aerospacedesignlab

Introduction to SU^2

THE OPEN-SOURCE CFD CODE

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INTRODUCTION

WHY SU^2?

SUPERSONIC AIRCRAFT DESIGN

UNSTEADY DESIGN

VERIFICATION AND VALIDATION

CONCLUSIONS

The Open-Source CFD Code

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SU^2

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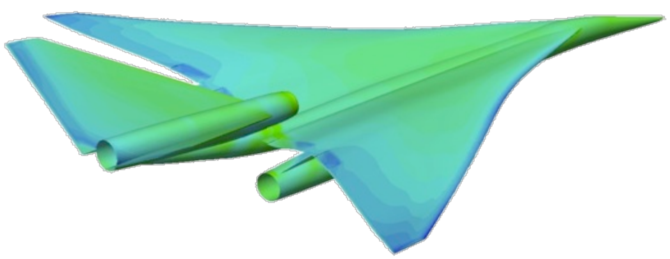
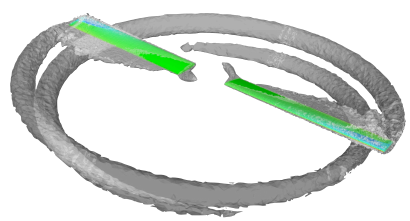
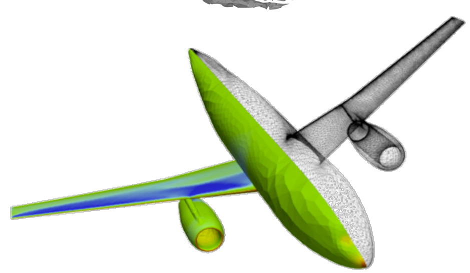
Introduction
Our objective

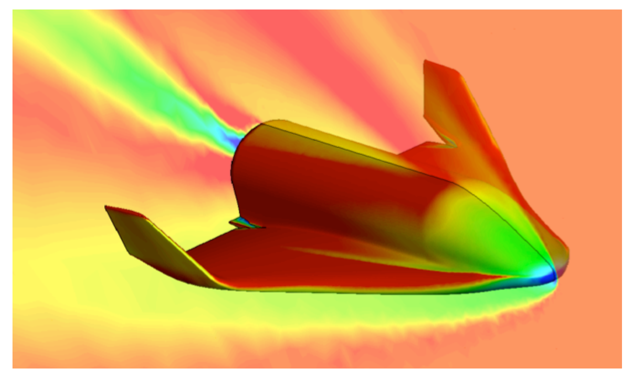
- **Computational analysis tools have revolutionized the way we design aerospace systems**.
- Unfortunately, **most established codes are close, proprietary, unavailable for some potential users, or prohibitively expensive**.
- The SU^2 team looks forward to making **CFD analysis and design freely available as open-source software, involving everyone in its creation, enhancement, and rapid development.**



NASA N+2 Supersonics Program (2013)







SOAR - S3 Swiss Space Systems (2014)

Introduction
Aerospace Design Lab @ Stanford Univ. Aero & Astro

- Our lab **has a long tradition of creating numerical tools for the analysis and design/optimization** of problems governed by the equations of fluid flow. We are interested in:
    1. Complex configurations of industrial interest.
    2. Multi-disciplinary optimization problems.
    3. Numerical methods in CFD.
    4. In university laboratory we are also very concerned about minimizing the required effort to add new capabilities.

- We **fully endorse the spirit of the open-source movement**: we are happy to support the efforts in the community adding capabilities that we would not have the chance/time/resources to add ourselves. Everyone benefits in this way.

Introduction
Optimal shape design

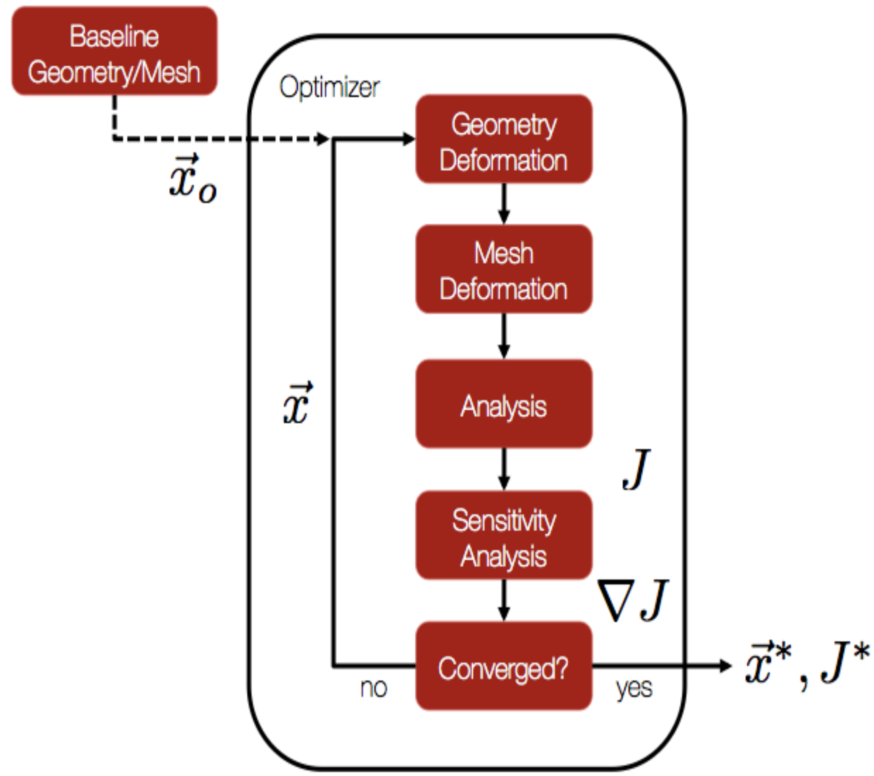
- **Optimal Shape Design** (OSD) is concerned with finding the optimal shape for an object or surface that **improves its performance**

- In aeronautics, aerodynamic performance typically depends on the shape of the vehicle or body, in **complex and often difficult to predict ways**

- Adjoint gradient-based optimization:
  - **Continuous** adjoint methodology to achieve cost-independence wrt number of design parameters
  - Analytic expression for the **gradient as a surface integral**.
  - No memory or time overhead compared with the direct solver.

$\vec{x}$ vector of design variables

J objective/constraint function(s)



CFD gives us J (lift, drag, etc.), but how do we get ∇J efficiently?

Introduction
Objective of this talk

- **Mature design tools are not always available** for novel engineering concepts.
- There is a well-established "basic" theory and it is time to face **complex novel concepts**: do we have **sufficiently mature design tools**?
- The objective of this talk is to introduce SU^2 and show an overview of **challenges and opportunities for analysis and shape design methodologies**.

The Open-Source CFD Code

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High-performance and industrial-grade shape design.
For everyone.

Introduction
Computational tool: SU^2 suite

The SU^2 suite is an open-source collection of C++ based software tools to perform PDE analysis and solve PDE-constrained optimization problems.

SU^2 is under active development at Stanford University in the Aerospace Design Lab (ADL) of the Department of Aeronautics and Astronautics.

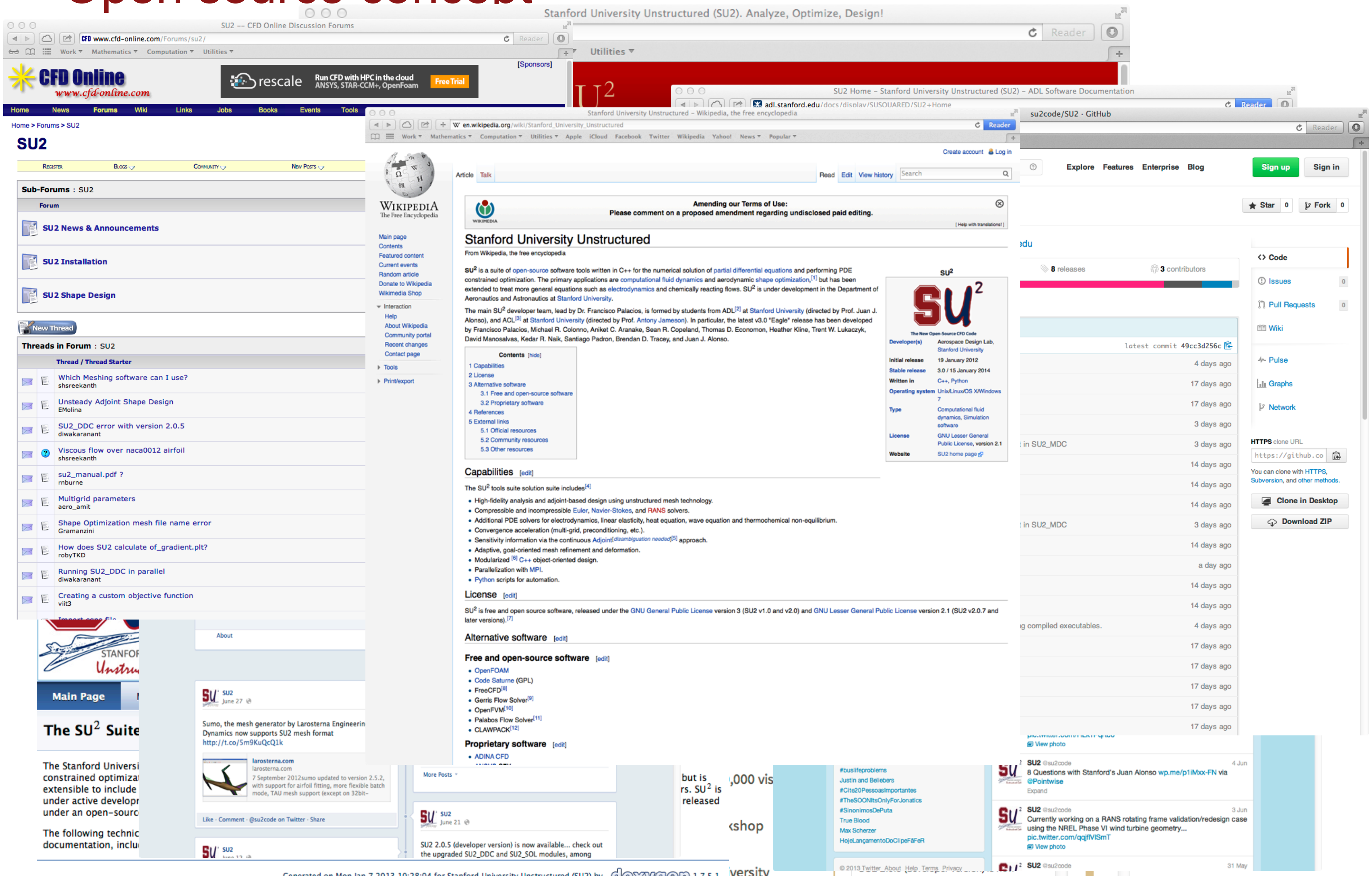
Web page with more than 90,000 visits (34% Europe, 30% USA, 11% China, 6% India, 19% others), more than 10,000 downloads since 2012.

http://su2.stanford.edu/

The Open-Source CFD Code

2012 SU^2 team, "Stanford University Unstructured (SU2): An open-source integrated computational environment for multi-physics simulation and design", AIAA Paper 2013-0287.
2013 SU^2 team, "Stanford University Unstructured (SU2): Open-source analysis and design technology for turbulent flows", AIAA Paper 2014-0243.

Introduction
Open source concept



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Why SU^2?
Software integration in aerodynamic shape design

Integrating existing software packages into coupled multi-physics analysis and design optimization solvers is a challenge.

The variety of approaches chosen for the independent components of the overall problem make it difficult to:

- Expand the range of applicability to situations not originally envisioned.
- Reduce the overall burden of creating integrated applications.
- Exploit fully-coupled approaches.

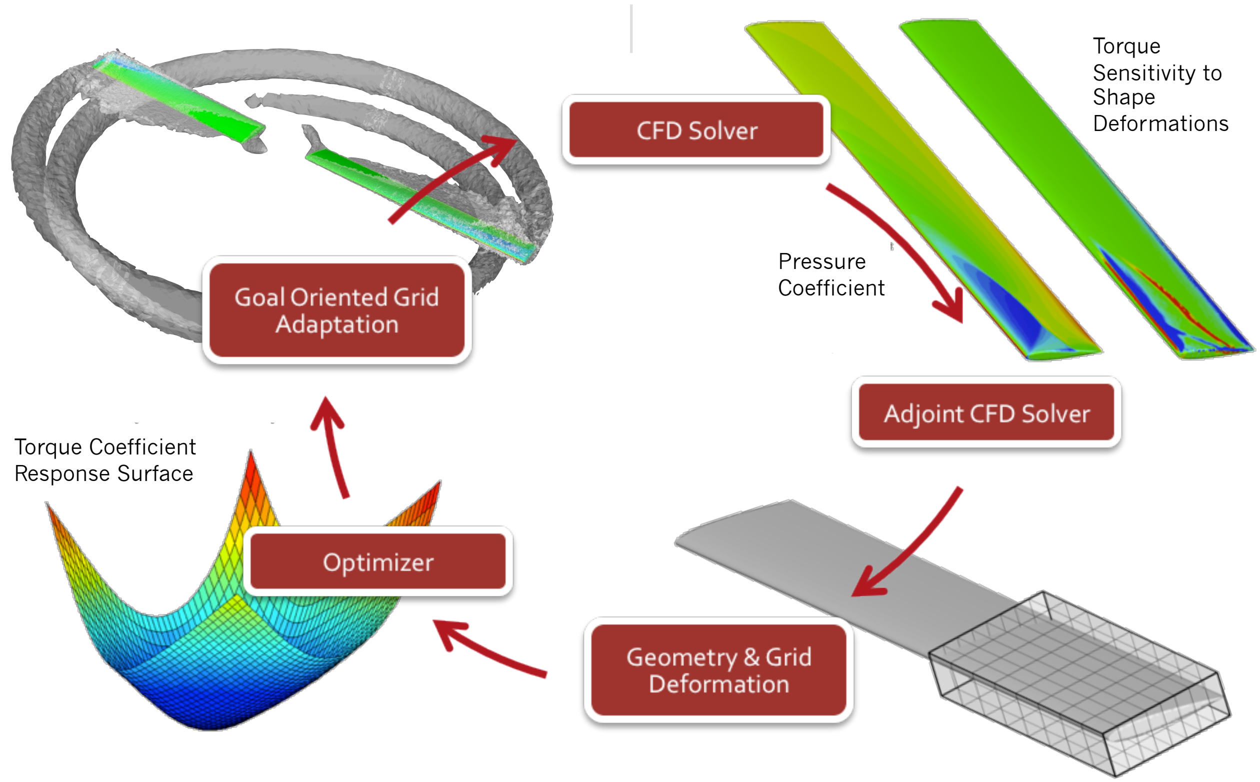
Why SU^2?

Lasting infrastructure for future efforts

1. **An open-source model:** basic formulation with a reasonable set of initial capabilities. We would like to see contributions from the community!
2. **Portability:** SU^2 has been developed using ANSI C++ and only relies on widely-available, well-supported, open-source software.
3. **Reusability and encapsulation:** SU^2 is built so that the main concepts (geometry, sol. algorithms, num. algorithms, etc) are abstracted to a very high-level. This abstraction promotes reusability of the code and enables modifications without adversely affecting other portions of the suite.
4. **Flexibility:** required to re-purpose existing software for new and different uses. Enabling a common interface for all the necessary components.
5. **Performance:** we have attempted to develop numerical solution algorithms that result in high-performance convergence of the solver in SU^2. Striving to strike balance between performance and flexibility.
6. **Gradient availability:** for many applications it is important to obtain sensitivities of the responses computed by SU^2 to variations in design parameters.

Why SU^2?
Multi-physics shape optimization

Shape Optimization
- Self-contained optimization env.
- Gradient computation using adjoint approach.
- 3D design variable definition and built-in geometry and mesh deformation.



Multi-Physics Simulations
- Simultaneous analysis of different equation sets with tight coupling.
- Free surface simulations, noise, fluid structure, etc.
- Multi-species plasma solver for simulating ionized flows.

Why SU²?
Easy to adapt

1a) Read Input
Class: CConfig
- Read the config file.

1b) Read Mesh
Class: CGeometry
- Read the mesh file.
- Set up multigrid meshes.

2) Solve Equations
Class: CSolution
- Euler Equations: CEulerSolution
- Plasma Equations: CPlasmaSolution
- Euler Adj. Eq.: CEulerAdjSolution
- Heat Equations: CHeatSolution
- And others…

3) Write Output
Class: COutput
- Print on screen
- Write solution file
- Write restart file
- Write history file

Store Flow Variables
Class: CVariable
- Stores variables at every mesh node.
- Declare & store all flow variables
  - CEulerVariable: Density, energy etc.
  - CNSVariable: CEulerVariable + Viscosity
  - CAdjVariable: Adjoint variables
  - And others…

Discretization
Class: CNumerics
Spatial Discretization
- Convective Flux, Jacobian
  - CNumerics:: Roe/JST/etc.
- Viscous Flux, Jacobian
  - CNumerics:: Avg_Grad/etc.
- Source Terms, Jacobian
  - CNumerics:: PieceWiseConst.

Temporal Discretization
- Implicit Time Integration
- Explicit Euler/ Runge-Kutta
- Dual Time

Solve Linear System
Class: CSparseMatrix
- Linear solvers
  - BiCSTAB
  - GMRES
- Preconditioners
  - Linelet
  - LU-SGS
  - Low Mach number
- Update solution vector

Why SU^2?
Verification and Validation

Verification and Validation is critical. It should address **the consistency of the numerical methods**, a solid **accuracy** assessment for different critical application cases, and **sensitivity studies** with respect to parameters.

1. **Unit/Test problems:** zero pressure gradient flat plate boundary layer, bump in a channel, and unsteady flow around a square cylinder.
2. **Subsonic airfoil geometries:** NACA 0012 with attached flow, NACA 4412 with a recirculation bubble, and the McDonnell-Douglas 30P30N three-element high-lift configuration.
3. **Subsonic wing and rotorcraft configurations:** delta wing at a high angle of attack, and the Caradonna & Tung rotor.
4. **Transonic airfoil geometries:** NACA 0012 with attached flow after a shock, RAE 2822 with flow separation.
5. **Transonic wing and full aircraft configurations:** ONERA M6, and the DLR F6 model.

2013 SU^2 team, "Stanford University Unstructured (SU2): Open-source analysis and design technology for turbulent flows", AIAA Paper 2014-0243.

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Image | Lockheed Martin

Supersonic aircraft design
Straight forward design

Our ability to fly at supersonic speeds over land in civil aircraft depends on our ability to reduce the perceived loudness of the sonic boom

Aerodynamic shape optimization.

- Solve Euler/RANS adjoint problem in complex geometries.

Inverse design problem (wave propagation).

- Given a pressure signature on the ground, compute the near-field pressure.
- Coupling.

Optimization algorithm.

- Gradient based, surrogated model, etc.

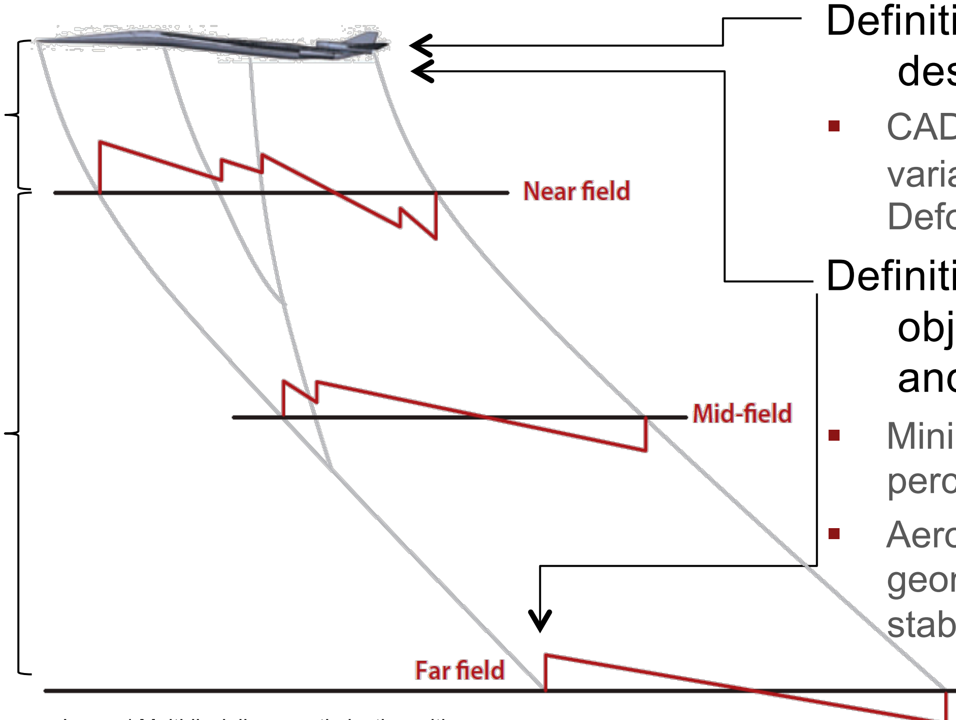


Image | Multidisciplinary optimization with applications to sonic-boom minimization by J. J. Alonso and M. R. Colonno

Definition of the design variables

- CAD based design variables, Free-Form Deformation, etc.

Definition of the objective function and constraints.

- Minimization of perceived noise, etc.
- Aerodynamic, geometric, and stability constraints.

Supersonic aircraft design
Equivalent Area design approach

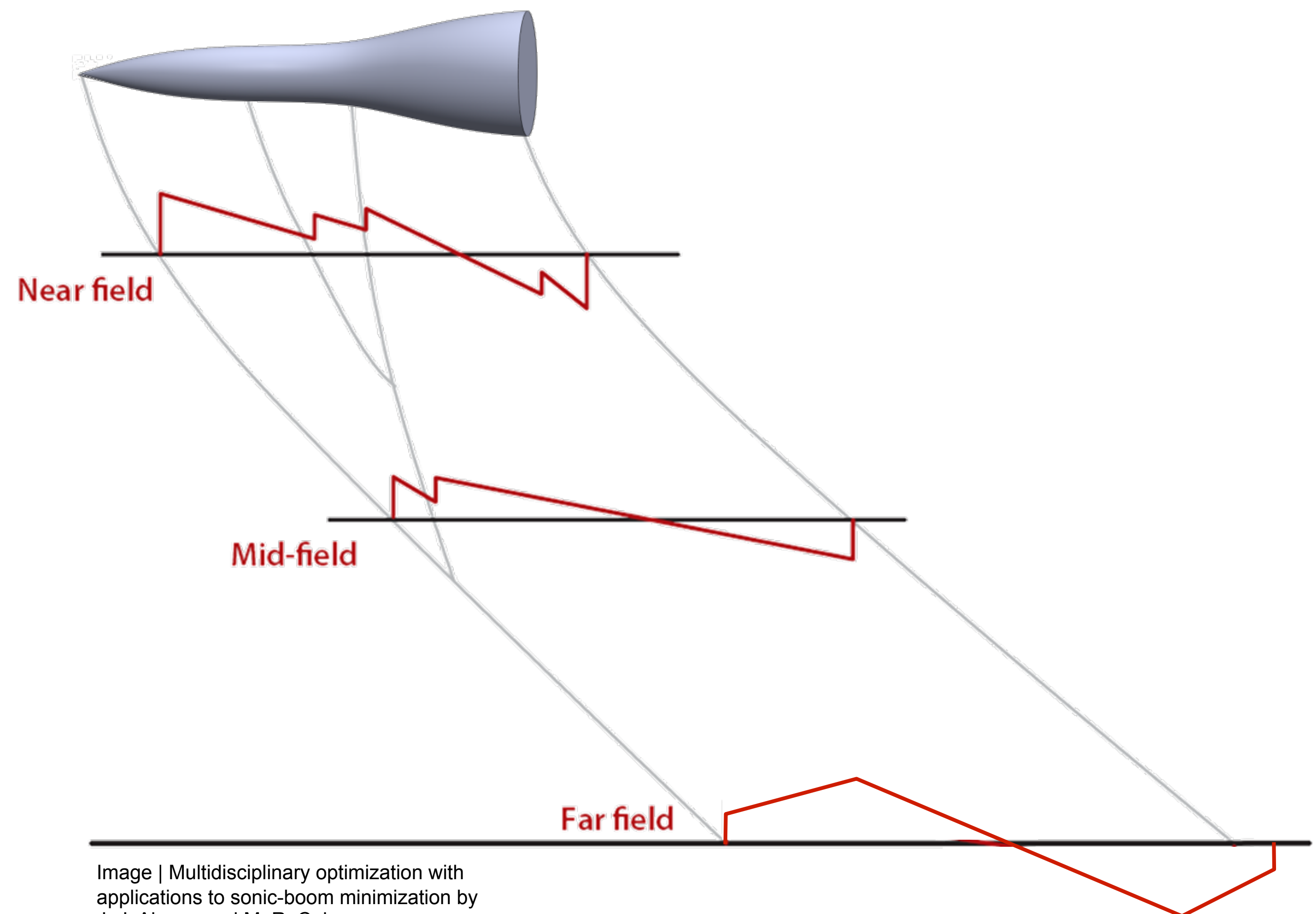


Image | Multidisciplinary optimization with applications to sonic-boom minimization by J. J. Alonso and M. R. Colonno

Supersonic aircraft design
Equivalent Area objective function

The Equiv. Area at a particular location and azimuthal angle is given by

$$A_e(x,\theta) = \int_0^x C(P-P_\infty)(x-t)^{1/2}\,dt, \text{ where } C = 4\frac{\sqrt{2\beta r}}{\gamma P_\infty M_\infty^2}$$

We are interested in the L-2 norm of the difference between the calculated equiv. area and a target at different azimuthal angles:

$$J = \sum_{k=0}^{M}\sum_{i=0}^{N-1} \omega_{ik}\left[A_e(x_i,\theta_k) - A_t(x_i,\theta_k)\right]^2$$

Can we handle this kind of objective function using the standard continuous adjoint formulation? Yes!

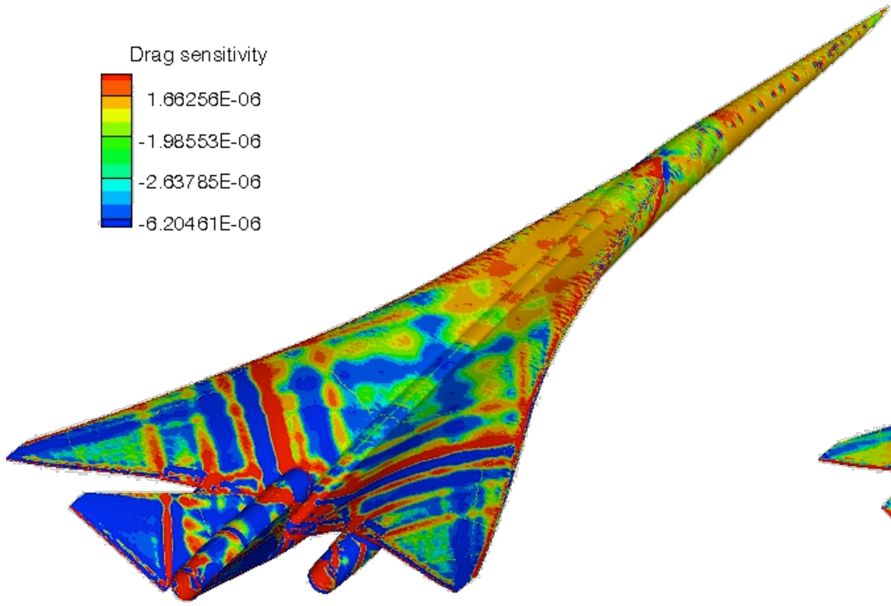
$$\boxed{\delta J = \int_S \left(\vec{d}\cdot\vec{\nabla}P + (\partial_n\vec{v}\cdot\vec{n}_S)\,\vartheta + \nabla_s(\vec{v}\,\vartheta)\right)\delta S\,ds = \int_S \frac{\partial J}{\partial S}\delta S\,ds.}$$

F. Palacios, J. J. Alonso, M. Colonno, J. Hicken, and T. Lukaczyk "Adjoint-Based method for supersonic aircraft design using equivalent area distribution", AIAA Paper 2012-0269

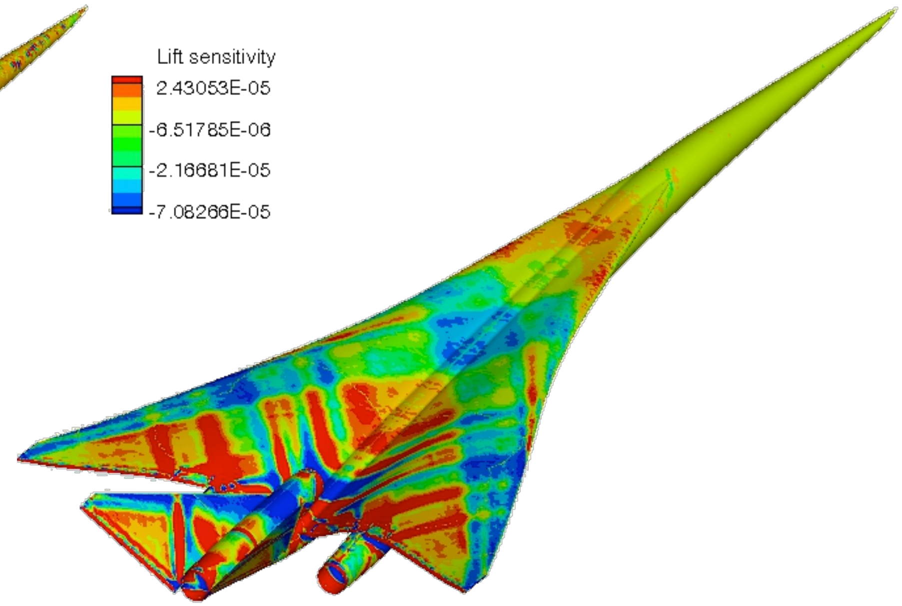
T. Lukaczyk, F. Palacios, and J. J. Alonso, "Response Surface Methodologies for Low-Boom Supersonic Aircraft Design using Equivalent Area Distributions", AIAA Paper 2012-5705

Supersonic aircraft design
Surface drag and lift sensitivities using the adjoint method

Magnitude of surface sensitivity represents changes in cost function caused by changes in geometry.



Drag sensitivity (Mach 1.6, AoA 2.3deg)



Lift sensitivity (Mach 1.6, AoA 2.3deg)

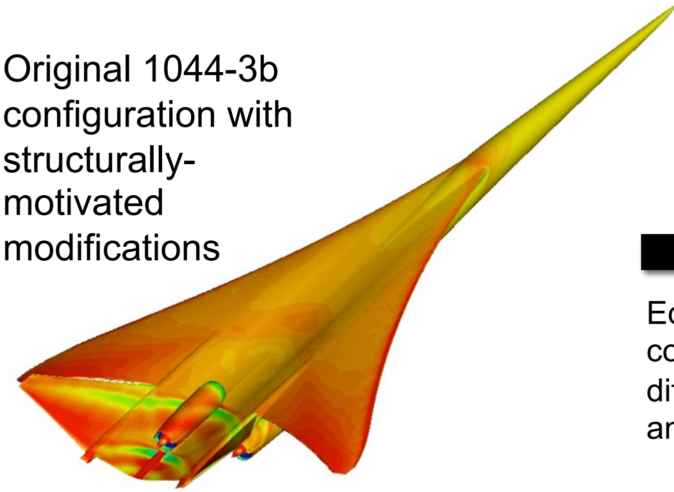
Designers can use this sensitivity information to determine appropriate parameterizations of the configuration prior to optimization.

Supersonic aircraft design

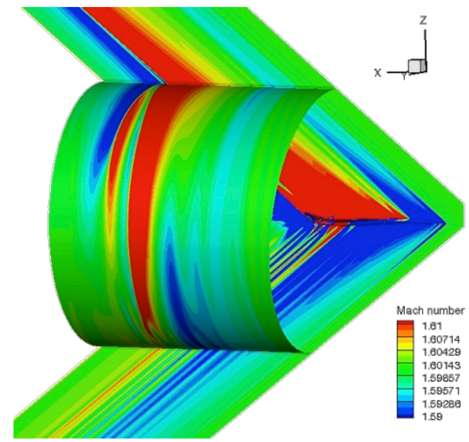
Recovering 1044-1 A_e starting from 1044-3b

It is possible to recover the boom performance after including structurally-motivated and engine modifications to the baseline aerodynamic shape?

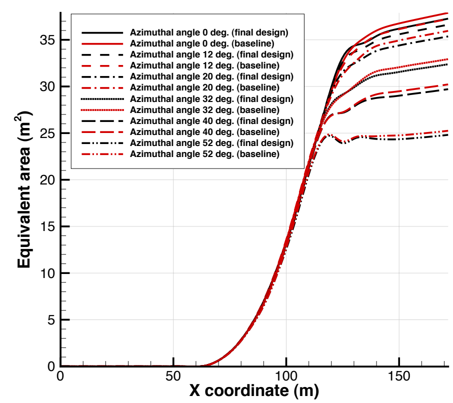
Original 1044-3b configuration with structurally-motivated modifications



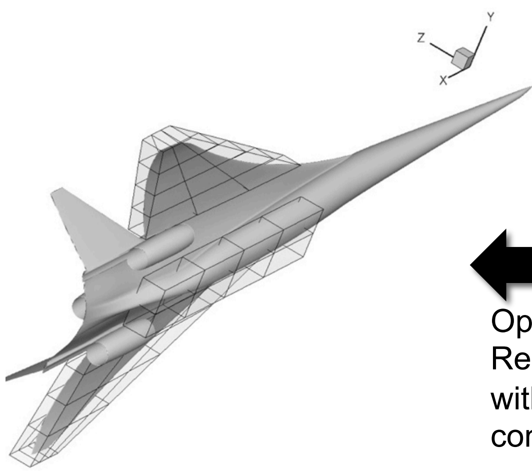
Equivalent area computation at different azimuthal angles



Comparison with baseline 1044-1 configuration without structurally-motivated modifications



?



Optimization to Recover Equivalent Area with C_L (and possibly C_D) constraint.

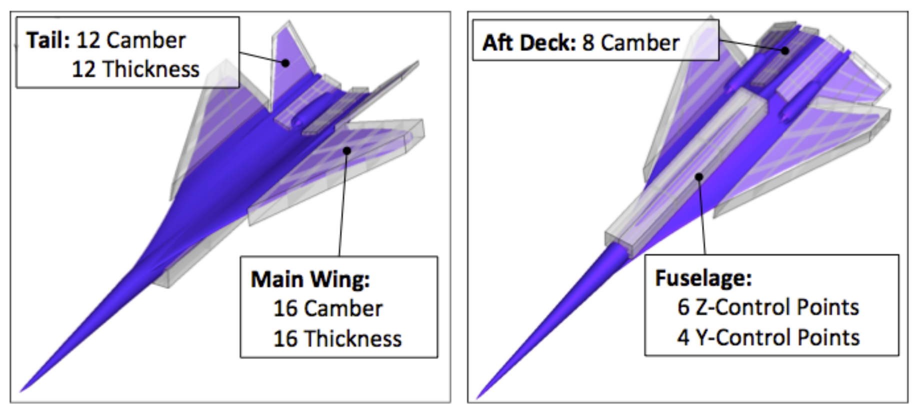
Supersonic aircraft design
Optimization problem description

Min.	J(x)	
	x ∊ R^N	
s.t.	$C_L(x) > 0.136$	

Ma = 1.7, AoA = 2.1deg, H = 50,000 ft
Recover 1044-1 target equivalent area distribution
Near-field at 2 body lengths
Maintain minimum lift
Free-Form Deformation (FFD) design variables

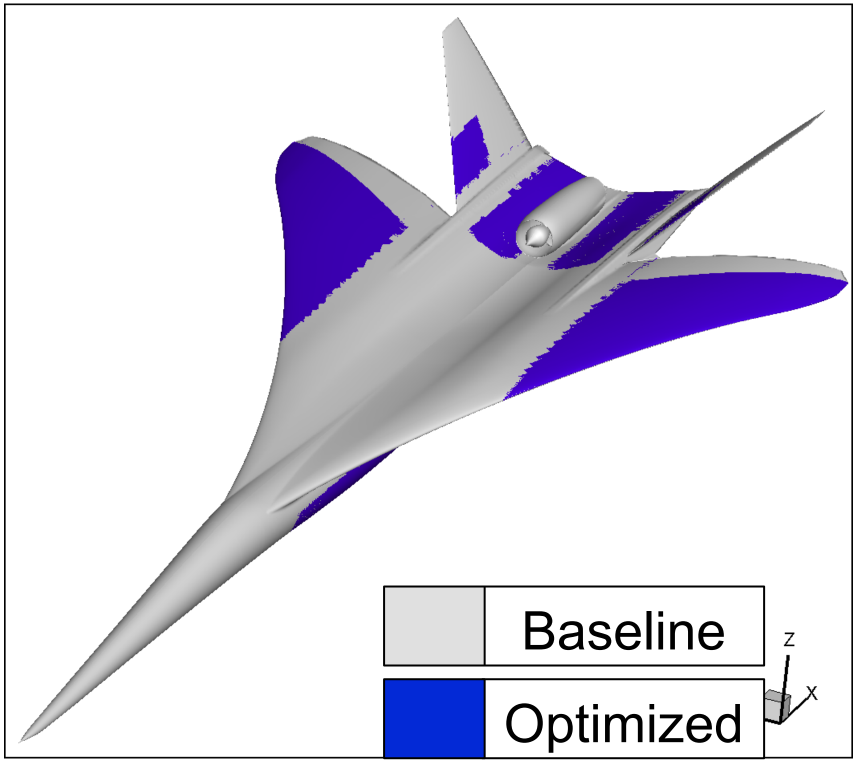
$$J = \sum_{k=0}^{M} \sum_{i=0}^{N-1} \omega_{ik} \left[A_e(x_i, \theta_k) - A_t(x_i, \theta_k)\right]^2$$

- Multiple azimuth formulation maintains off-track performance
- Azimuth angle ranges: 0^o to 60^o, 2^o increments



* Mirrored half-body shown

Supersonic aircraft design
Baseline and optimized shape

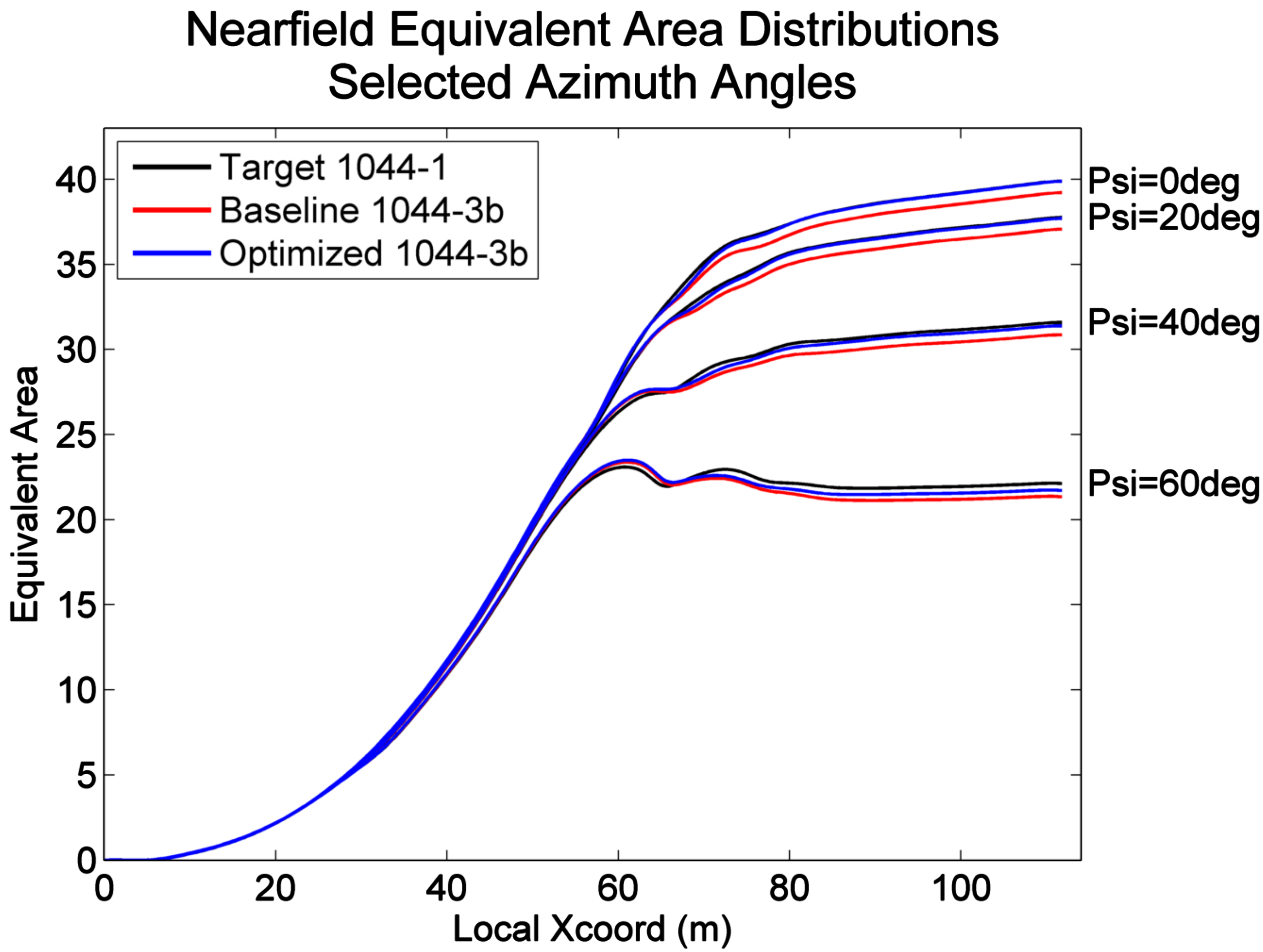


- 85.5% Reduction in Equivalent Area Objective
- +1.8% C_L, +1.1% C_D
- Drag may be minimized by a second optimization with Ae and C_L constraints or an optimization with multiple constraints

- Main wing dihedral increased, trailing edge de-cambered
- Tail angle of attack increased near root
- Fuselage volume increased

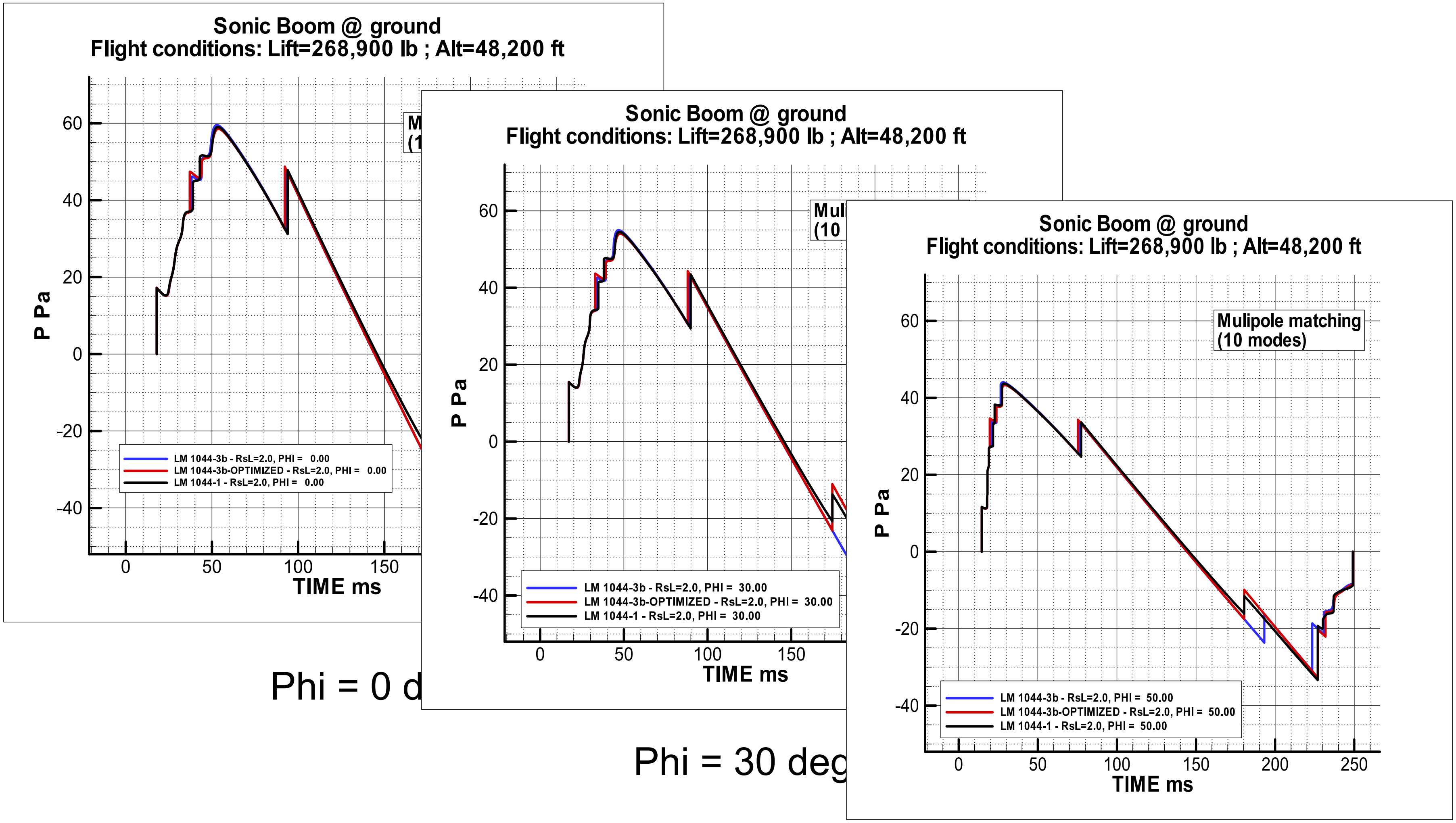
Supersonic aircraft design

Equivalent area distribution comparison



Supersonic aircraft design

Comparison of ground boom signatures

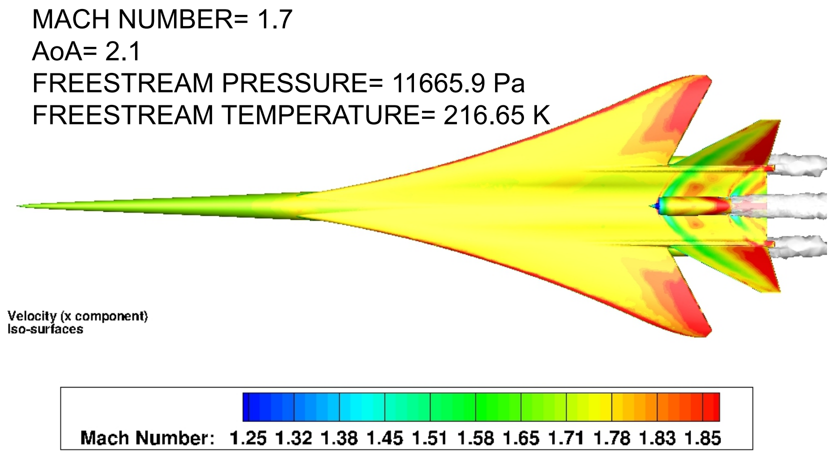


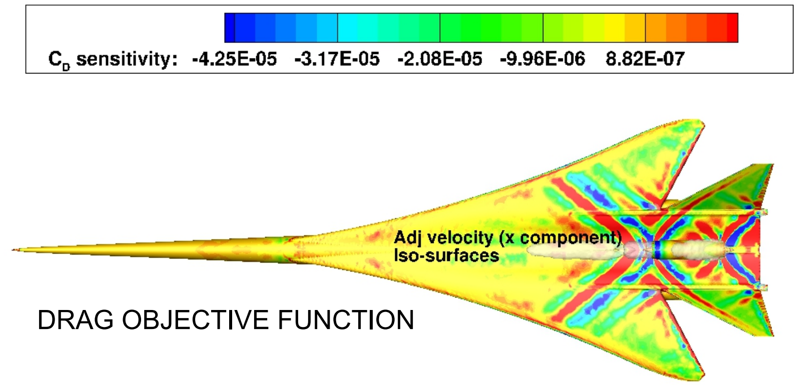
Phi = 0 d

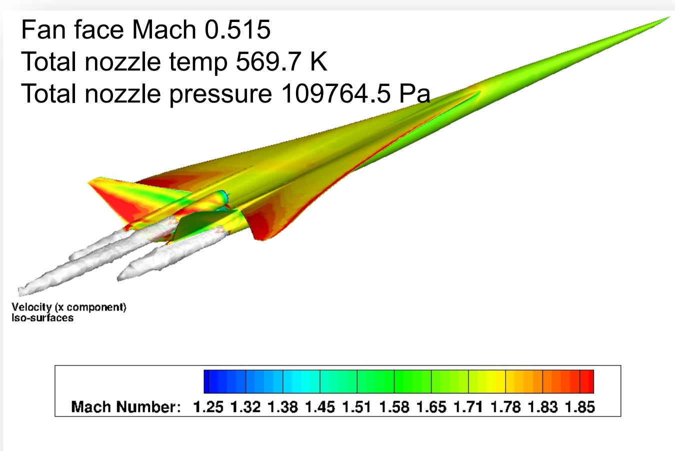
Phi = 30 deg

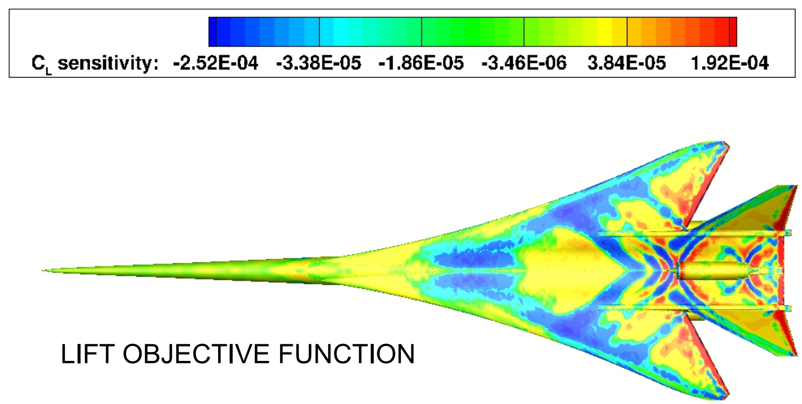
Phi = 50 deg

Direct and Adjoint Simulations with Engines









Trim (C_M = 0.0) and A_e Optimization

Min. $C_{Ae}(x)$, $x \in R^N$, N=124,

s.t. $C_D(x) < 0.0295$

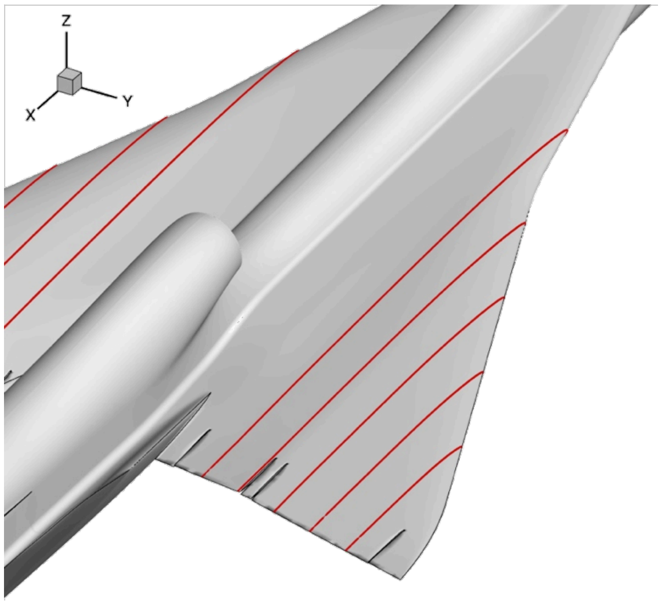
$C_L(x) > 0.1062$

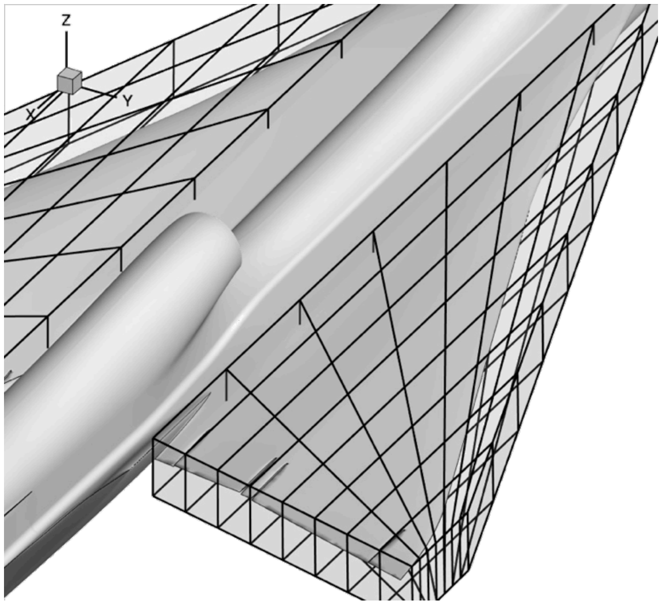
$C_{My}(x) > 0.0$

t/c @ 2y/b = (0.1, 0.3, 0.5, 0.7, 0.9) @ x/c = (0.25, 0.5, 0.75) > 95% or 90% of baseline

- LBFD configuration: C435
- Euler simulation with propulsion effects
- 124 design variables (Free-Form Deformation)
- 3 flow-derived constraints (C_D, C_L and C_{My}) => 4 adjoint runs every design iteration
- 15 geometric constraints

Main challenge: trim the aircraft, reduce C_D, and maintain C_L, with minimal impact on the equivalent area





Optimization Using a "Direct" Approach

Min. $C_{Ae}(x)$, $x \in R^N$, N=124,

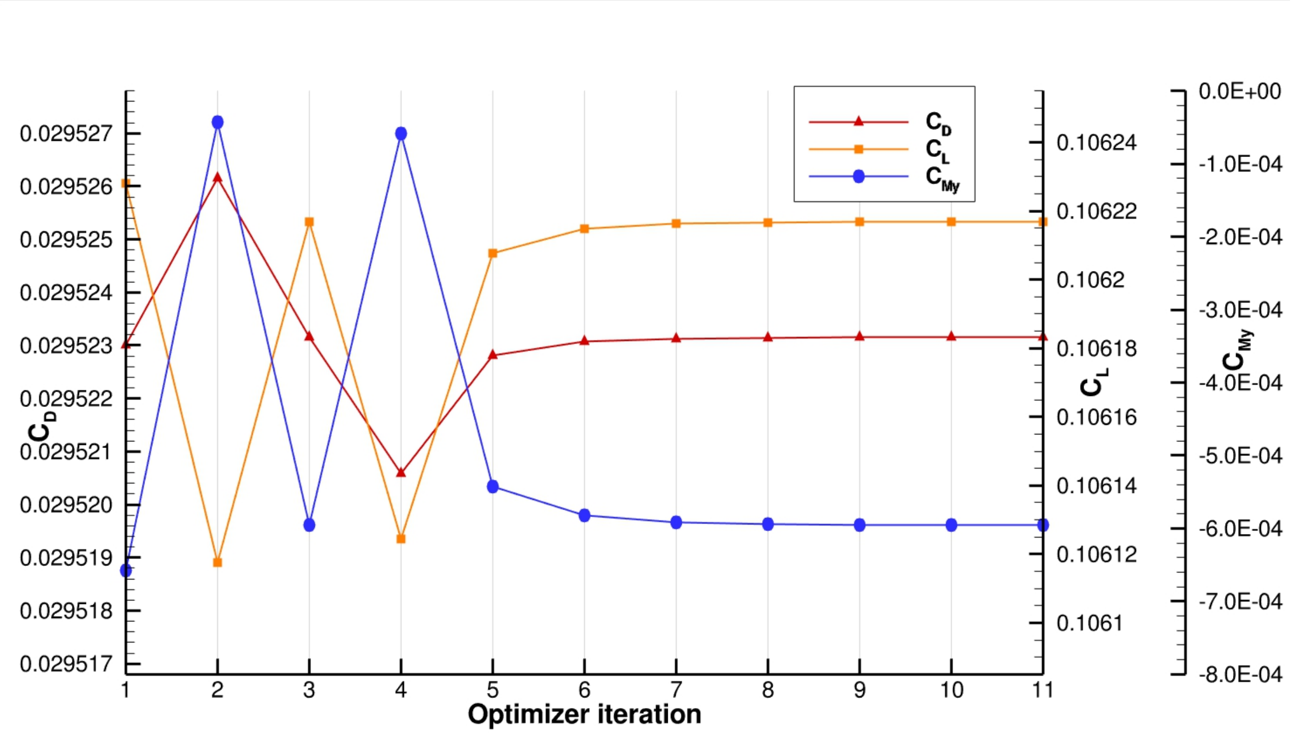
s.t. $C_D(x) < 0.0295$

$C_L(x) > 0.1062$

$C_{My}(x) > 0.0$

t/c @ 2y/b = (0.1, 0.3, 0.5, 0.7, 0.9) @ x/c = (0.25, 0.5, 0.75) > 90% of baseline

After 10 iterations no significant improvement in the objective function or C_{My}



Optimization using an "Indirect" approach

1st step) Increase C_M (positive value).

Max. $C_{My}(x)$, $x \in R^N$, N=124,

s.t. $C_L(x) > 0.1062$

t/c @ 2y/b = (0.1, 0.3, 0.5, 0.7, 0.9) @ x/c = (0.25, 0.5, 0.75) > 90% of baseline

2st step) Minimize C_D with constraints.

Min. $C_D(x)$, $x \in R^N$, N=124,

s.t. $C_L(x) > 0.1062$

$C_{My}(x) > 0.0$

t/c @ 2y/b = (0.1, 0.3, 0.5, 0.7, 0.9) @ x/c = (0.25, 0.5, 0.75) > 90% of baseline

3st step) Minimize C_{Ae} with constraints.

Min. $C_{Ae}(x)$, $x \in R^N$, N=124,

s.t. $C_D(x) < 0.0295$

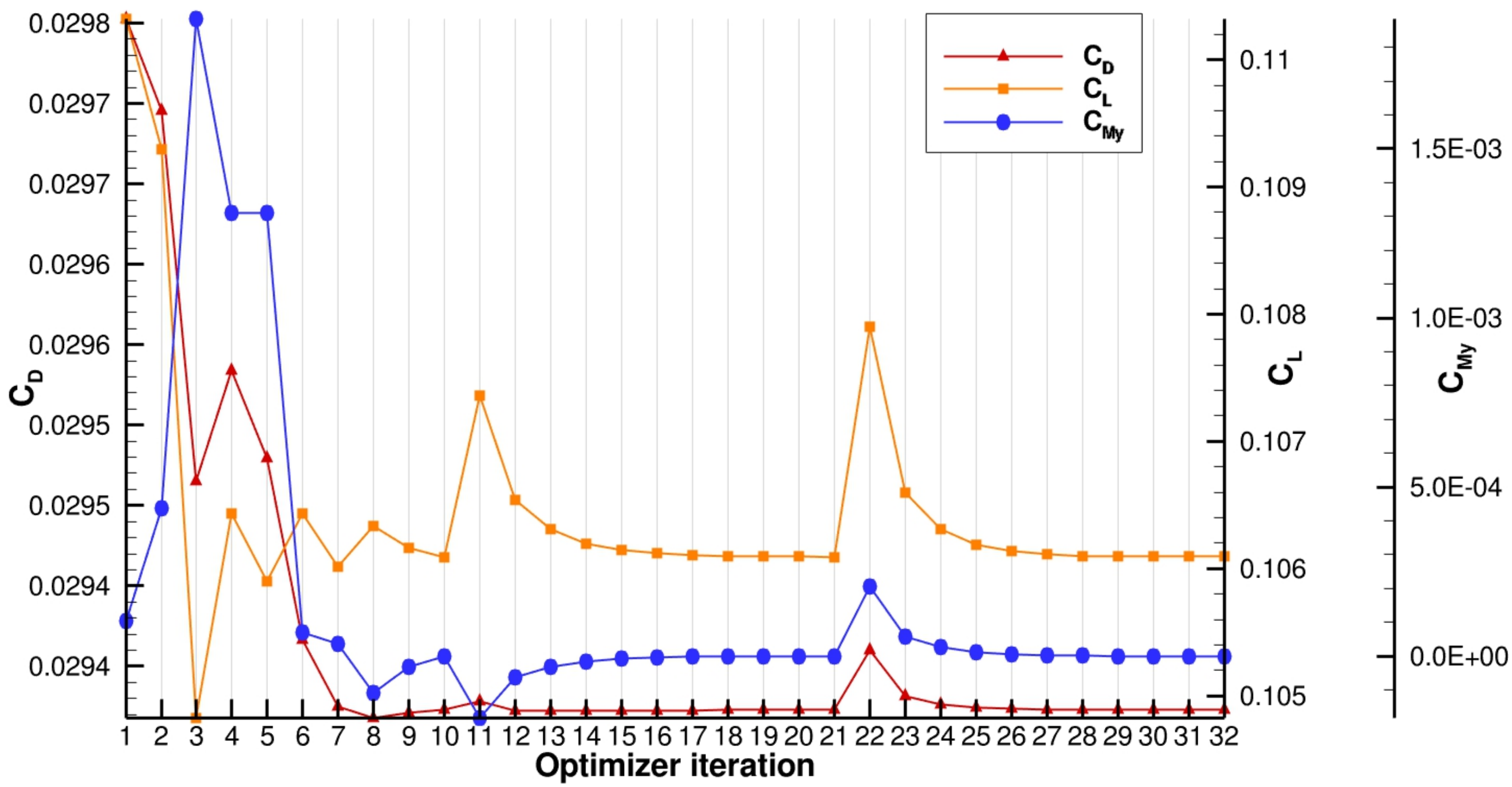
$C_L(x) > 0.1062$

$C_{My}(x) > 0.0$

t/c @ 2y/b = (0.1, 0.3, 0.5, 0.7, 0.9) @ x/c = (0.25, 0.5, 0.75) > 90% of baseline

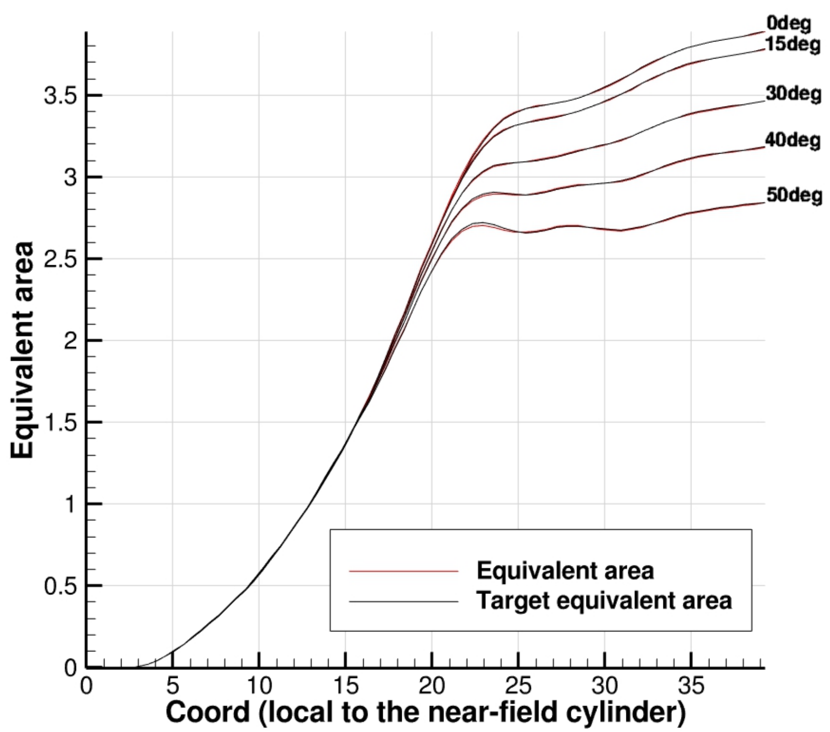
2^{st} step) Minimize C_D with Constraints

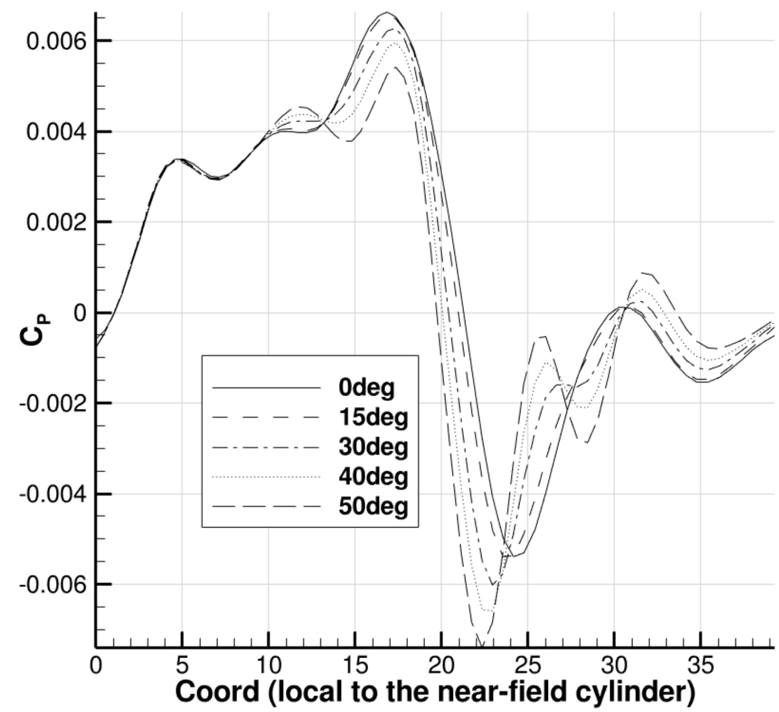
Including pitching, lift and geometric constraints



3^{st} step) Minimize C_{Ae} with Constraints

Final design recovers the original target equivalent area





Final result: C_M=0.0 maintaining C_D, C_L and equivalent area.

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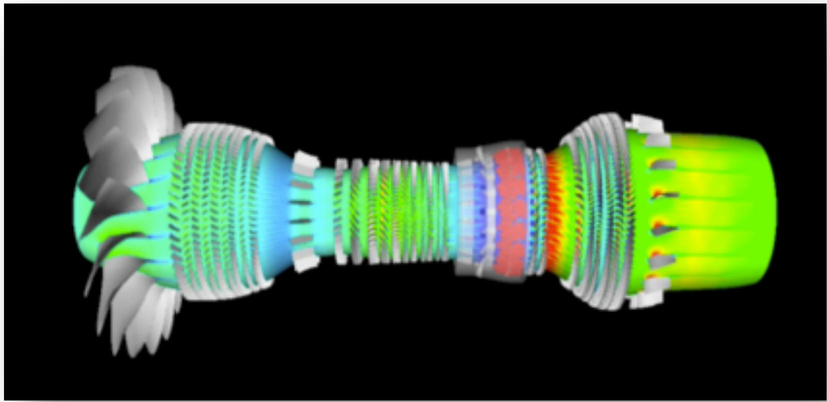


Image | Stanford University

Unsteady aerodynamic shape design
Introduction

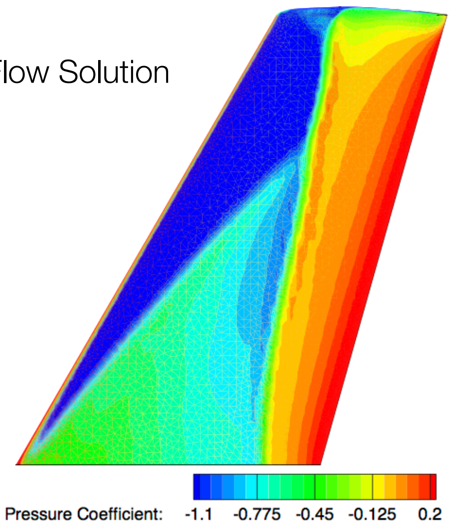
- Challenges for unsteady design:
  - Computational cost can increase dramatically for time-accurate simulations
  - Need to manage large amounts of solution data (adjoint requires reverse time integration)
  - Handling moving surfaces / dynamic meshes in the formulation requires the Arbitrary Lagrangian-Eulerian (ALE) form of the flow equations.

- Due to the complexity of the unsteady design problem, a continuous adjoint approach is appealing due to…
  - Recovering a surface formulation for the gradient with no dependence on the volume mesh (use differential geometry)
  - Flexibility in numerical methods to help mitigate convergence issues for stiff problems
  - The time-accurate, continuous adjoint PDE can also be discretized for different problems immediately (rotating frame or time-spectral approaches for instance)

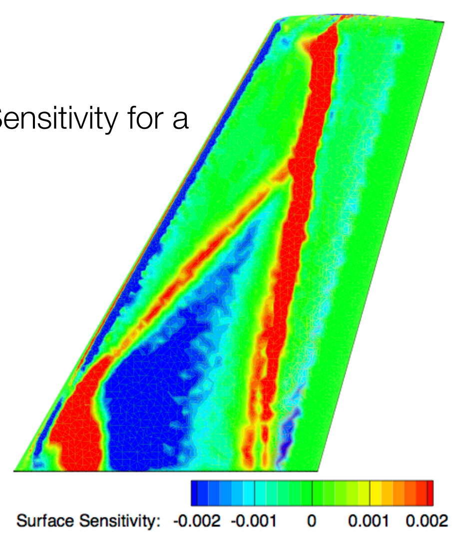
Unsteady aerodynamic shape design

Shape sensitivity

Instantaneous Flow Solution



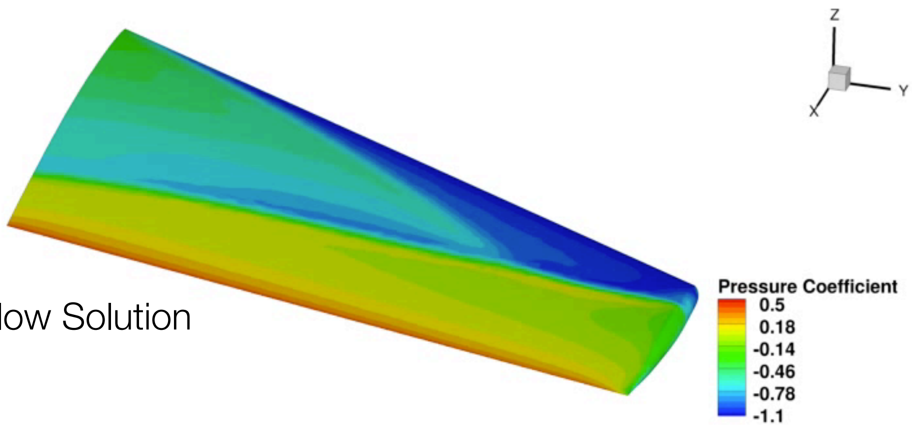
Instantaneous Sensitivity for a Drag Objective



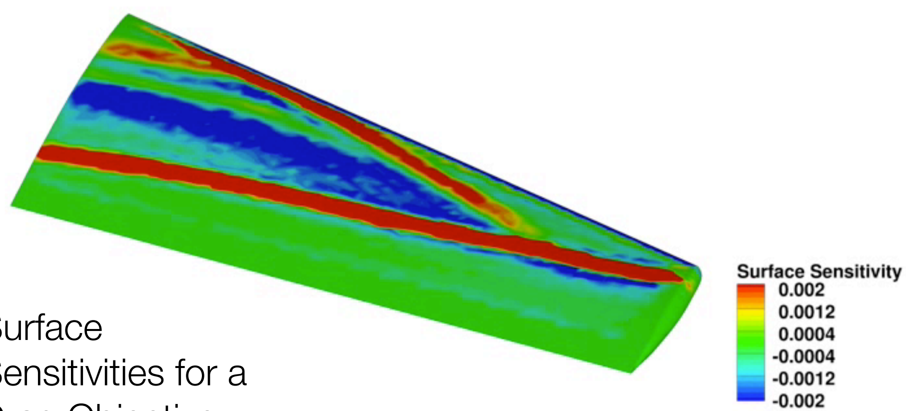
- Key result of the continuous adjoint derivation
- Measures change in the objective function w.r.t. small perturbations in the local normal direction
- Computed at each surface mesh node at negligible cost from the flow and adjoint variables on the surface
- Gradient expression is a surface integral: **no dependence on the volume mesh**
- Offers physical insight and designer intuition

T. D. Economon, F. Palacios, J. J. Alonso, "Optimal Shape Design for Open Rotor Blades," AIAA Paper 2012-3018
T. D. Economon, F. Palacios, J. J. Alonso, "Unsteady Aerodynamic Design on Unstructured Meshes with Sliding Interfaces," AIAA Paper 2013-0632
T. D. Economon, F. Palacios, J. J. Alonso, "A Viscous Continuous Adjoint Approach for the Design of Rotating Engineering Applications," AIAA Paper 2013-2580

Unsteady aerodynamic shape design
ONERA M6



Flow Solution

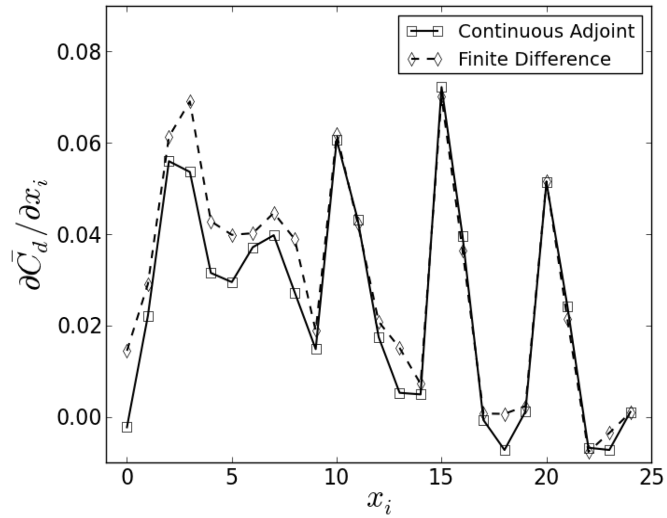


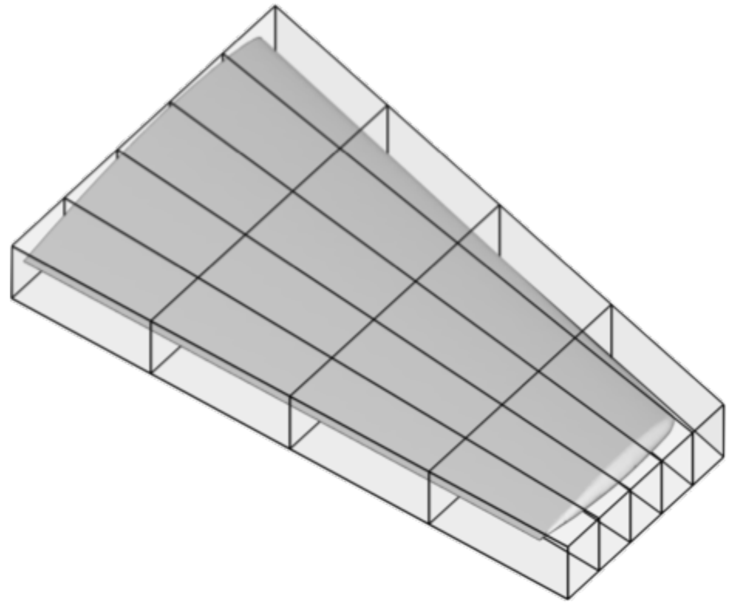
Surface Sensitivities for a Drag Objective

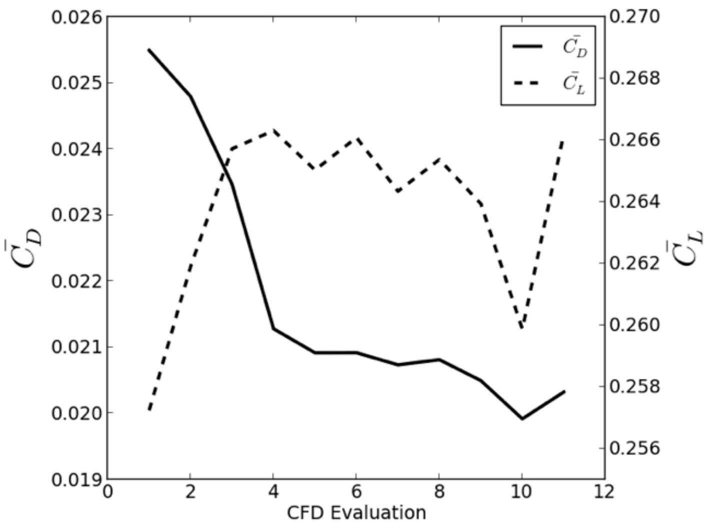
- Pitching wing in transonic flow:
  - Mach = 0.8395
  - Reduced frequency of 0.1682
  - Mean alpha of 3.06 degrees
  - Pitching amplitude of 2.5 degrees
  - Reynolds number = 11.72 million
- Pitching about the y-axis through the root quarter-chord
- 25 time steps per period for 7 periods.
- Unsteady RANS (S-A) equations on rigidly transforming meshes

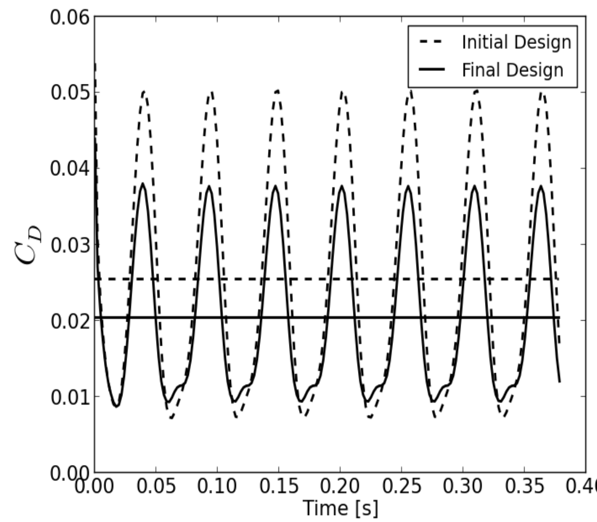
Unsteady aerodynamic shape design
ONERA M6

25 upper surface control point variables





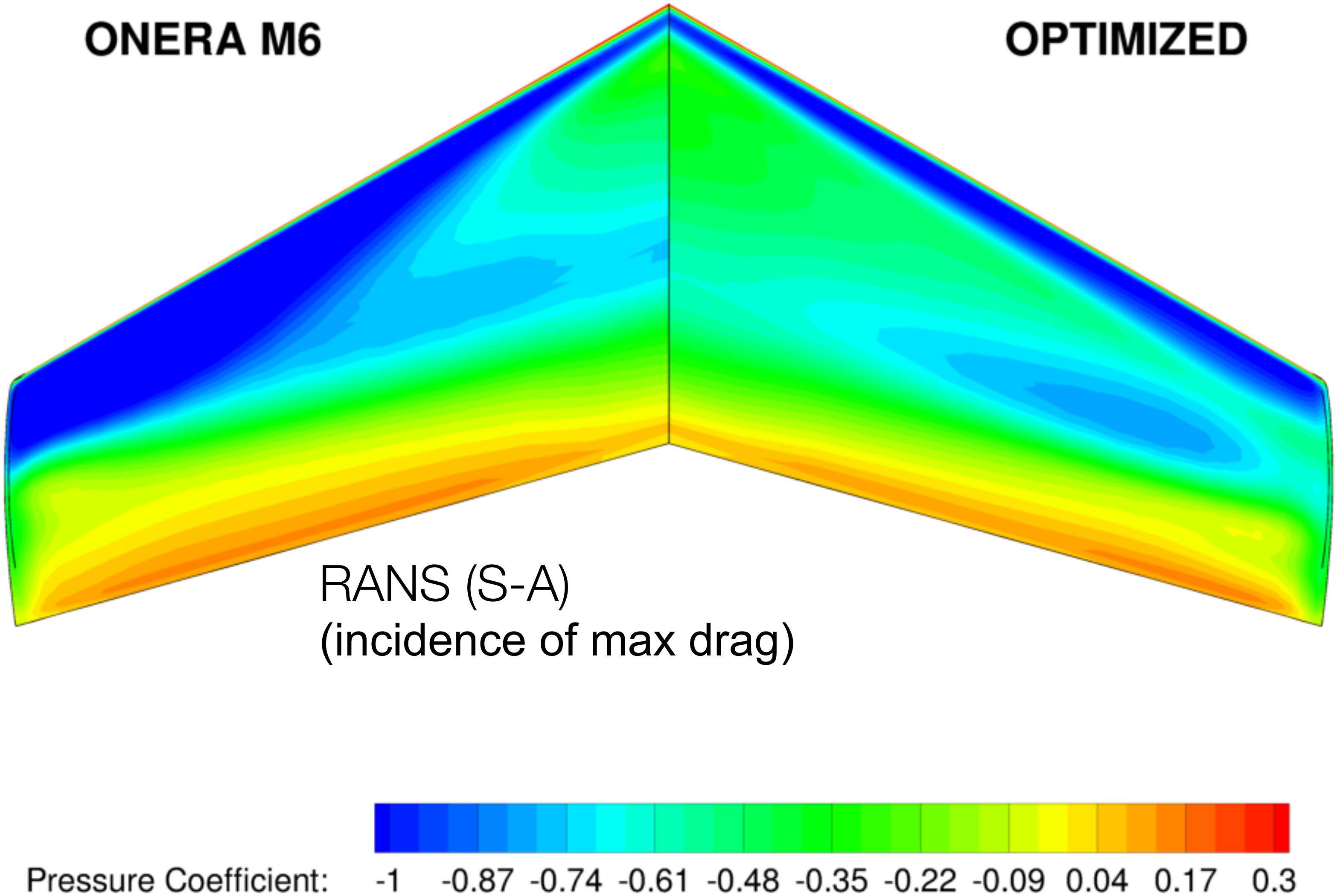




20.3 % Reduction in Time-averaged Drag

Unsteady aerodynamic shape design

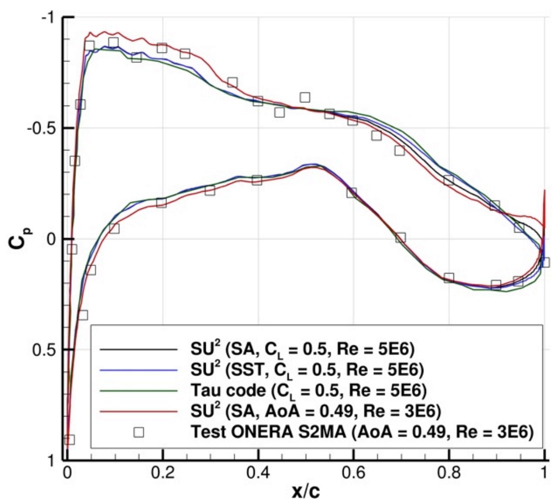
ONERA M6

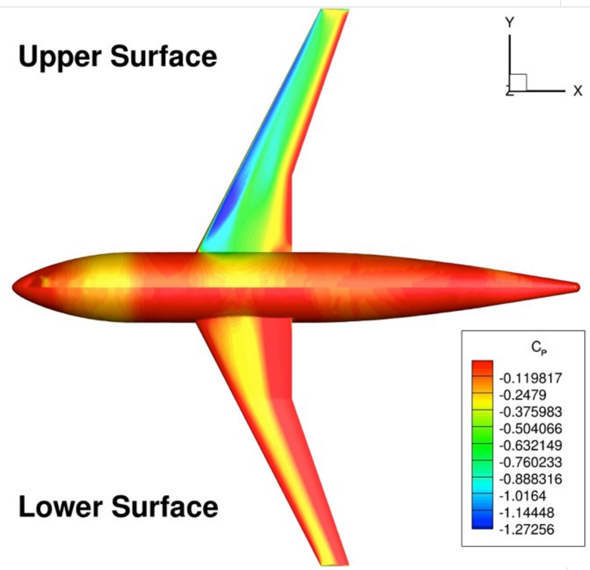


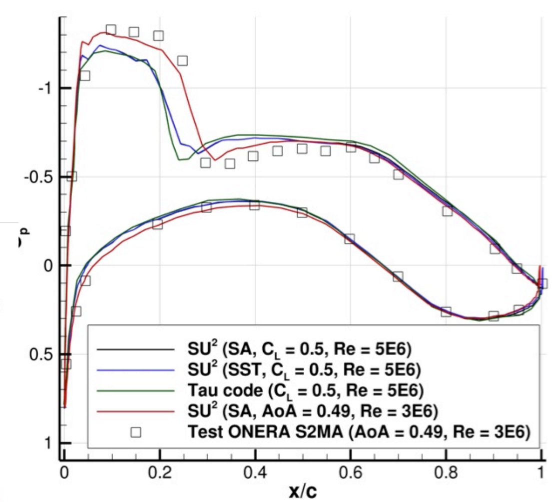
The Open-Source CFD Code

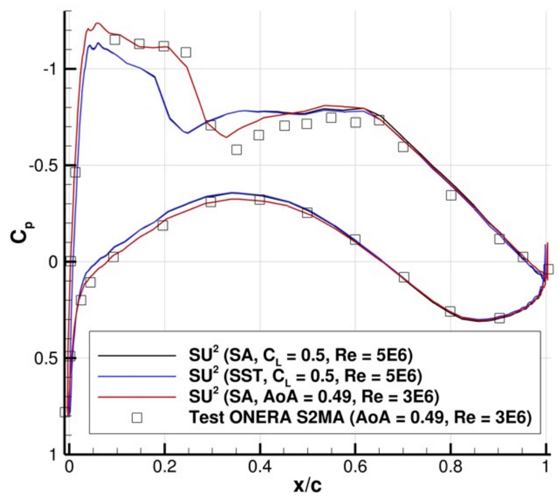
Verification and Validation
High fidelity analysis (I/IV)

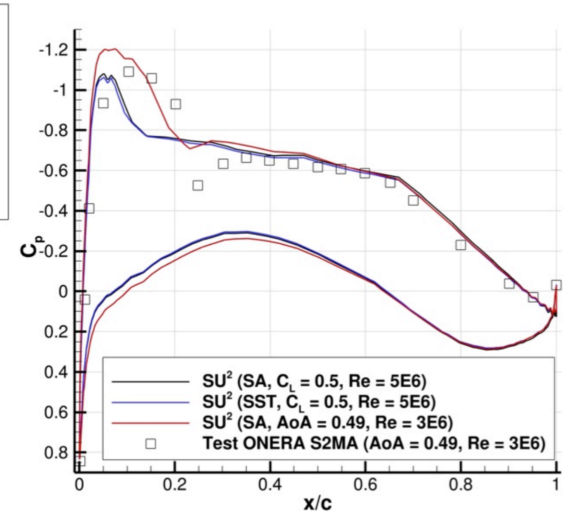
DLR F6



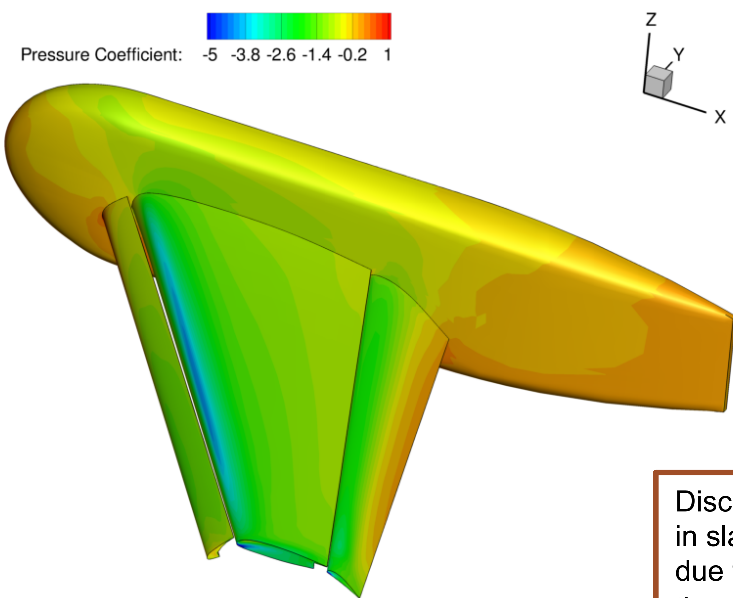




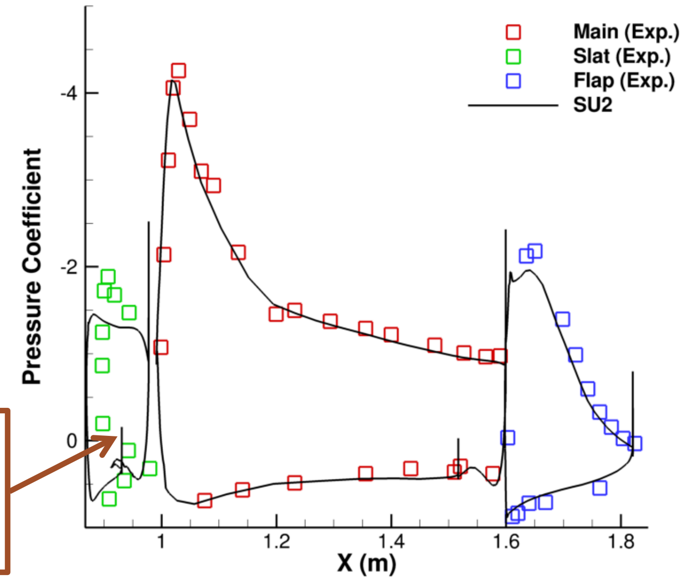




Verification and Validation
High fidelity analysis (II/IV)



Discrepancy in slat C_p due to the cut plane

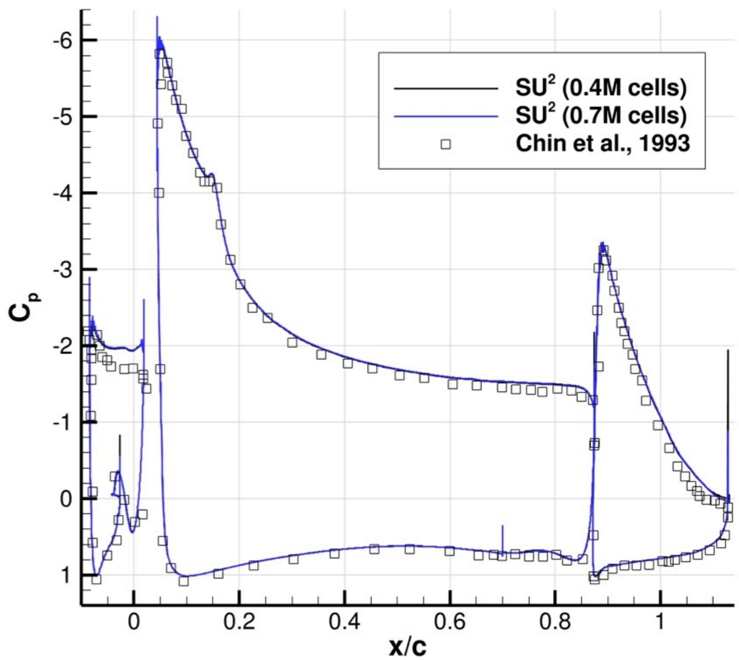


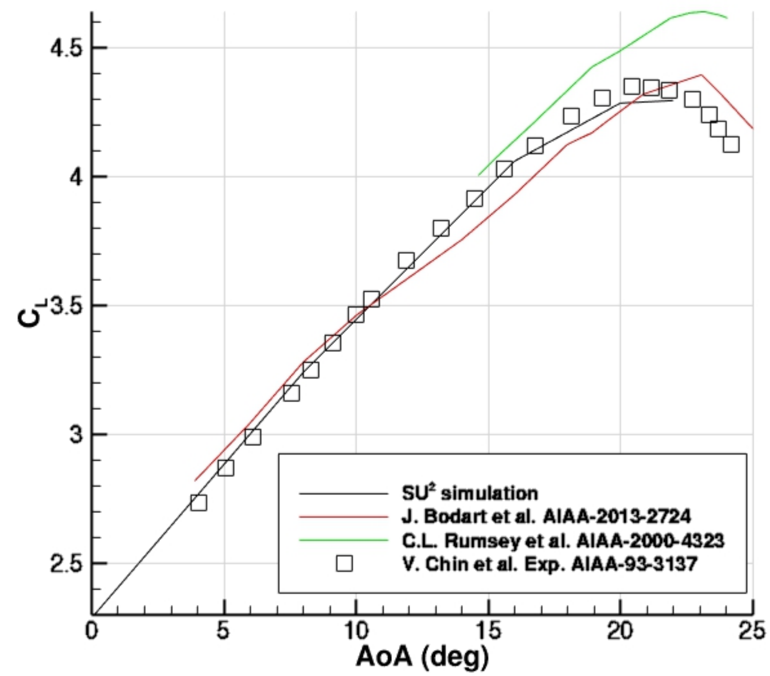
NASA Trap Wing (config 1)
Slat 30 deg, Flap 25 deg

1st AIAA CFD High Lift Prediction Workshop

C_p distributions for the three elements from experiment as compared to SU^2. This is for eta = 0.65 (65% span).

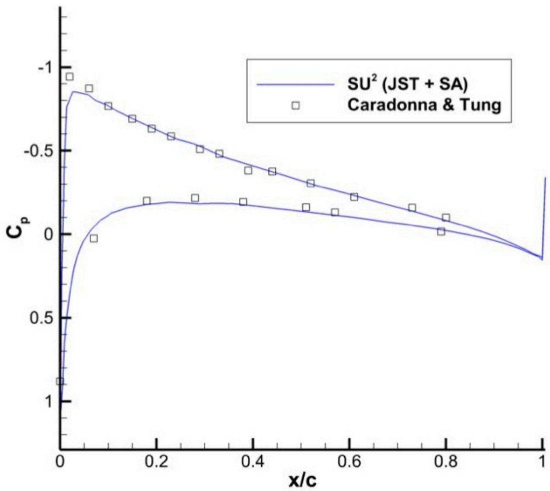
Verification and Validation
High fidelity analysis (III/IV)



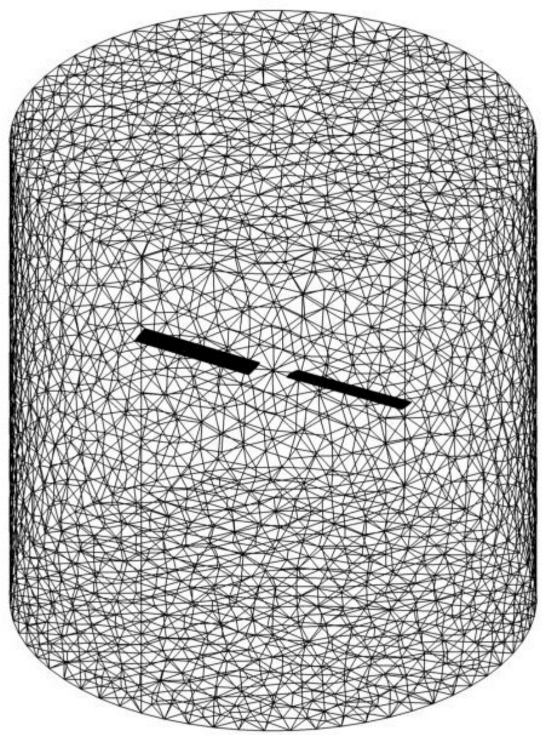


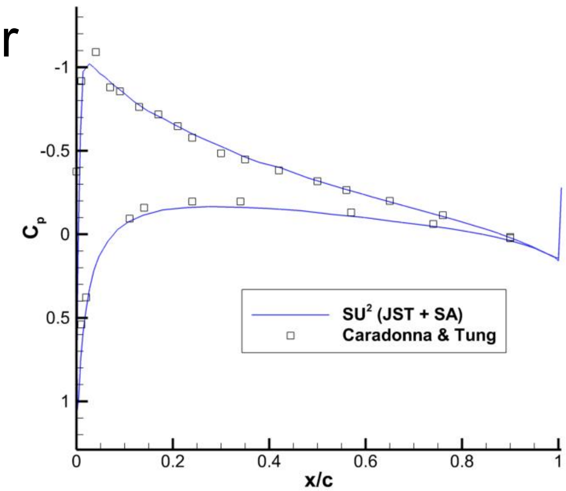
McDonnell-Douglas 30P30N three-element high-lift configuration

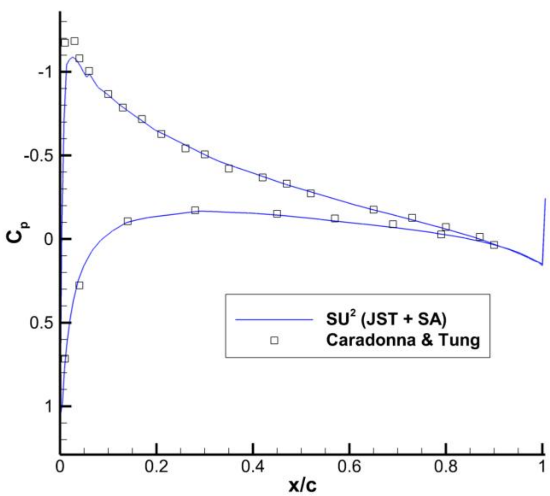
Verification and Validation
High fidelity analysis (IV/IV)

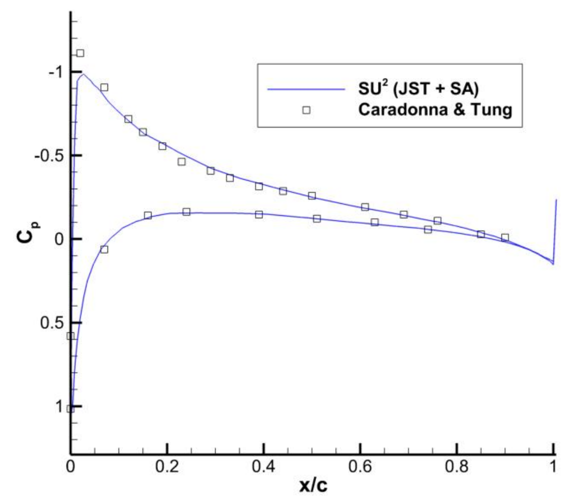


Caradonna & Tung rotor









INTRODUCTION

WHY SU^2?

SUPERSONIC AIRCRAFT DESIGN

UNSTEADY DESIGN

V&V

CONCLUSIONS

The Open-Source CFD Code

Conclusions
Optimal Shape Design

- Aerodynamic Optimal Shape Design is a **high-impact field with a need for sophisticated engineering, mathematical and computational developments**.

- We have completed a comprehensive V&V process for the RANS flow solver portion of the SU^2 software suite. SU^2 solutions are shown to be in excellent agreement with both the available experimental data and other numerical simulations.

- Since the framework is tailor-made for coupled analyses, SU2 dramatically lowers the implementation barrier for tackling aeroelastic, aeroacoustic, and aerothermodynamic problems of critical interest to the aerospace community.

- The release of the SU^2 under the GNU LGPL (v2.1) provides **worldwide access to industry-standard analysis tools for tackling industrial-scale research problems**.

Conclusions
Ongoing Work

- Recently selected as Intel Parallel Computing Center: SU2_PHI, improving performance and scalability while retaining flexibility. Porting to advanced Xeon and Phi architectures with high performance? Design in a box?
- U. Braunschweig: improving turbulence models
- Univ. of Aachen (Prof. Nico Gauger): automatic differentiation for steady and unsteady flow control
- Delft University: real gas models
- VKI: mutation++ library for non-eq flows and combustion
- VSSC (India): Launch vehicle configurations
- NASA: Integration with OpenMDAO, advanced propulsion architectures
- Others: transition models, UAVs, learning CFD, etc.

The Open-Source CFD Code

Thanks a lot for your attention!

Questions & Answers

More details in http://su2.stanford.edu/