Toward Efficient Aerodynamic and Aerostructural Optimization

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OUTLINE

- Methods
- Progress
- Future Work

METHODS

- Flow solution: steady/unsteady/RANS/LES
- Geometry parameterization & mesh movement
- Gradients: adjoint method
- Optimization algorithms

FLOW SOLVER

- Structured multi-block grids
- High-order finite-difference method with summation-by-parts operators and simultaneous approximation terms
- Parallel Newton-Krylov-Schur solver
- Jacobian-free Newton-Krylov algorithm with approximate Schur parallel preconditioning
- Promising dissipation-based continuation method for globalization

➡ Hicken, J.E., and Zingg, D.W., A parallel Newton-Krylov solver for the Euler equations discretized using simultaneous approximation terms, AIAA Journal, Vol. 46, No. 11, 2008

➡ Osusky, M., and Zingg, D.W., A parallel Newton-Krylov flow solver for the Reynolds-Averaged Navier-Stokes equations, AIAA ASM, Jan. 2012

Summation-by-Parts (SBP) Operators

- Satisfy a discrete summation-by parts property that mimics the continuous operator
- Used in combination with simultaneous approximation terms (SATs) at boundaries
- Rigorous development of time-stable boundary schemes for higher-order methods
- Superconvergent functional estimates if scheme is dual consistent
    - ➡ For example, the fourth-order scheme produces sixth-order convergence in functionals

➡ Hicken, J.E., and Zingg, D.W., Superconvergent Functional Estimates from Summation-by-Parts Finite-Difference Discretizations, SIAM Journal on Scientific Computing, Vol. 33, 2011

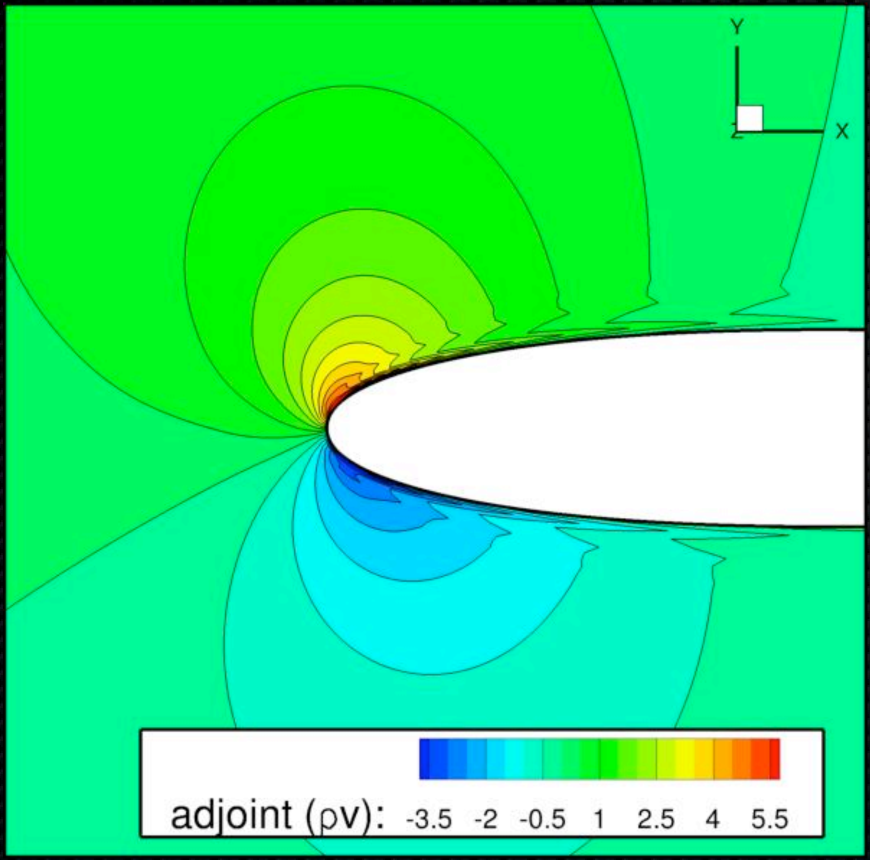
Dual Consistency

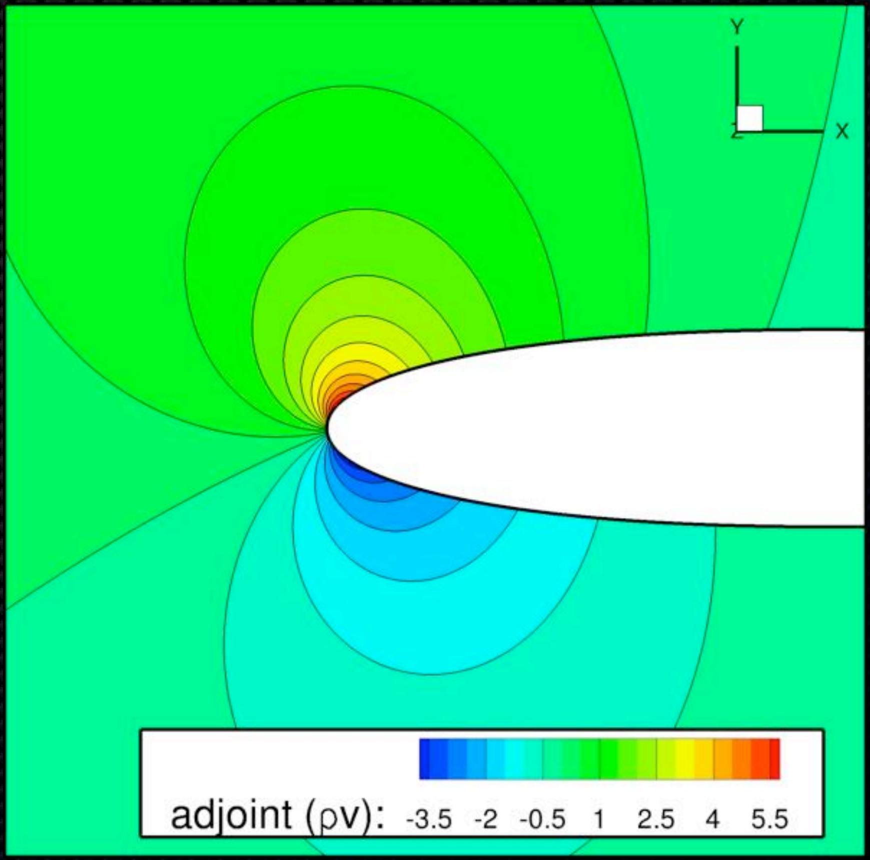
- A scheme is dual consistent if the associated discrete dual (or adjoint) problem is a consistent discretization of the continuous adjoint problem
    - ➡ Dual consistency requires suitable boundary conditions and a particular numerical integration method for the functional
    - ➡ Can lead to superconvergence of functionals
    - ➡ Can lead to much better error estimates based on adjoint-weighted residuals (than dual inconsistent schemes)

➡ Hicken, J.E., and Zingg, D.W., The Role of Dual Consistency in Functional Accuracy: Error Estimation and Superconvergence, 20th AIAA CFD Conference, June 2011.

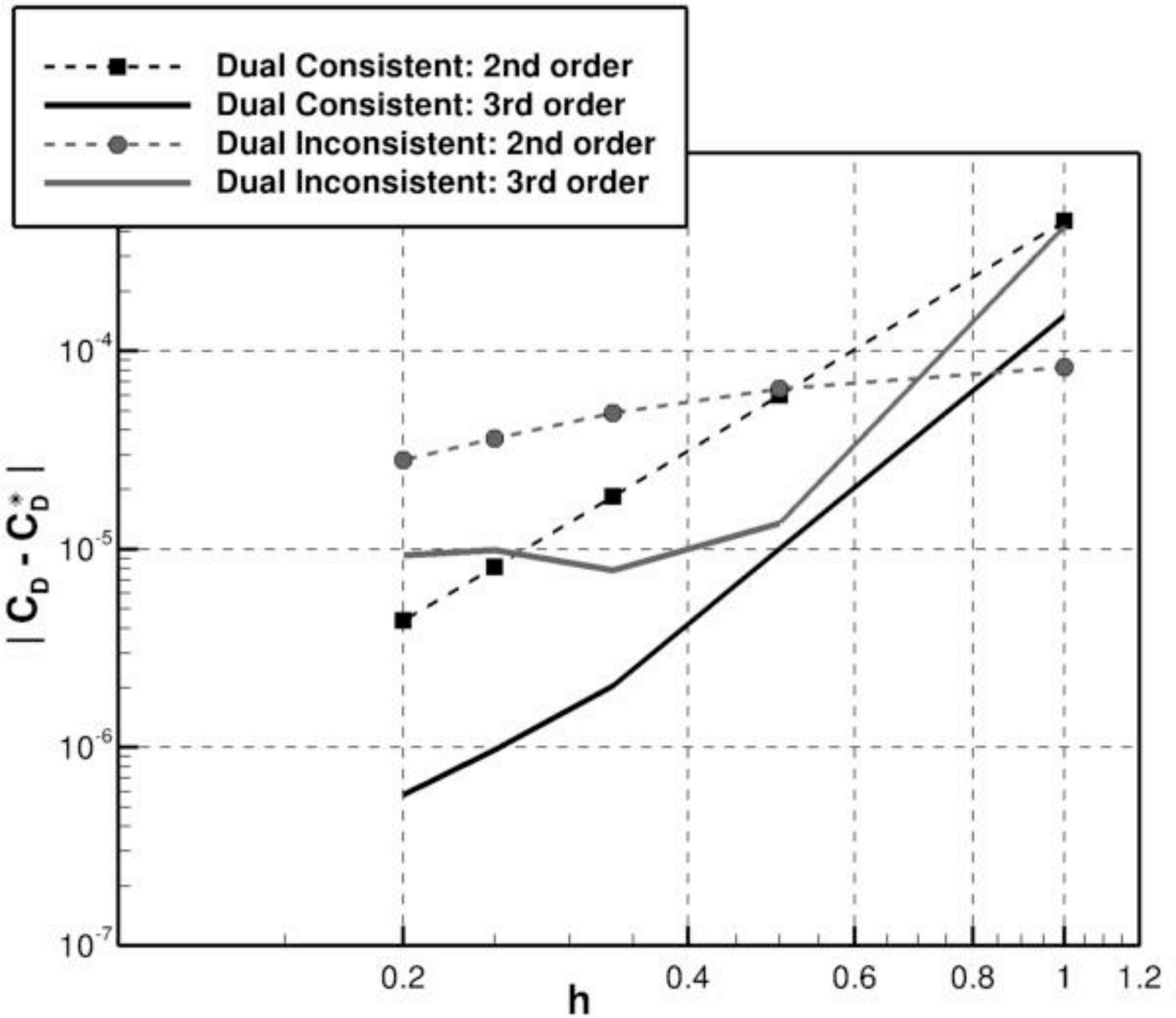
Dual Consistency

Example: adjoint field shows oscillations in dual inconsistent case



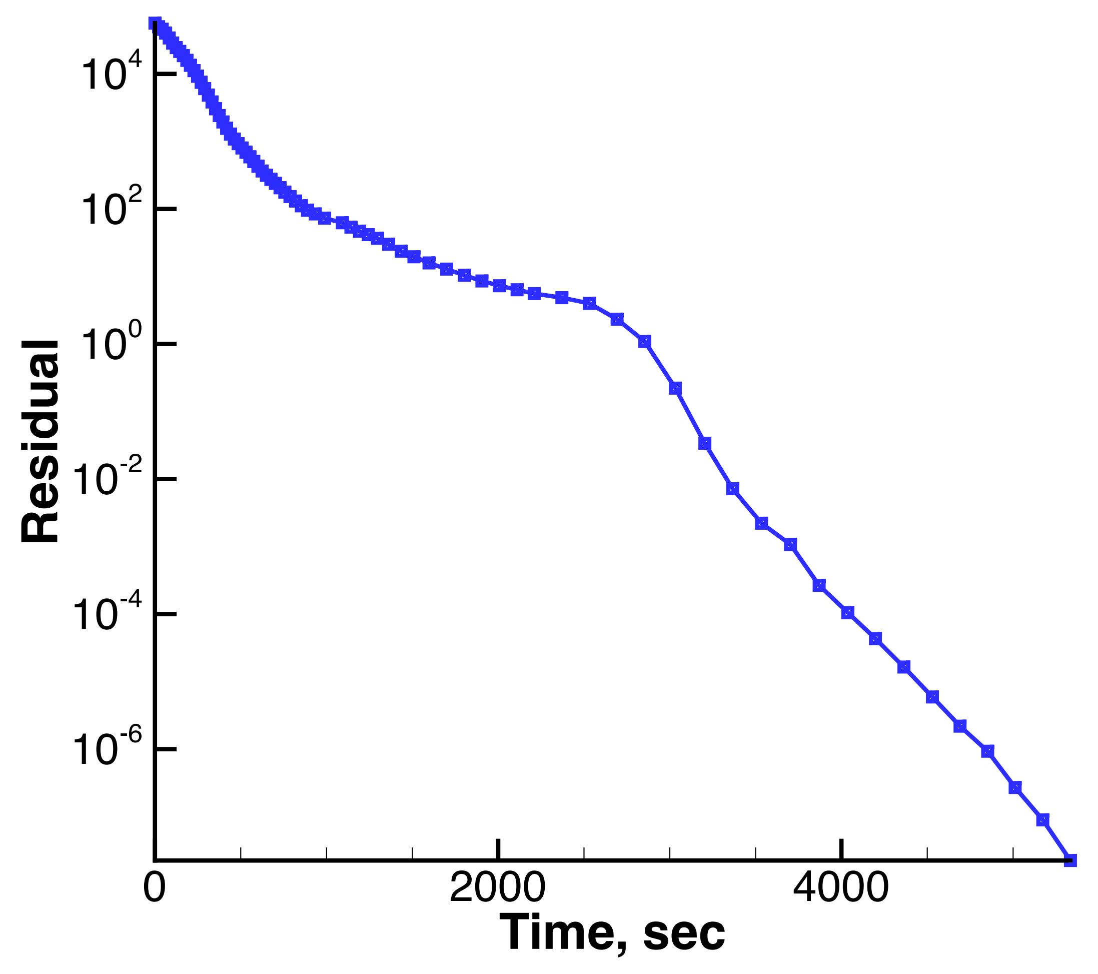


Results for ONERA M6 wing

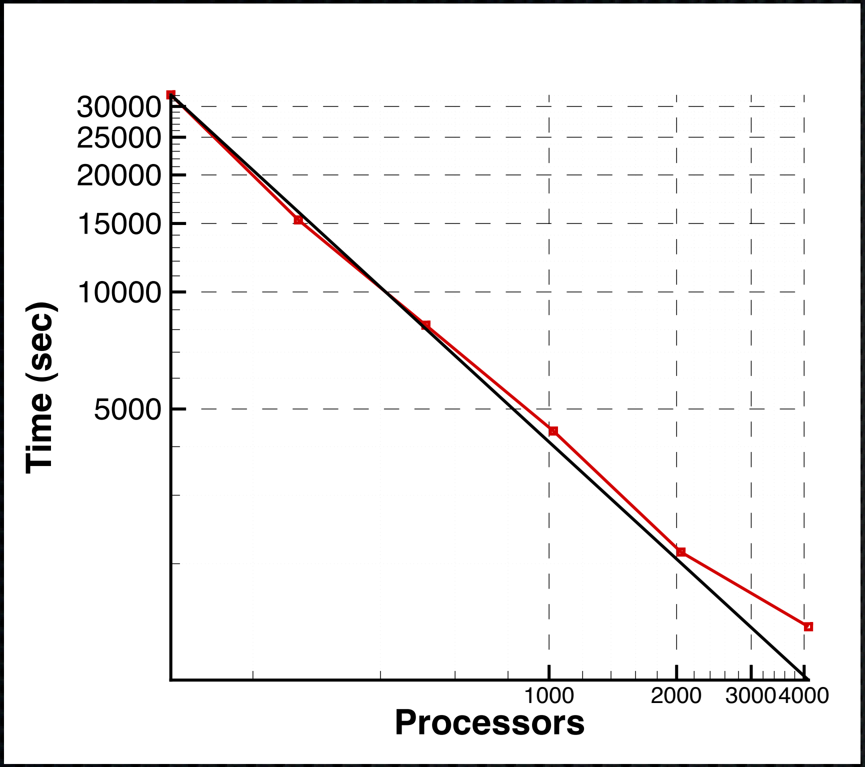


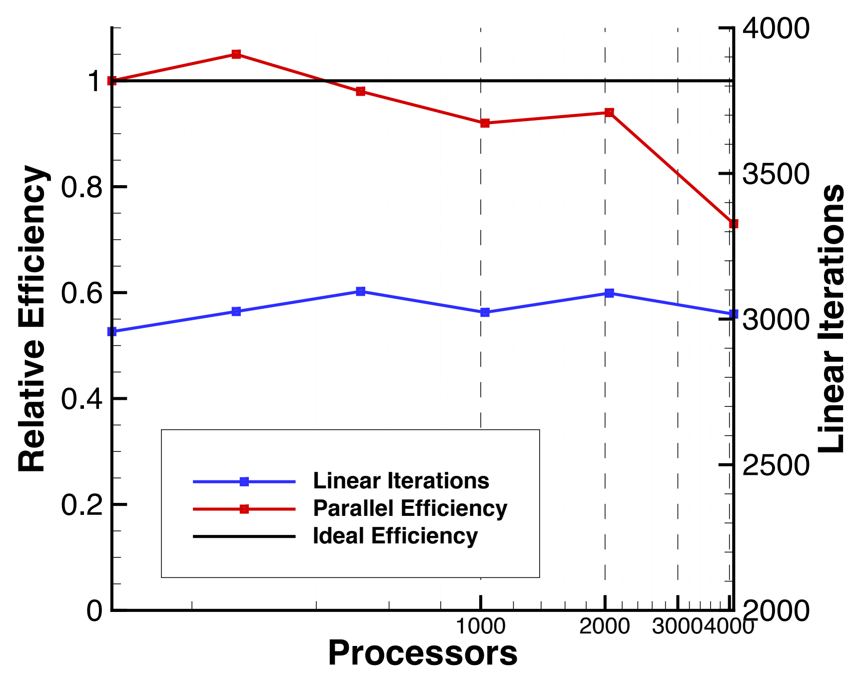
Turbulent Flow Solver

ONERA M6 wing: M=0.8395, alpha=3.06 degrees
Re=11.72 million, 15.1 million mesh nodes, 128 processors



Parallel Scalability (RANS)

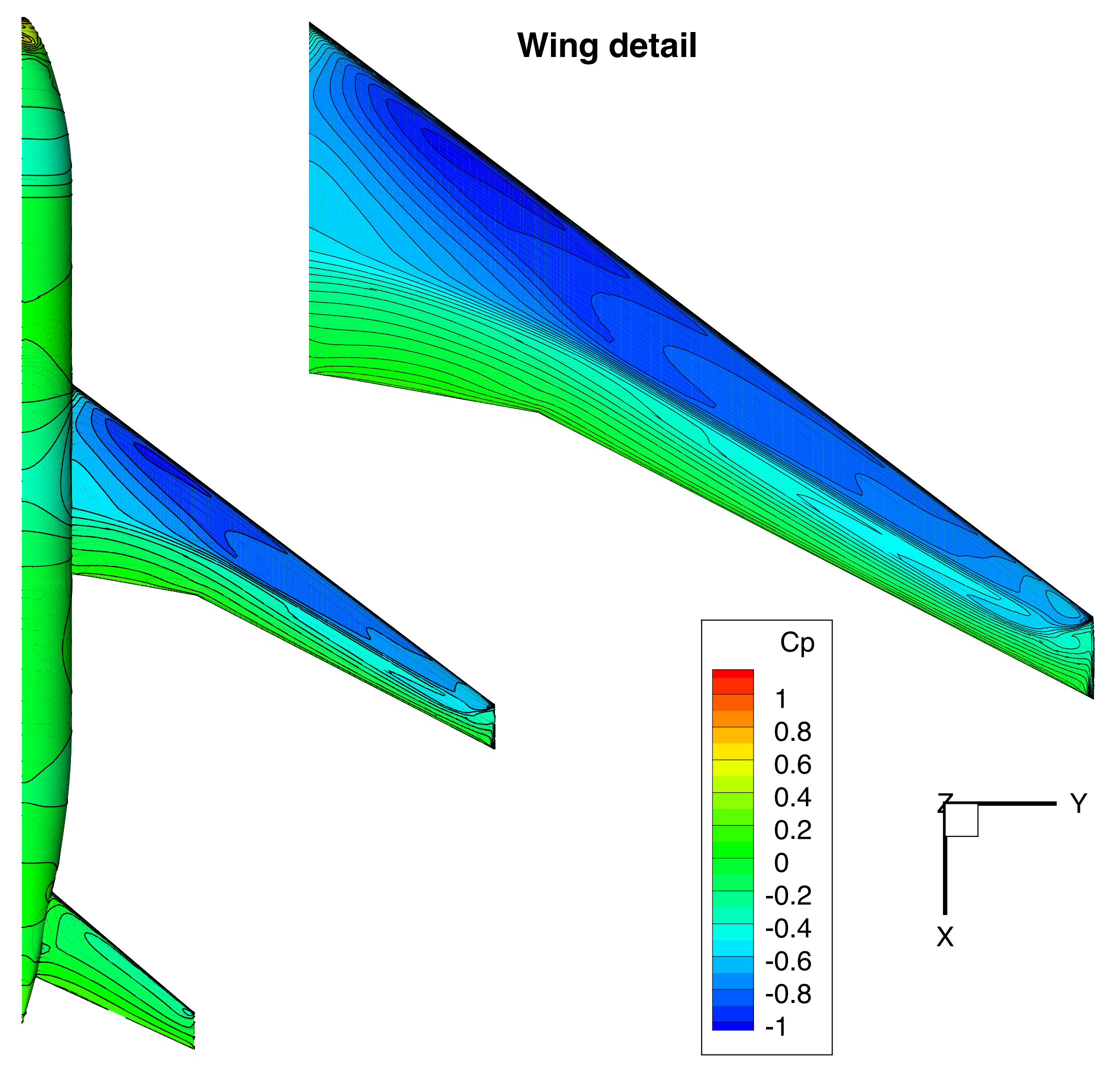




- 12 order residual reduction in 23 mins on 4096 processors (40 million mesh nodes)

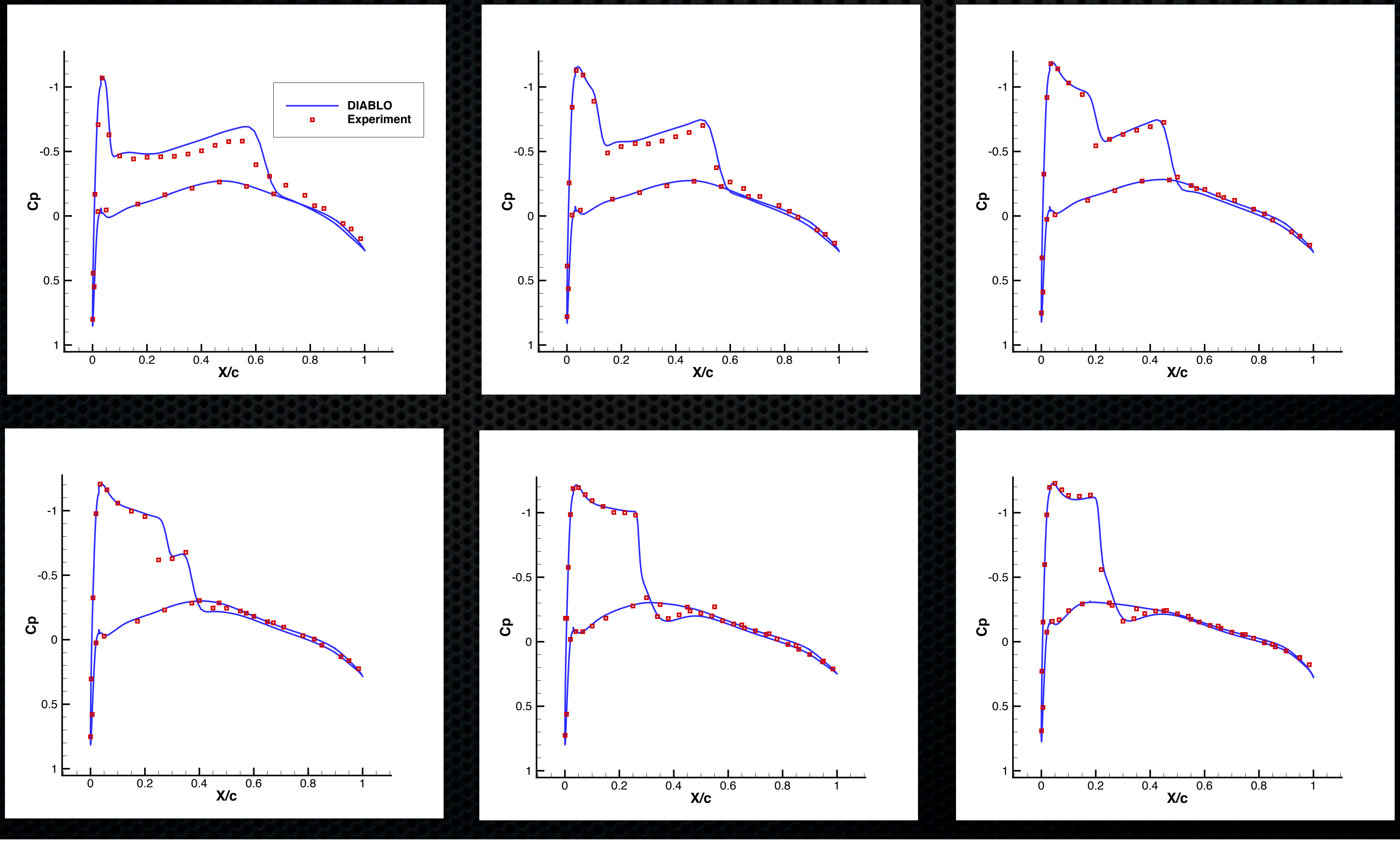
Turbulent Flow Solver

Common Research Model: M=0.85, C_L=0.5
Re=5 million, 10.1 million mesh nodes



Turbulent Flow Solver

ONERA M6 wing: M=0.8395, alpha=3.06 degrees
Re=11.72 million, 15.1 million mesh nodes
20, 44, 65, 80, 90, 95 percent span

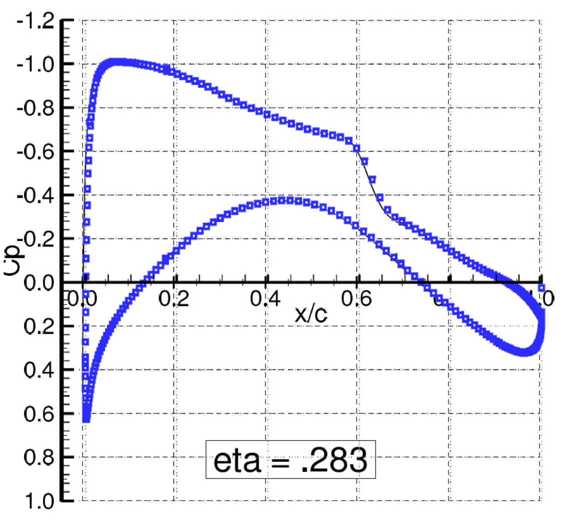


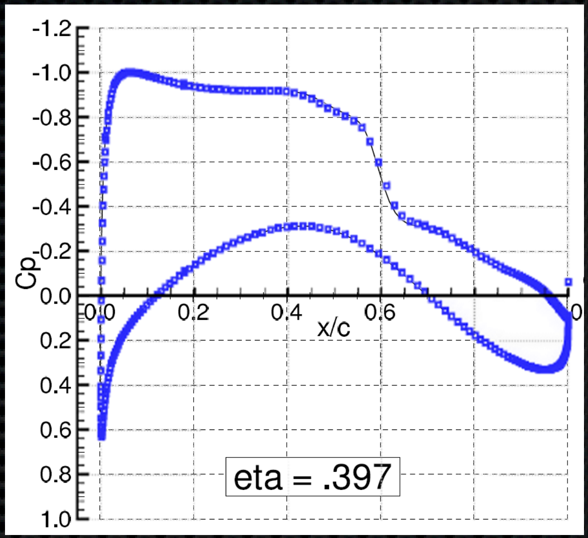
Comparison with OVERFLOW

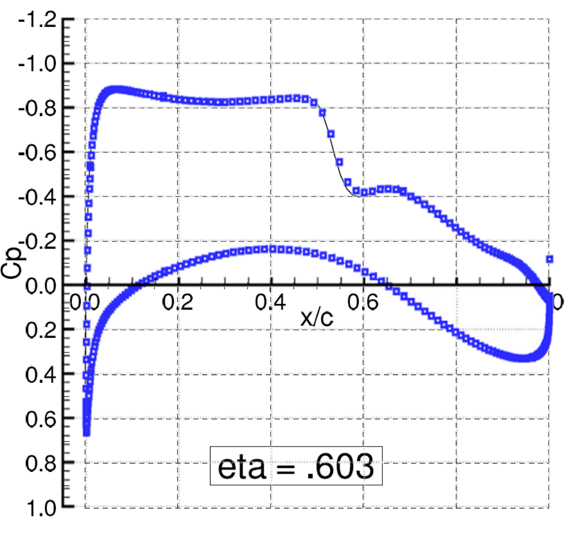
CRM wing-body-tail: M=0.85, C_L=0.5, Re=5 million

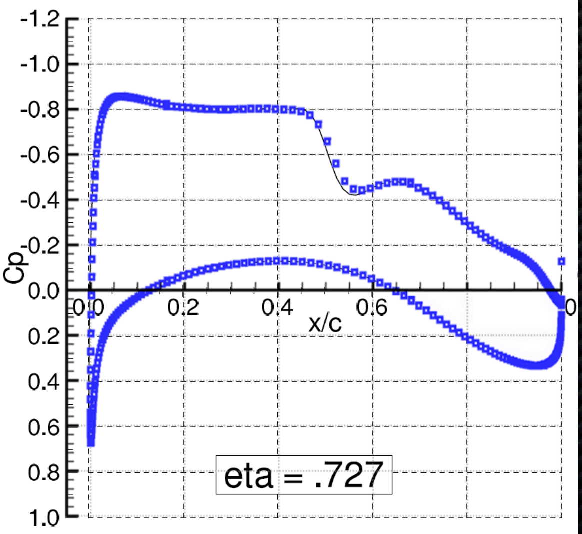
34 million mesh nodes

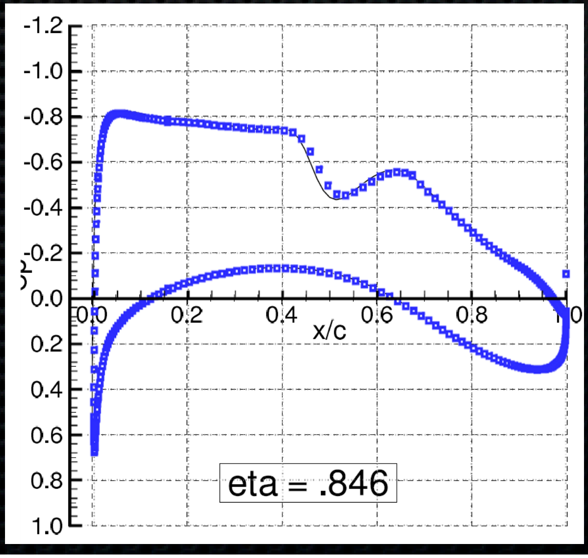
Diablo in blue, OVERFLOW in black

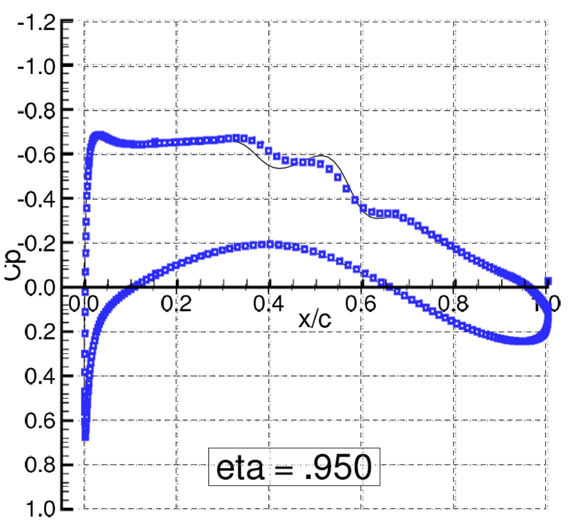










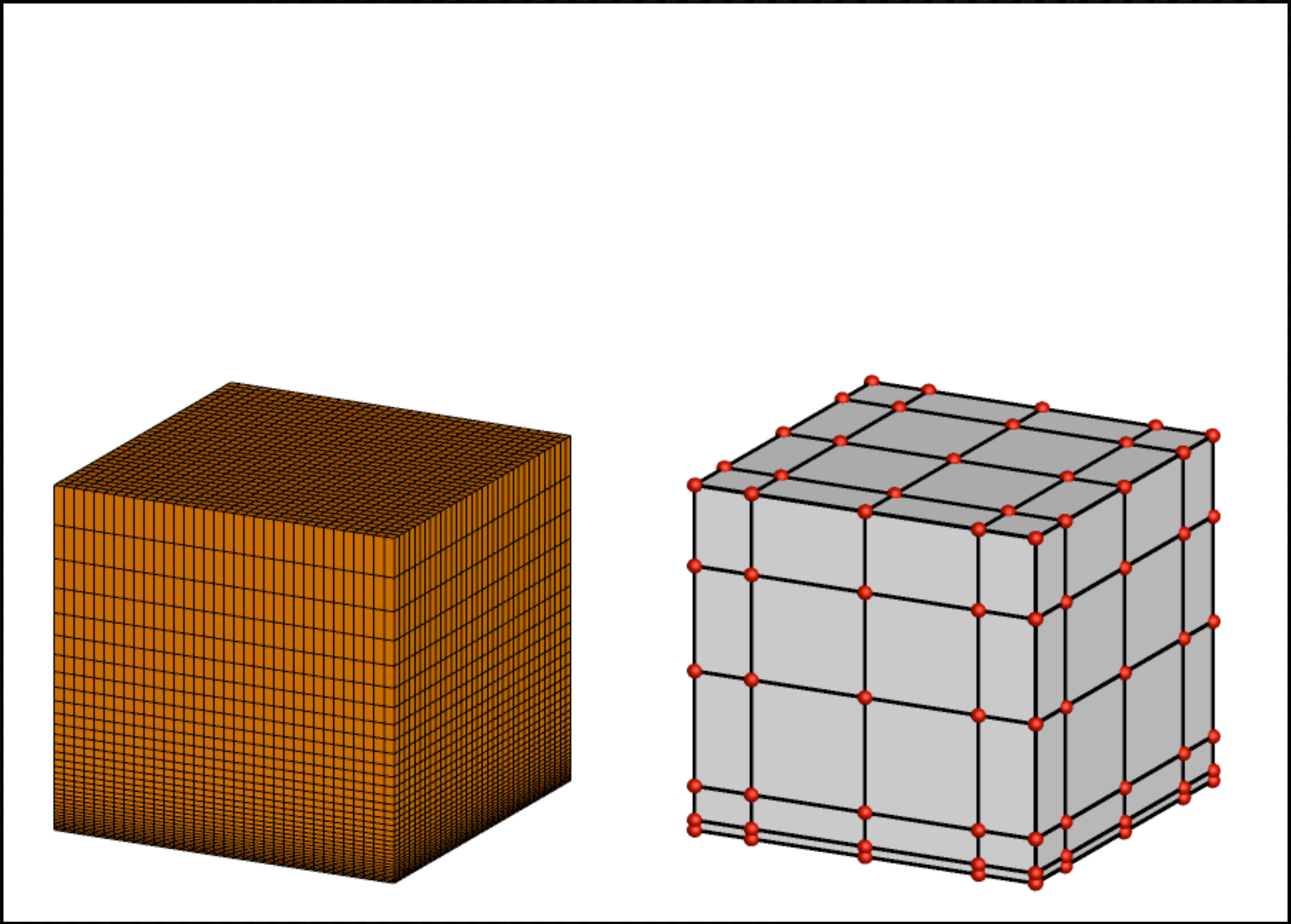


INTEGRATED GEOMETRY PARAMETERIZATION AND MESH MOVEMENT

- Must provide flexibility for large shape changes with a modest number of design variables
  - B-spline patches represent surfaces
  - B-spline control points are design variables
- Mesh movement must maintain quality through large shape changes
  - through tensor products, B-spline volumes map a cube to an arbitrary volume with the appropriate topology
  - can be arbitrarily discretized in the cube domain to create a mesh
  - B-spline volume control points can be manipulated to move the mesh in response to changes in the surface control points
  - efficiently generates a high quality mesh

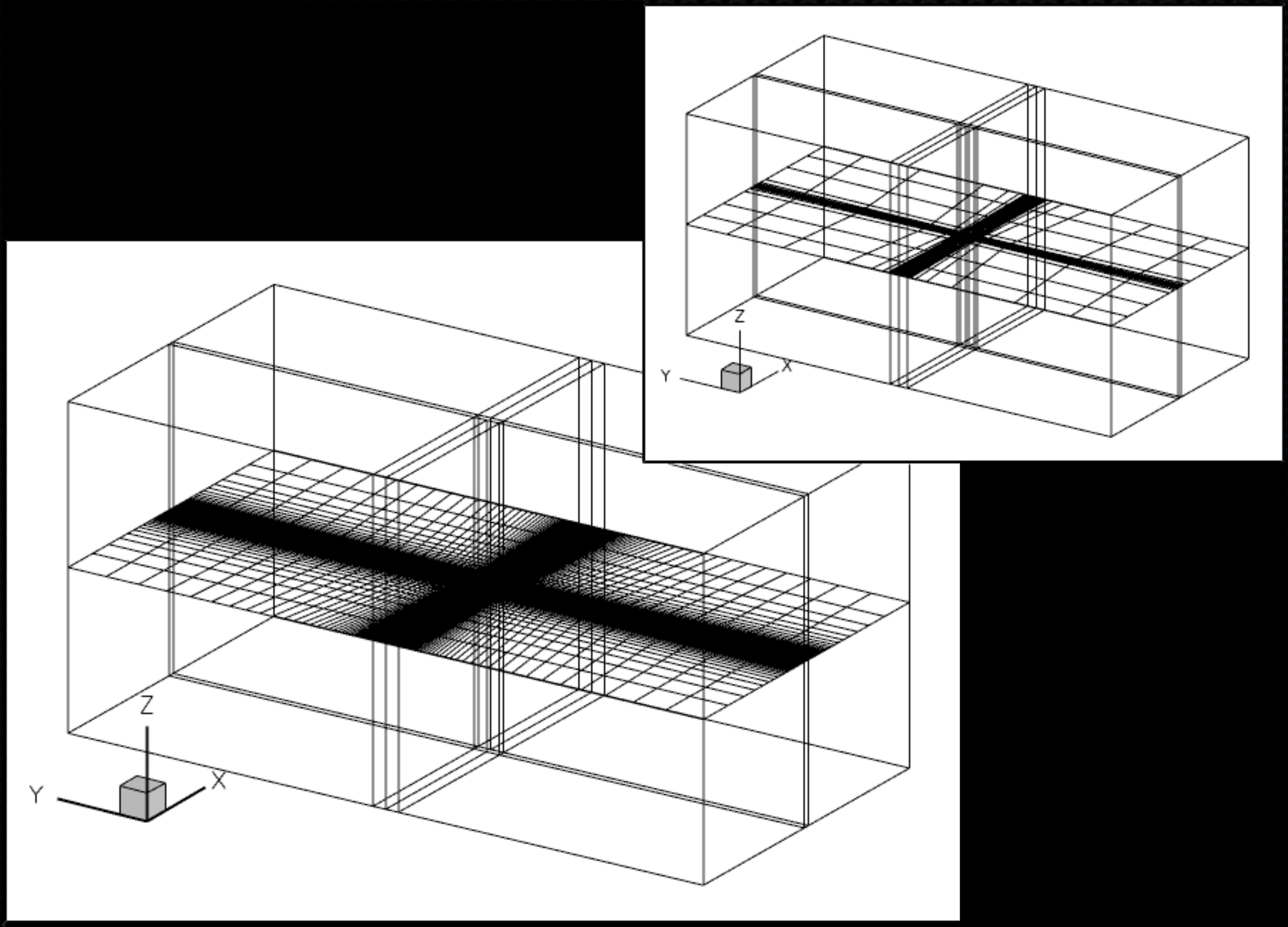
➡ Hicken, J.E., and Zingg, D.W., Aerodynamic Optimization Algorithm with Integrated Geometry Parameterization and Mesh Movement, AIAA Journal, Vol. 48, No. 2, 2010

B-spline Volumes



Mesh Movement Example

flat plate to blended-wing body: ≈ 1 million nodes



DISCRETE-ADJOINT GRADIENT COMPUTATION

- Cost independent of the number of design variables
- Efficient if the number of design variables exceeds the number of constraints
- Hand linearization complemented by judicious use of the complex step method for difficult terms
- Adjoint equation solved by parallel Schur-preconditioned modified Krylov method GCROT(m,k)

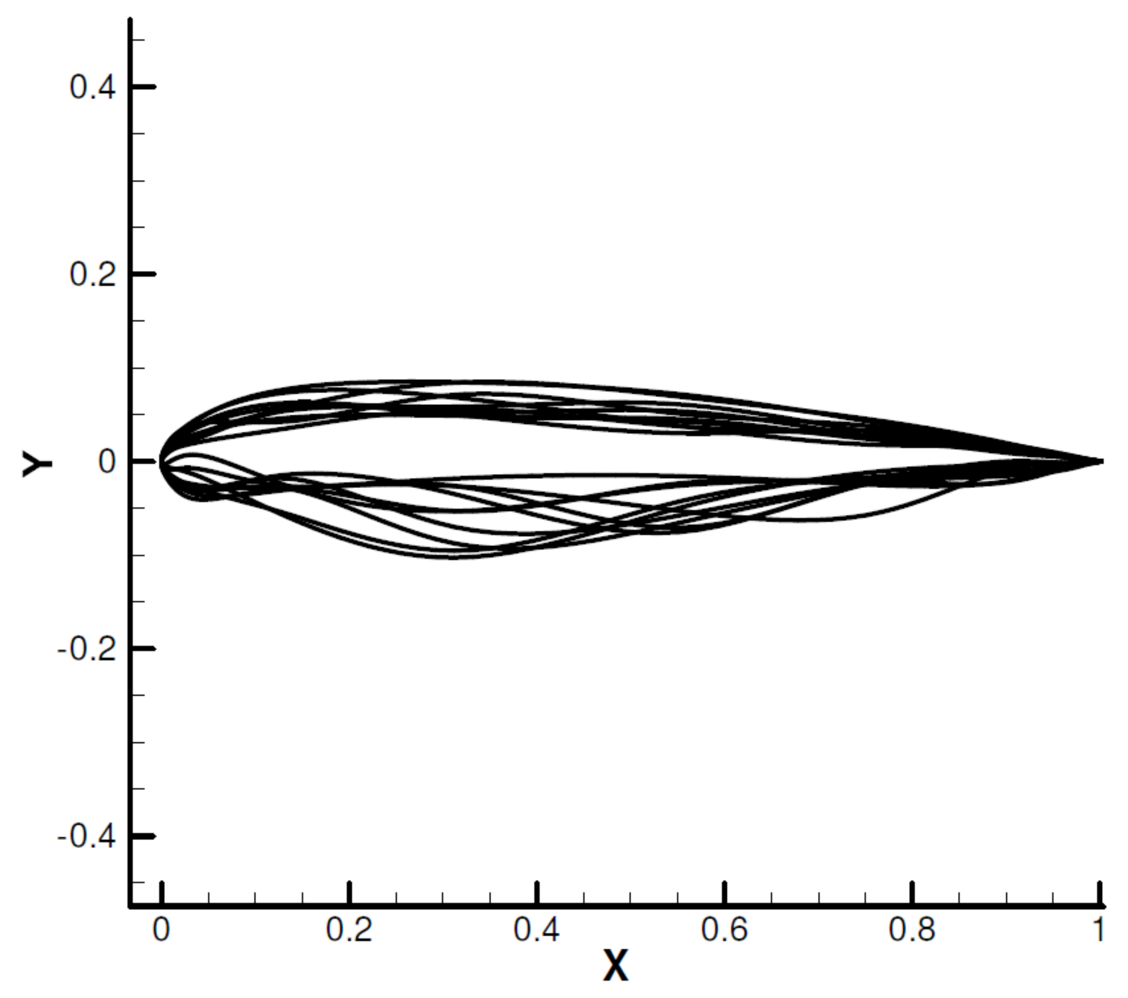
➡ Hicken, J.E., and Zingg, D.W., A Simplified and Flexible Variant of GCROT for Solving Nonsymmetric Linear Systems, SIAM Journal on Scientific Computing, Vol. 32, No. 3, March 2010

Optimization Algorithms

- Gradient-based algorithm (SNOPT) - converges to a local minimum
- Multi-start Sobol: initial guesses based on Sobol sequences cover the design space in a deterministic manner (sampling in linear feasible region)
- Hybrid method: combination of genetic algorithm, Sobol sampling, and gradient-based algorithm (SNOPT is run on each chromosome)
- Genetic algorithm

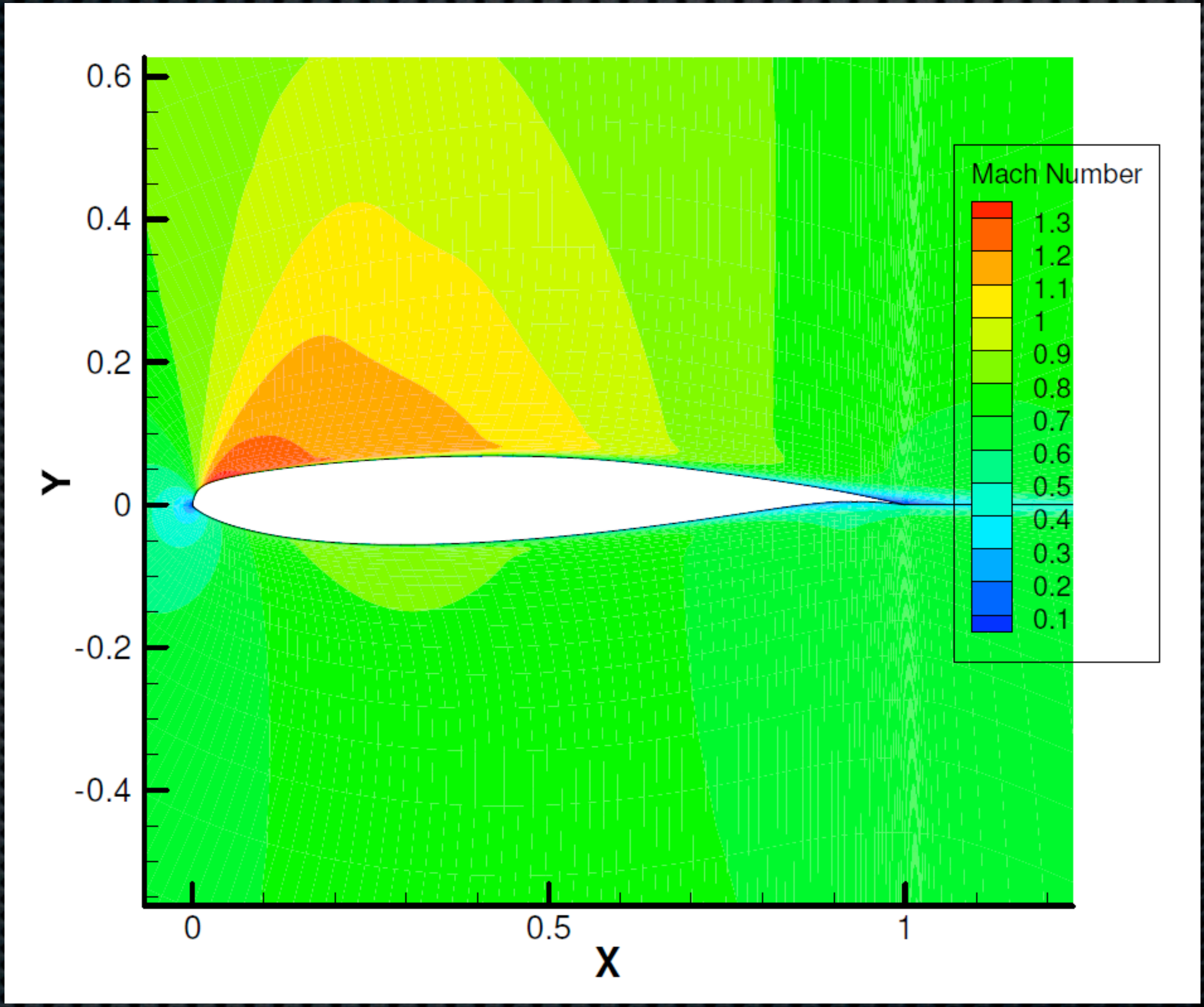
Multimodality in 2D (RANS)

Multistart procedure for 2D airfoil optimization (transonic lift-constrained drag minimization, 6 DVs)



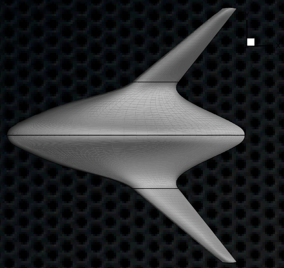
Multimodality?

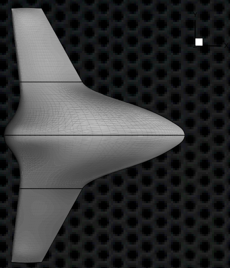
A unique global optimum in 2D - no local optima!

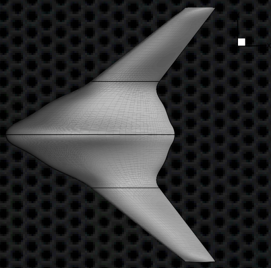


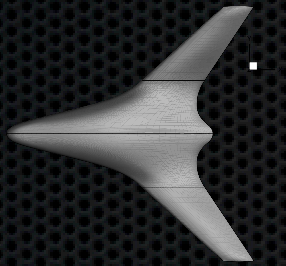
Multimodality

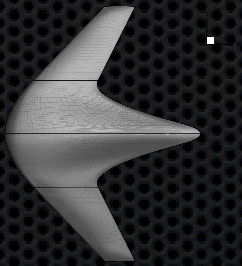
- BWB optimization: 8 local minima from 34 initial geometries using GB-MS

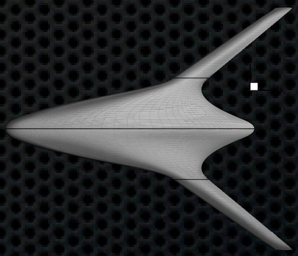

(a) Local Optimum 1

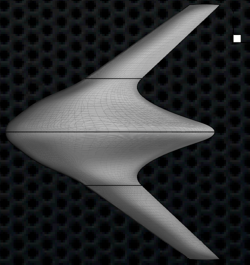

(b) Local Optimum 2

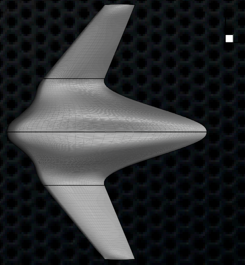

(c) Local Optimum 3


(d) Local Optimum 4


(e) Local Optimum 5

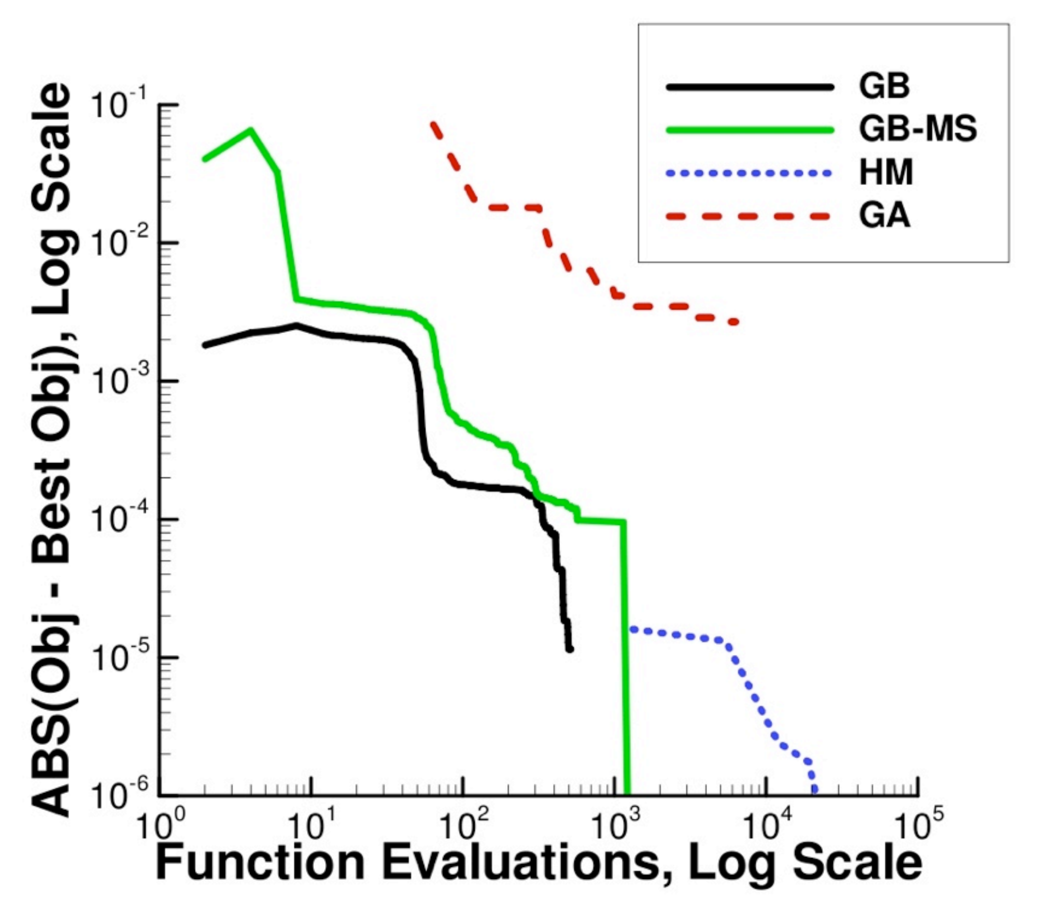

(f) Local Optimum 6


(g) Local Optimum 7


(h) Local Optimum 8

Convergence to the global minimum

- GB - gradient-based
- GB-MS - gradient-based multi-start
- HM - hybrid method
- GA - genetic algorithm

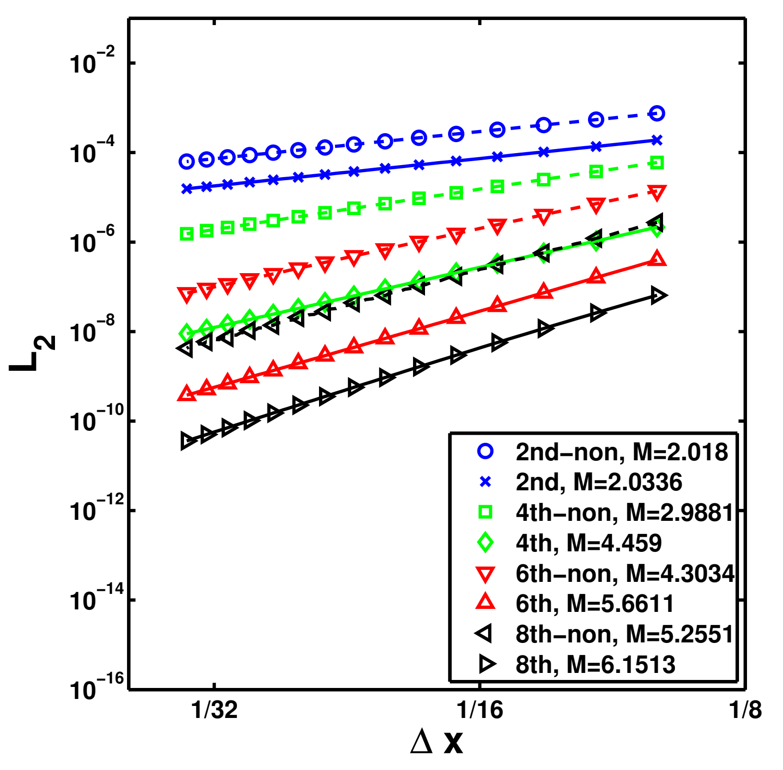


PROGRESS

- Higher-order methods in space and time
- Laminar-turbulent transition prediction
- Large eddy simulation (LES)
- Two-level free-form deformation
- RANS-based aerodynamic shape optimization
- Aerostructural analysis

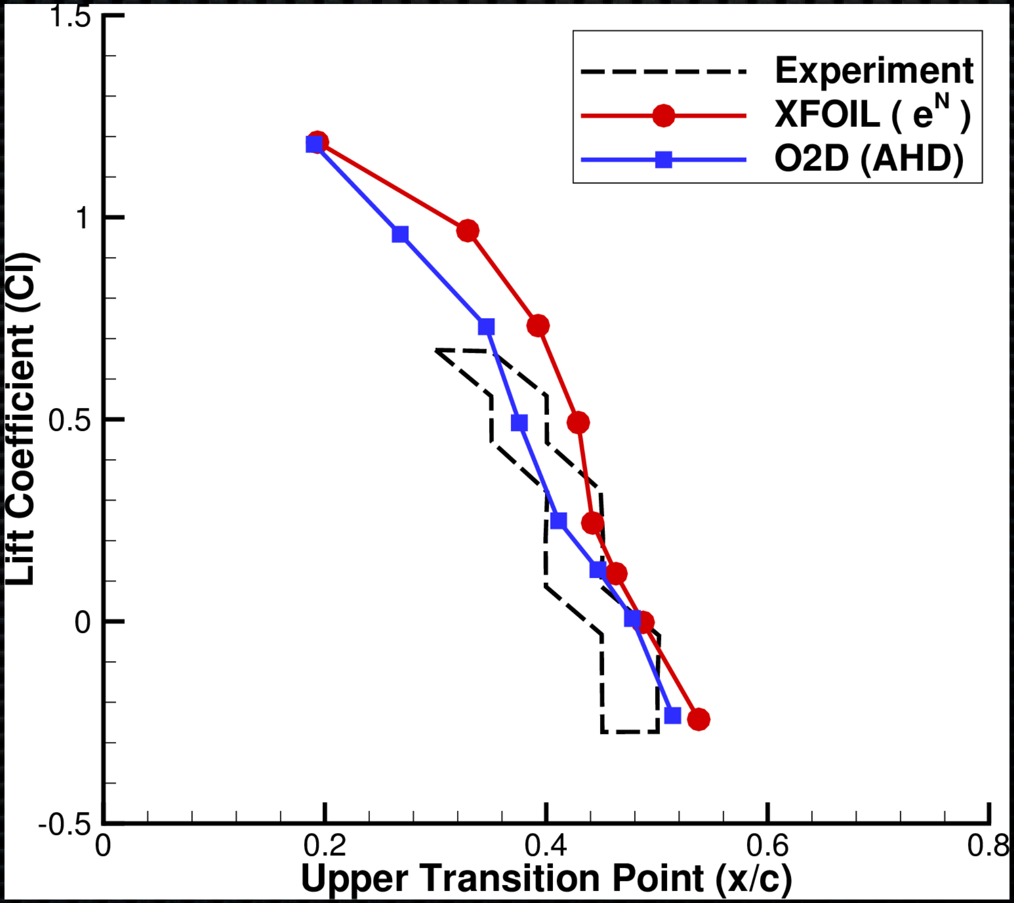
Higher-order methods in space and time

- high-order implicit Runge-Kutta methods in time
- high-order SBP operators for first and second derivatives
- maximally-compact-stencil operators for second derivative with variable coefficients



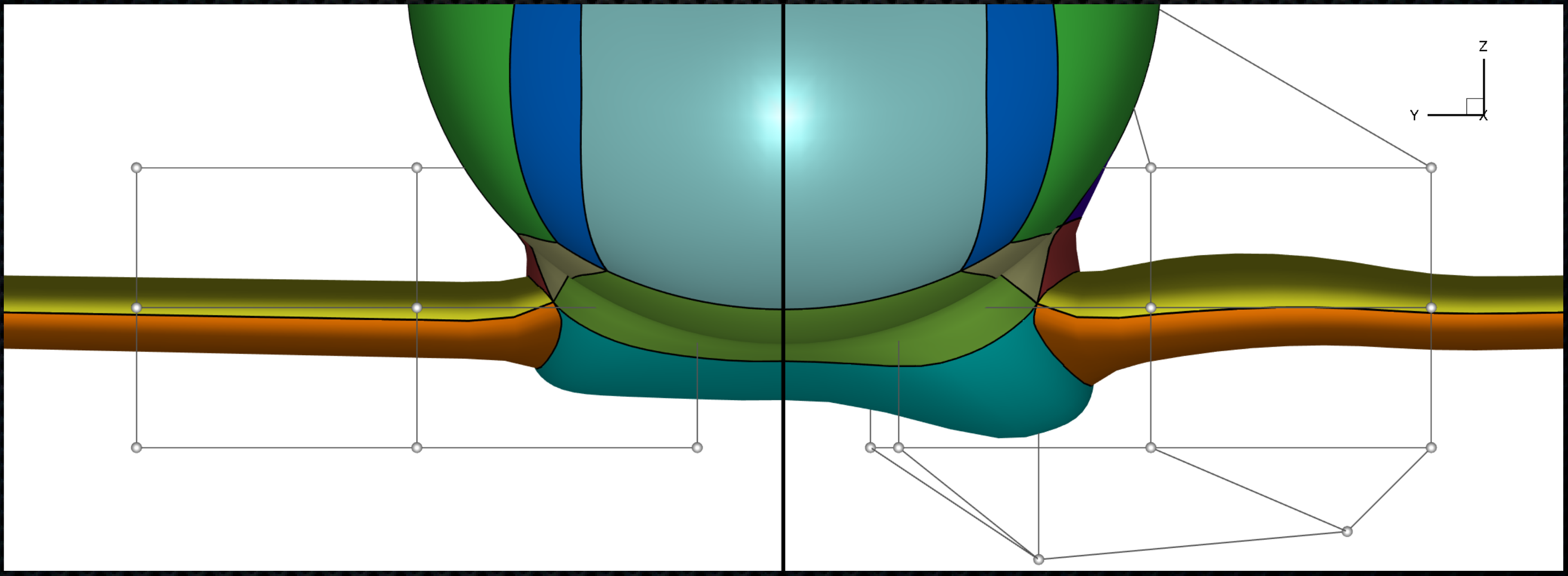
Laminar-turbulent transition prediction

- simple criterion
- sample comparison with experiment and XFOIL



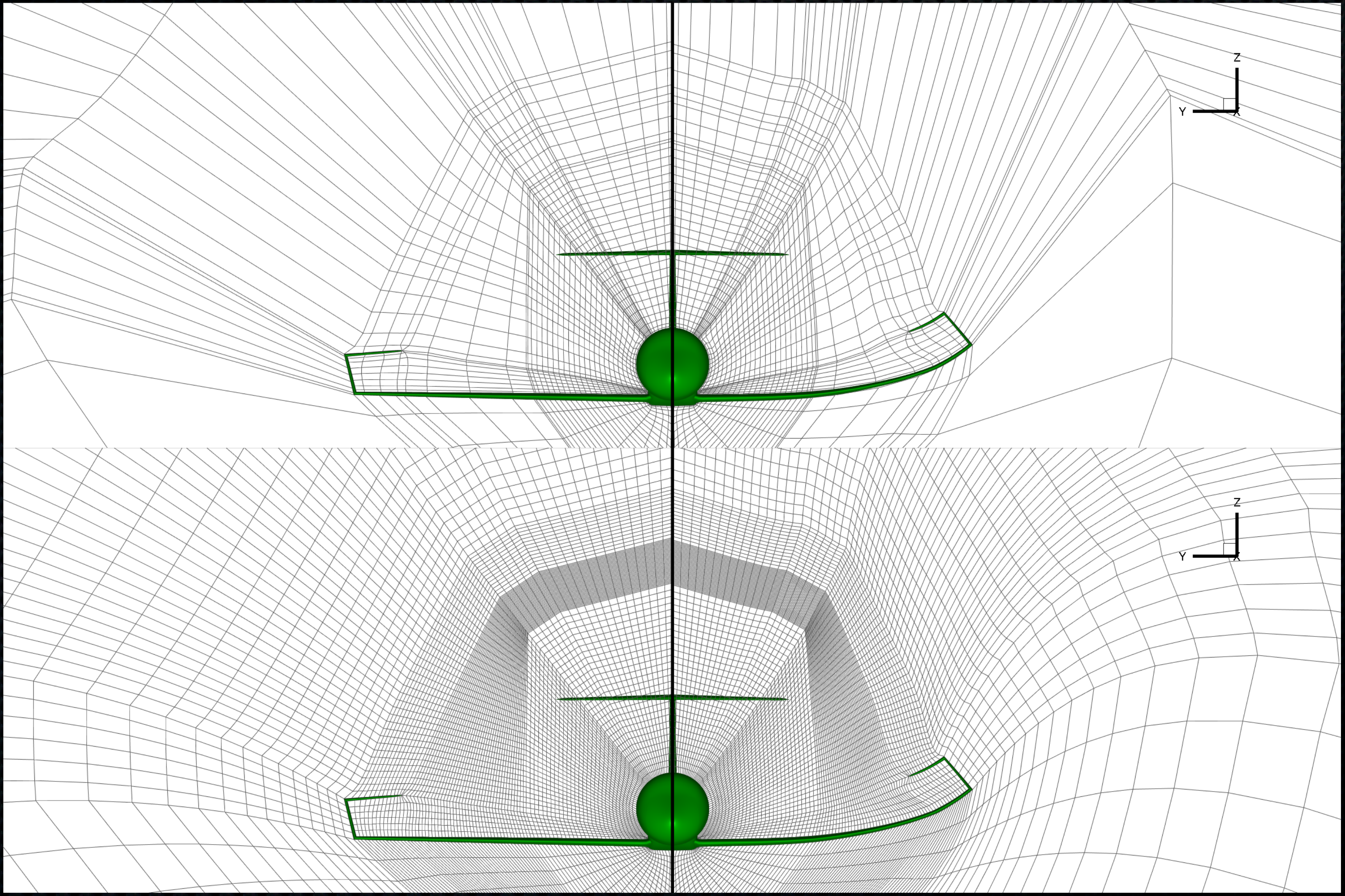
Geometry Parameterization

- Two-level free-form deformation (FFD)
- FFD controls the B-spline control points
- Retains integrated geometry/mesh



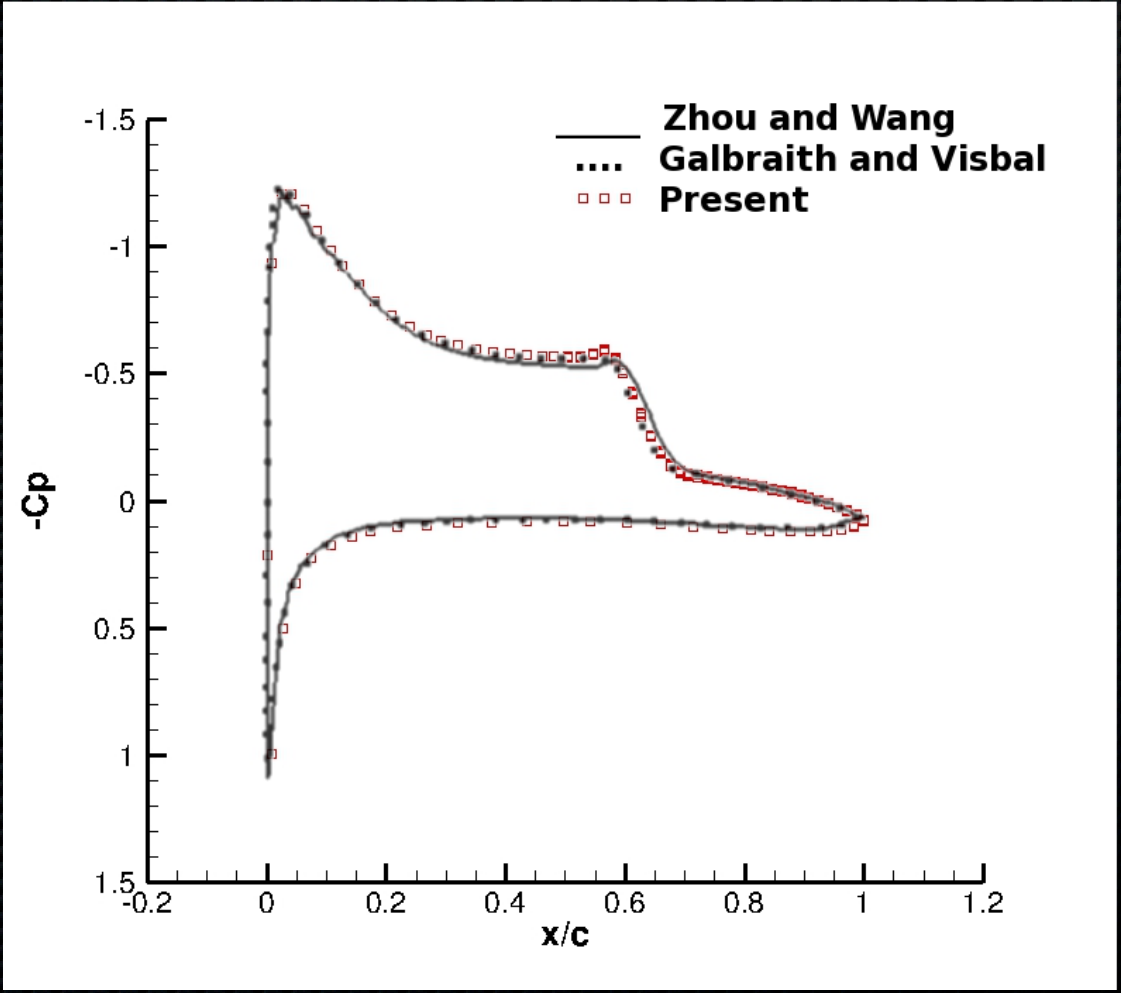
Two-level free-form deformation

- B-spline volume based mesh movement



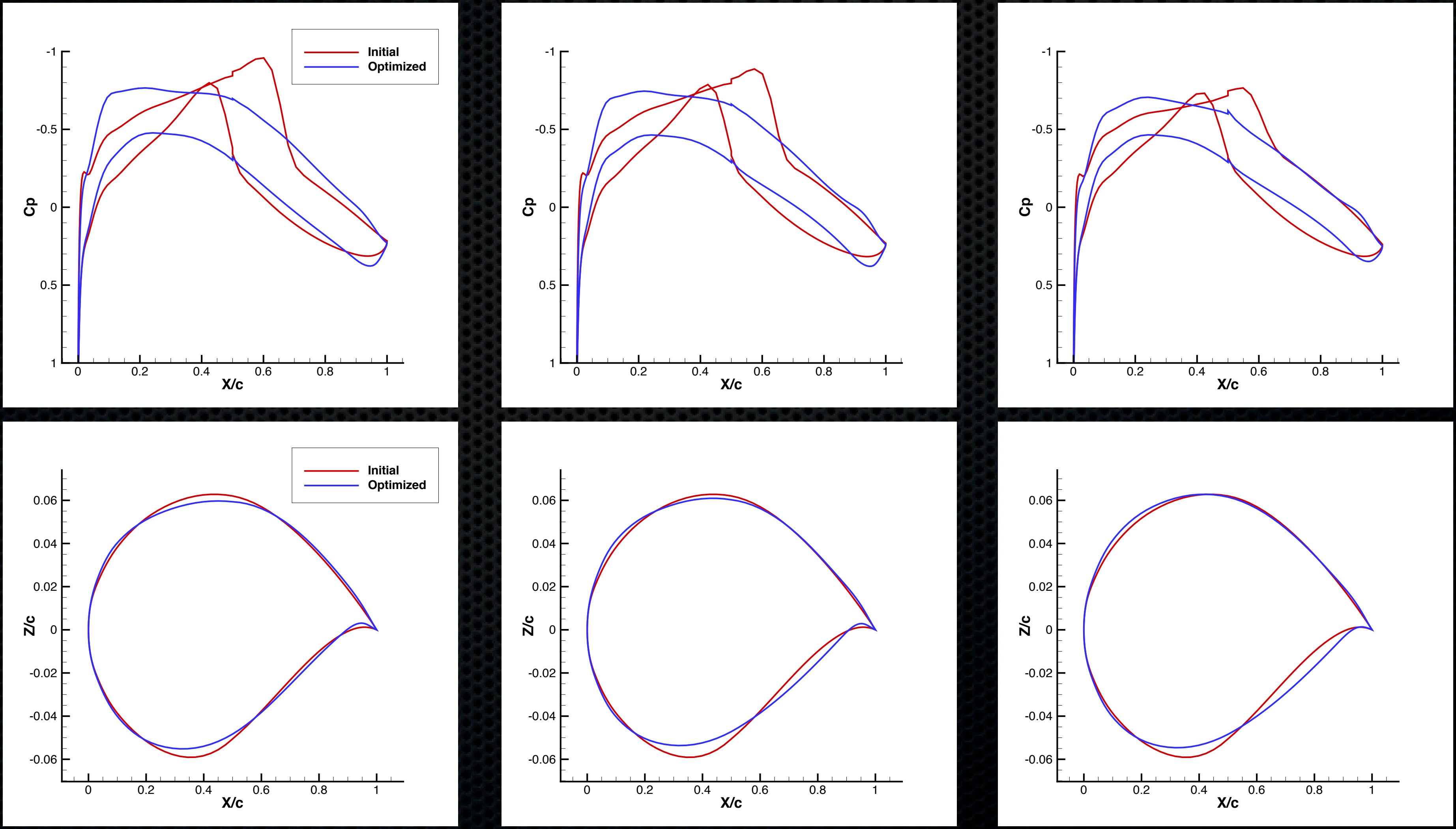
Large-eddy simulation results

- transitional flow around SD7003 airfoil at a Reynolds number of 60,000
- long laminar separation bubble exists that is difficult for a RANS solver



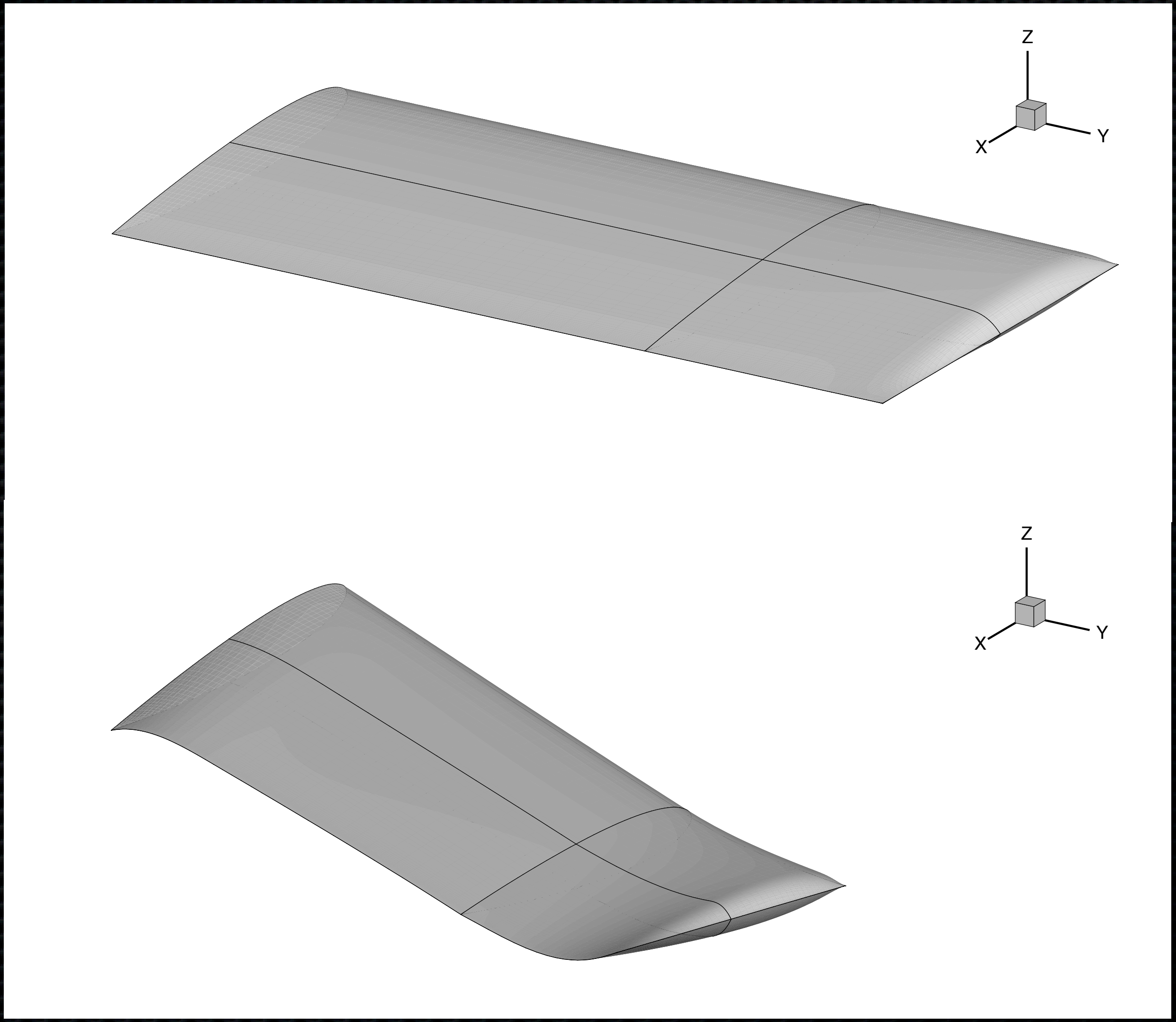
RANS-based aerodynamic shape optimization

- drag minimization of a wing at M=0.8, Re=6.5 million
- drag coefficient reduced by 15.7%
- 2%, 44%, and 65% span shown



RANS-based aerodynamic shape optimization

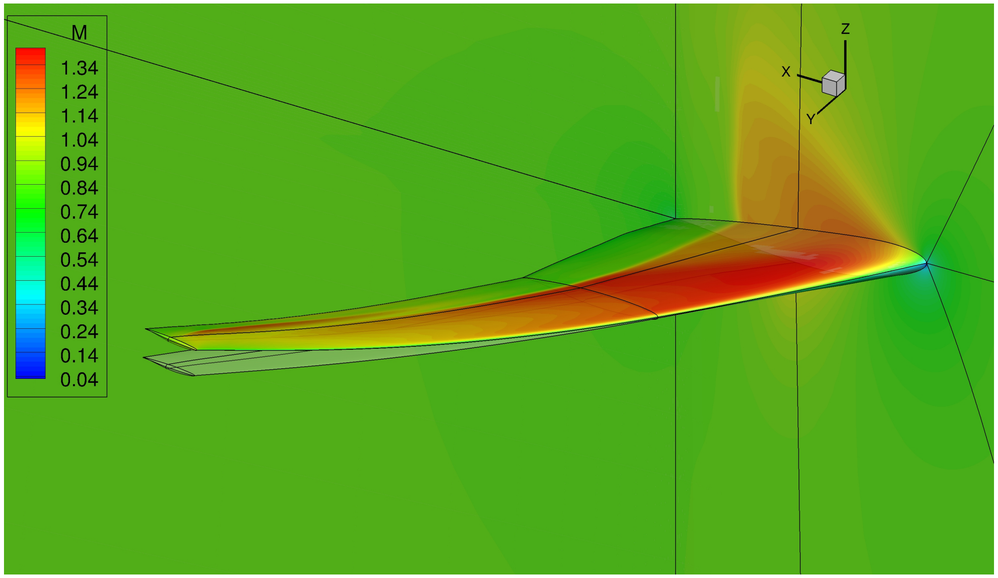
- drag minimization based on planform variables, including dihedral
- 41% reduction in drag coefficient



Aerostructural analysis

CRM Wing Example

Results: Wing Deflections & Performance



- Undeflected wing: $C_L = 0.481$, $C_D = 0.0132$
- Deflected wing $C_L = 0.50$, $C_D = 0.0139$
- A 5% deflection at the wingtip
- A slight washout angle (negative twist)
- Time for flow solution: 4889*sec* (processors *not* load balanced)
- Time for structural solution: 0.67*sec*

Future Work

- numerous research projects underway toward efficient high-fidelity aerostructural optimization including transition prediction
- e.g. incorporating laminar-turbulent transition prediction into 3D optimization, monolithic aerostructural optimization, higher-order methods, global optimization algorithms
- efficiency remains a major issue, especially given the need for global optimization
- LES (unsteady) optimization?
- problem formulation is a major topic: brute force is not feasible
- http://goldfinger.utias.utoronto.ca/dwz/