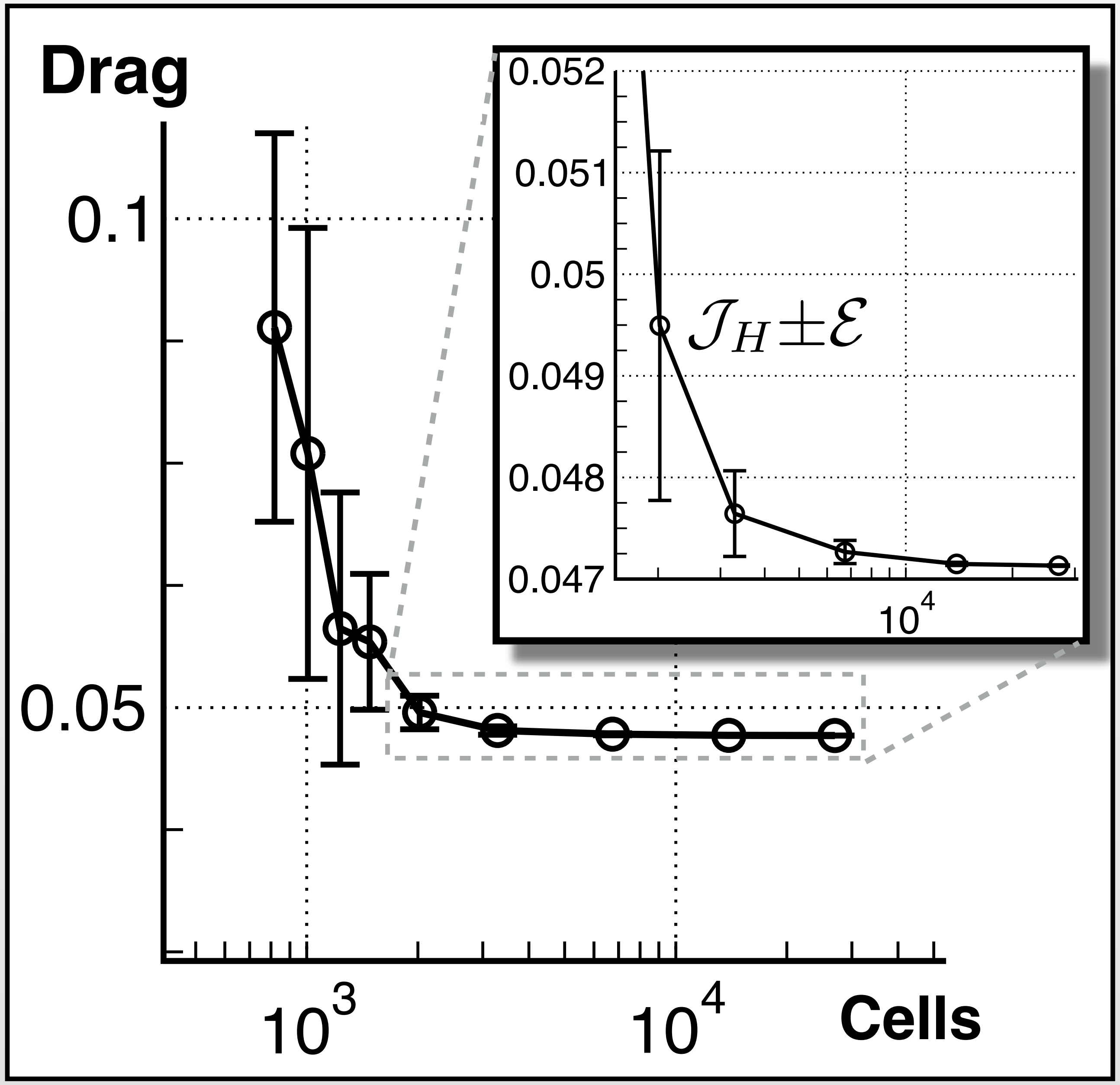


† **(2014)** Nemec and Aftosmis, ***"Toward Automatic Verification of Goal-Oriented Flow Simulations."*** *NASA TM-2014-218386*

# Discretization Error Control

**Error tolerance** is set low enough to ensure **reliable** design improvement.†



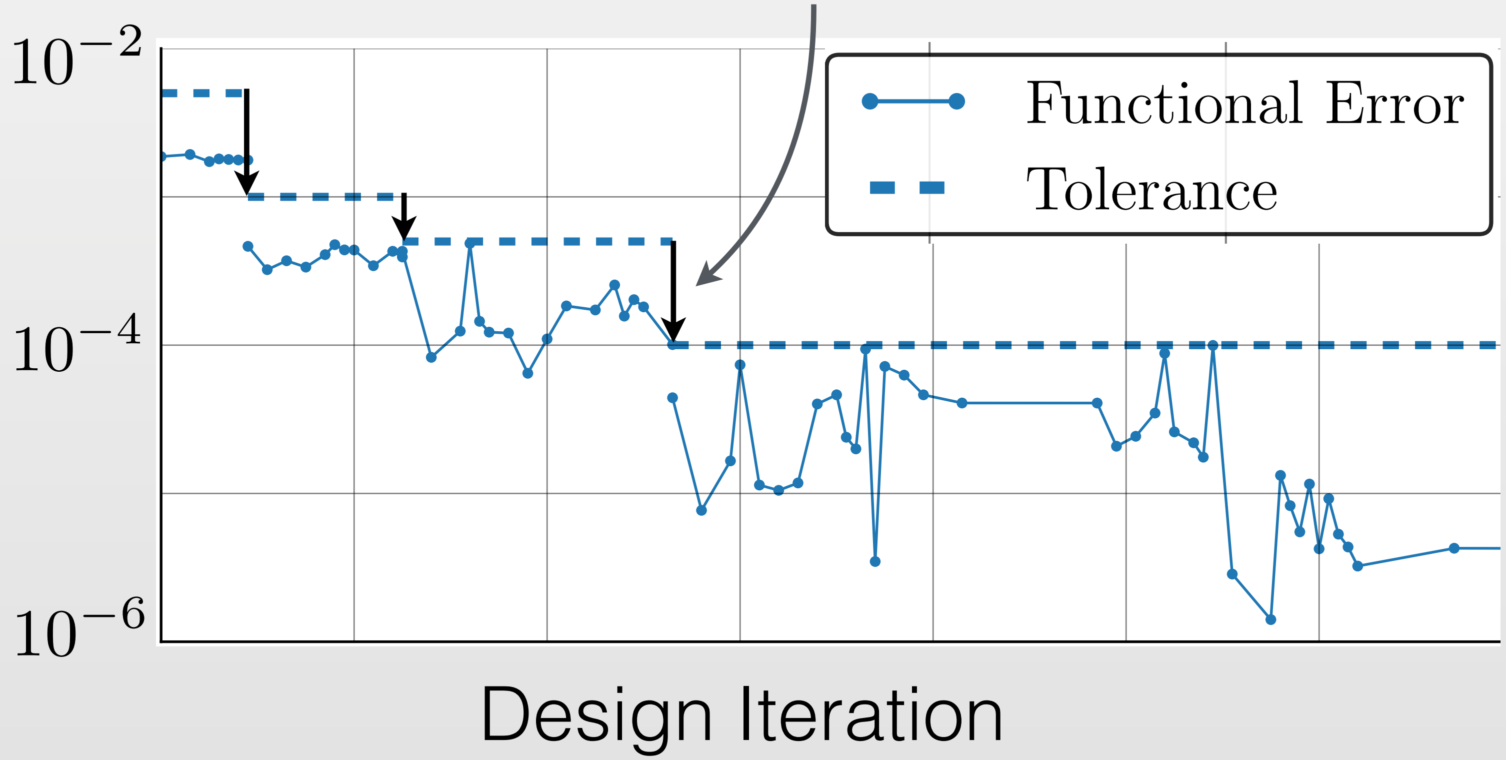


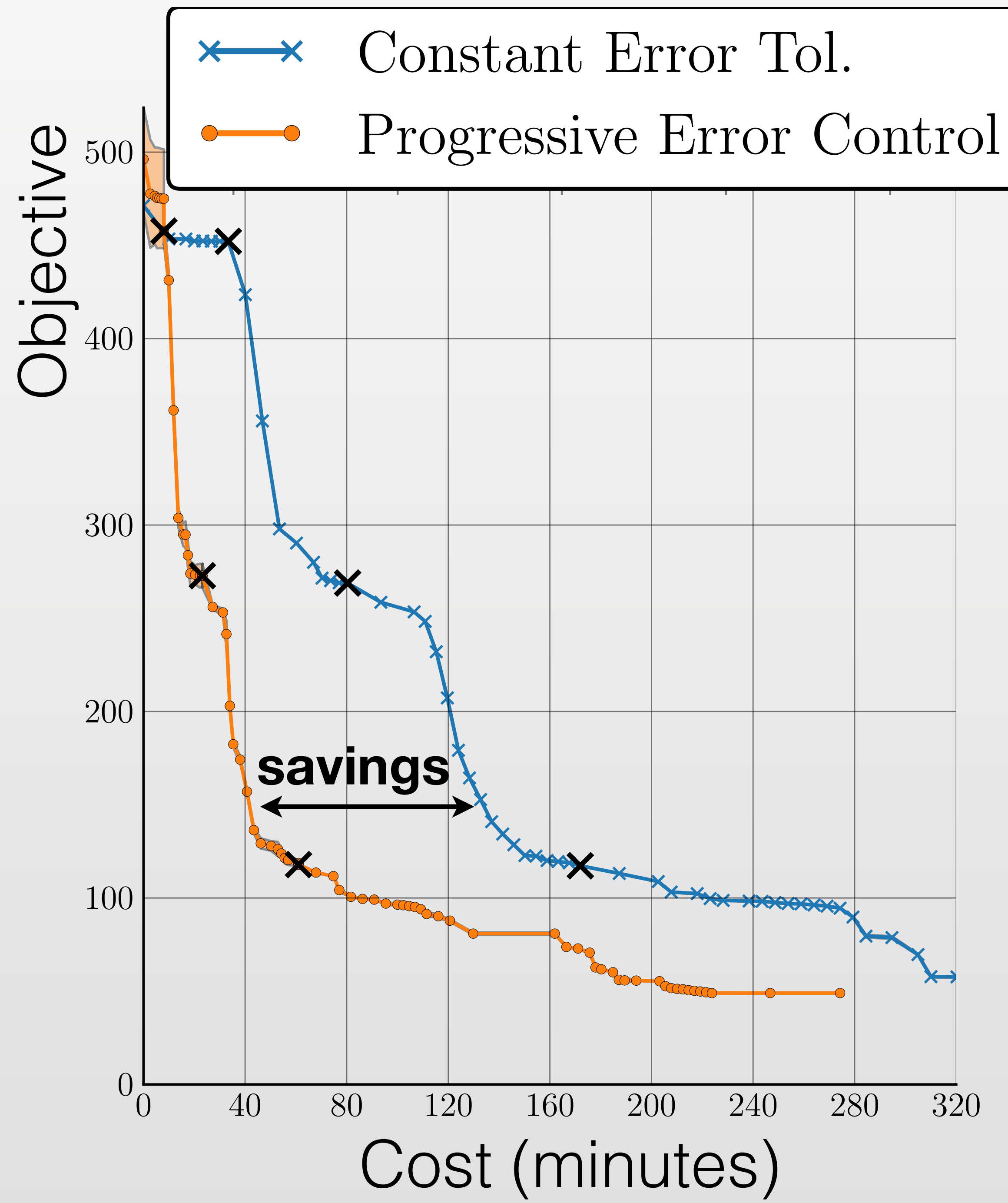

† **(2013)** Nemec and Aftosmis, “***Output Error Estimates and Mesh Refinement in Aerodynamic Shape Optimization.***” *AIAA 2013-0865*

# Error Control Scheduling

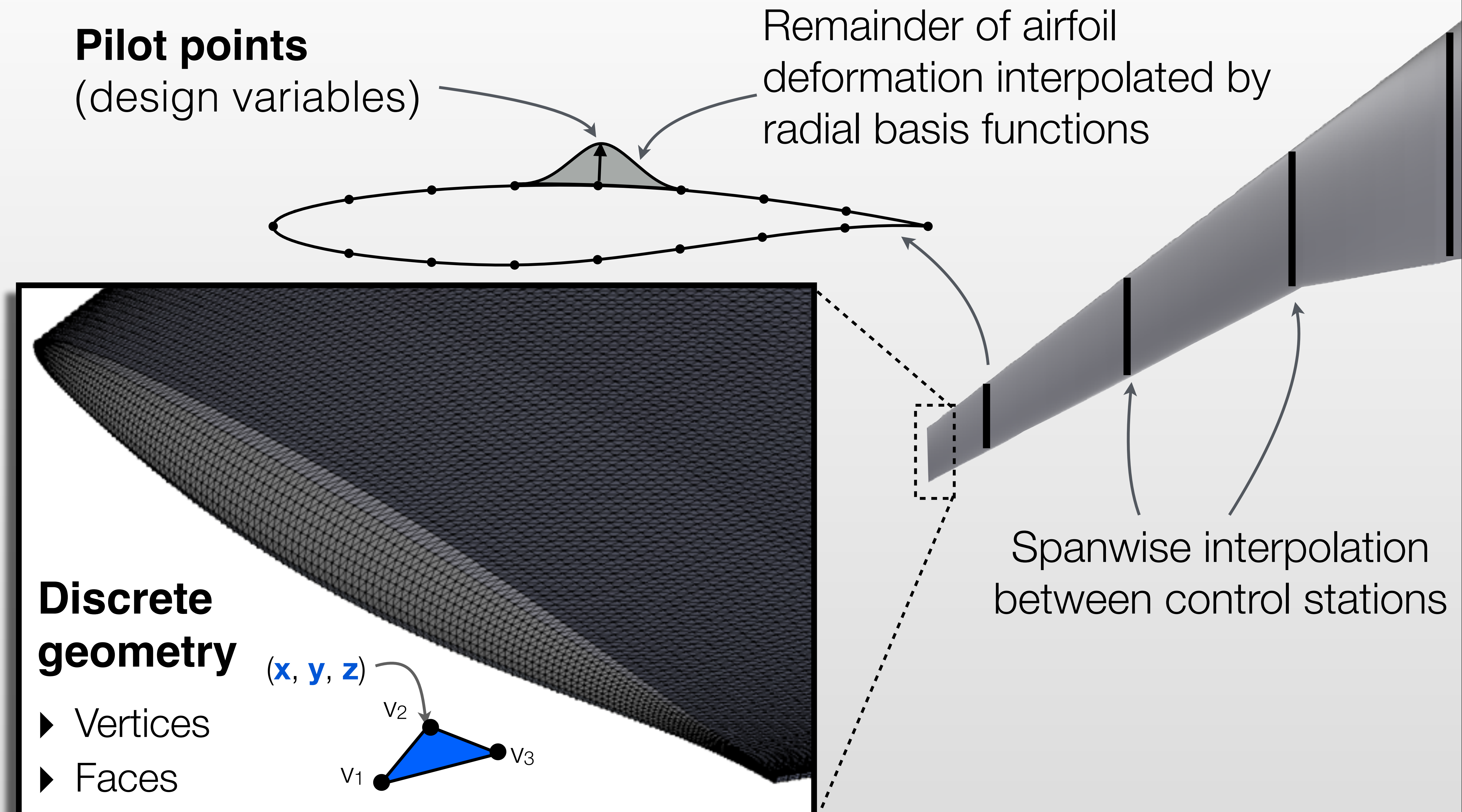
Use **progressive** error targets to accelerate the optimization.

*Coarser meshes used early on, then tolerance is tightened.*



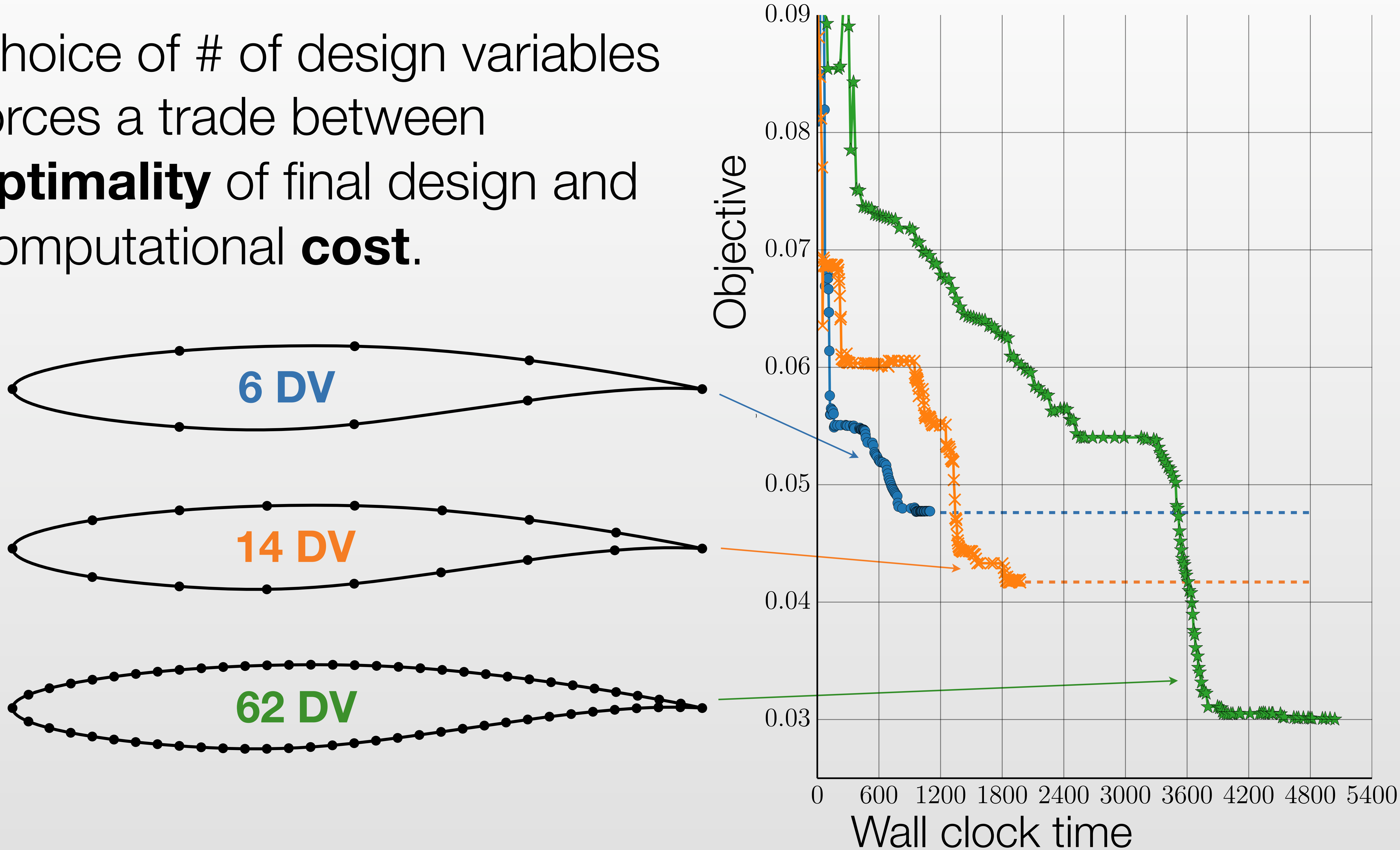
# Shape Manipulation




† **(2012)** Anderson, *et al.*, ***"Constraint-based Shape Parameterization for Aerodynamic Design."*** *ICCFD7-2001.*

# Shape Parameterization

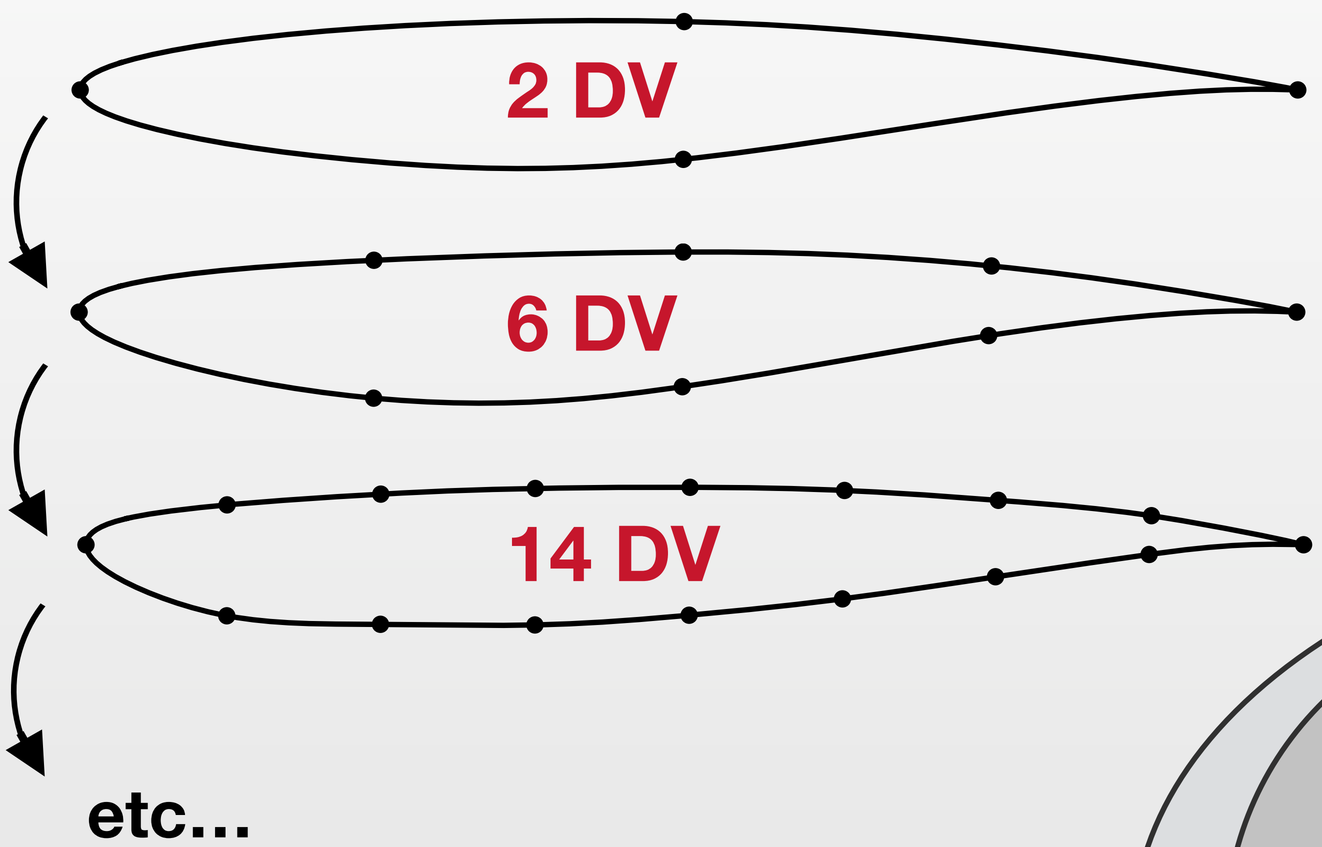
Choice of # of design variables forces a trade between **optimality** of final design and computational **cost**.

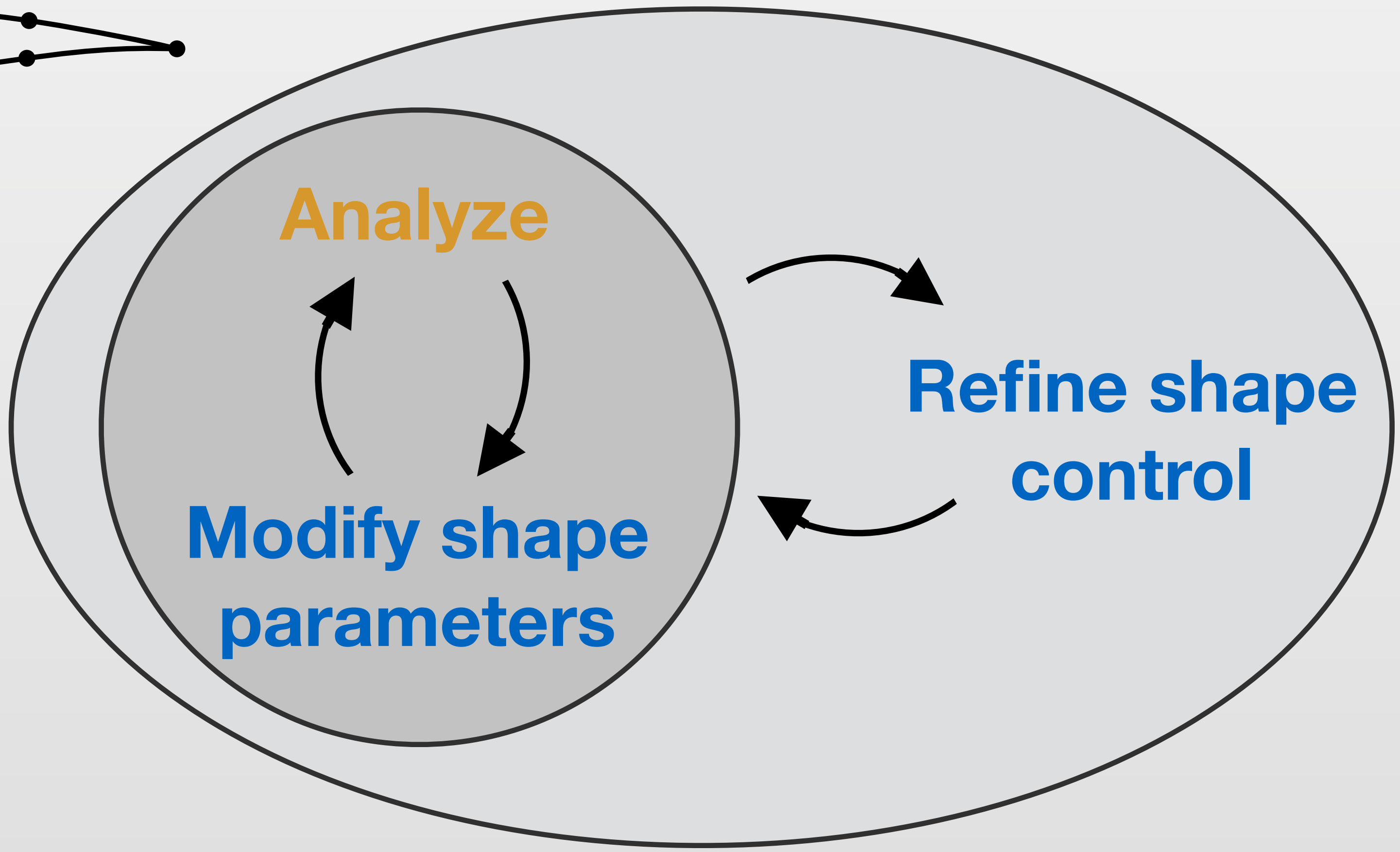



In minutes, plotted at major search iterations, on Ivybridge node — 20 cores

# Progressive Parameterization

**"Progressive"** search spaces†

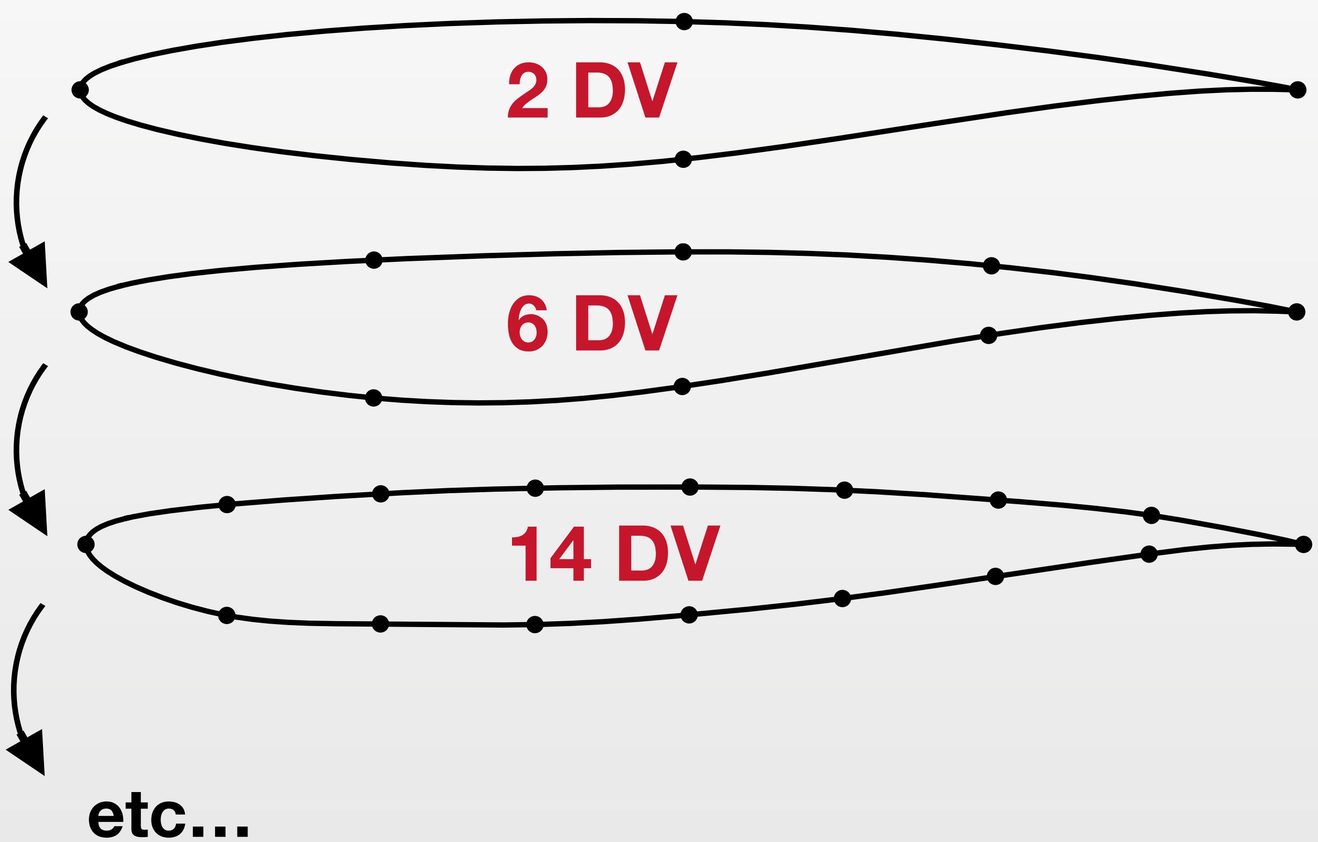


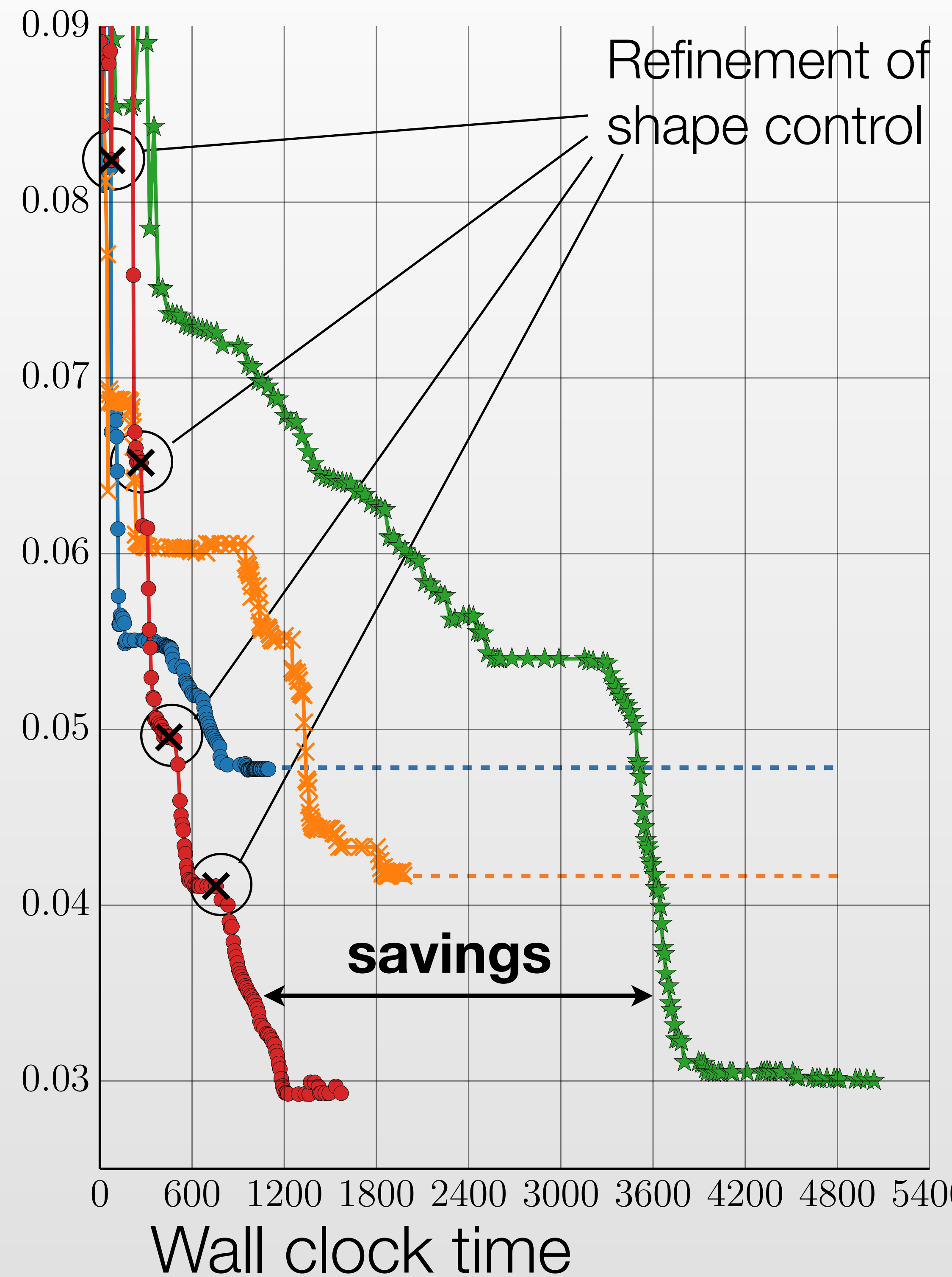

† **(2015)** Anderson and Aftosmis, ***"Adaptive Shape Control for Aerodynamic Design."*** *AIAA 2015-0398*

# Progressive Parameterization

**“Progressive”** search spaces†




**Fast** improvement in coarse search spaces, but ultimately approaching **full design space**.†




In minutes, plotted at major search iterations, on Ivybridge node — 20 cores

† **(2015)** Anderson and Aftosmis, ***“Adaptive Shape Control for Aerodynamic Design.”*** *AIAA 2015-0398*

# Approach Summary

Discussion group suggested results:

1. Demonstrate **accuracy** of the flow solutions driving the optimization:
    - **Automatically adapt the flow mesh** to control discretization error in the aerodynamic functionals.
    - *(Provides mesh convergence information at each design iteration.)*
2. Address the **adequacy** of shape parameterization to explore the design space:
    - **Automatically refine the shape parameterization** during design, until objective stops improving with additional shape control.

# Outline

## Approach

- ✓ Adaptive mesh refinement
- ✓ Progressive shape parameterization

## Optimization results:

- **Case 1** - Symmetric transonic airfoil design
- **Case 3** - Twist for minimal induced drag
- **Case 2** - Transonic airfoil
- **Case 4** - Transonic wing

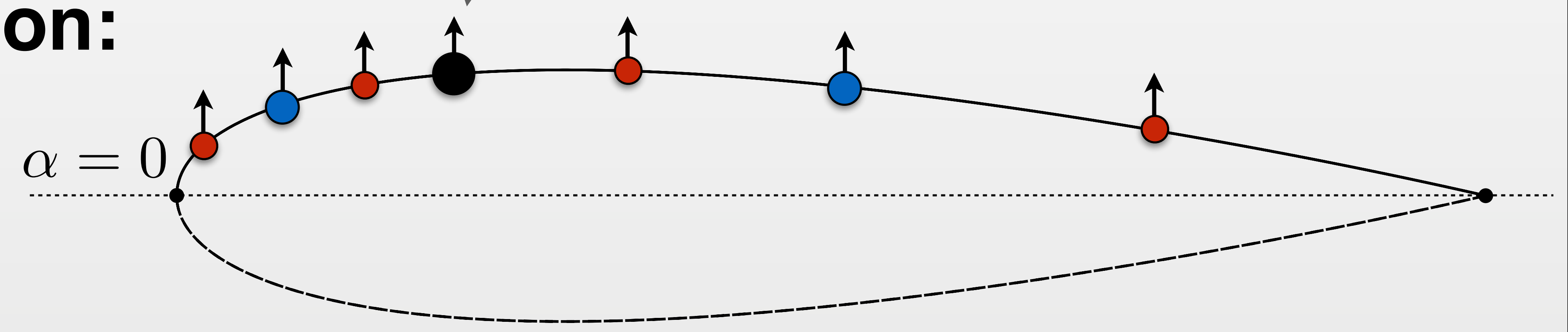
# Case 1: Symmetric Transonic Airfoil Design

**Objective:** Minimize drag at Mach 0.85

**Constraints:** Symmetric, contain original NACA0012*

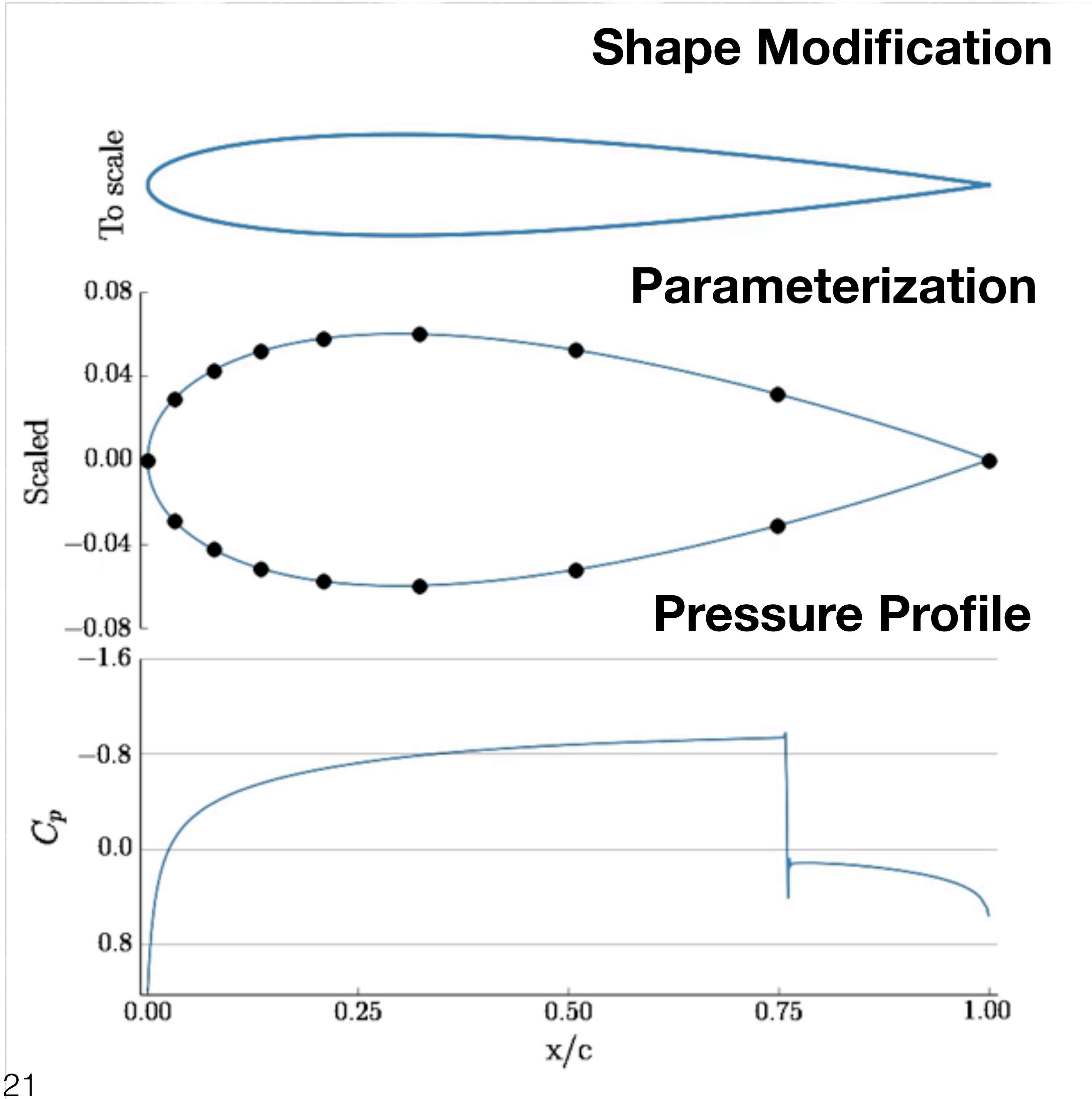
**enforced via DV bounds*

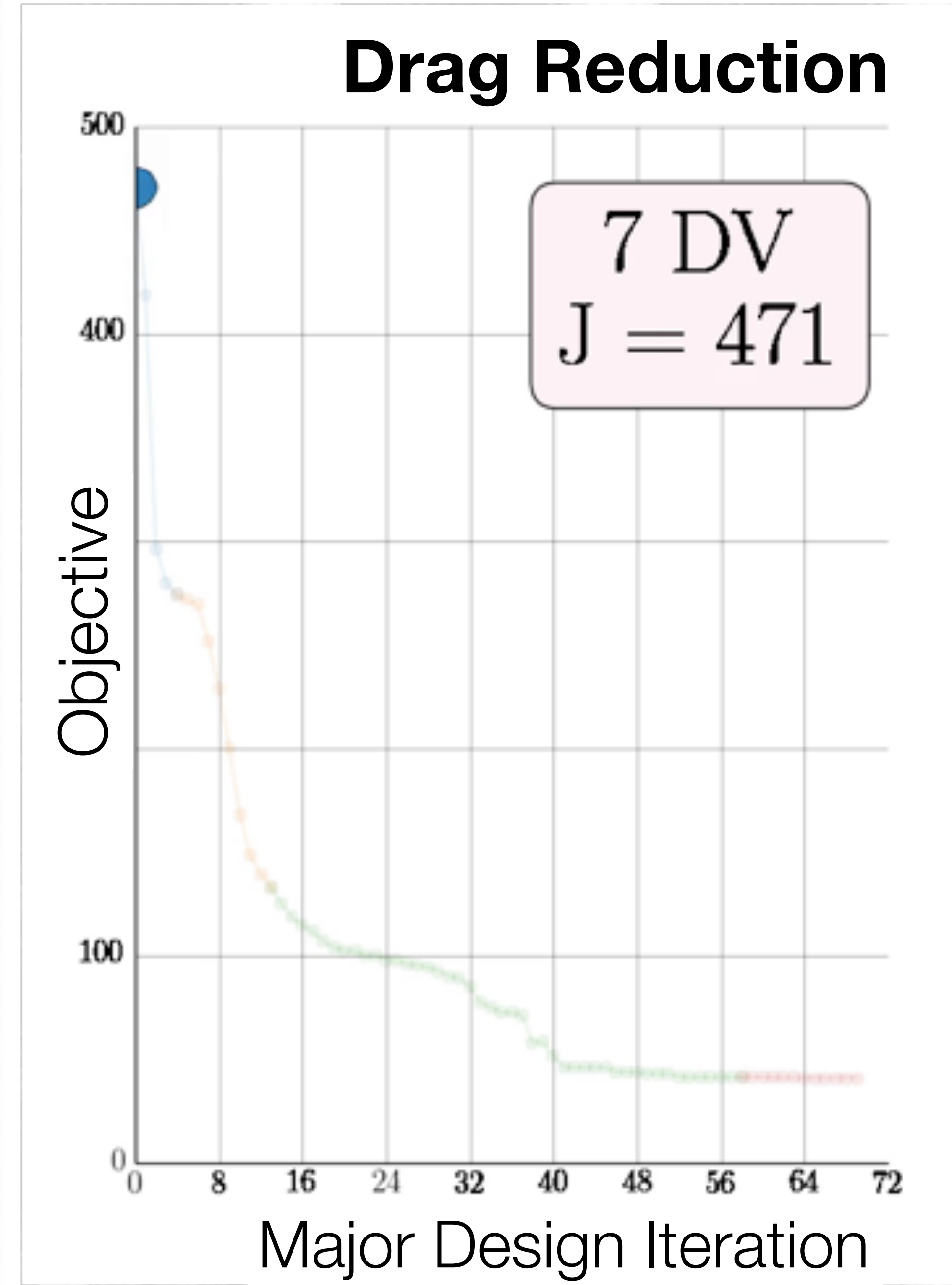
**Parameterization:**




Start with **7** design variables,
uniformly refine to **15**, then **31**.

# Case 1: Optimization History



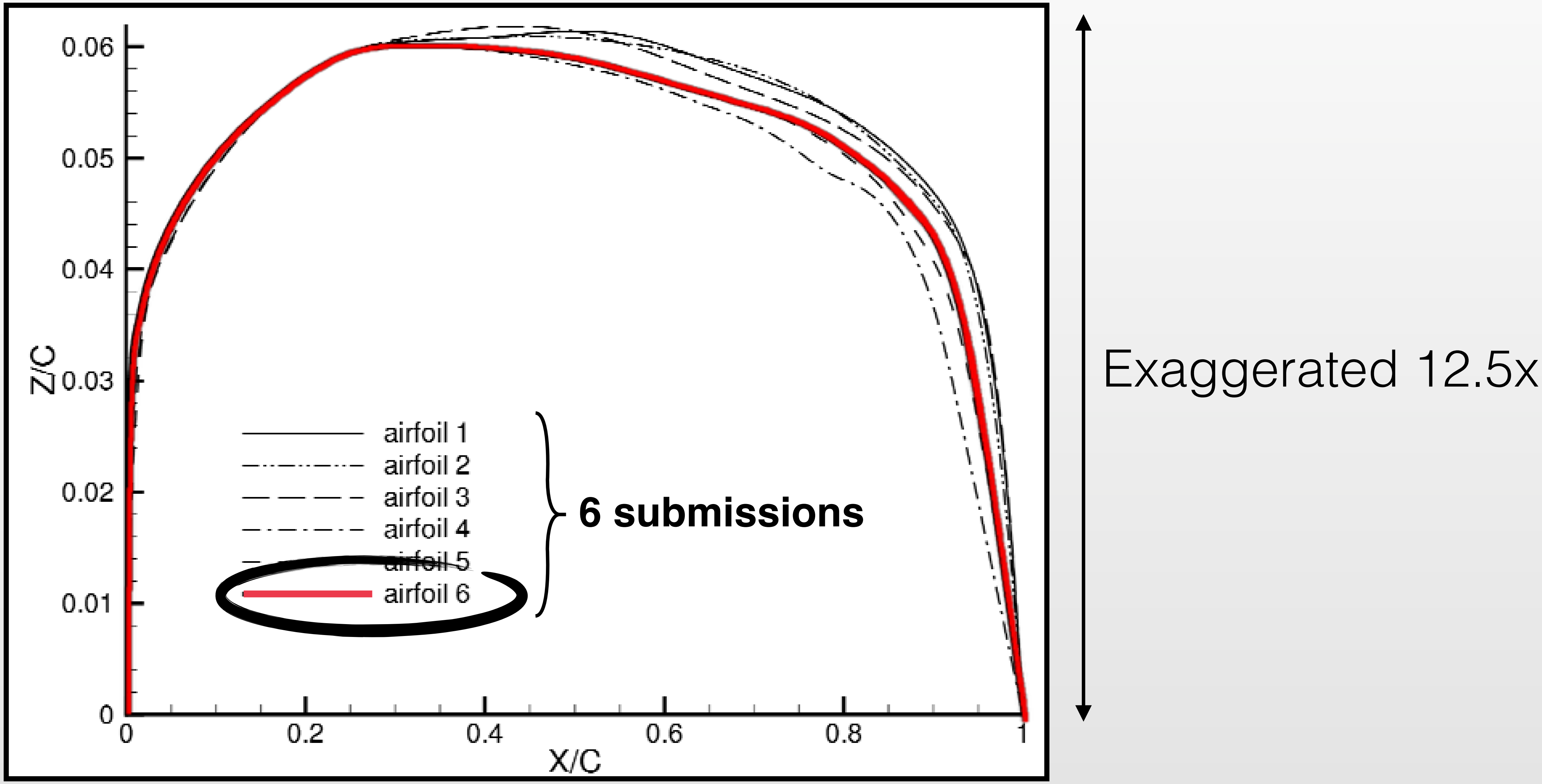



# Case 1: Final Shape


| | Baseline | 7-DV | 15-DV | 31-DV |
|---|---|---|---|---|
| $C_D$ | 471.3 | 273.8 | 133.0 | 41.3 |
| Error estimate | ±0.1 | ±0.1 | ±0.1 | ±0.35 |
| Cells | 26 K | 49 K | 50 K | 61 K |

Over **10x** reduction in inviscid drag

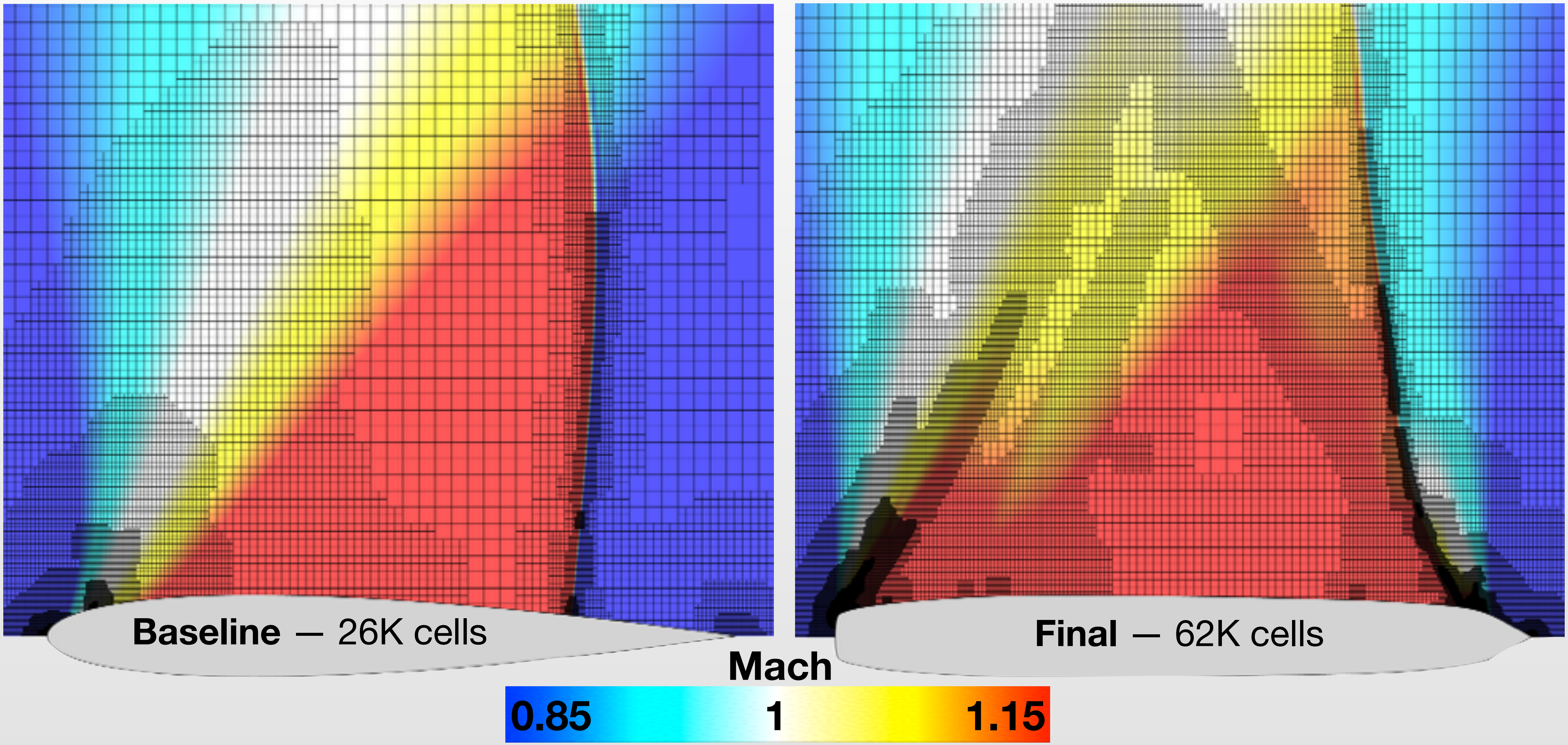
# Cross-Comparison




Courtesy of ONERA†

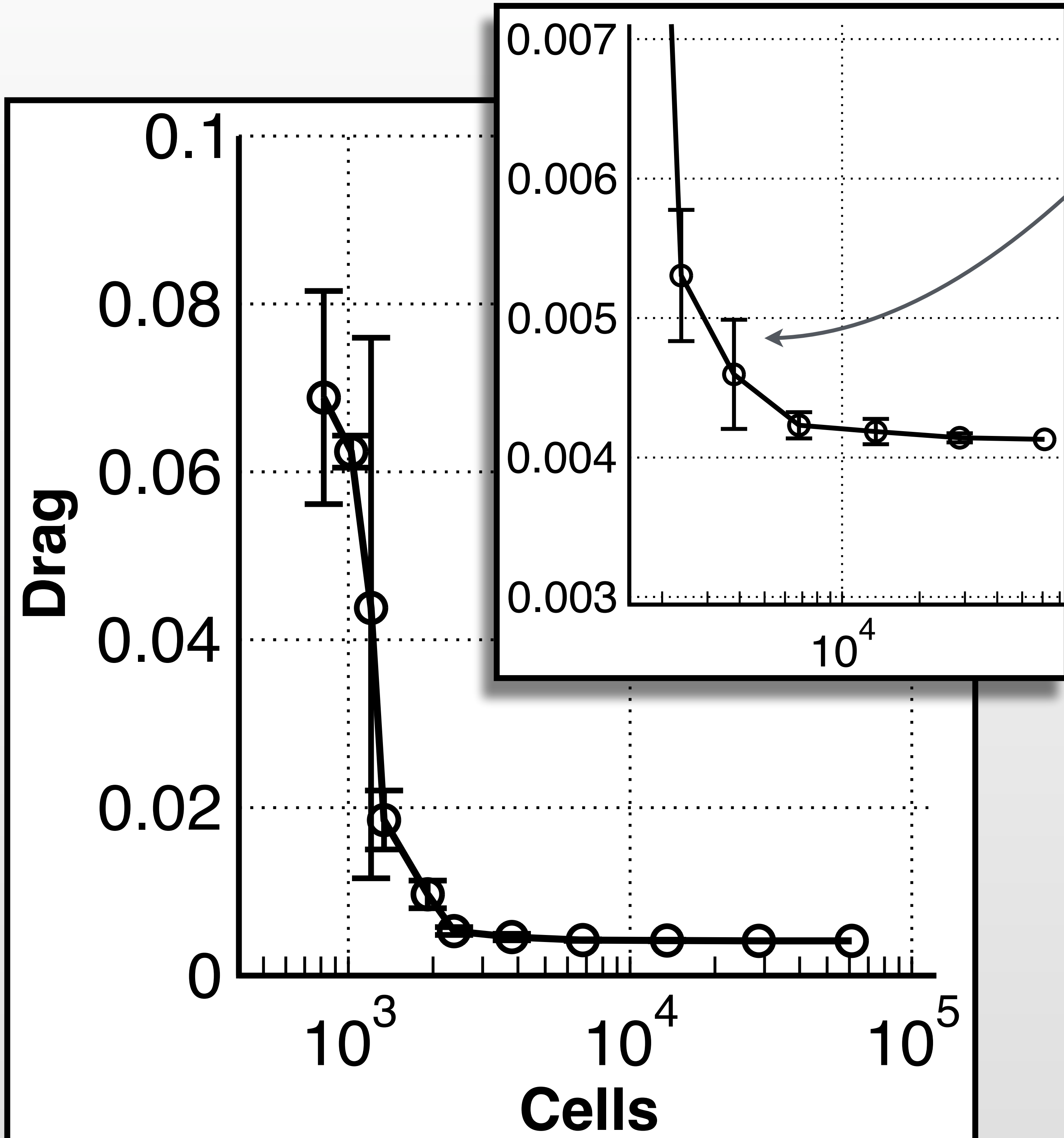
† **(2015)** Meheut *et al.*, ***"Gradient-Based Single and Multi-point Aerodynamic Optimizations with the elsA Software."***

# Mesh Comparison

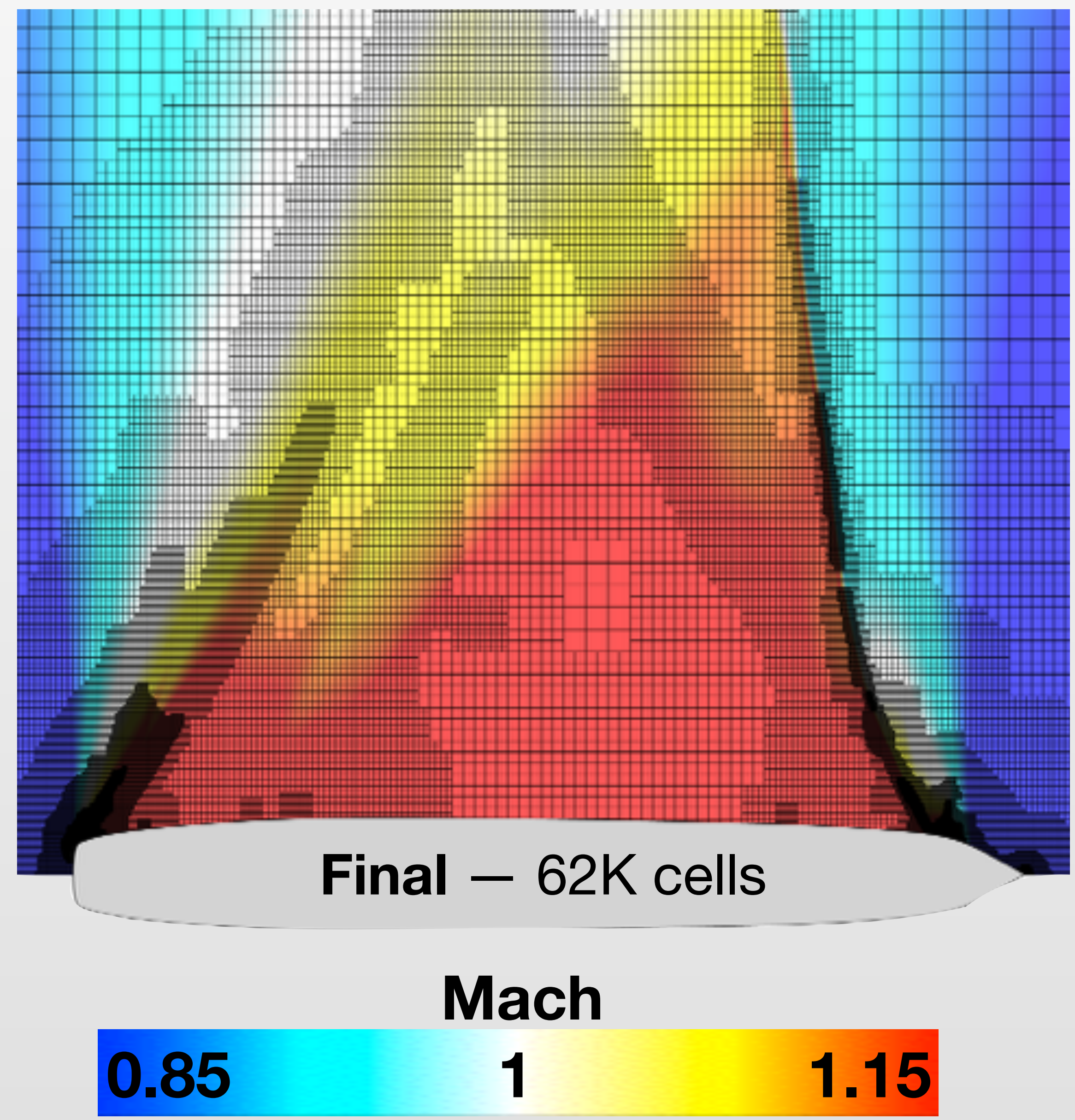



Farfield distance: 96 chords

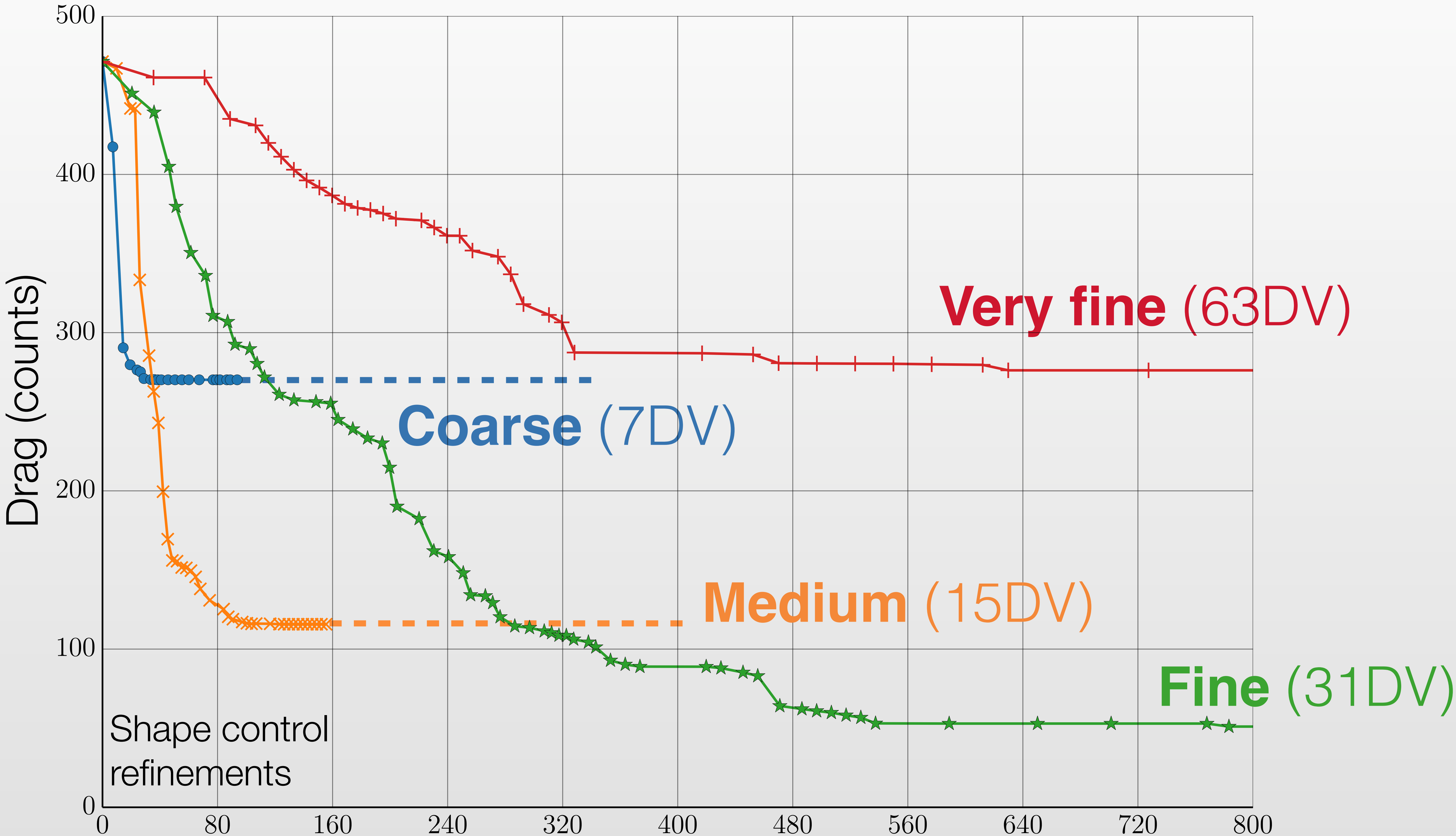
# Mesh Convergence




Error target:
$\mathcal{E}(C_D) \leq 0.1$ counts



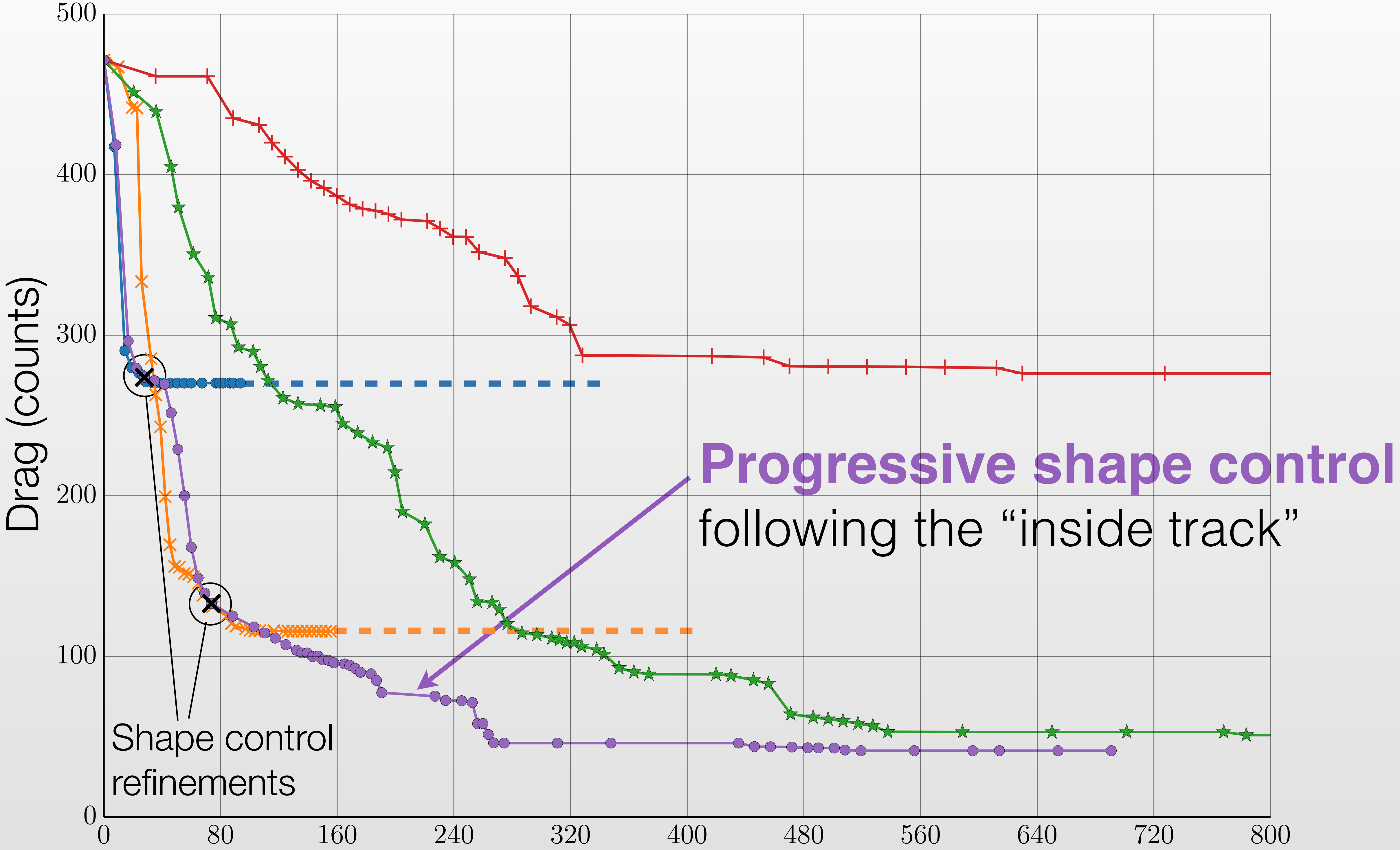
# Impact of Parameterization




Wall clock time

In minutes, plotted at major search iterations, on Ivybridge node — 20 cores

# Impact of Parameterization

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# Outline

## Approach

- ✓ Adaptive mesh refinement
- ✓ Progressive shape parameterization

## Optimization results:

- ✓ **Case 1** - Symmetric transonic airfoil design
- ‣ **Case 3** - Twist for minimal induced drag
- • **Case 2** - Transonic airfoil
- • **Case 4** - Transonic wing

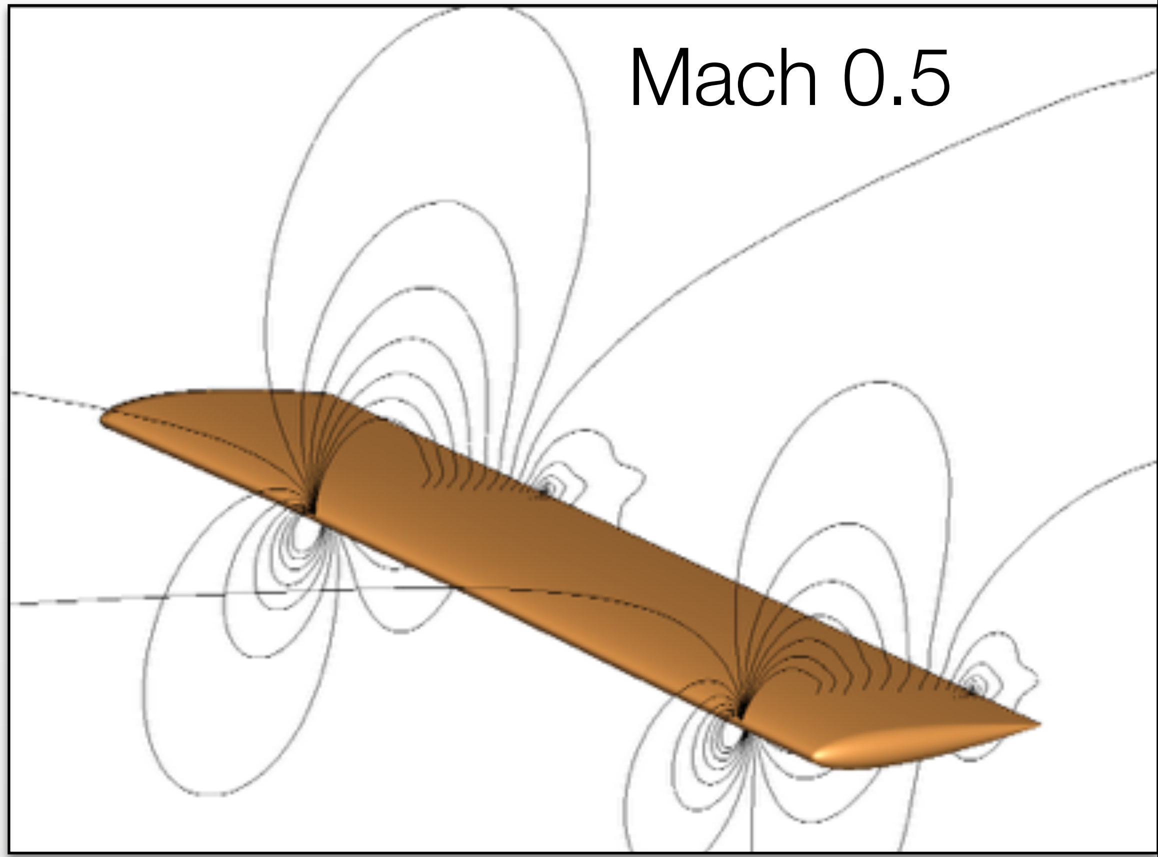
# Case 3: Twist Optimization

**Geometry:** NACA 0012 wing, Æ 6

**Objective:**

Minimize drag at Mach 0.5

**Constraint:** $C_L = 0.375$



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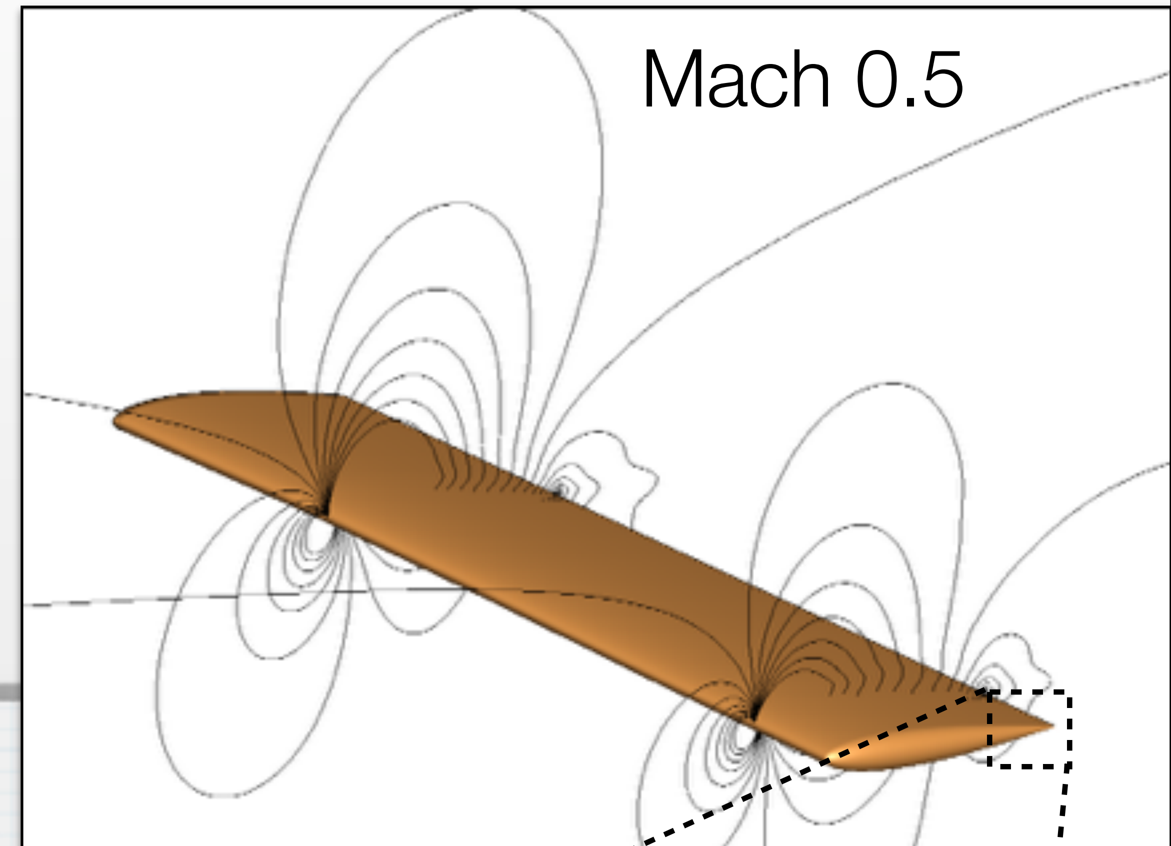



*Baseline* $C_D = 76.7 \text{ counts}$

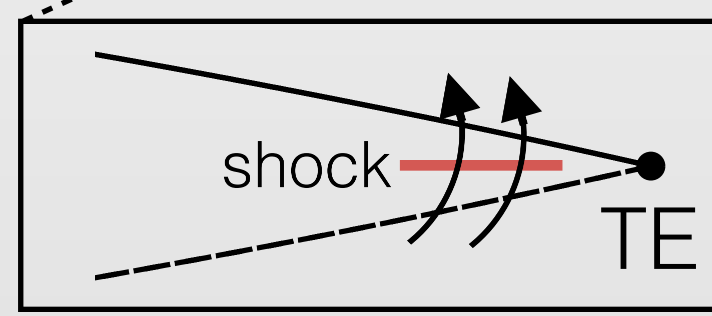
*Theoretical minimum drag*

$$C_{D_{min}} = \frac{C_L^2}{\pi e_0 \text{Æ}} = \frac{0.375^2}{6.0\pi} = 74.6 \text{ counts}$$

**But…**

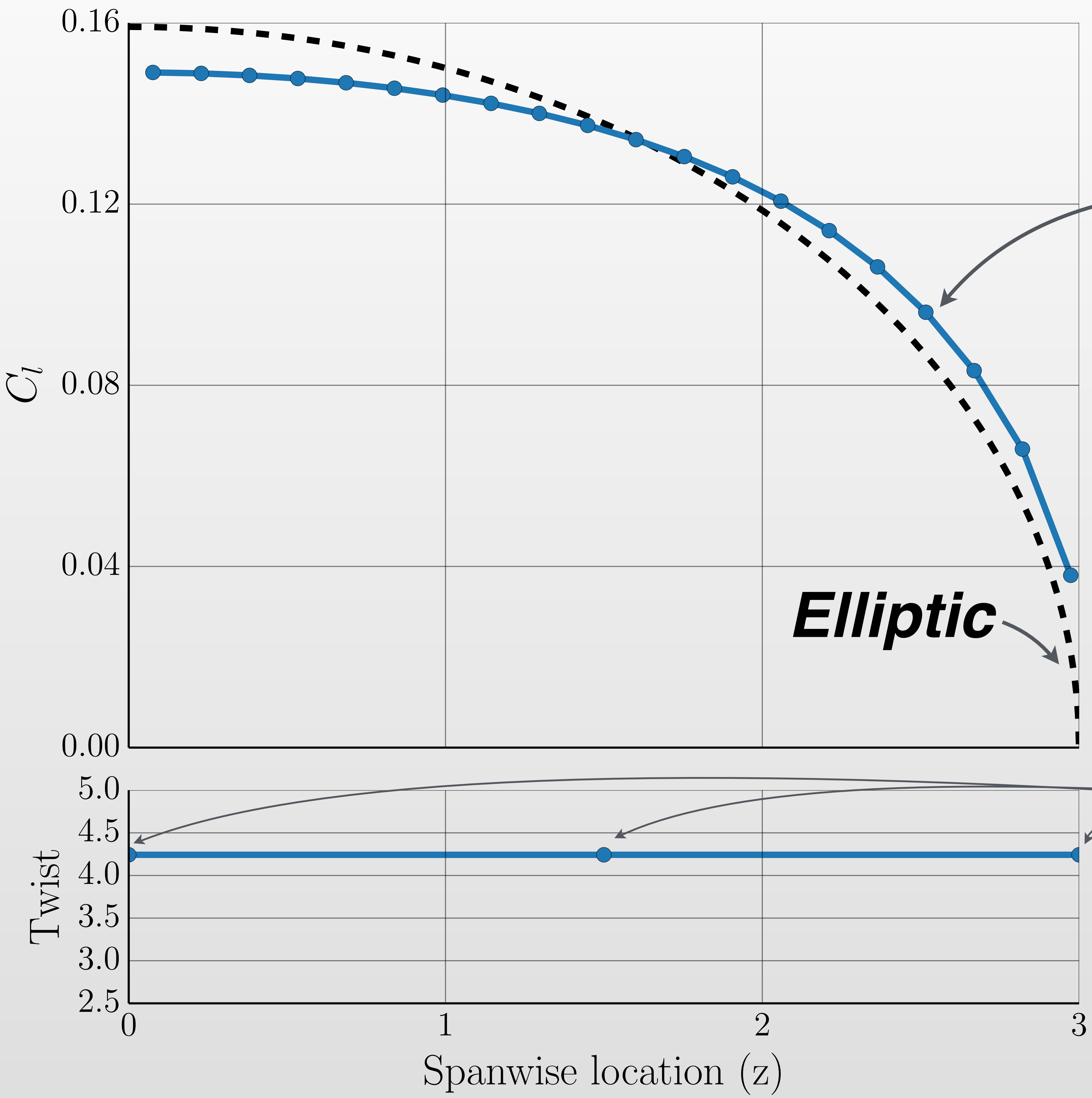
1) not perfectly planar

2) small shock on wing tip




Wingtip cap generated by simple revolution

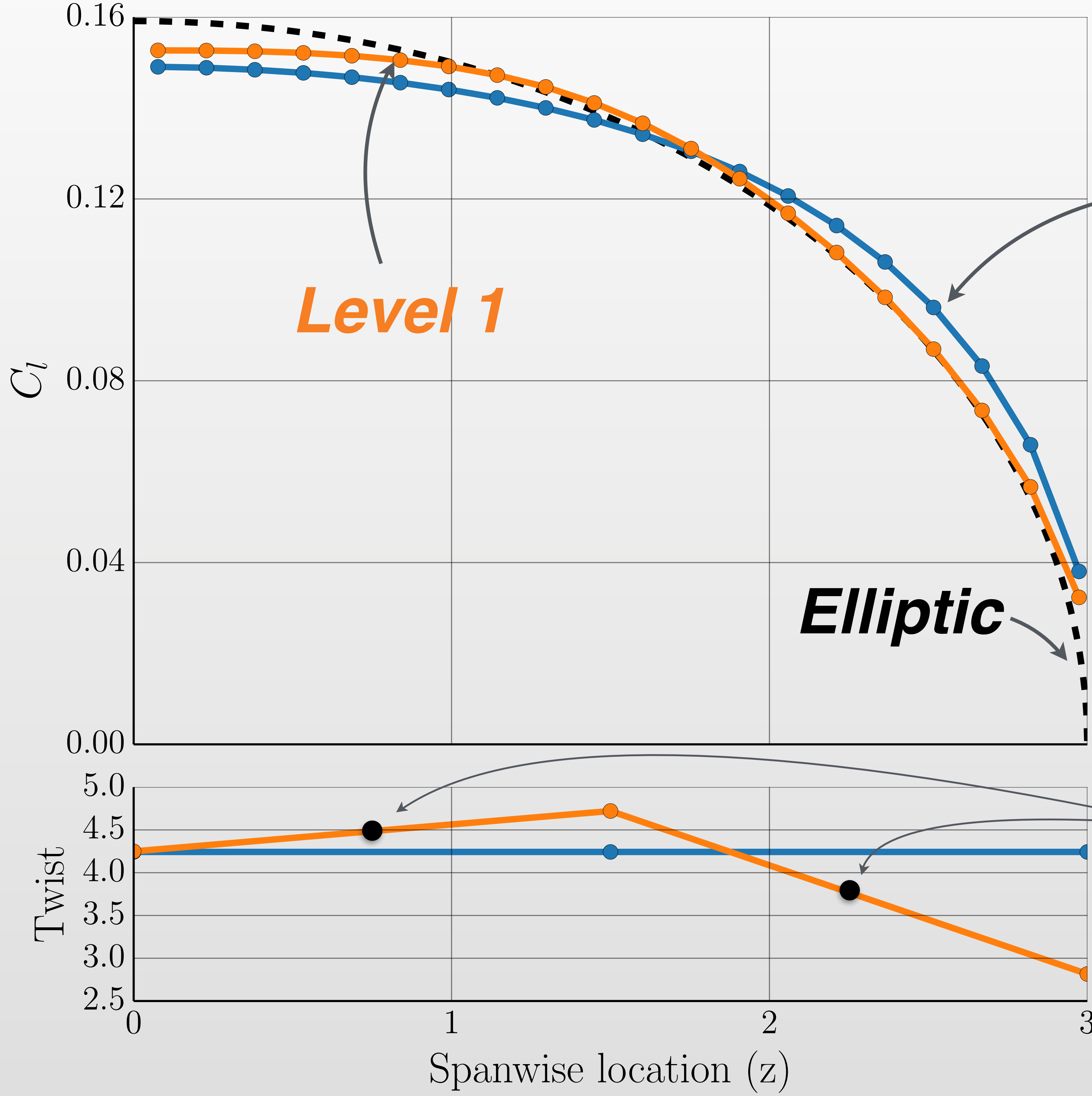
# Case 3: Results




$$C_D = 76.7 \text{ counts}$$
$$e = 0.973 \pm 0.005$$

Initially **3** twist design variables

# Case 3: Results

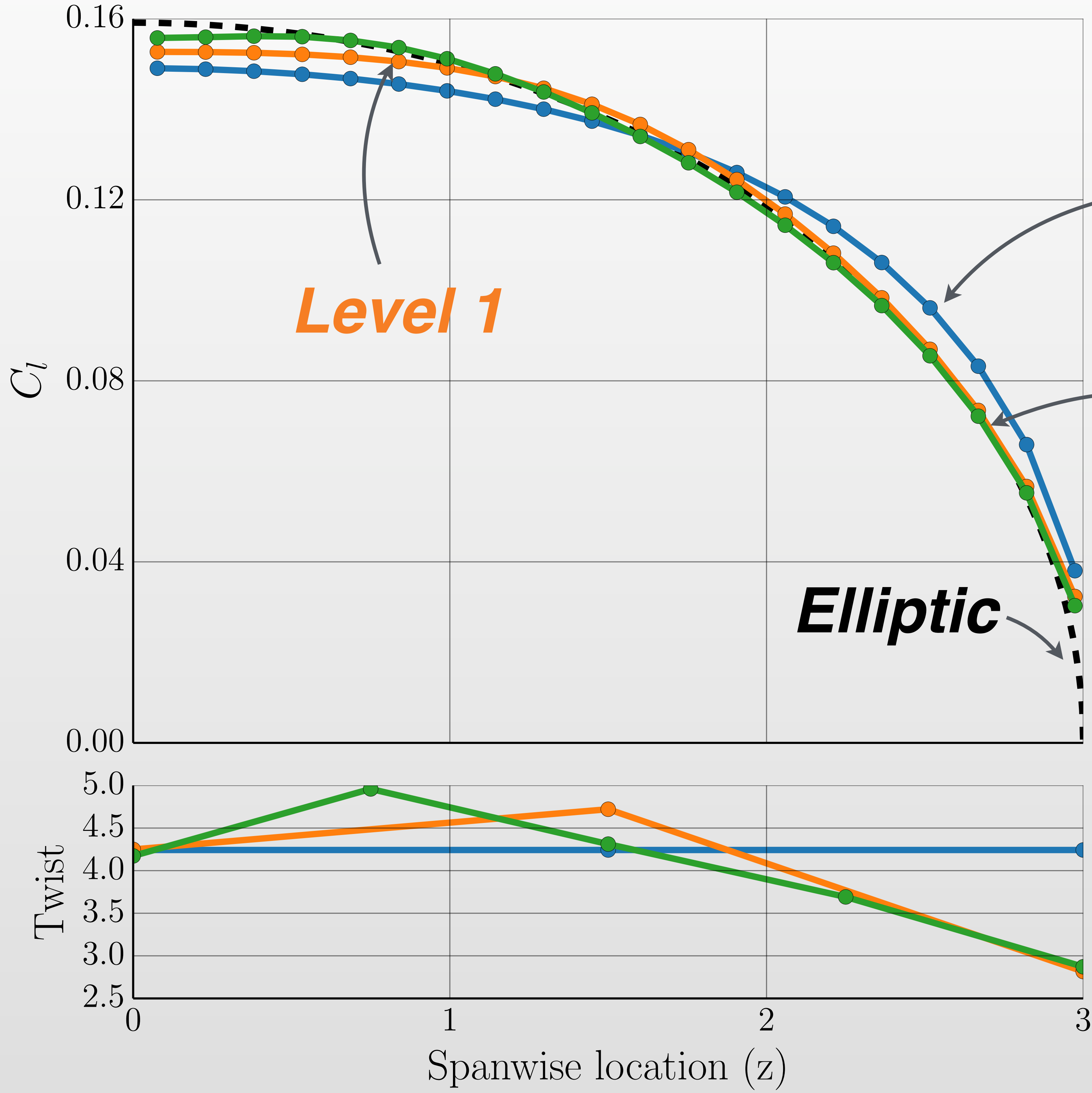



$$C_D = 76.7 \text{ counts}$$
$$e = 0.973 \pm 0.005$$

**Uniformly refine:**

Add 2 new control stations.

# Case 3: Results




***Baseline***

$C_D = 76.7$ counts

$e = 0.973 \pm 0.005$

***Level 2 (Final)***

*(5 design variables)*

$C_D = 75.6$ counts

$e = 0.987 \pm 0.003$

# Outline

## Approach

- ✓ Adaptive mesh refinement
- ✓ Progressive shape parameterization

## Optimization results:

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- ✓ **Case 3** - Twist for minimal induced drag
- ‣ **Case 2** - Transonic airfoil
- • **Case 4** - Transonic wing

# Case 2: Transonic Airfoil Design

**Baseline:** RAE 2822

**Objective:**
Minimize drag at Mach 0.734

**Constraints:**

$$C_L = 0.824$$

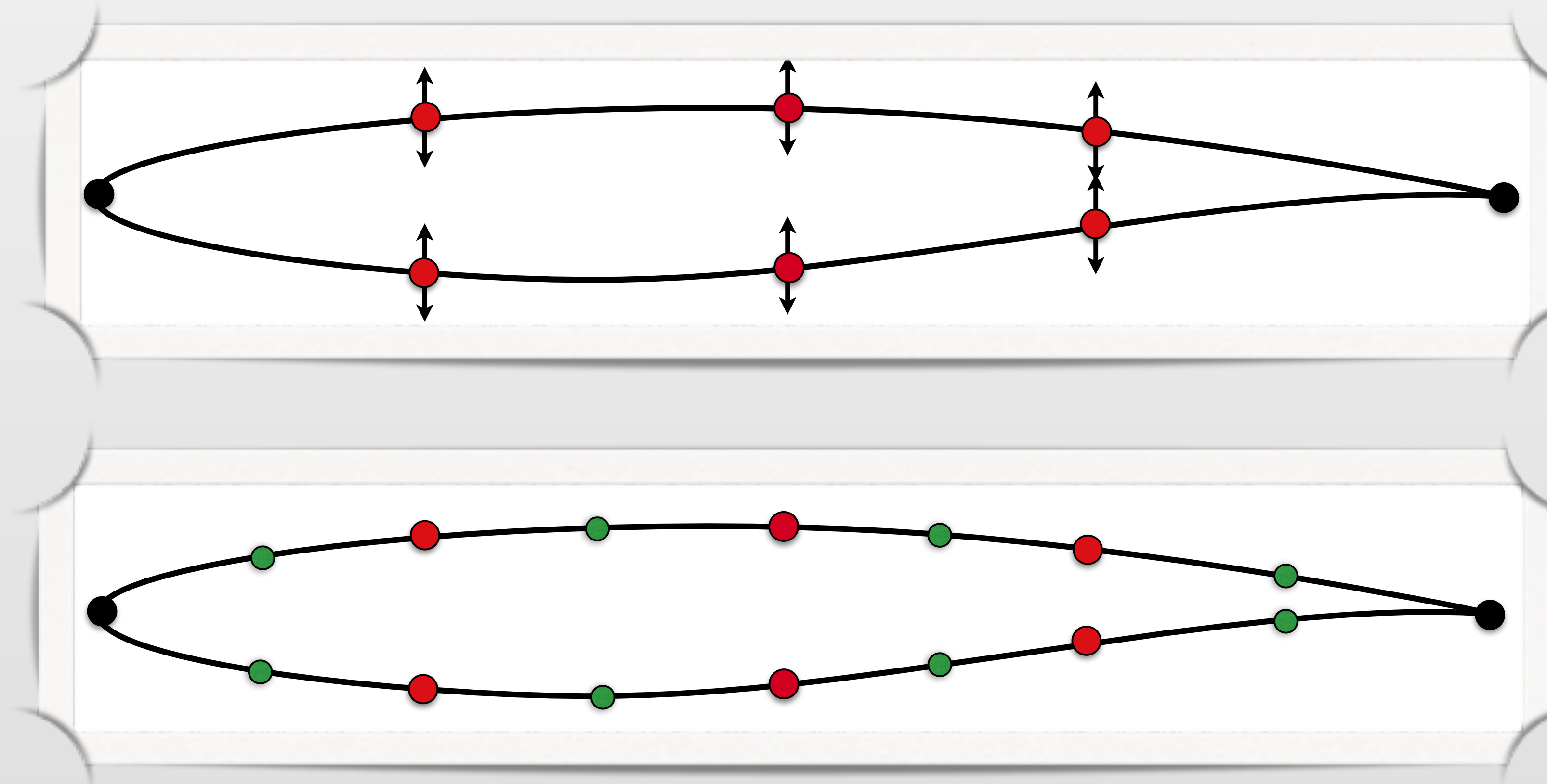
$$C_M \geq -0.092$$ *(initially violated)*

$$A \geq A_{RAE} \approx 0.07787$$

**Parameterization**

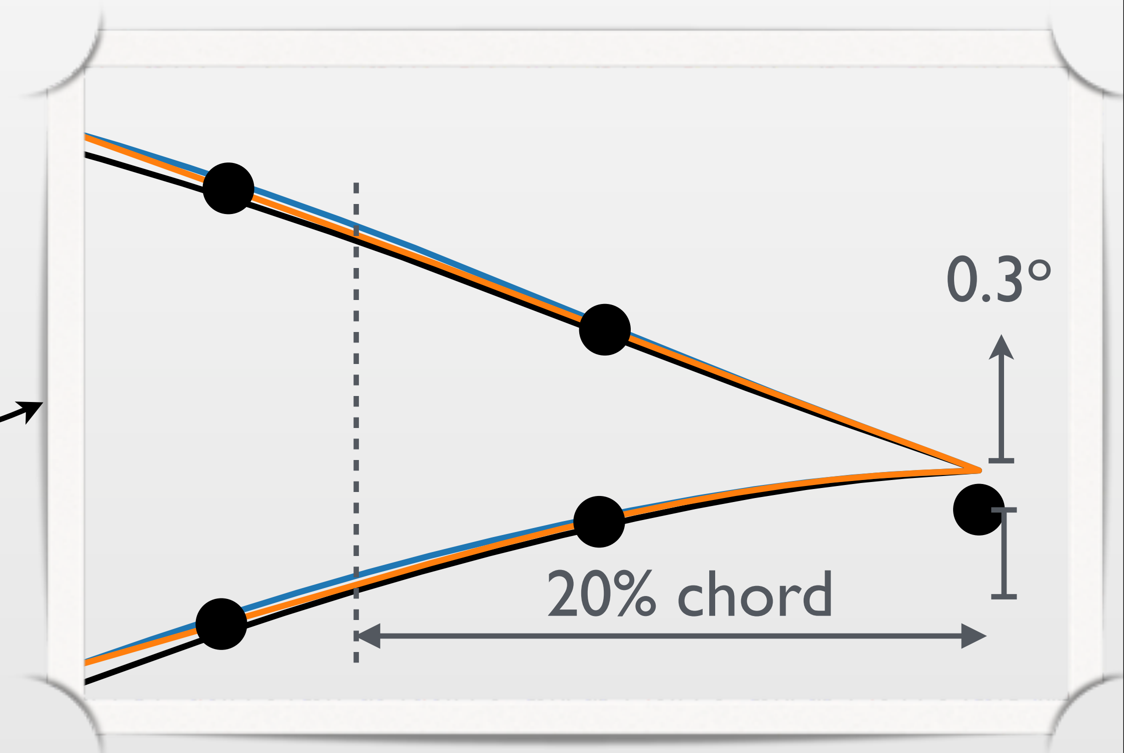
Level 1: **6 DVs**

Level 2: **14 DVs**



# Case 2: Inviscid Approach

- Use **inviscid** flow solutions to drive optimization.
- Verify improvement with **viscous** analysis.
- To encourage good viscous performance, slightly decamber the trailing edge during inviscid analyses.†

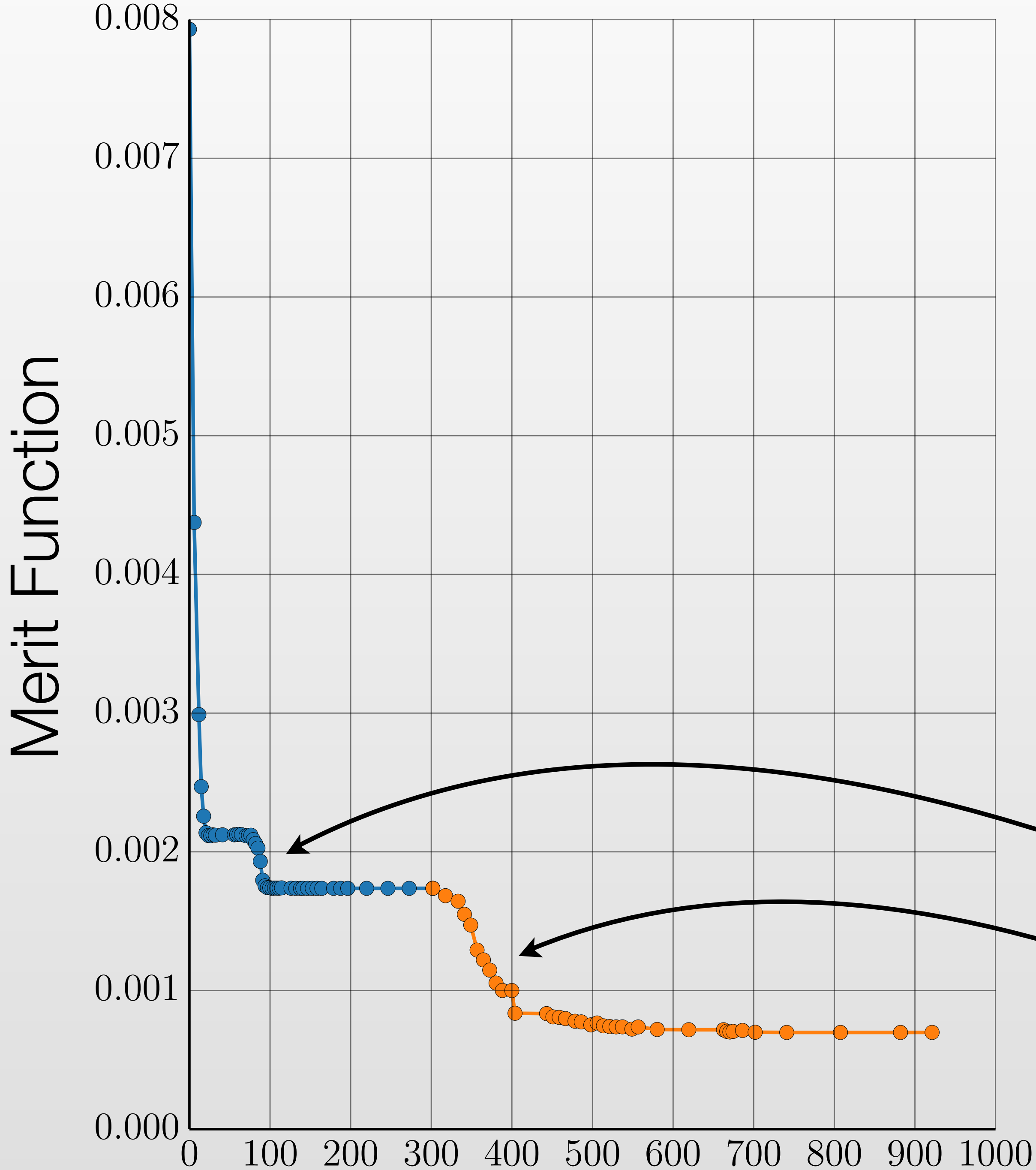



$$y = y + \left(\frac{x - 0.8}{0.2}\right)^3 sin(\theta)$$

†**(1998)** Campbell, R. L., *“**Efficient Viscous Design of Realistic Aircraft Configurations**,” AIAA 98-2539*

**(2013)** Smith, Nemec and Krist, *“**Integrated Nacelle-Wing Shape Optimization for an Ultra-High Bypass Fanjet Installation on a Single-Aisle Transport Configuration.**” AIAA 2013-0543*

# Case 2: Cost

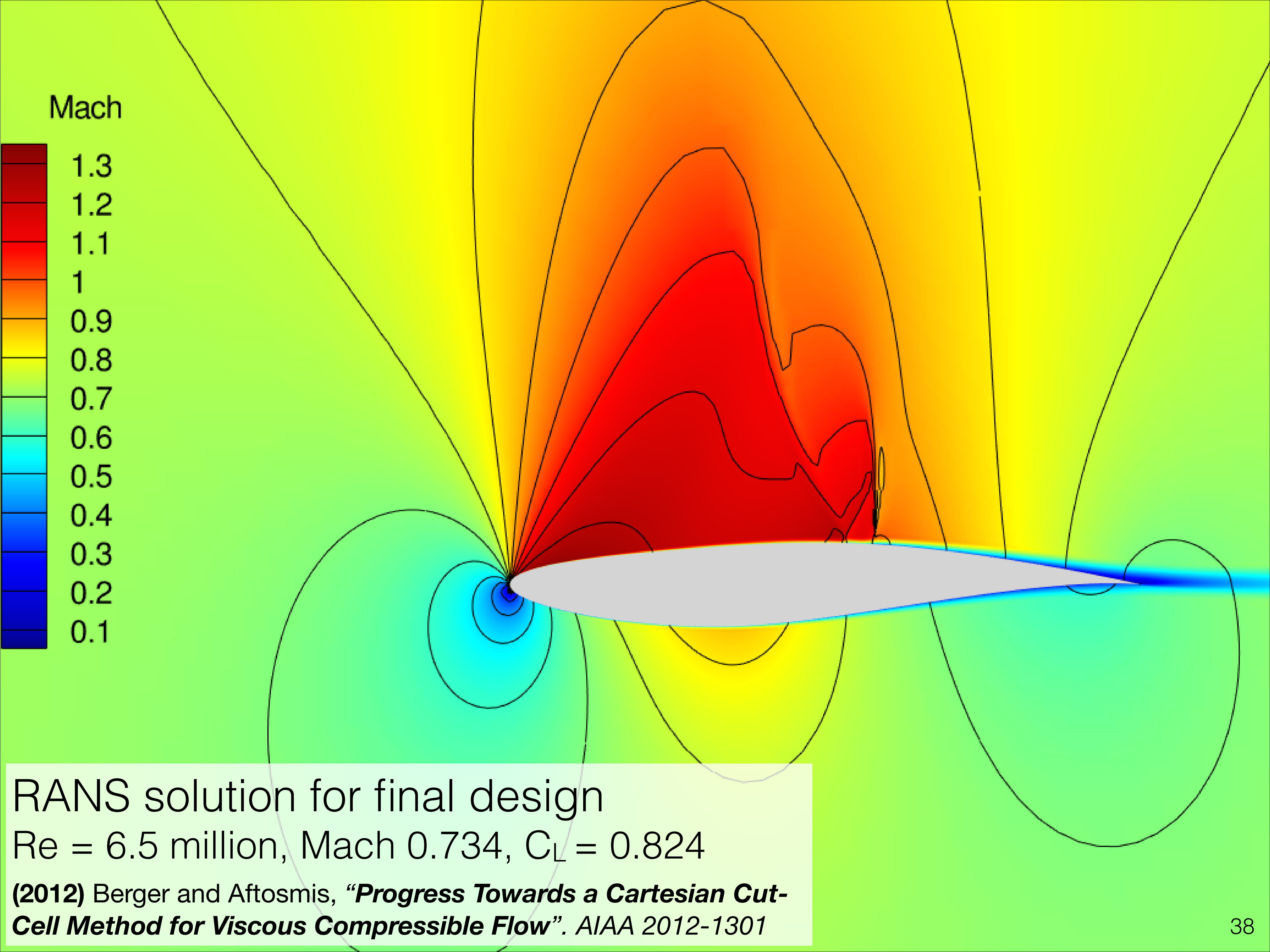



Wall clock time

In minutes, plotted at major search iterations, on 64 Intel Xeon E5 cores

**Cost per design iteration:**

- Geometry generation
- 1 Adaptively meshed flow solution
- 3 adjoints (drag, lift, pitching moment)
- 6-14 shape derivative computations
- 24-56 gradient projections
- **Total time per design iteration:**
  - **Level 1:** ~2.5 minutes/iteration
  - **Level 2:** ~3.5 minutes/iteration



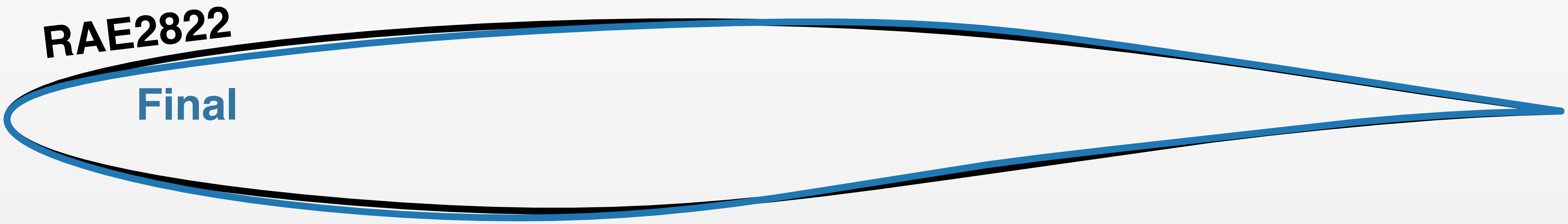

# RANS solution for final design

Re = 6.5 million, Mach 0.734, $C_L$ = 0.824

**(2012)** Berger and Aftosmis, ***“Progress Towards a Cartesian Cut-Cell Method for Viscous Compressible Flow”***. *AIAA 2012-1301*

# Case 2: Results

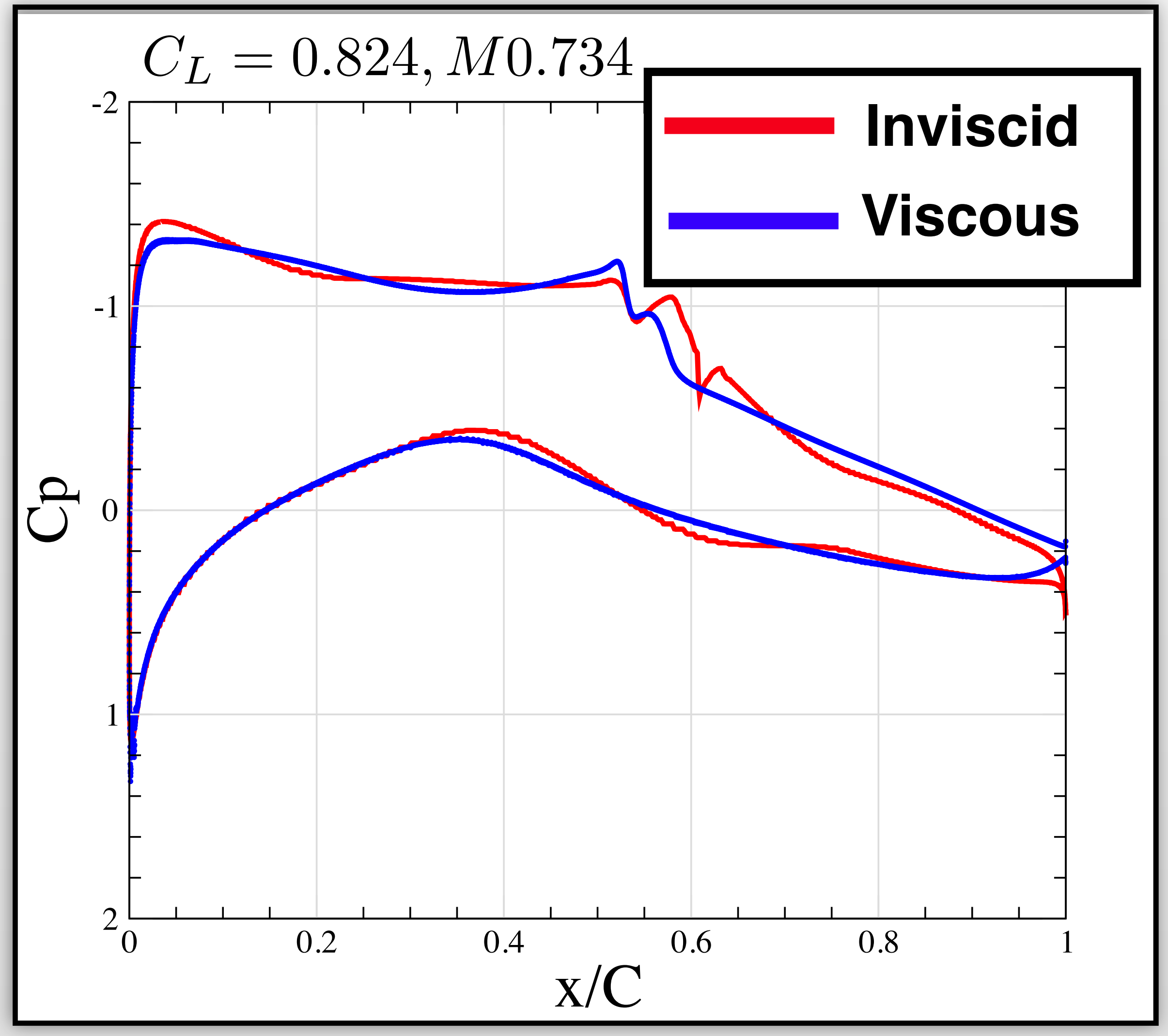
Inviscid approach reduced **total** drag by 72 counts.




| | | Baseline | Final |
|---|---|---|---|
| Inviscid | $C_D$ | 0.0068 | 0.0007 |
| | Error | $\pm 0.0001$ | $\pm 0.00006$ |
| | Cells | 21K | 27 K |
| | $\alpha_{trim}$ | 1.73° | 2.72° |
| Viscous | $C_D$ | 0.0196 | 0.0124 |
| | $\alpha_{trim}$ | 2.76° | 2.61° |

Decambering helped maintain parity between trimmed angle of attack for inviscid and viscous solutions.

**Final design pressure profile**



# Outline

## Approach

- ✓ Adaptive mesh refinement
- ✓ Progressive shape parameterization

## Optimization results:

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- ✓ **Case 2** - Transonic airfoil
- ‣ **Case 4** - Transonic wing

# Case 4: Transonic Wing Design

**Baseline:** Common Research Model (CRM) *(wing only)*

**Objective:** Minimize drag

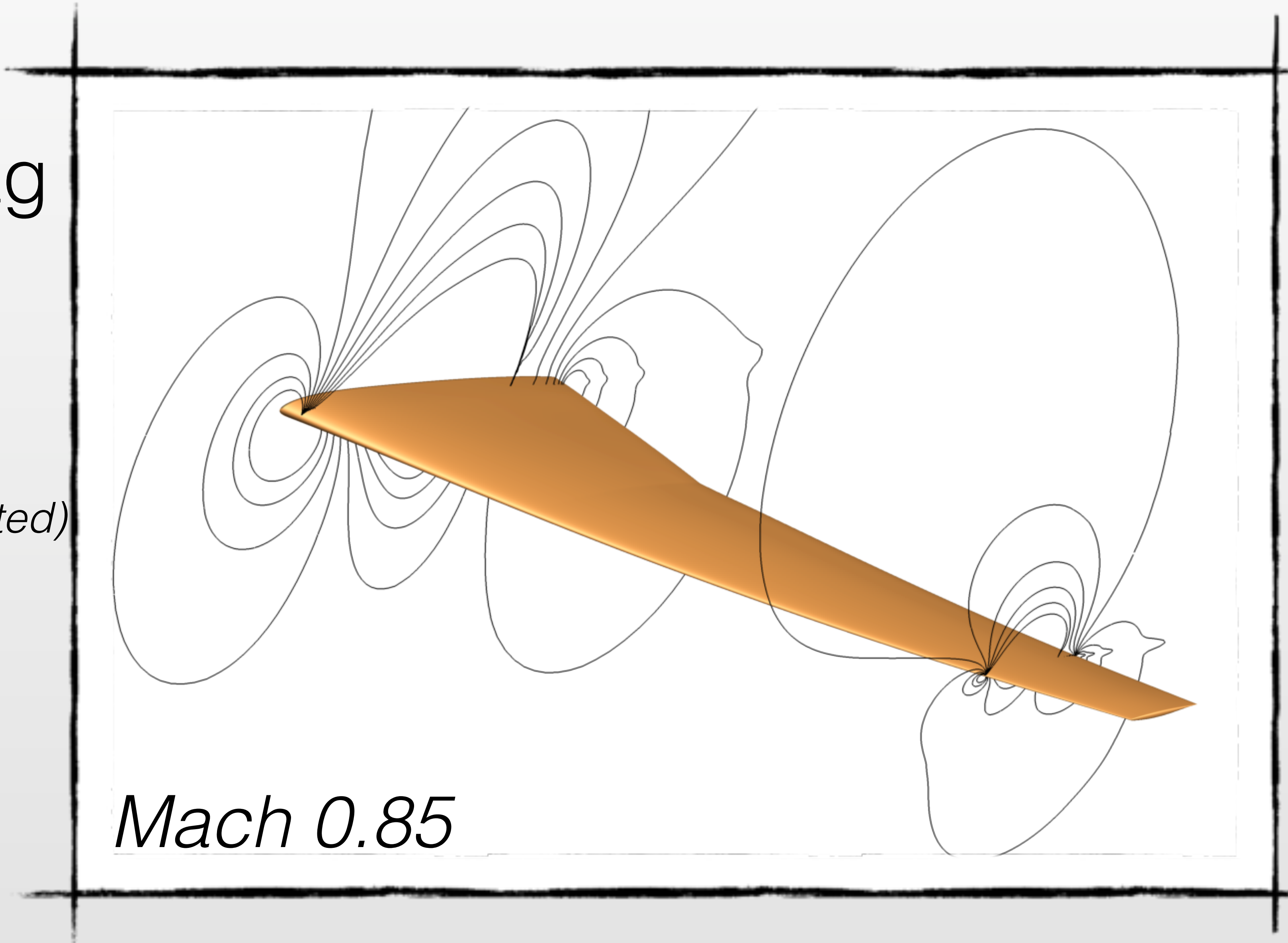
**Constraints:**

$$C_L = 0.5$$

$$C_M \geq -0.17$$ *(initially violated)*

$$V \geq V_0 \approx 0.26291$$

$$t_i \geq 0.25 t_{i_0} \forall i$$



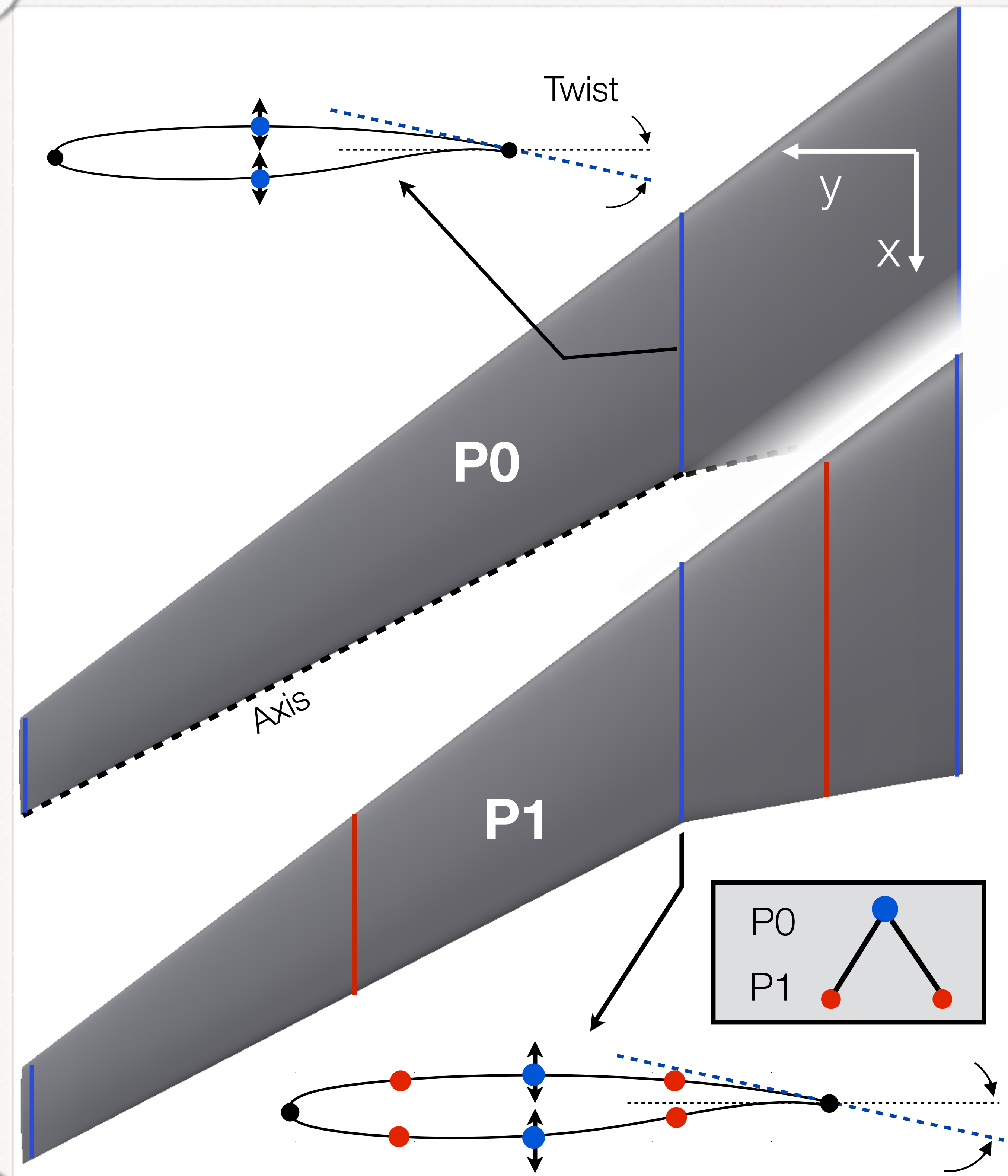
# Case 4: Transonic Wing Design

## Parameterization

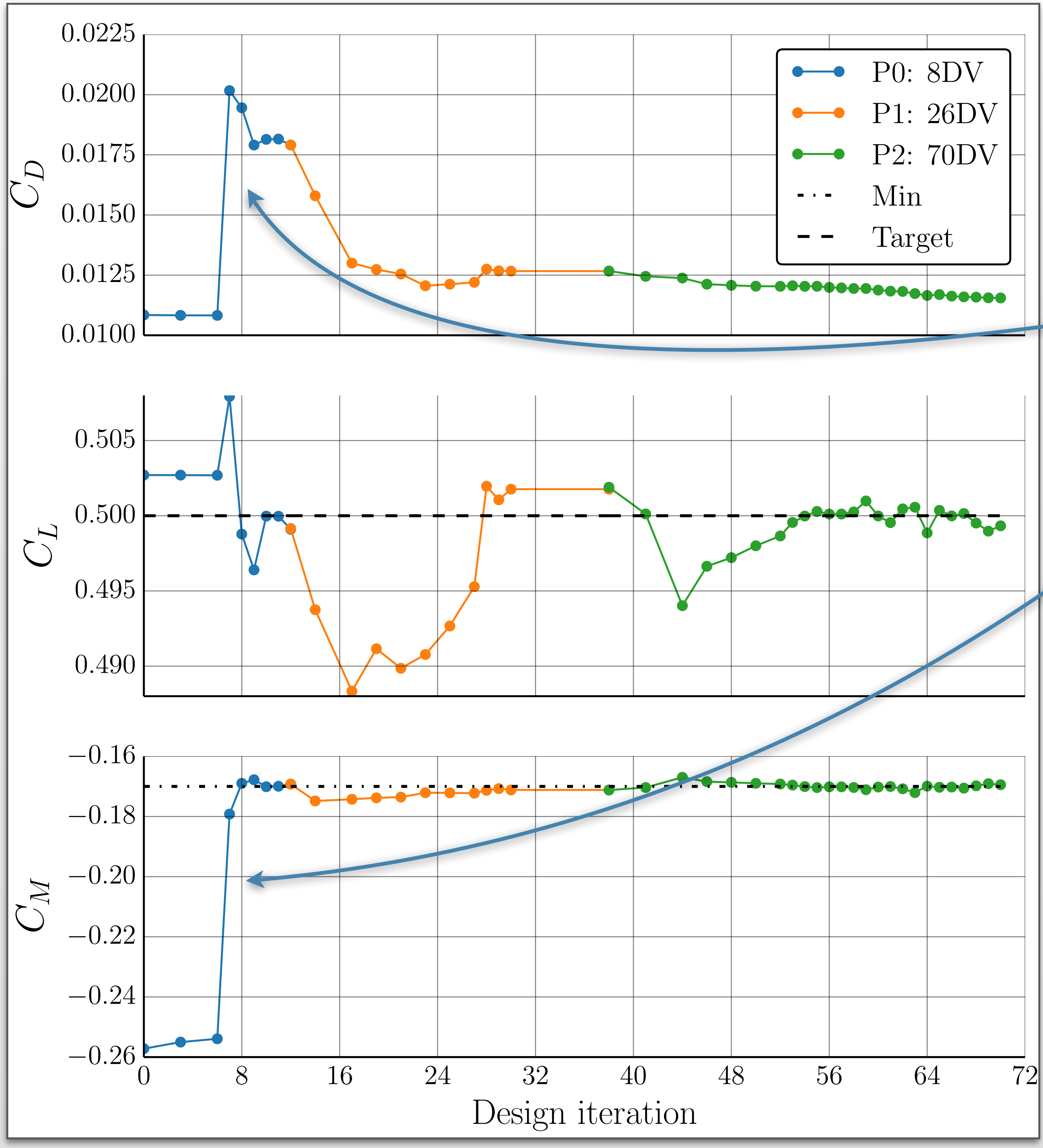
**P0:** 9 design variables
- 2 twist, 6 airfoil + alpha

**P1:** 27 design variables
- 4 twist, 22 airfoil + alpha

**P2:** 71 design variables
- 8 twist, 62 airfoil + alpha

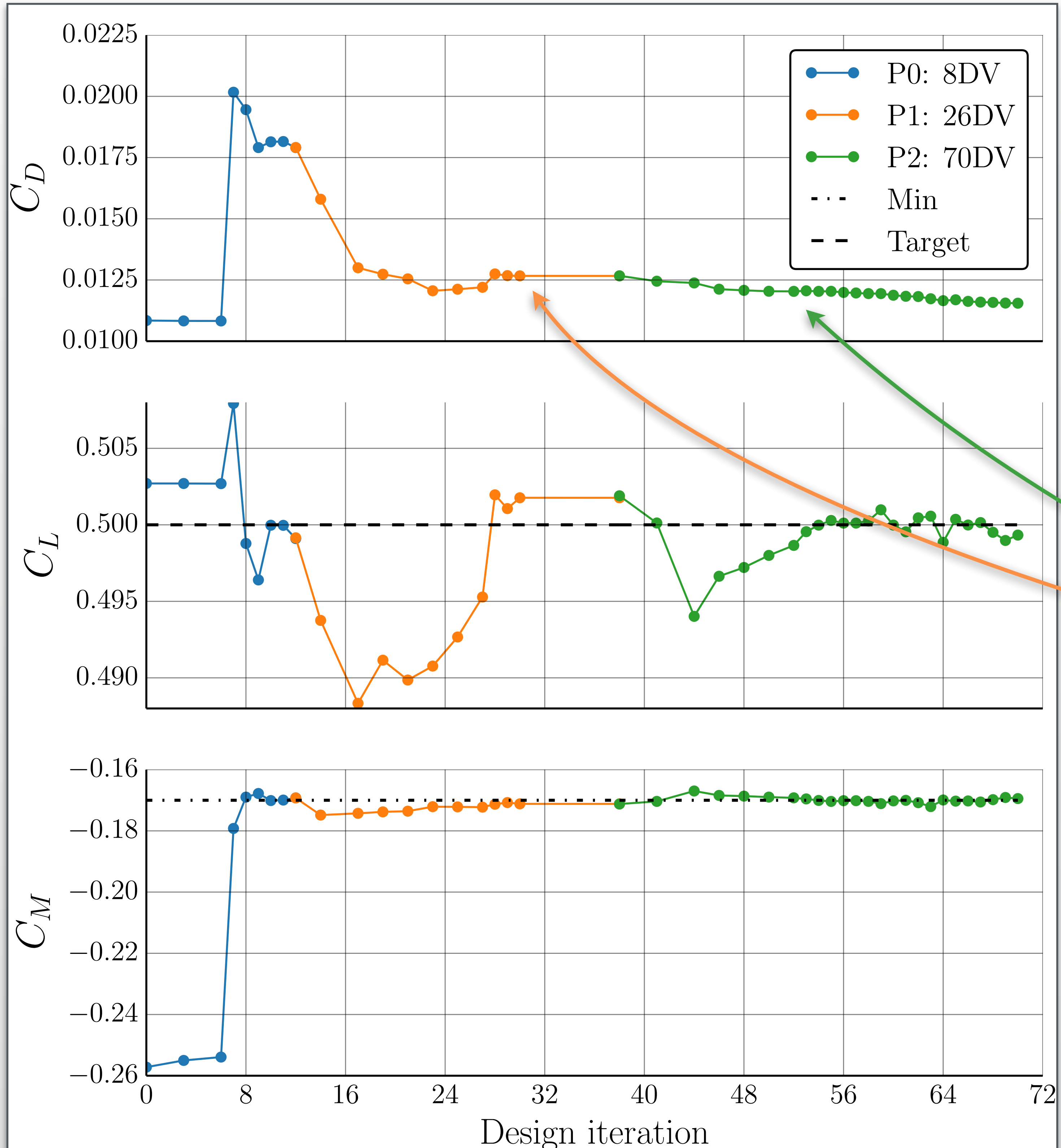


# Case 4: Results




Under **P0**, pitching moment constraint is satisfied by sacrificing drag.

# Case 4: Results

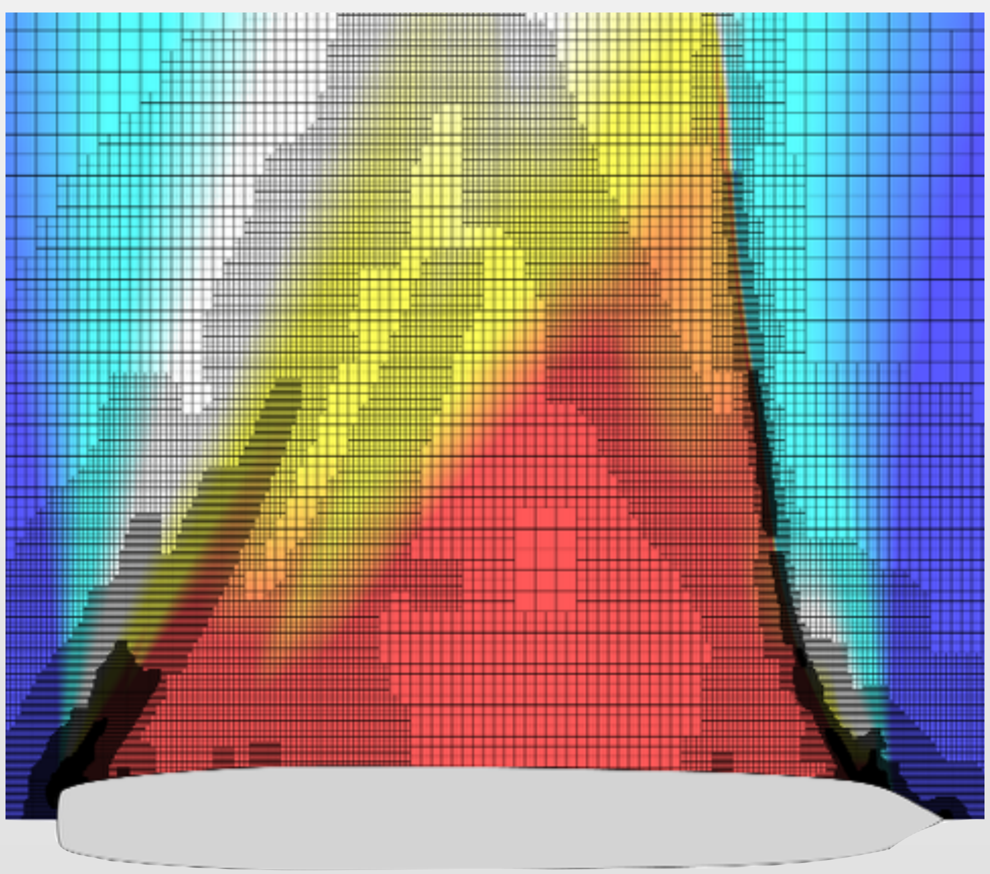



Under **P0**, pitching moment constraint is satisfied by sacrificing drag.

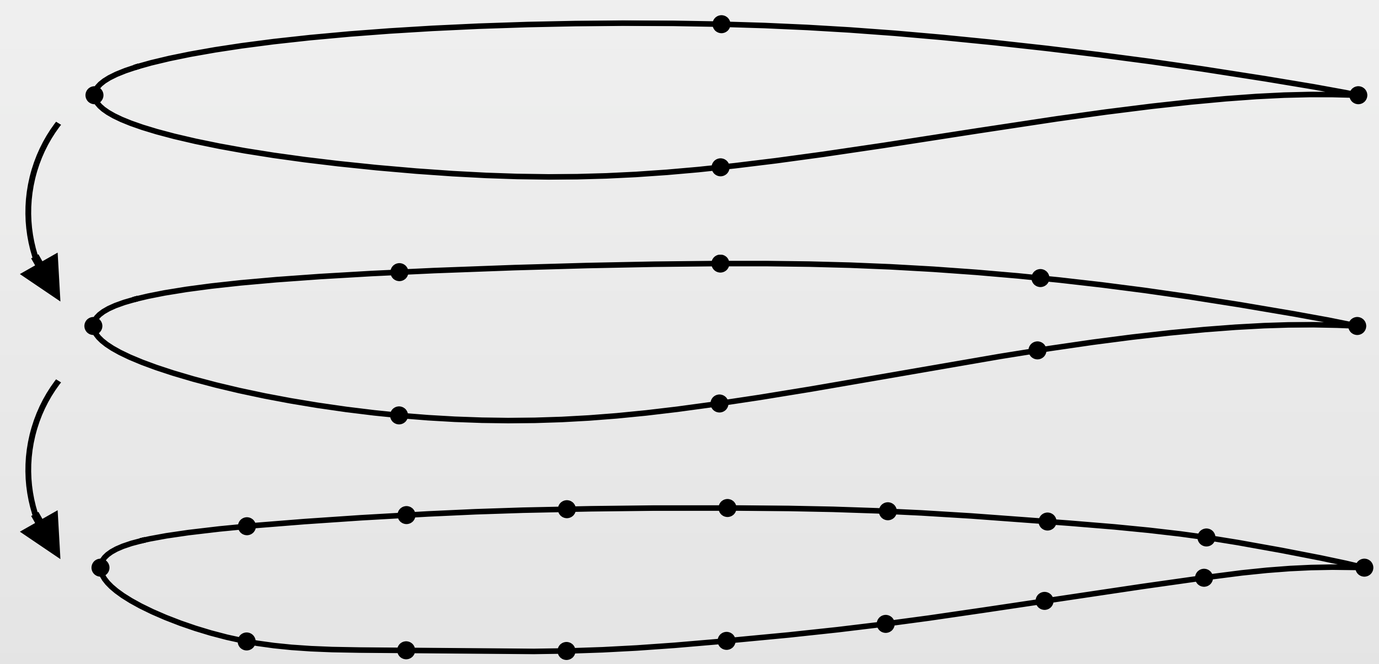
**P1**, **P2** drive down drag while holding constraints.

# Summary

- Used Cart3D inviscid design framework to solve benchmark problems.
- Combined two **automated, adaptive** elements:



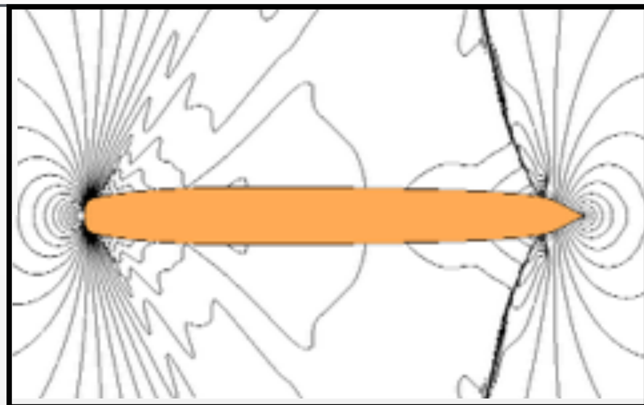
Adaptive mesh refinement



Progressive parameterization

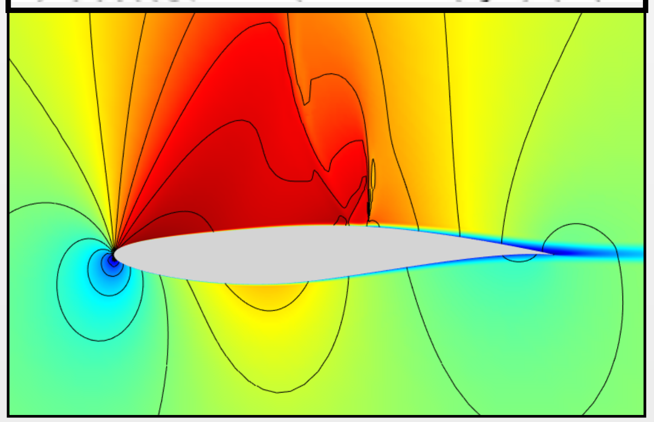
# Summary

**1**



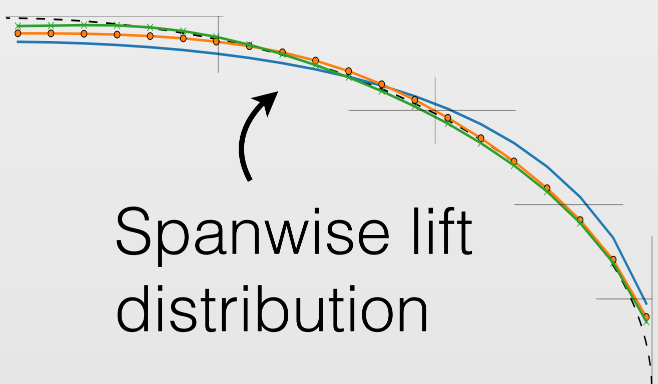
Achieved 10x inviscid drag reduction with fully automated approach.

**2**



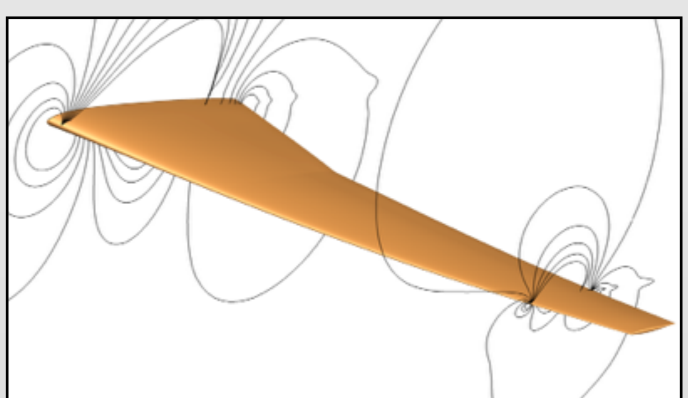
Used inviscid design approach to achieve 72 counts **total** drag reduction.

**3**




Twisted wing to improve span efficiency.

**4**



Demonstrated **automated system** on full wing design problem with constraints.