Stanford Scientific Computing Research with Potential Payoffs to the Boeing Company

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Presentation to Dr. Robert Krieger, President, Boeing Phantom Works
St. Louis, May 17, 2004

Overall Goal of Our Research

Promote a Lean Design Process

- Reduced Human and Computational Costs
- Potential for Superior Designs

University Role

Expand the Knowledge Base which will Enable Improved Designs

Three-Pronged Strategy

- More Cost Effective Computer Hardware
- More Efficient Algorithms
- Automatic Shape Design

Presenters

Overview:	Antony Jameson
Part1: Sci-Station	Gurjeet Singh
Part2: New Algorithms	Georg May
Part3: Shape Optimization	Kasidit Leoviriyakit

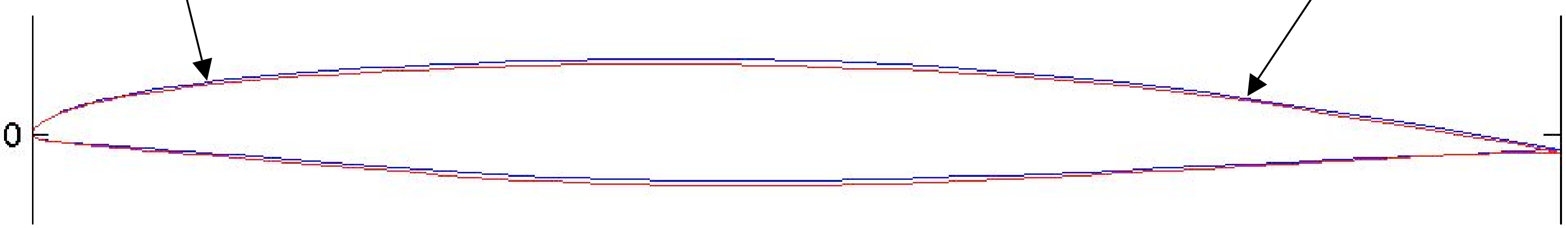
Bios

Gurjeet Singh		
	Masters Student, Stanford University	2003-Present
	B.Eng , Delhi University, India	2001
Georg May		
	Doctoral Candidate, Stanford University,	2001-Present
	Dipl.Ing. Aachen Technical University, Germany	2001
	B.E Dartmouth College	2000
Kasidit Leoviriyakit		
	Doctoral Candidate, Stanford University	2000-Present
	M.S. Stanford University, Stanford University	1999-2000
	B.Eng Kasetsart University, Thailand	1994-1998

Section Shape Redesign of the Boeing 747

Baseline profile (red)

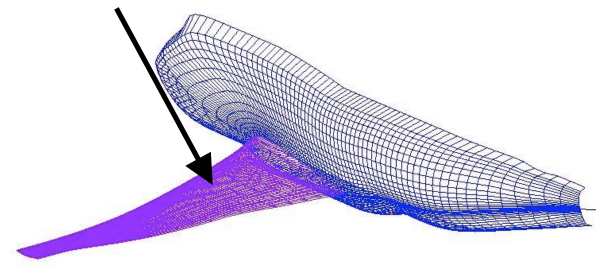
Redesigned profile (blue)



Profile at 50% span

Drag-Divergence Mach Number Increased by 0.02

Design Variables:
4224 points on the wing

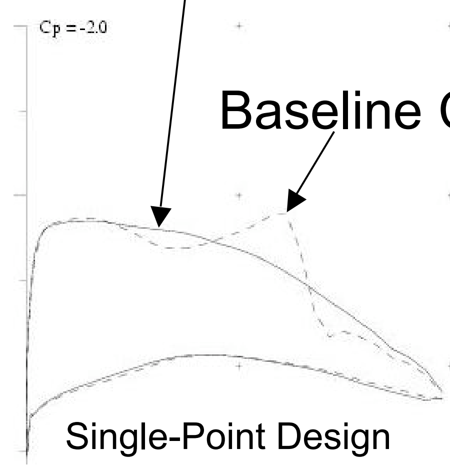


Boeing 747

RANS simulation Re 100 million
3 design points - 30 design cycles
93 flow calculations
25000 sec with 8 - 1.7 gHz cpu
~ 340 trillion computer instructions

Redesign Cp

Baseline Cp



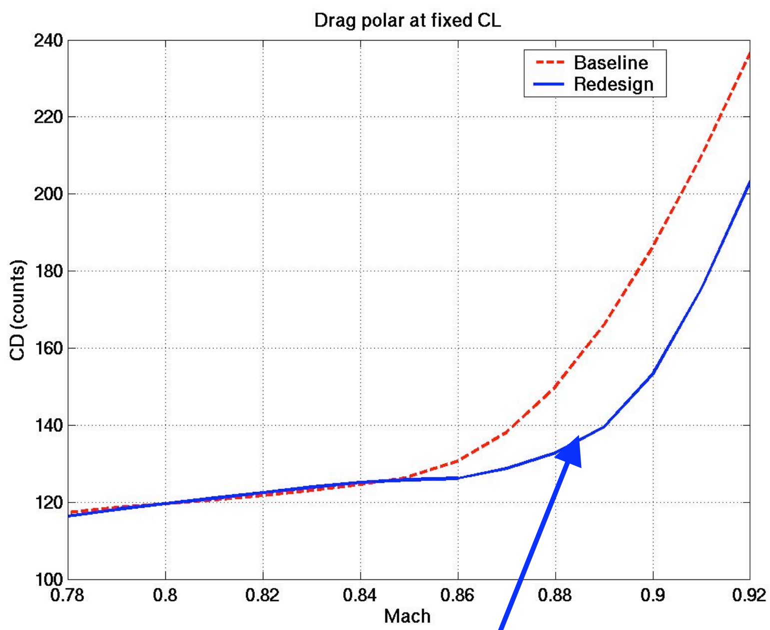
Single-Point Design

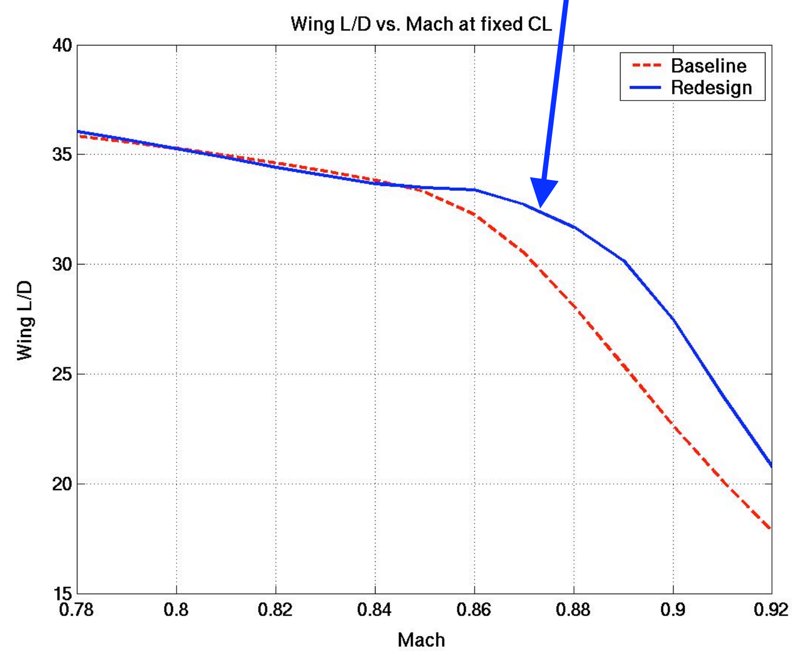
Redesign of the Boeing 747: Drag Rise

(Three-Point Design)

Constraints : Fixed C_L = 0.42
: Fixed span-load distribution
: Fixed thickness

Improved wing L/D





Improved M_{DD}

benefit → Lower drag at the same Mach Number

benefit → Fly faster with the same drag

Intelligent Aerodynamics Inc.

Executive Summary

This presentation covers three areas of research which could strengthen the Boeing Company's engineering processes:

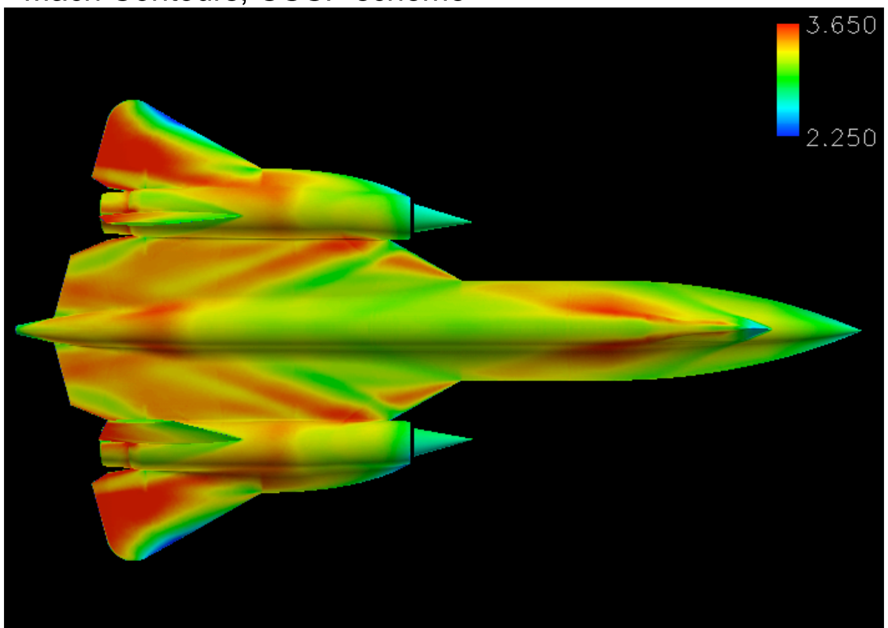
1. The design of a "Sci-Station" for scientific computation on the desktop to provide an order of magnitude increase in throughput

2. New computational algorithms which could provide an order of magnitude increase in throughput for steady flow simulations and two orders of magnitude for unsteady flow

3. Automatic aerodynamic design procedures based on control theory which could provide:
   - An order of magnitude reduction in human and computational costs
   - Potential for superior and unconventional designs
   - Freedom to design shapes as free surfaces with scalability to arbitrarily large numbers of design variables, and no need for user specified shape functions

Computation of SR71 with Flo3xx

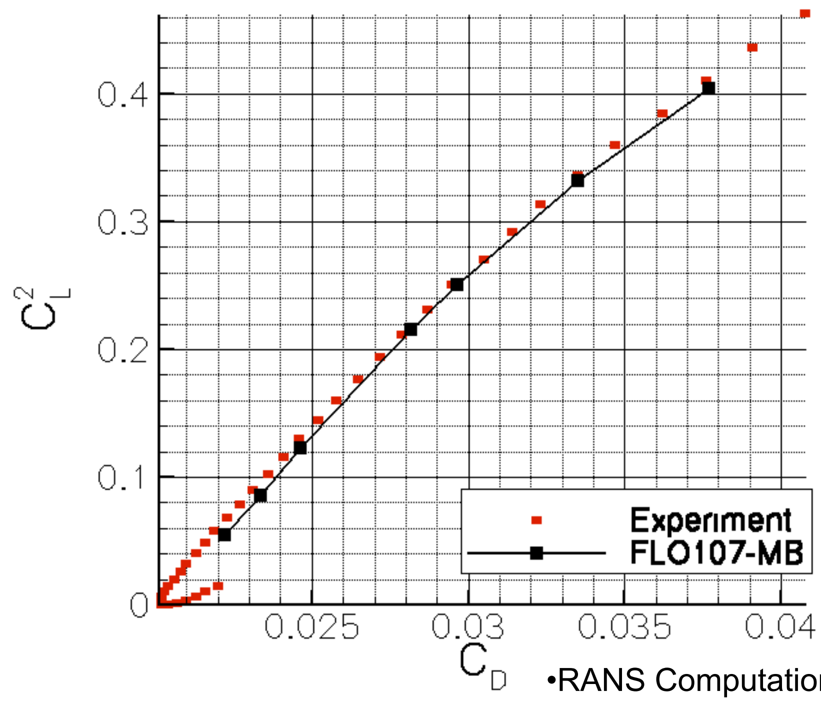
Mach Contours, CUSP scheme



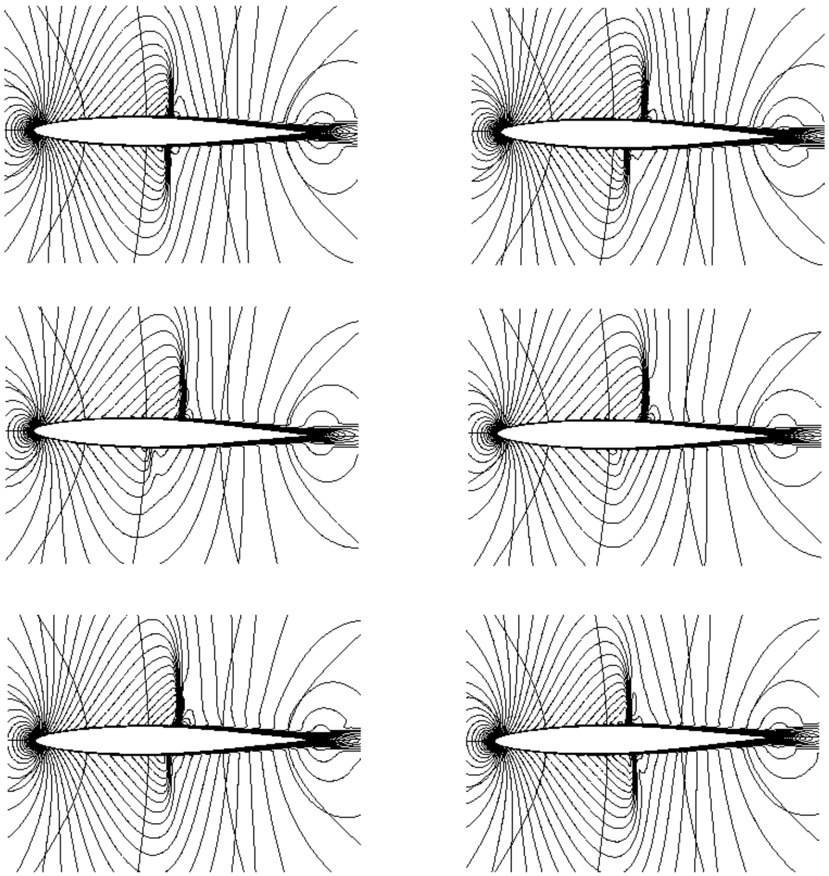
- Euler Computation
- Geometry Courtesy of Lockheed Skunk Works

From IGES definition to completed result in one week, including CAD fixes, mesh generation

Validation of Flo107-MB for Drag Prediction Workshop on the DLR-F6 Configuration

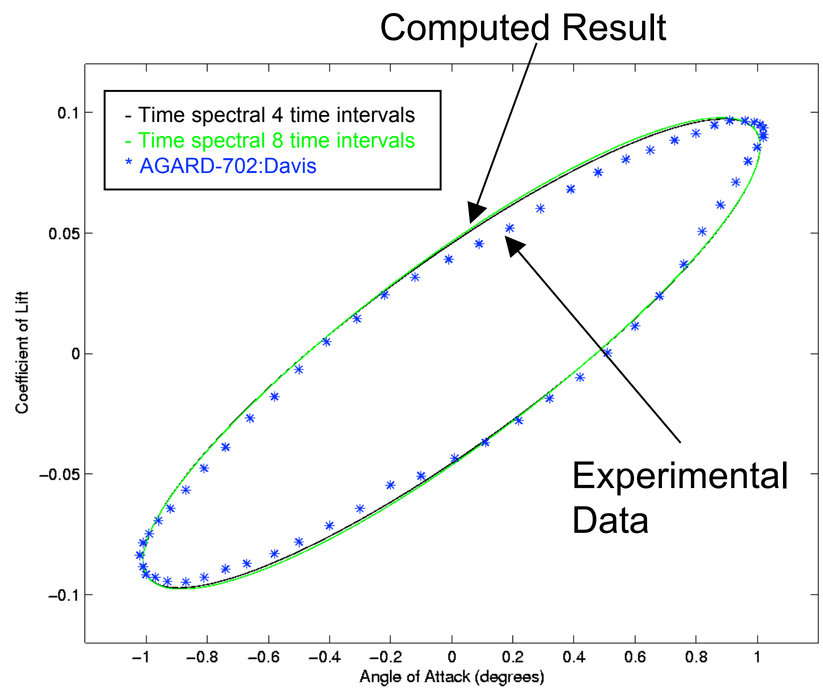


- RANS Computation
- CUSP Scheme
- k-/ / Turbulence Model



Results of Time Spectral Method

Periodic solution with 4 and 8 time intervals

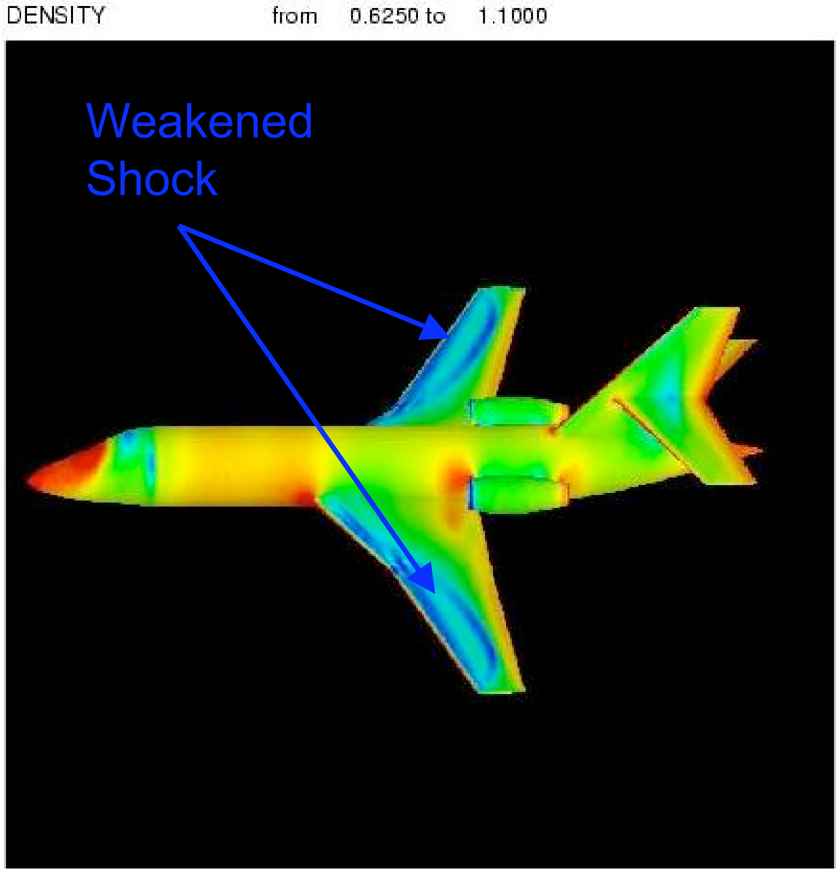


Pitching Airfoil (AGARD 702)

Pressure Contours at Various Time Instances

Automatic Redesign of Falcon Business Jet

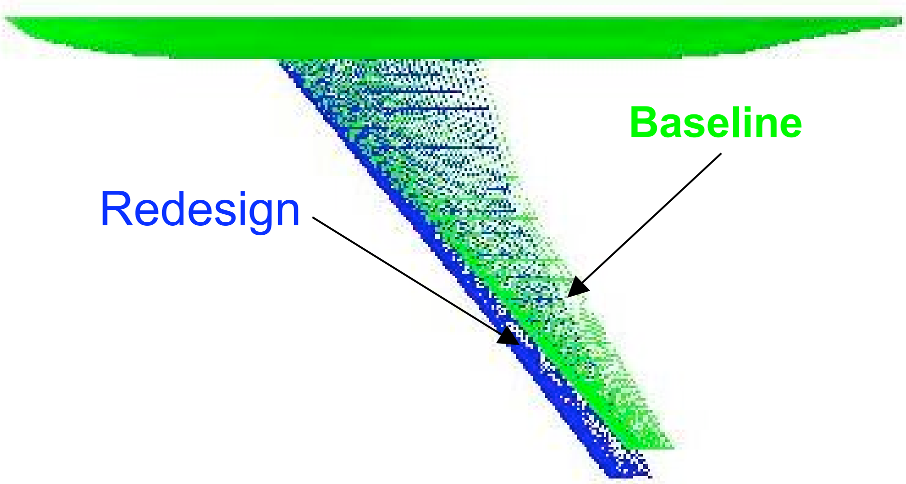
Using SYNPLANE
Drag reduction 18 counts
at fixed $C_L = 0.4$



C_D = 216 counts

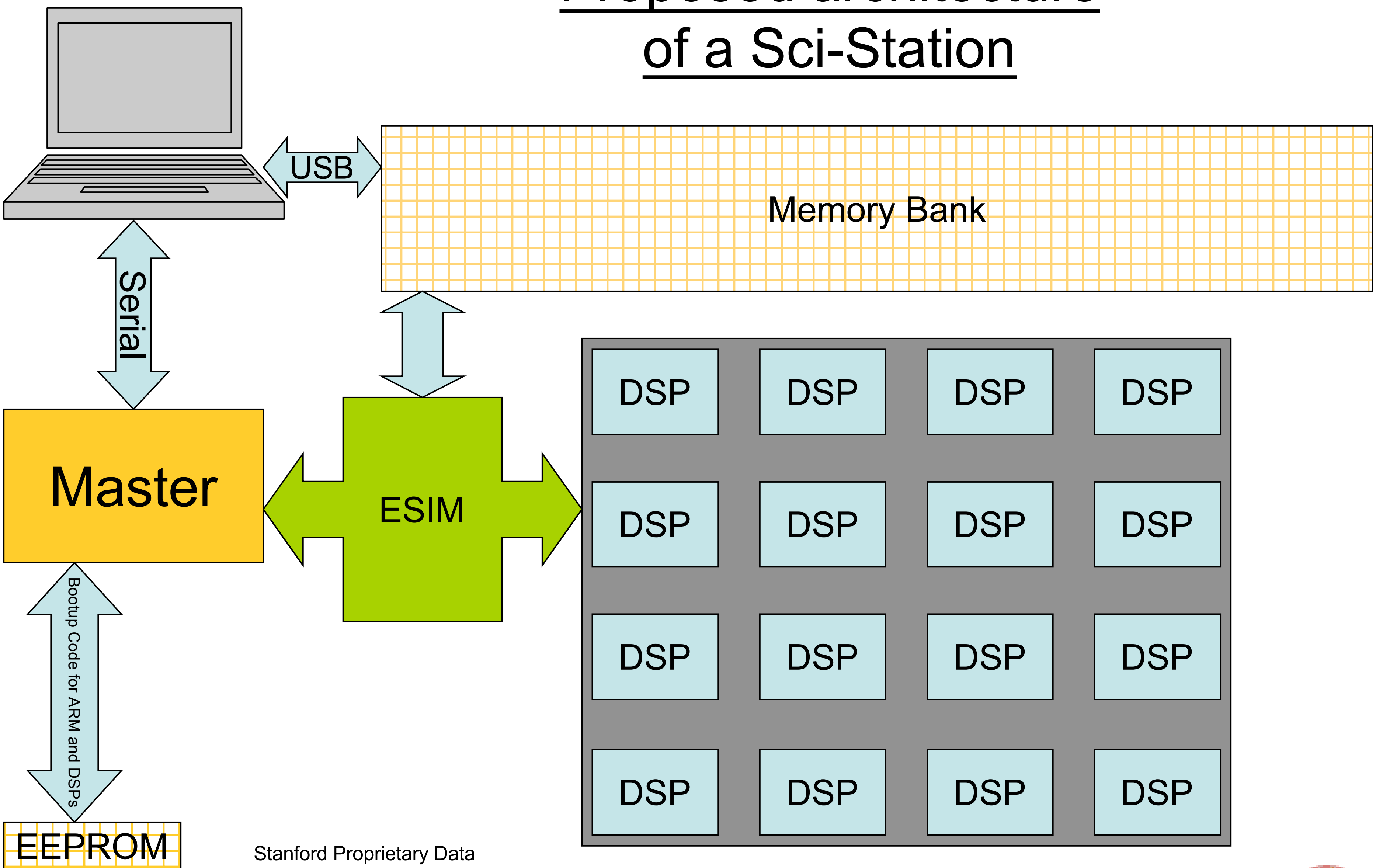
Automatic Redesign of Boeing 747 Planform

Using SYN88*
Drag reduction 21 counts
Weight reduction 800 pound
at fixed $C_L = 0.42$



$C_{D,wing}$ = 87 counts
$C_{w,wing}$ = 450 counts

Proposed architecture of a Sci-Station



Stanford Proprietary Data

Propriety data

Contents

Part 1

Concept of a SciStation

on each engineer's desktop

Presented by Gurjeet Singh

Goal : Enable all the calculations shown above to be routinely performed on the desktop

Payoff : Improved productivity in design and engineering

Patents pending

Outline of the SciStation

- Need for specialized hardware
- Requirements
- Proposed architecture
- Steps of execution
- Programming
- Comparison with FPGA
- Comparison with ASIC
- Other applications
- Performance
- Limitations
- Resource requirements
- Proposal for work on a SciStation

Need for Specialized Hardware (1)

- Flow simulations are very time consuming
  - Current hardware is not optimized for scientific calculations
  - Most of crunching power is devoted to ‘peripheral’ computations

- Aerodynamic loads need eventually to be predicted for many thousands of points in the flight envelope

- We are moving towards aerodynamic shape optimization (ASO)
  - Each cycle of optimization may require multiple simulations

- Jet engine and helicopter wake simulations are still more complex

Need for Specialized Hardware (2)

- Increased computing power at the desktop level could enable engineers to obtain important data on the spot, and eliminate costs, management procedures and delays associated with a remote central computing system

- This could both accelerate the design process and increase productivity.

Need for Specialized Hardware (3)

- Current desktop equipment using general purpose processors (Athlon, Pentium etc.) have overtaken the previous generation of scientific workstations (Apollo, Sun, SGI etc), because of the dramatic increase in performance and decrease in cost of microprocessors, DRAM and disks.

- But there is a potential order of magnitude increase in desktop performance by optimizing machine's architecture for scientific computing In which, the general microprocessor and PC manufacturers have little interest)

- A SciStation should be designed for a wide range of engineering applications:
  - Fluid mechanics
  - Solid mechanics
  - Heat transfer
  - Acoustics
  - Electromagnetics

Requirements

- For fluid mechanics, a system that can handle
  - 10 Million grid cells
  - 500 time steps
  - 4000 operations per time step
- Parallel decomposition of the problem
- Easy re-programmability
- Accuracy of simulation
- Speed

Proposed Architecture

- One master processor
- Several ‘slave’ processors
- One huge memory bank
- Interface with the PC
- Is the SciStation a co-processor to be added to a standard PC ?
  - YES (though its not a single chip co-processor)

Proposed Architecture

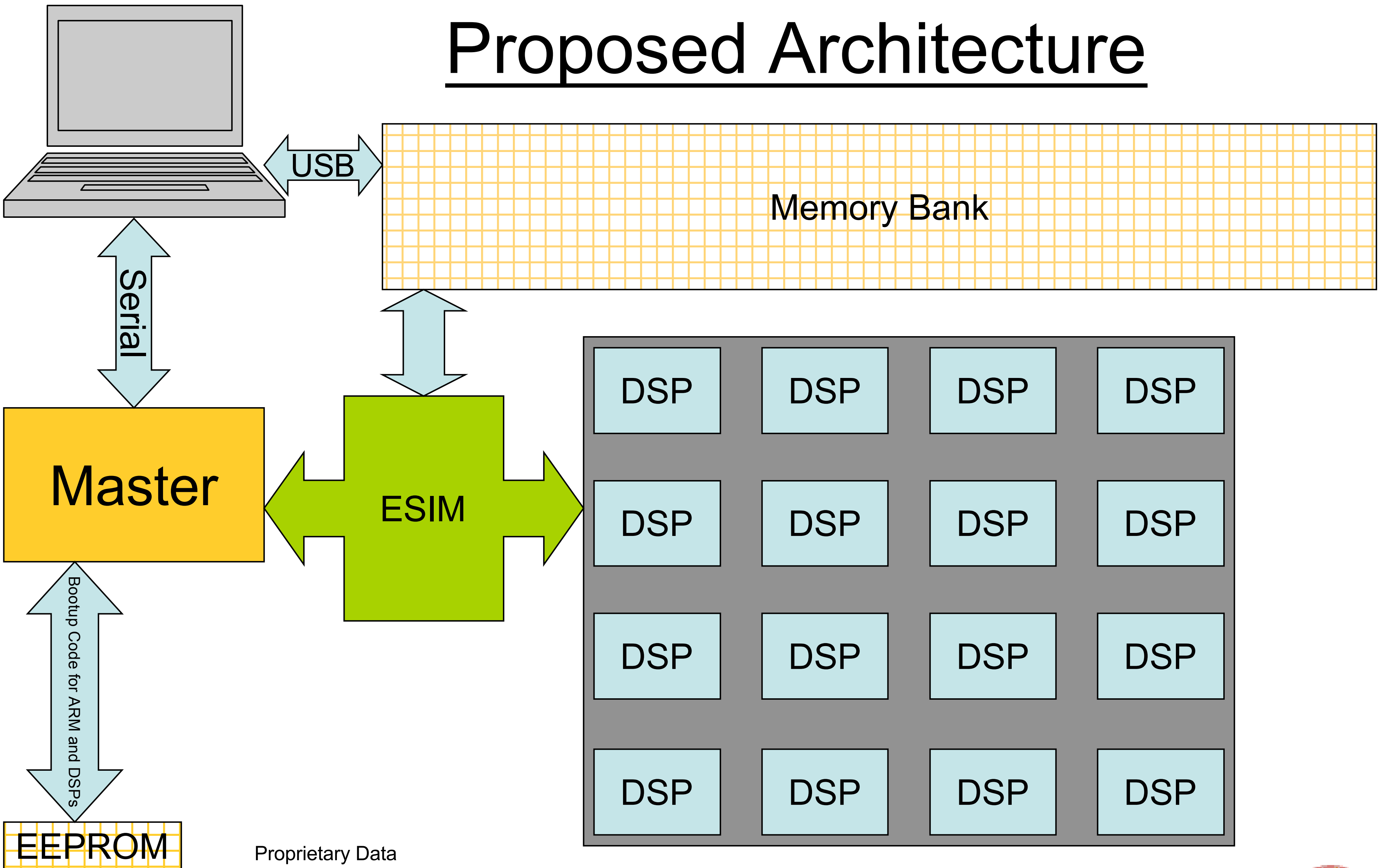
- Which slave processors to use ?
- Digital Signal Processors(DSP)
  - Originally designed for real time applications
  - Being used in data and processing intensive tasks such as digital cameras, MP3 players, nearly any smart electronic device
  - Extremely capable of handling large amounts of data
  - Extremely fast (because of real-time applications)
  - Double precision accuracy without overhead
    - Designed such because applications such as professional audio decoding and image processing etc. require high numerical precision
  - Technology scaling as Moore's law
  - Fastest processor available today : TI Cxx Raptor core
    - ~800Mhz, but if programmed optimally, can give max output ~3Ghz
    - IEEE Double precision compliant

Proposed Architecture

- Master processor
  - Communicates with the PC
    - Fetches initial data
    - Pushes back the result
  - Delegates work packets to the DSPs.
  - Manages control signals and memory

- DSP
  - Computes solution ‘chunks’ as and when data is provided by the master processor.

Proposed Architecture



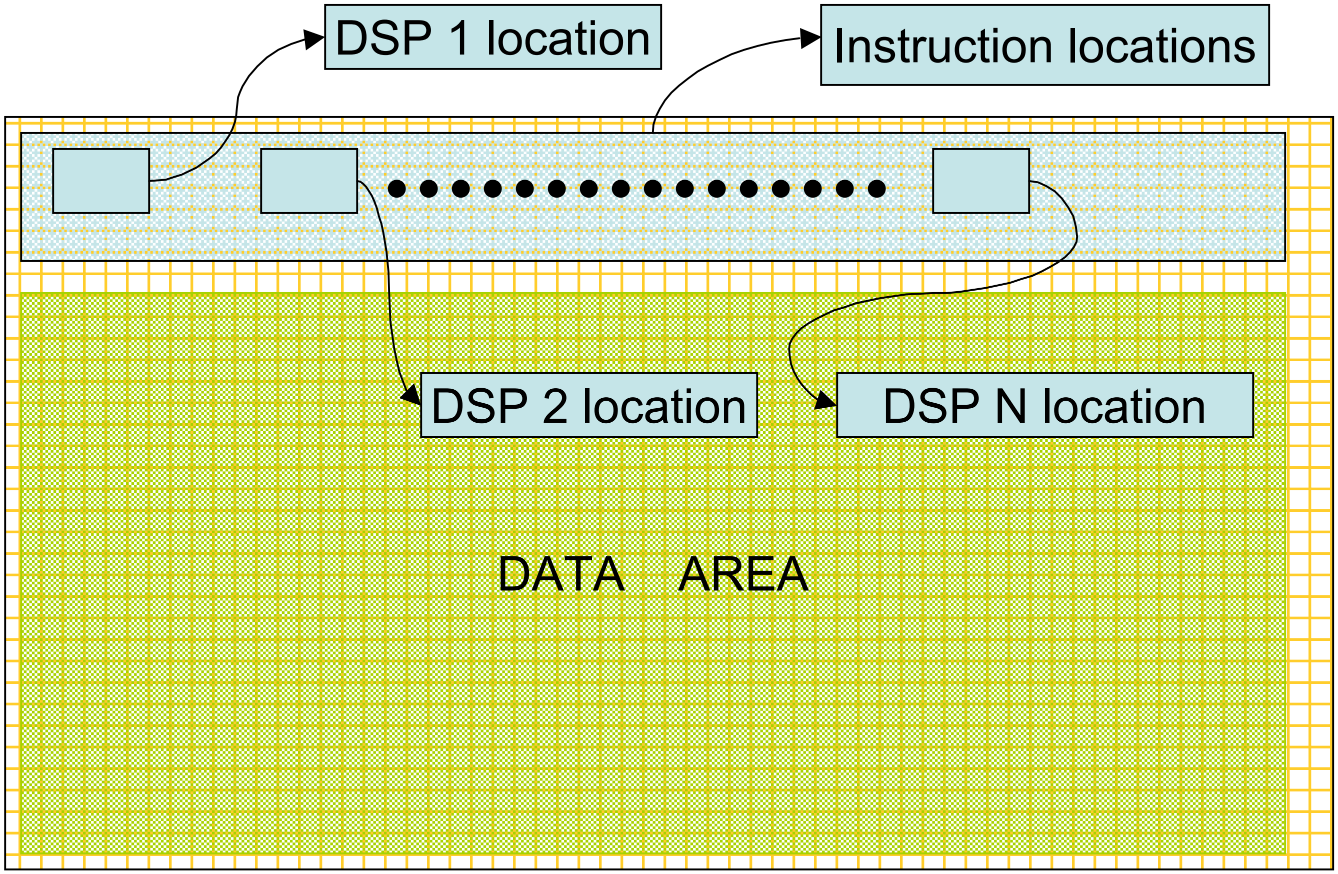
Proprietary Data

Patents pending

Proposed Architecture

- Shared memory parallelism
  - Each DSP has a fixed location and memory segment in the memory
  - The master processor installs data in the memory
  - The DSP's poll the memory for fresh data
  - The DSP's push results onto the memory

Proposed Architecture Shared Memory

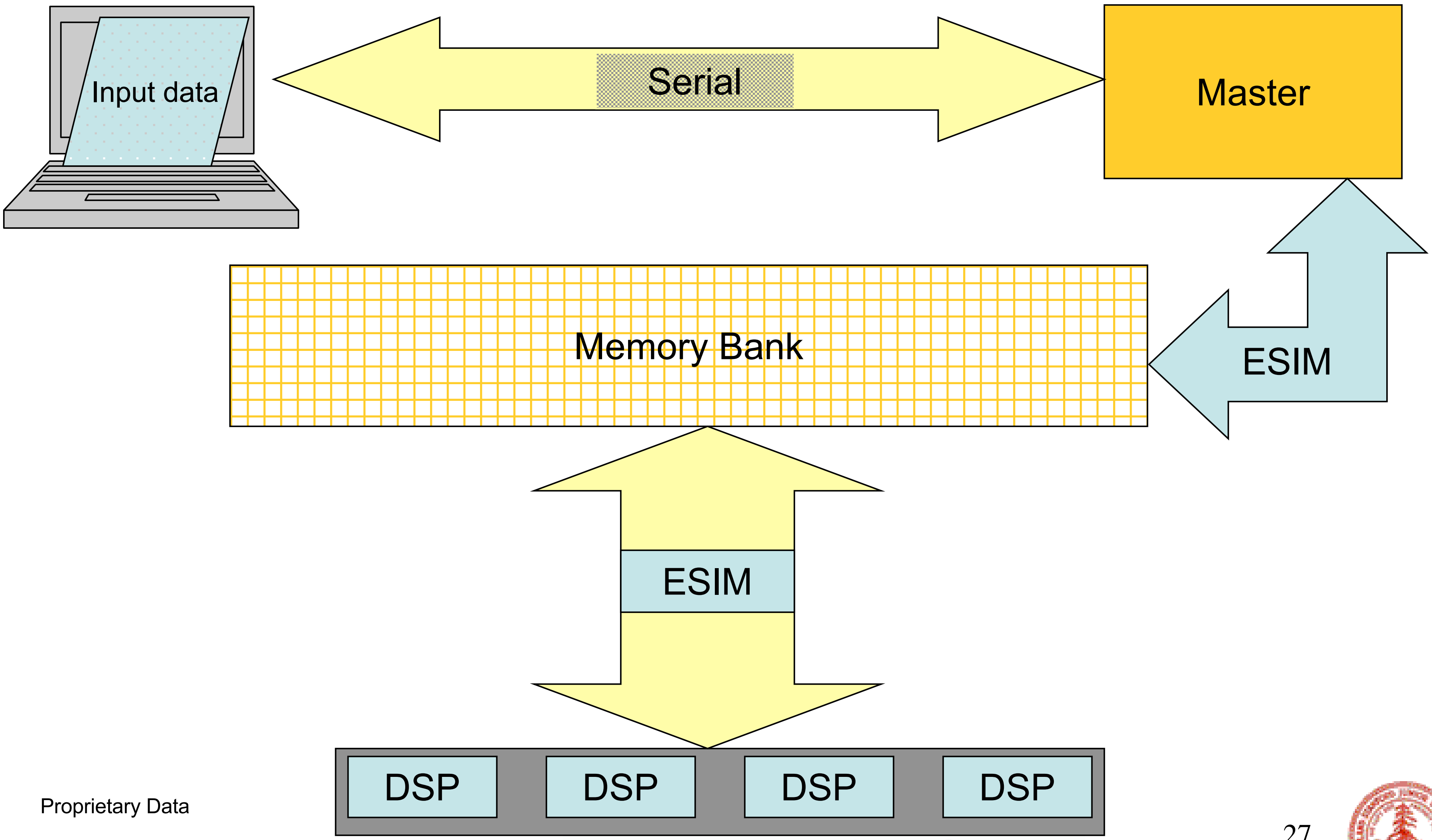


Proprietary Data

Steps of Execution

- Master processor receives data from the computer and stores it in the memory
- The master processor, burns code into each DSP from the memory
- DSP's poll the memory for their data
- DSP's complete computation and push the finished data back into the memory.

Steps of Execution



Proprietary Data

Patents pending

Programming (Types of Codes)

- 2 – Tier programming
  - Code for each of the DSP's
    - Flow solver
    - Code installed at run-time by the master processor
  - Code for the Master processor
    - Parallelization schemes and data division
    - Communication and signal handling

Programming (Language Break-down)

- All the scientific code is in high level languages (such as C and Java), for easy re-programmability

- The basic operating code for the Master processor and DSP primitive polling code is in Assembly language. This code should not need to be changed too frequently

Programming (Code Break-down)

- Assembly language code
  - Used for bootstrap process
    - Find out system setup (such as number of processors)
    - Load up DSP code from memory
    - Load up Master processor code
    - Extremely light-weight and efficient
- High level language code
  - The main PDE solver
  - Loaded into DSP and Master memory by assembly code
  - Can be arbitrarily large

Comparison with Field Programmable Gate Arrays (FPGAs)

- Pros of FPGAs
  - Relatively easy to re-program
- Cons of FPGAs
  - Need to code ALU for any operation
  - Slower than DSPs
  - For parallelization, most of FPGA silicon will be engaged in IO instead of number crunching

Comparison with Application Specific Integrated Circuits (ASICs)

- Pros of ASICs
  - Extremely fast
  - Optimized performance
  - Make sense for large numbers

- Cons of ASICs
  - Not re-programmable
  - Made to order
  - Extremely expensive

Applications

- The architecture is good for parallelizable problems, in particular
  - Navier Stokes solver
  - Radar Cross-Section equations
  - FEM calculations
  - Any problem requiring solution to PDE's

Expected Performance using Currently Available Hardware

- Each DSP operates at ~800Mhz
  - Capability should track with Moore's law

- For
  - 1 Million grid cells
  - 500 time steps
  - 4000 operations per step

- One DSP takes 7 Hours

- Eight DSP's can do the work in an hour at max.

Limitations

- Memory access is not quick
  - Due to data access rates on inexpensive large memories(4-16GB)
    - Could be alleviated by local cache on each DSP

- Time required to shuttle data to and from PC may be a bottleneck

- The architecture is good for parallelizable problems, but less suited for serial problems
  - Could be alleviated by code kernels

- 32-bit data addressing
  - Could be alleviated by using a serial data access standard (e.g. USB 2/FireWire)

Resource Requirements

- Proof of concept with 3 DSP processors could be built by a single person (Knowledgeable of both computer hardware and numerical algorithms (Gurjeet Singh) ($75,000 over 18 Months)

- 3 people might be needed to design a full prototype system with 16 processors

- Recurring Estimated Parts cost per unit : $7700 for 16 processors

Proposal for Work on a SciStation

- Phase 1
  - Proof of Concept
    - Time : 18 Months
    - Funding : $75,000
    - Gate Review
- Phase 2
  - Design of a prototype RANS SciStation
    - Time : 18 Months
    - Funding : $225,000
    - Gate Review
- Phase 3
  - Prototype Assembly and port other problems
- Phase 4
  - Manufacturing

Part 2

Enabling Algorithms in CFD

Embedded in a Unified Code Architecture:
Flo3xx

Presented by Georg May

CFD Is Now on a Plateau

- Existing codes can reliably and accurately predict steady inviscid flow
- There are major issues in mesh generation, convergence, and accuracy for turbulent viscous flows over complex configurations, including prediction of transition and separation
- We aim to provide a better framework to tackle these issues

Overview

A. Flo3xx: The latest addition to the widely used "FLO" series of codes

B. The Nonlinear SGS Multigrid Method: Achieving textbook multigrid convergence

C. The BGK Method: Using kinetic gas theory for aerodynamic problems of practical engineering interest

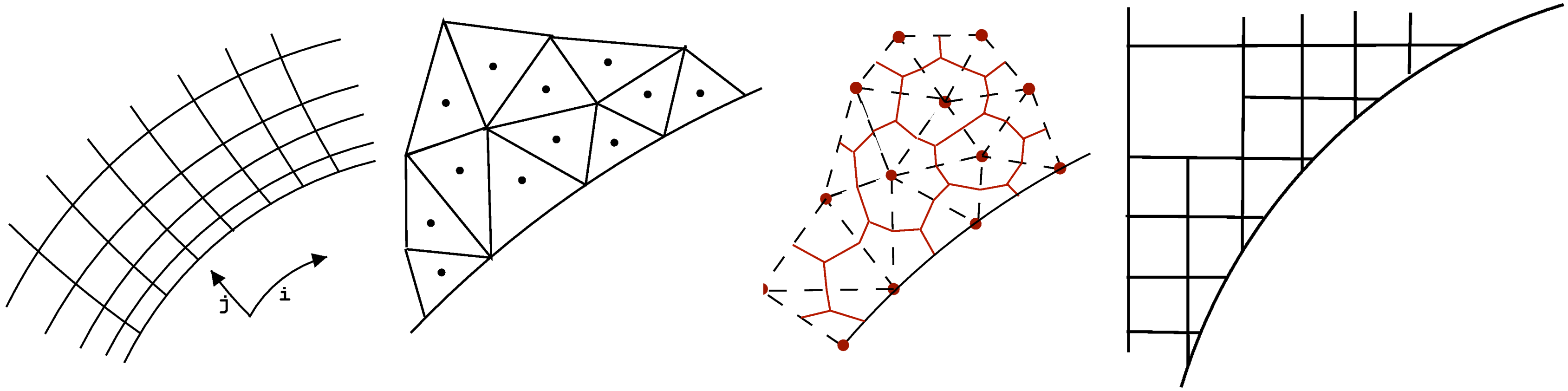
D. The Time-Spectral Method: Time accurate solution of complex, periodically unsteady flow

Part 2A

Flo3xx
Computational Aerodynamics on Arbitrary Meshes

Support for Arbitrary Meshes

- Examples of mesh types which are being used in computational aerodynamics

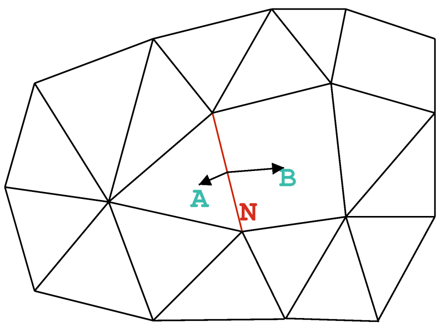


Structured | Unstructured Cell-Centered | Unstructured Cell-Vertex | Nested Cartesian With Cut Cells

- In Flo3xx a unified mesh-blind formulation supports all of these in one code
- Designed to meet the following objectives:
  - Platform for automatic mesh adaptation
  - Migration path to emerging mesh generation technologies
  - A robust algorithm that is tolerant to bad meshes

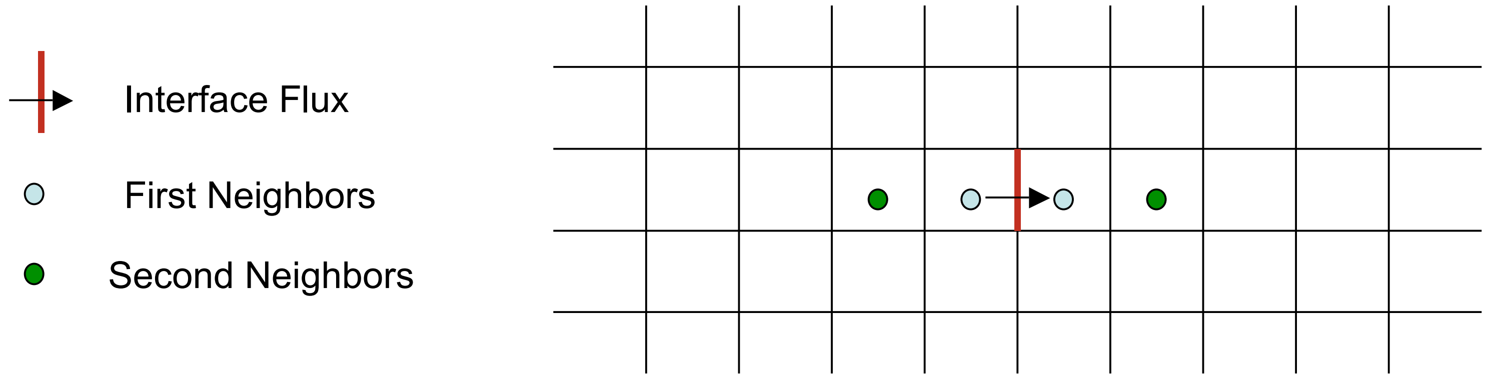
Support for Arbitrary Meshes

- Conservation laws are enforced on discrete control volumes
- Fluxes of conserved variables are exchanged through interfaces between these cells
- Independent of the mesh topology, each interface separates exactly two control volumes (on the right, face N separates cells A and B)



All algorithms are expressed in terms of a generic interface-based data structure

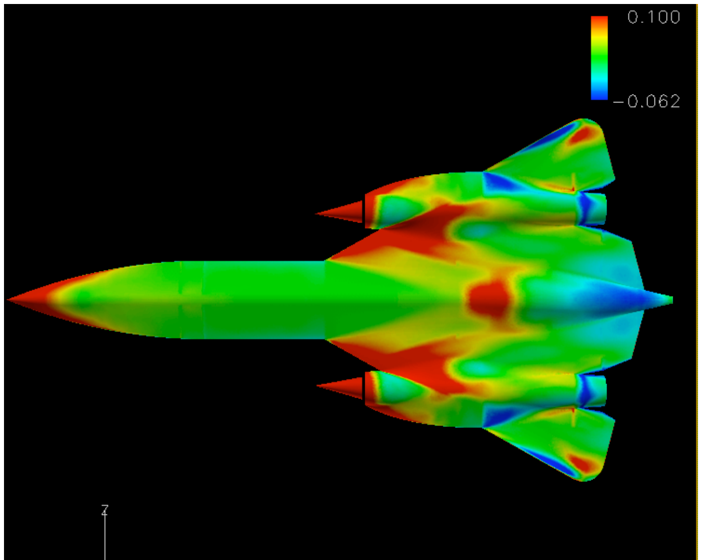
Treatment of Structured Meshes



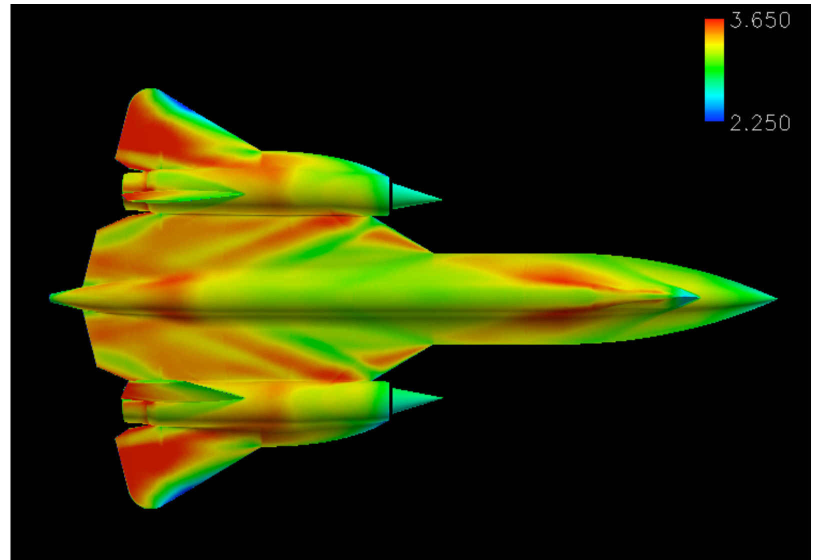
- Associate first and second neighbors with each face
- Allows implementation of standard schemes with five-point stencils (Jameson-Schmidt-Turkel JST, SLIP) in the same code
- Eliminates the need for gradient reconstruction
- Numerical experiments verify 25% overhead due to indirect addressing in comparison with standard structured-code implementation (FLO107)

Flo3xx in Action…

Pressure Coefficient - Lower



Mach Number - Upper

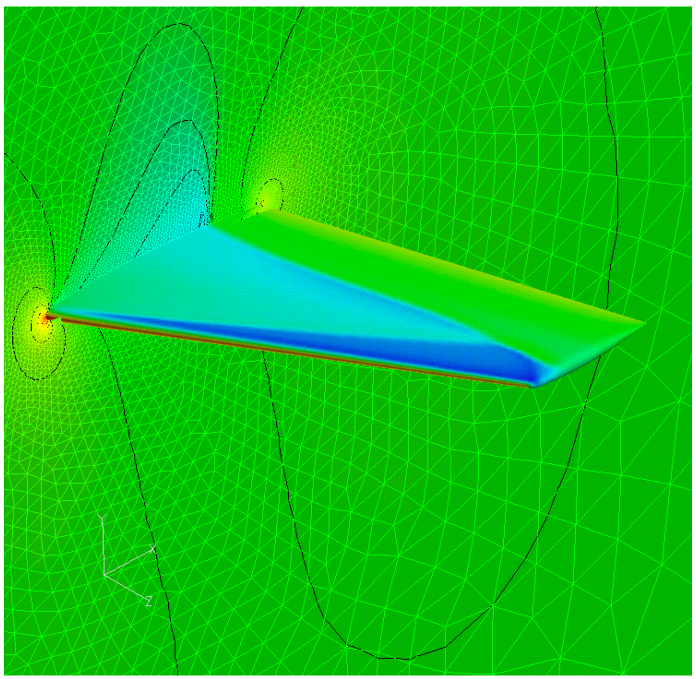


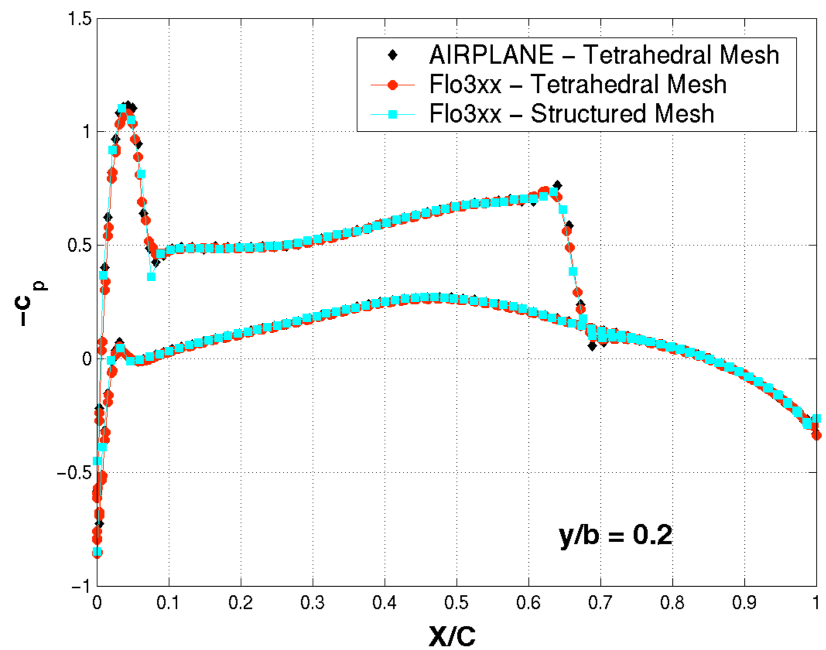
Geometry Courtesy of Lockheed Skunk Works

Lockheed SR71 at M= 3.2, / / = 5 deg. - Euler calculation with 1.5 Million grid points

- **From IGES definition to completed result in one week, including CAD fixes, mesh generation**
- **We need to be able to compute extreme test cases**
- **This concerns both complexity of geometry and flow conditions**

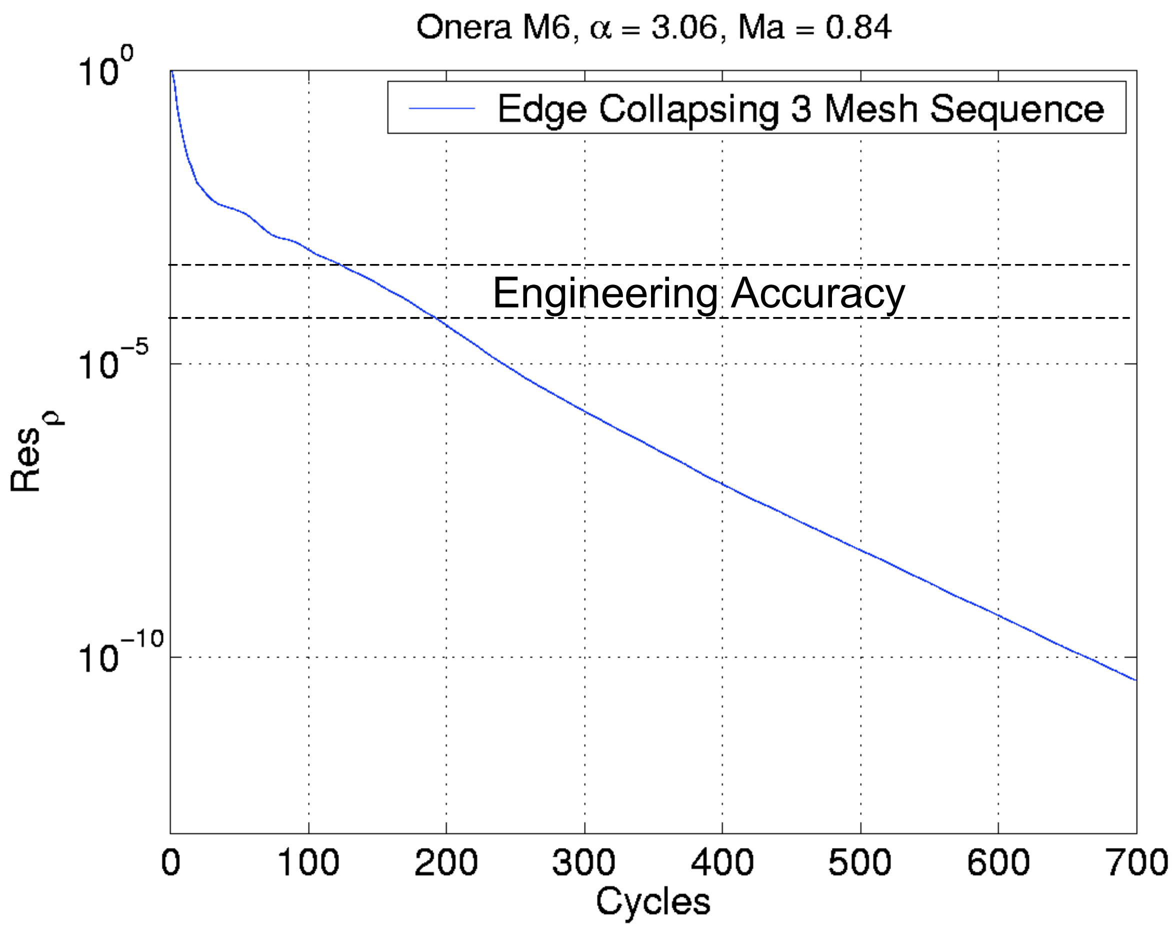
Validation of Unified Solution Algorithm in Flo3xx: Inviscid Transonic Flow

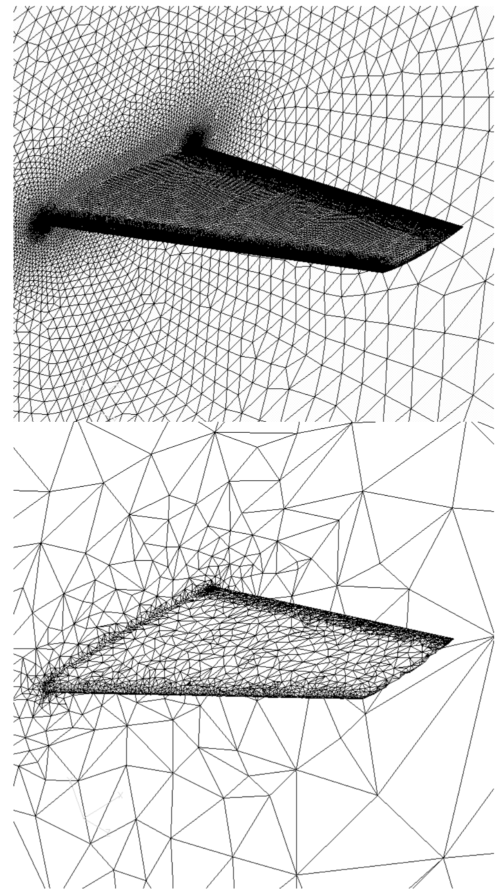




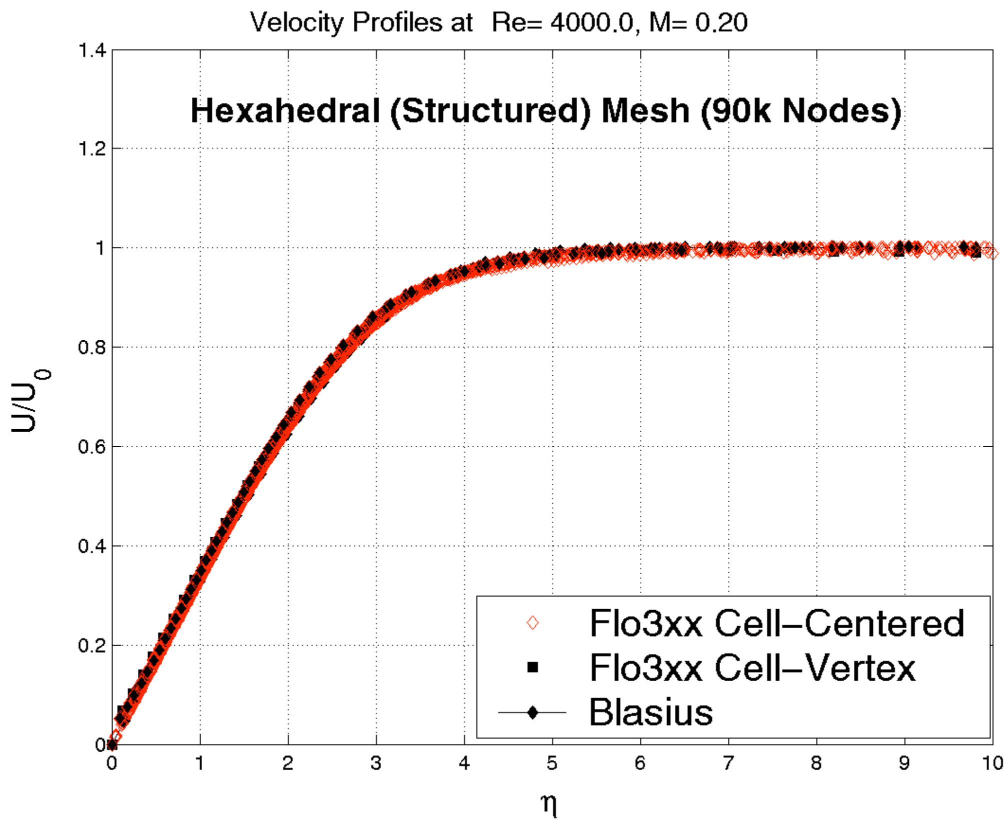
- Onera M6 Wing at M=0.84 and / / = 3.06 degrees

Convergence Using Automatic Multigrid



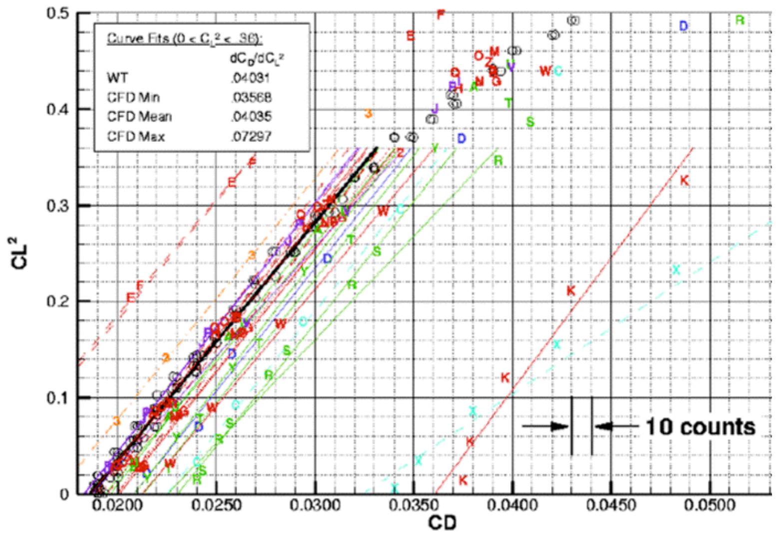


Initial Validation for Viscous Flow: Zero-Pressure-Gradient Boundary Layer

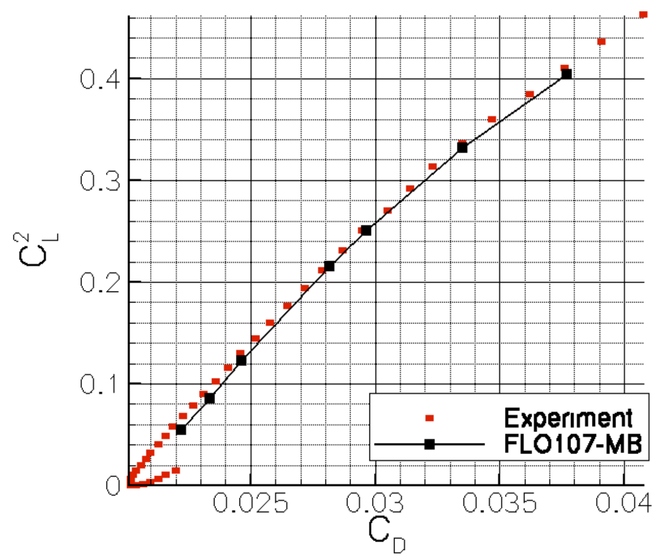


RANS Results Using FLO107-MB For Drag Prediction Workshop

Statistical Evaluation DPW1 – All Participants



Flo107-MB (DPW2)



- Accurate drag prediction for complex geometries in transonic flow is still very hard
- Flo3xx is currently in viscous validation phase.
- FLO107-MB has been thoroughly validated.
- Results of right figure were obtained with CUSP scheme and k-/ / turbulence model

Flo3xx Payoffs

- Highly flexible platform for all applied aerodynamics problems and other problems governed by conservation laws
- Fast turnaround through convergence acceleration techniques
- Framework can be used to support advanced research, such as the BGK method or the Time-Spectral Method, which will be addressed in this talk
- This means, take advanced research out of a laboratory setting and apply it to problems of practical engineering interest, which is ultimately the only way to make an impact on the state-of-the art

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Part 2B

Non Linear Symmetric Gauss-Seidel Multigrid Scheme

Jameson + Caughey 2001
Evolved from LUSGS scheme
Yoon + Jameson (1986)
Rieger + Jameson (1986)
Achieved "Text Book" Multigrid Convergence

Nonlinear Symmetric Gauss-Seidel (SGS) Scheme

Forward and reverse sweeps:

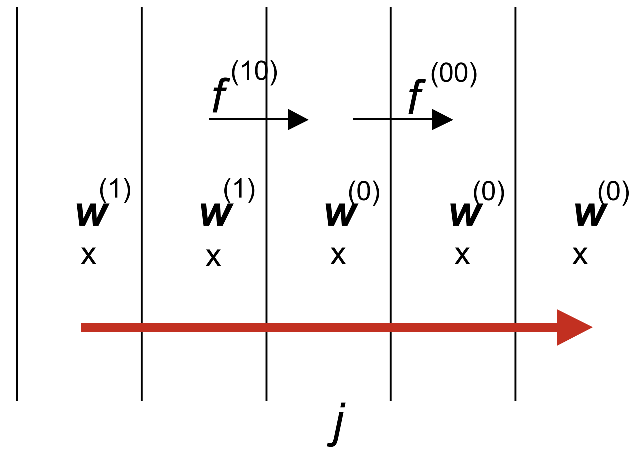
For 1D case: $\frac{\partial w}{\partial t} + \frac{\partial}{\partial x} f(w) = 0$

Sweep (1): Increasing j →

$$w_j^{(1)} = w_j^{(0)} - |A|^{-1}\left[f^{(00)}_{j+\frac{1}{2}} - f^{(10)}_{j-\frac{1}{2}} \right]$$

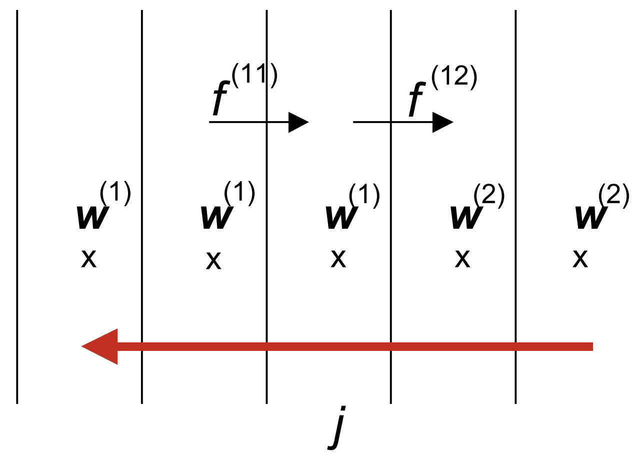
$$f^{(01)}_{j-\frac{1}{2}} = f\left(w_j^{(0)}, w_{j-1}^{(1)}\right)$$

$$A = \frac{\partial f}{\partial w}$$



Sweep (2): Decreasing j →

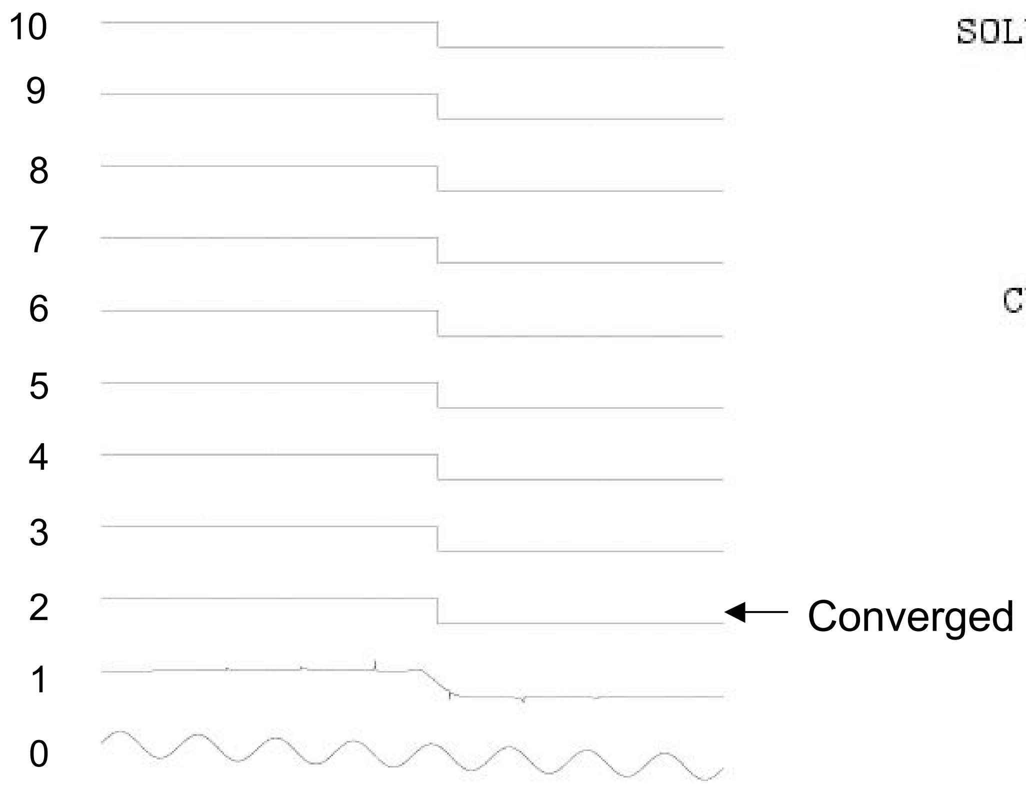
$$w_j^{(2)} = w_j^{(1)} - |A|^{-1}\left[f^{(12)}_{j+\frac{1}{2}} - f^{(11)}_{j-\frac{1}{2}} \right]$$



4 Flux evaluations in each double sweep

Cost per iteration similar to 4 - stage Runge - Kutta scheme

Solution of Burgers Equation on 131,072 Cells in Two Steps With 15 Levels of Multigrid



SOLUTION OF BURGERS EQUATION BY SYMMETRIC RELAXATION
131072 CELLS 15 LEVELS
CFL 1.000 RAVG 0.0

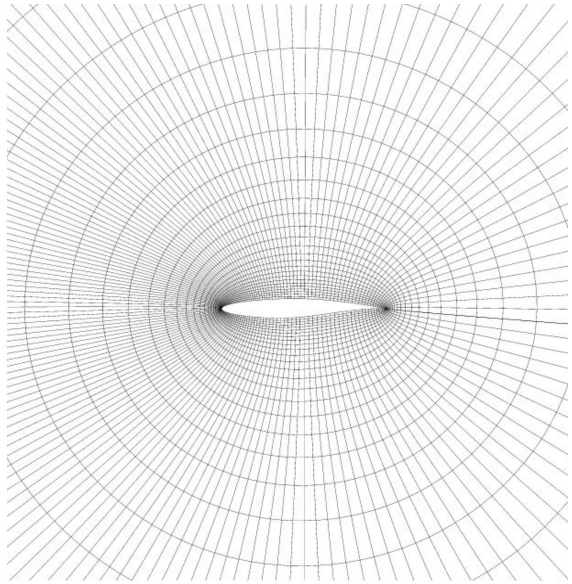
SOLUTION OF UT +UUX = 0.

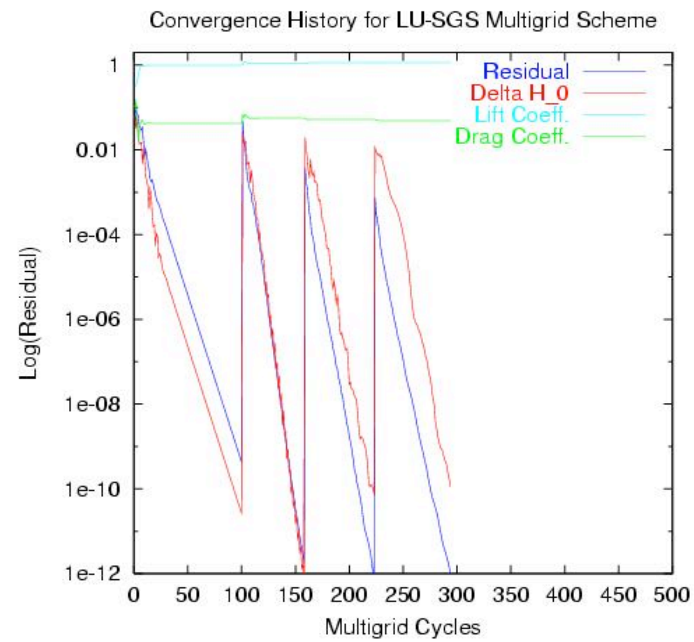
NX	N MESH
131072	15

CFL
1.0000

CYCLE	AVG RESIDL	MAX RESIDL	IMAX
1	0.8038E-02	0.1295E+01	57667
2	0.3413E-04	0.4337E+00	70962
3	0.2773E-06	0.9391E-01	70961
4	0.1576E-14	0.9567E-05	70959
5	0.3037E-28	0.7905E-13	70960
6	0.3037E-28	0.7905E-13	70960
7	0.3037E-28	0.7905E-13	70960
8	0.3037E-28	0.7905E-13	70960
9	0.3037E-28	0.7905E-13	70960
10	0.3037E-28	0.7905E-13	70960

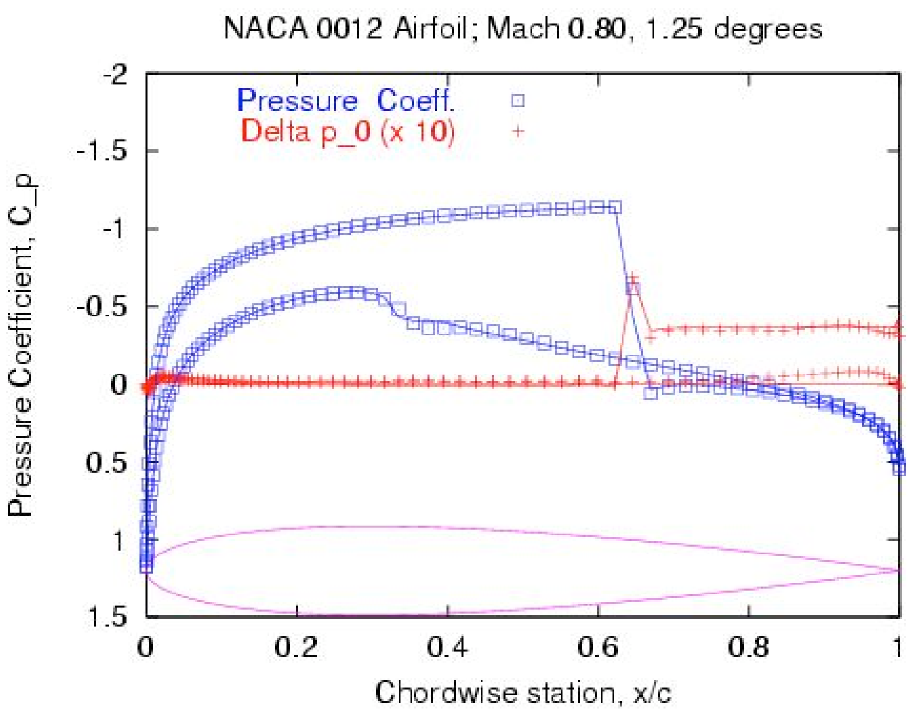
Solution of 2D Euler Equations: Convergence for NACA0012



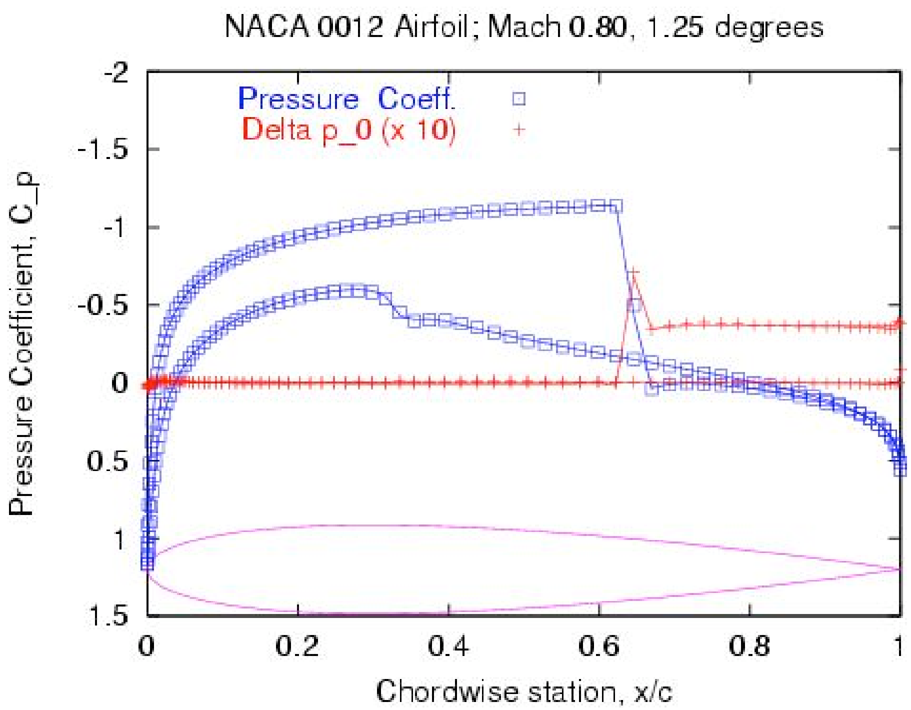


- The convergence history shows the successive computation on meshes of different sizes
- The convergence rate is independent of the mesh size
- Convergence rate ~ .75 per cycle

Solution of 2D Euler Equations
NACA0012 Airfoil



Solution after 3 multigrid cycles

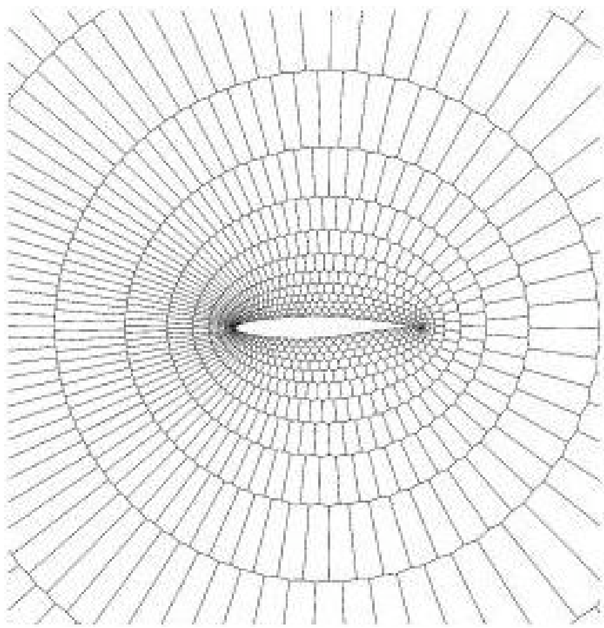


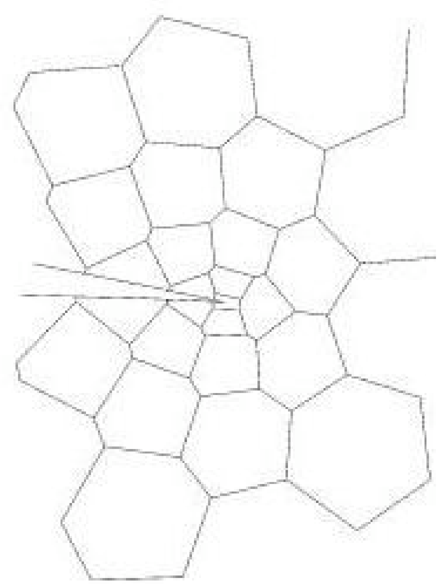
Solution after 5 multigrid cycles

Solid lines: fully converged result

Face-based Gauss Seidel (FBGS) Scheme

(Following a suggestion by John Vassberg)





- On an arbitrary grid, loop over faces instead of looping over cells
- Update the cells adjacent to a face as you go along
- Updated state will be used on next visit to a cell

Payoff of Fast Convergence (Solution in 10 - 300 Iterations)

- Faster turnaround
- Increased throughput
- Increased productivity
- Improved accuracy
- Increased reliability

Note: Gulfstream engineers report that the WIND code needs 30,000 iterations to produce a converged RANS solution for a supersonic inlet

Overview

A. Flo3xx: The latest addition to the widely used "FLO" series of codes

B. The Nonlinear SGS Multigrid Method: Achieving textbook multigrid convergence

C. The BGK Method: Using kinetic gas theory for aerodynamic problems of practical engineering interest

D. The Time-Spectral Method: Time accurate solution of complex, periodically unsteady flow

Part 2C

The Finite-Volume BGK Scheme

Using Statistical Mechanics to Enhance Computational Aerodynamics

A Major Conceptual Difference Between Continuum Mechanics and Statistical Mechanics

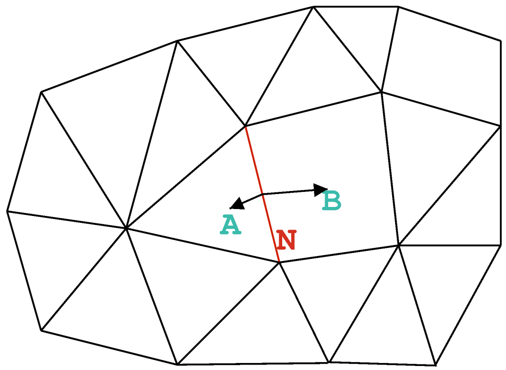
- In continuum mechanics the unknown solution variables are defined "pointwise" with precise values:

$$U = U(x, y, z, t)$$

- In statistical mechanics the solution variables exist only as moments of a statistical distribution in physical and phase space, or as "expectation values":

$$U = \int u\, f(x, y, z, u, v, w, \square, t)\, du\, dv\, dw\, d\square$$

The Key Idea of the Finite-Volume BGK Scheme



- Compute the fluxes for the Navier-Stokes equations at interface N from the distribution functions in cells A and B
- A time-dependent distribution function needs to be constructed at each time step for each cell

Finding the Distribution Function

- The equilibrium distribution function
  is known from Boltzmann statistics:

$$f_{eq} = g(x, y, z, u, v, w, \xi) = A(x, y, z)e^{-\lambda(x,y,z)\left\{(U-u)^2 + (V-v)^2 + (W-w)^2 + \xi^2\right\}}$$

- The nonequilibrium distribution function
  is unknown, but its evolution is given by the Boltzmann equation:

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} + w\frac{\partial f}{\partial z} = Q(f, f)$$

Collision Integral

- Global numerical solution infeasible, because of high dimensionality

A Crucial Simplification
(Bhatnagar, Gross & Krook - BGK)

- Replace the Collision Integral *Q* with a linear relaxation term:

$$Q = -\frac{f - g}{\tau} \quad | \, | \quad \boxed{\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} + w\frac{\partial f}{\partial z} = -\frac{f - g}{\tau}}$$

Collision Time

- This equation can be solved analytically:

$$f(\vec{x},\vec{u},t,\tau) = \int_0^t g(\vec{x} - \vec{u}(t - t'),\vec{u},t',\tau)\, e^{-\frac{(t - t')}{\tau}}\, dt' + e^{-\frac{t}{\tau}} f_0(\vec{x} - \vec{u}t,\vec{u},\tau)$$

A Key Observation

- By Chapman-Enskog expansion the Navier Stokes equations can be recovered from the BGK equation, with the viscosity coefficient

$$\mu = \tau p$$

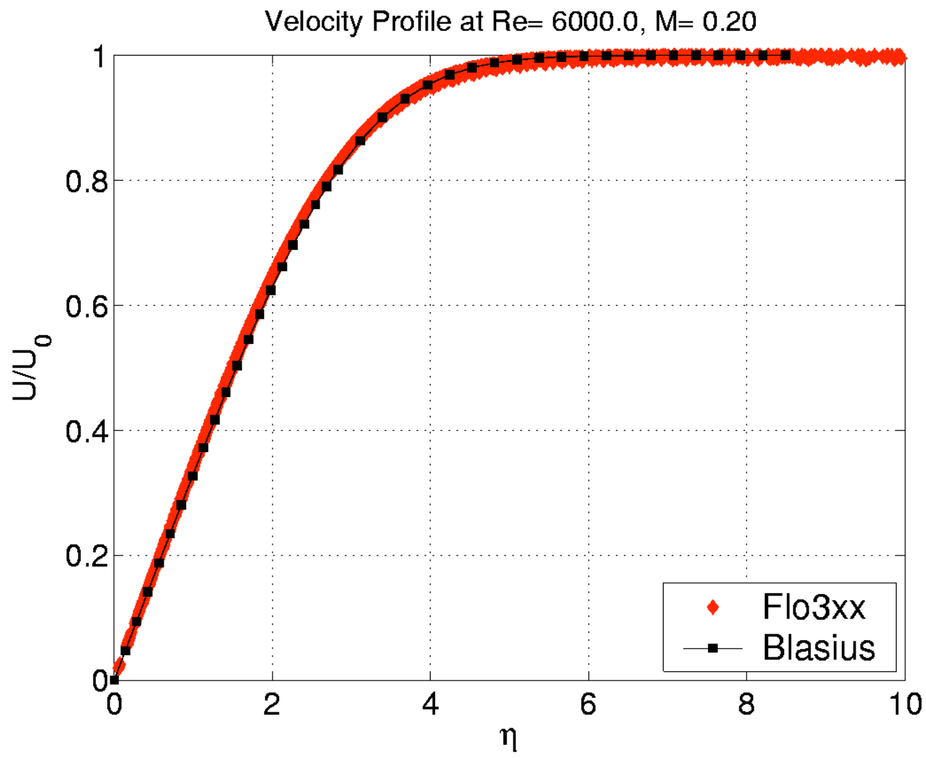
- By setting the collision time τ appropriately, Navier-Stokes fluxes can be computed directly from the distribution function

Payoff

- It is not necessary to compute the rate of strain tensor in order to calculate viscous fluxes
- This eliminates the need to perform two levels of numerical differentiation, which is difficult on arbitrary meshes
- Improved accuracy and reduced sensitivity to the quality of the mesh
- Automatic upwinding via the kinetic model, with no need for explicit artificial diffusion, thus reduced computational complexity

Validation of the BGK Scheme: Zero-Pressure-Gradient Boundary Layer

Blasius Profile



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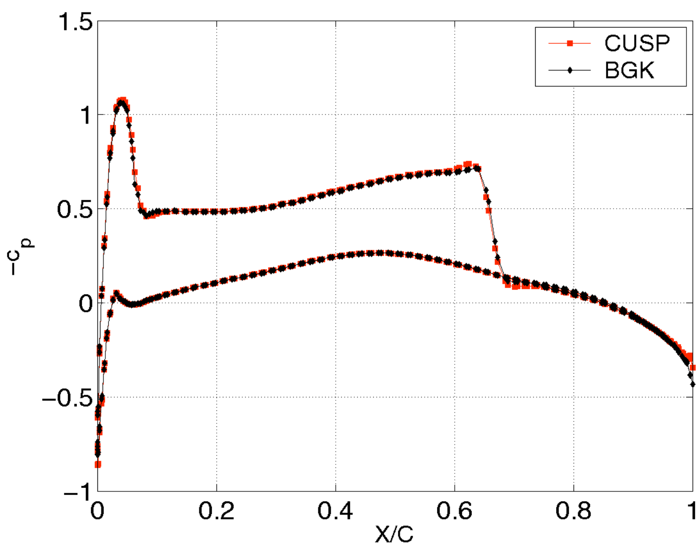
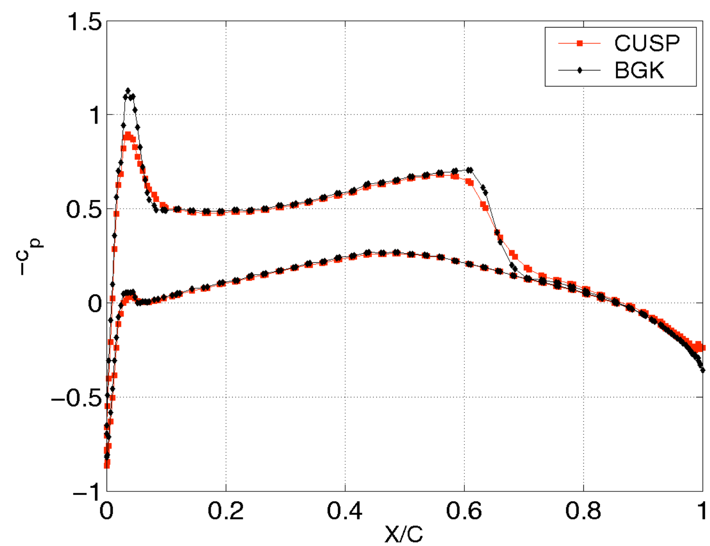
Validation of the BGK Scheme: Inviscid Transonic Flow

Finer Mesh (316k Nodes)



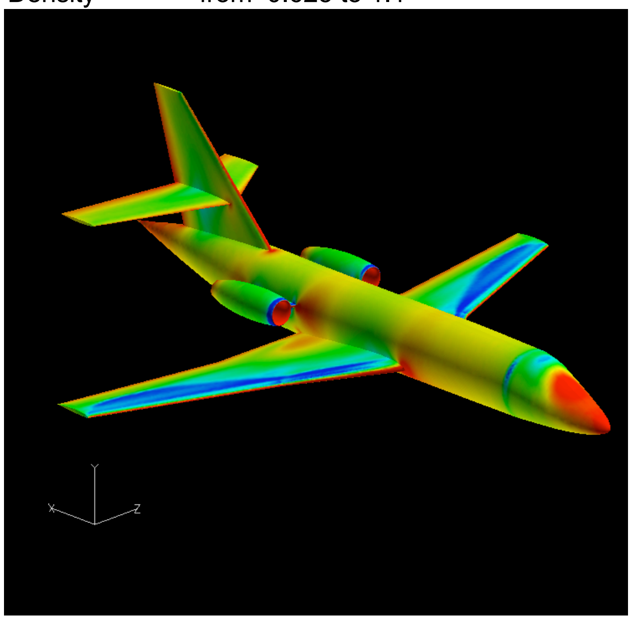
Coarser Mesh (94k Nodes)

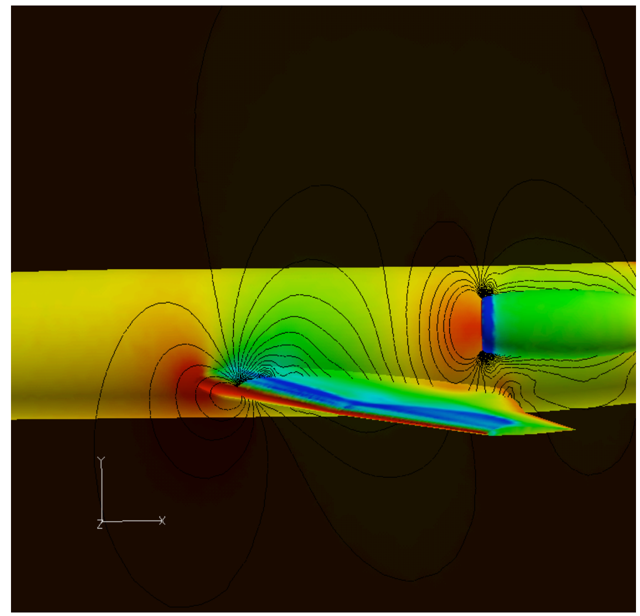


- Onera M6 Wing at M=0.84, / / = 3.06 degrees
- With sufficient resolution CUSP and BGK give similar results
- BGK seems to handle lower-resolution meshes better
- This might allow a reduction in the number of mesh points

Validation of the BGK Scheme using Flo3xx: Inviscid Transonic Flow

Density from 0.625 to 1.1





- Falcon Business Jet
- M = 0.8
- Angle of Attack: 2 degrees

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Part 2D

Fast Time Integration Methods for Unsteady Problems

Potential Applications

- Flutter Analysis,
- Flow past Helicopter blades,
- Rotor-Stator Combinations in Turbomachinery,
- Zero-Mass Synthetic Jets for Flow Control

Dual Time Stepping BDF

The kth-order accurate backward difference formula (BDF) is of the form

$$D_t = \frac{1}{\Delta t} \sum_{q=1}^{k} \frac{1}{q} (\Delta^-)^q \qquad \text{where} \quad \Delta^- w^{n+1} = w^{n+1} - w^n$$

The non-linear BDF is solved by inner iterations which advance in pseudo-time t*

The second-order BDF solves

$$\frac{dw}{dt^*} + \left[\frac{3w - 4w^n + w^{n-1}}{2\Delta t} + R(w) \right] = 0$$

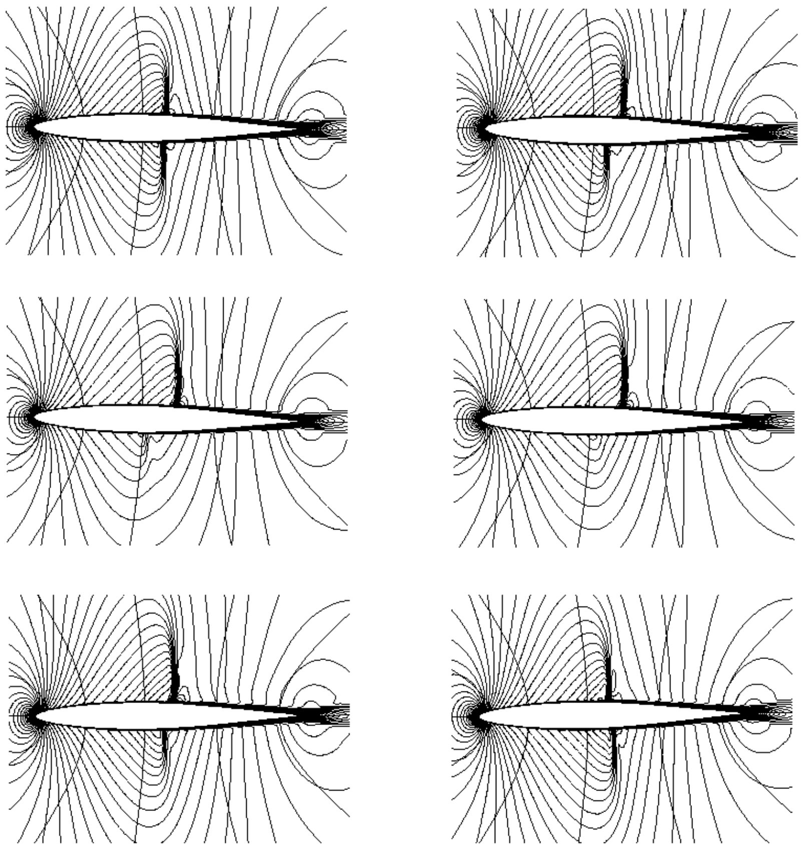
Implementation via

- RK "dual time stepping" scheme with variable local Δt^* (RK-BDF)
- Nonlinear SGS "dual time stepping" scheme (SGS-BDF)

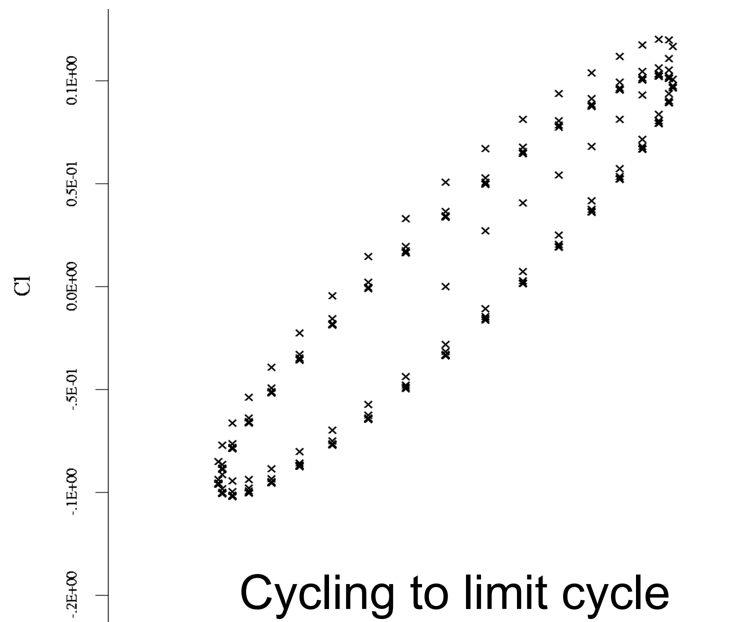
with Multigrid

Test Case: NACA64A010 pitching airfoil (CT6 Case)

Mach Number	0.796
Pitching amplitude	+/- 1.01deg.
Reduced Freq.	0.202
Reynolds Number	12.36 million



Pressure Contours at Various Time Instances (AGARD 702)



Results of SGS-BDF Scheme

(36 time steps per pitching cycle, 3 iterations per time step)

Payoff of Dual-time Stepping BDF Schemes

- Accurate simulations with an order of magnitude reduction in time steps.

- For the pitching airfoil:
  from ~ 1000 to 36 time steps per pitching cycle
  with three sub-iterations in each step.

Frequency Domain and Global Space-Time Multigrid Spectral Methods

Application : Time-periodic flows

Using a Fourier representation in time, the time period T is divided into N steps.

Then,

$$\hat{w}_k = \frac{1}{N}\sum_{n=0}^{N-1} w^n e^{-ikn\Delta t}$$

The discretization operator is given by

$$D_t w^n = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} ik\hat{w}_k e^{ikn\Delta t}$$

Method 1 (McMullen et.al.) : Transform the equations into frequency domain and solve them in pseudo-time t*

$$\frac{d\hat{w}_k}{dt^*} + ik\hat{w}_k + \hat{R}_k = 0$$

Method 2 (Gopinath et.al.) : Solve the equations in the time-domain. The space-time spectral discretization operator is

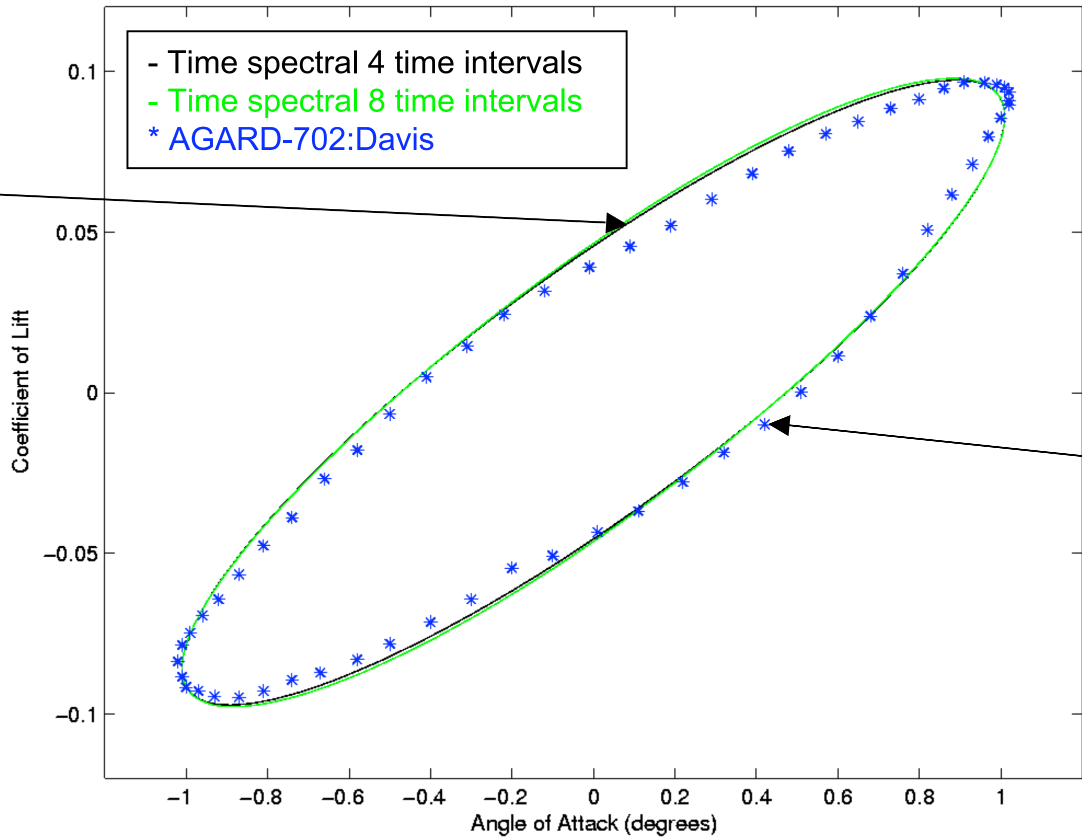
$$D_t w^n = \sum_{m=-\frac{N}{2}+1}^{\frac{N}{2}-1} d_m w^{n+m}, \qquad d_m = \frac{1}{2}(-1)^{m+1}\cot\left(\frac{\pi m}{N}\right), m \neq 0$$

This is a central difference operator connecting all time levels, yielding an integrated space-time formulation which requires simultaneous solution of the equations at all time levels.

Comparison with Experimental Data - C_L vs.

RANS Time-Spectral Solution with 4 and 8 intervals per pitching cycle

Computed Results



Experimental Data

Payoff of Time Spectral Schemes

- Engineering accuracy with very small number of time intervals and same rate of convergence as the BDF.

- Spectral accuracy for sufficiently smooth solutions.

- Periodic solutions directly without the need to evolve through 5-10 cycles, yielding an order of magnitude reduction in computing cost beyond the reduction already achieved with the BDF,
for a total of two orders of magnitude.

CFD Algorithms: Open Issues

- Capability of turbulence models to predict transition and separation
- Prediction of transitional flows - which may be very important for small UAVs
- Reliable a posteriori error bounds based on the computed result
- Fast convergence of viscous solutions on arbitrary meshes (perhaps with the SGS multigrid scheme)
- BGK Scheme for RANS equations, hypersonic and rarefied gas flows

Proposal

• Collaborative development between Boeing, Intelligent Aerodynamic Inc. and Stanford University of advanced algorithms to be incorporated in industrial-strength software to provide:
assured accuracy, throughput, and turnaround.

• Funding, and distribution of intellectual property rights of derivative software, to be negotiated.

Part 3

Application of Shape Optimization via Control Theory

to Aerodynamic Design, with Potential for Other Disciplines

Presented by Antony Jameson and
Kasidit Leoviriyakit

Intelligent Aerodynamics Inc.

STANFORD UNIVERSITY
Aerospace Computing Laboratory

Outline

- Automatic Design via Control Theory
- Planform and Aero-Structural Optimization
- Design using an Unstructured Mesh

Note on the History of the Adjoint Method for Transonic and Supersonic Wing Design

- Since the original proposal to apply the adjoint method to transonic wing design (Jameson, 1988), shape optimization via control theory has been the subject of 15 years intensive development.

- Multiple sources of funding, including Air Force Office of Scientific Research.

- First numerical results: *Jameson 1989, Science Vol 245, 361 - 371*

- Applications to Beech Premier, MDXX 1995 - 1996

- Application to HSCT 1997 - 2000

Levels of CFD

HIGHEST

Automatic Design

• Integrate the predictive capability into an automatic design method that incorporates computer optimization.

Interactive Calculation

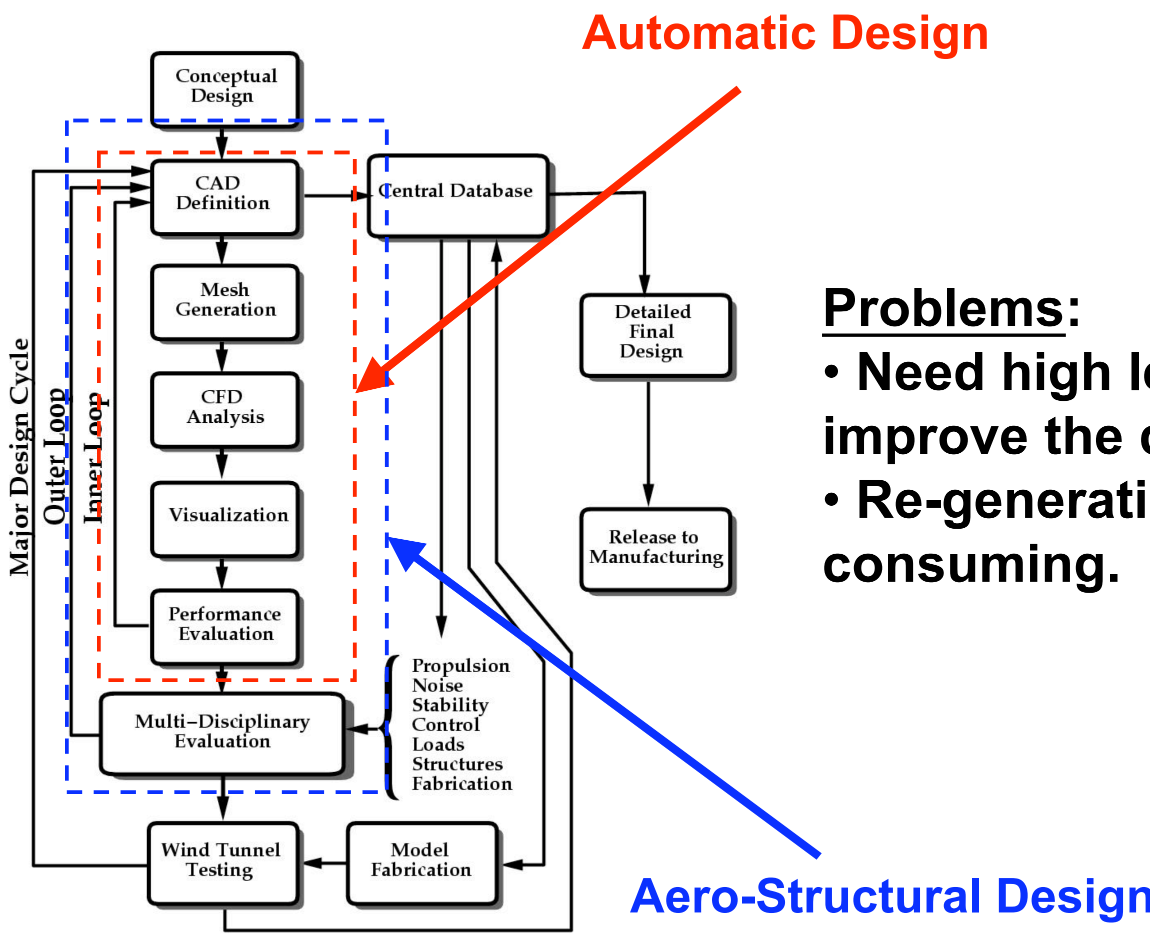
• Attainable when flow calculation can be performed fast enough
• But does NOT provide any guidance on how to change the shape if performance is unsatisfactory.

Flow Prediction

• Predict the flow past an airplane or its important components in different flight regimes such as take-off or cruise and off-design conditions such as flutter.
• Substantial progress has been made during the last decade.

LOWEST

Aerodynamic Design Process



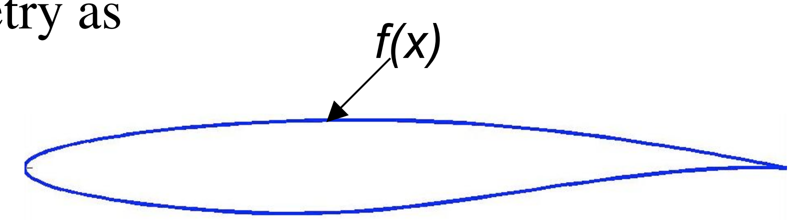
Problems:

- **Need high level of expertise to improve the design.**
- **Re-generating mesh is time consuming.**

Preliminary Design Level

Optimization and Design using Sensitivities Calculated by the Finite Difference Method

The simplest approach is to define the geometry as



$$f(x) = \sum \alpha_i b_i(x)$$

where α_i = weight,

$b_i(x)$ = set of shape functions

Then using the finite difference method, a cost function

$$I = I(w, \alpha) \qquad \text{(such as } C_D \text{ at constant } C_L\text{)}$$

has sensitivities

$$\frac{\partial I}{\partial \alpha_i} \approx \frac{I(\alpha_i + \delta\alpha_i) - I(\alpha_i)}{\delta\alpha_i}$$

If the shape changes is

$$\alpha^{n+1} = \alpha^n - \lambda \frac{\partial I}{\partial \alpha_i} \qquad \text{(with small positive } \lambda\text{)}$$

The resulting improvements is

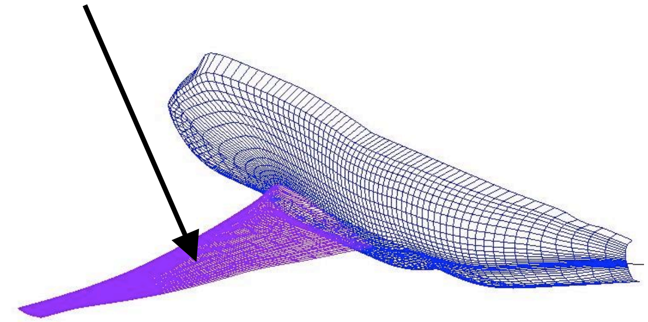
$$I + \delta I = I - \frac{\partial I^T}{\partial \alpha}\delta\alpha = I - \lambda \frac{\partial I^T}{\partial \alpha}\frac{\partial I}{\partial \alpha} < I$$

More sophisticated search may be used, such as quasi - Newton.

Disadvantage of the Finite Difference Method

The need for a number of flow calculations proportional to the number of design variables

Using 4224 mesh points on the wing as design variables



Boeing 747

4225 flow calculations
~ 30 minutes each (RANS)

Too Expensive

Application of Control Theory

GOAL : Drastic Reduction of the Computational Costs

Drag Minimization	$\equiv$	***Optimal Control of Flow Equations*** **subject to** ***Shape(wing) Variations***

Define the cost function

$$I = I(w, F) \qquad \text{(for example } C_D \text{ at fixed } C_L\text{)}$$

and a change in F results in a change

$$\delta I = \left(\frac{\partial I}{\partial w}\right)^T \delta w + \left(\frac{\partial I}{\partial F}\right)^T \delta F$$

Suppose that the governing equation R which expresses the dependencd of w and F as

$$R(w, F) = 0$$

and

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

Application of Control Theory

Since the variation δR is zero, it can be multiplied by a Lagrange Multiplier ψ and subtracted from the variation δI without changing the result.

$$\delta I = \frac{\partial I^T}{\partial w}\delta w + \frac{\partial I^T}{\partial F}\delta F - \psi^T\left(\left[\frac{\partial R}{\partial w}\right]\delta w + \left[\frac{\partial R}{\partial F}\right]\delta F\right)$$

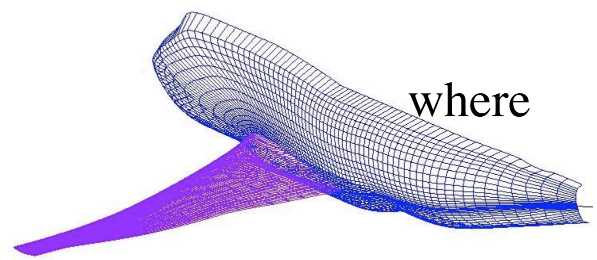
$$= \left\{\frac{\partial I^T}{\partial w} - \psi^T\left[\frac{\partial R}{\partial w}\right]\right\}\delta w + \left\{\frac{\partial I^T}{\partial F} - \psi^T\left[\frac{\partial R}{\partial F}\right]\right\}\delta F$$

Choosing ψ to satisfy the adjoint equation

$$\left[\frac{\partial R}{\partial w}\right]^T\psi = \frac{\partial I}{\partial w} \qquad \text{(Adjoint Equation)}$$

the first term is eliminated, and we find that

$$\delta I = G^T\delta F$$



where

$$G^T = \frac{\partial I^T}{\partial F} - \psi^T\left[\frac{\partial R}{\partial F}\right] \qquad \text{(Gradient)}$$

4224 design variables

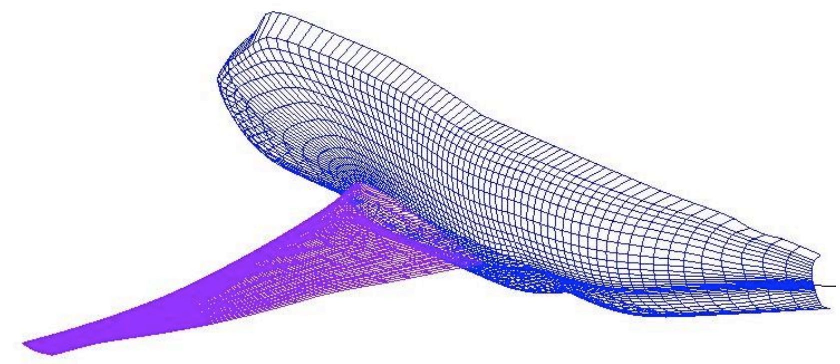
One Flow Solution + One Adjoint Solution

Advantages of the Adjoint Method:

• Gradient for N design variables with cost equivalent to two flow solutions

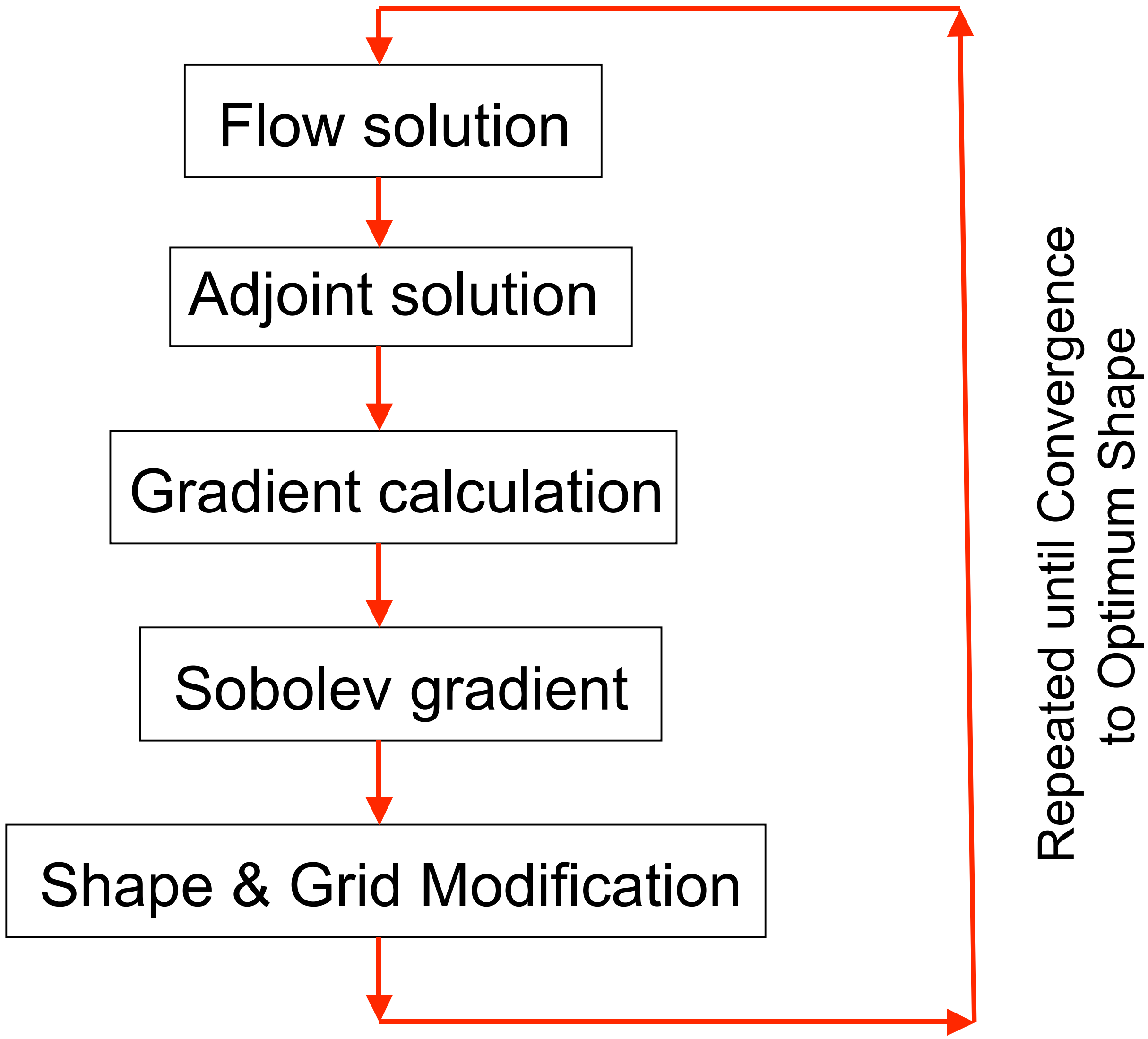
• Minimal memory requirement in comparison with automatic differentiation

• Enables shapes to be designed as free surface
  - No need for user defined shape function
  - No restriction on the design space



4224 design variables

Outline of the Design Process



Discrete versus Continuous Adjoint Methods

- The discrete adjoint method evaluates the adjoint and gradient equations algebraically from the discretized flow equations.

- The continuous adjoint method evaluates the costate solution from the partial differential adjoint equation.

- The continuous adjoint method leads to no inconsistency as long as it is combined with a compatible search method

- In the limit of grid convergence the two approaches yield identical gradients.

- Numerical tests of a model problem verify slightly superior accuracy with the continuous formulation ***(Jameson and Vassberg 2000)***

Summary of the Continuous Flow and Adjoint Equations

With computational coordinates ξ_i

Euler equations for the flow :

(1) $$\frac{\partial}{\partial \xi_i} S_{ij} f_j(w) = 0$$

where S_{ij} are metrices, $f_j(w)$ the fluxes.

Adjoint equation

(2) $$C_i \frac{\partial \psi}{\partial \xi_i} = 0, \quad C_i = S_{ij} \frac{\partial f_j}{\partial w}$$

Boundary condition for the Inverse problem

(3) $$I = \frac{1}{2} \int (p - p_t)^2 \, ds$$

$$\phi_2 n_x + \phi_3 n_y + \phi_3 n_z = p - p_t$$

Gradient

(4) $$\delta I = -\int_D \frac{\partial \psi^T}{\partial \xi_i} \delta S_{ij} f_j \, dD - \iint_{B_w} (\delta S_{21}\phi_2 + \delta S_{22}\phi_3 + \delta S_{23}\phi_4) p \, d\xi_1 d\xi_3$$

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Sobolev Gradient

Key issue for successful implementation of the Continuous adjoint method.

Define the gradient with respect to the Sobolev inner product

$$\delta I = <\bar{g}, \delta f> = \int \left(\bar{g}\,\delta f + \epsilon\, \bar{g}'\,\delta f' \right) dx$$

Set

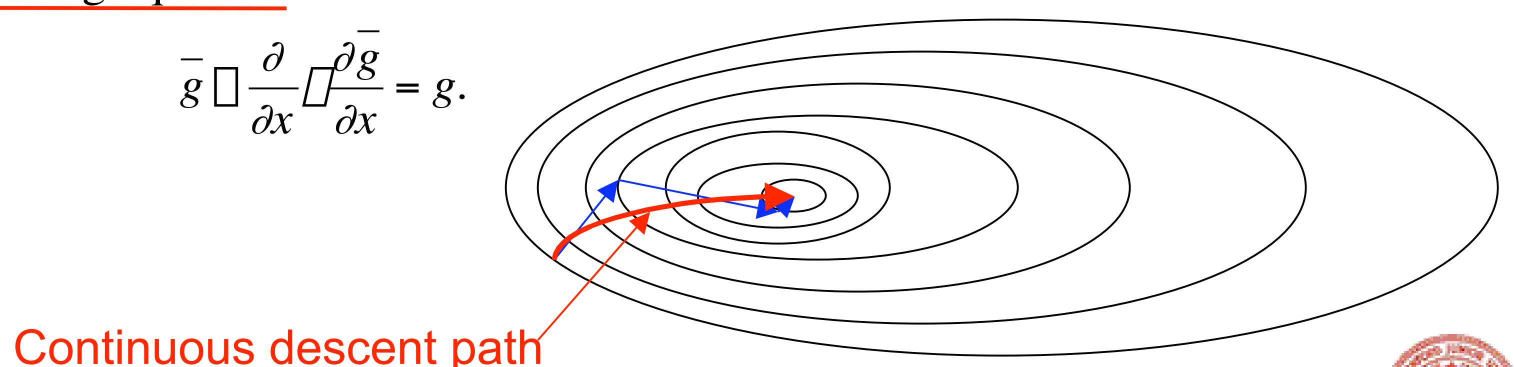
$$\delta f = -\lambda \bar{g}, \quad \delta I = -\lambda <\bar{g}, \bar{g}>$$

This approximates a continuous descent process

$$\frac{df}{dt} = -\bar{g}$$

The Sobolev gradient $\bar{g}$ is obtained from the simple gradient g by the smoothing equation

$$\bar{g} - \frac{\partial}{\partial x} \epsilon \frac{\partial \bar{g}}{\partial x} = g.$$



Computational Costs with N Design Variables

(Jameson and Vassberg 2000)

Cost of Search Algorithm

Steepest Descent	$O(N^2)$
Quasi-Newton	$O(N)$
Sobolev Gradient	$O(K)$

(Note: *K* is independent of *N*)

Total Computational Cost of Design

Finite Difference Gradients + Steepest Descent	$O(N^3)$
Finite Difference Gradients + Quasi-Newton Search or Response surface	$O(N^2)$
Adjoint Gradient + Quasi-Newton Search	$O(N)$
Adjoint Gradient + Sobolev Gradient	$O(K)$

(Note: *K* is independent of *N*)

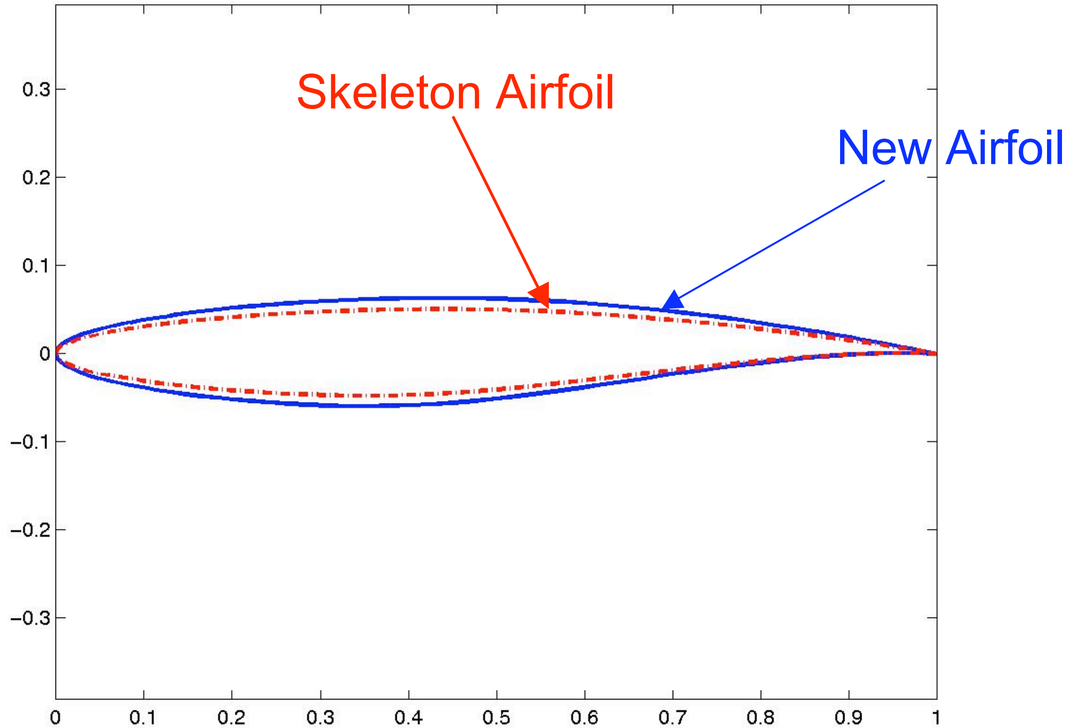
- N~2000
- Big Savings
- Enables Calculations on a Laptop

Constraints Enforced in SYN107

For drag minimization

1. Fixed C_L
2. Fixed span load
   - Keep out-board C_L low enough to prevent buffet
   - Fixed root bending moment
3. Maintain specified thickness
   - Sustain root bending moment with equal structure weight
   - Maintain fuel volume
4. Smooth curvature variations via Sobolev gradient

Application of Thickness Constraint



- Prevent shape change penetrating a specified skeleton
- Separate thickness and camber to allow free camber variations
- Minimal user input required.

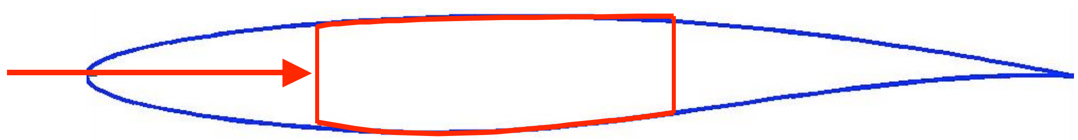
Multi-Point Design

- Drag minimization at a single design point typically produces a shock free flow but may adversely affect performance at other points. (Double shocks below design point, drag creep due to leading edge shock)
- Good all round performance can be enhanced by multi-point design

e.g.	Mach = 0.75	C_L = 0.5	(drag creep)
	Mach = 0.86	C_L = 0.42	(cruise)
	Mach = 0.89	C_L = 0.40	(drag divergence)

Partial Redesign with Structural Constraints

Fixed (Structure box)



- Design changes can be limited to a specified spanwise range of the wing
- Section changes can be limited to a specified chordwise range
- The shape changes are blended smoothly via the Sobolev gradient

Inverse Design

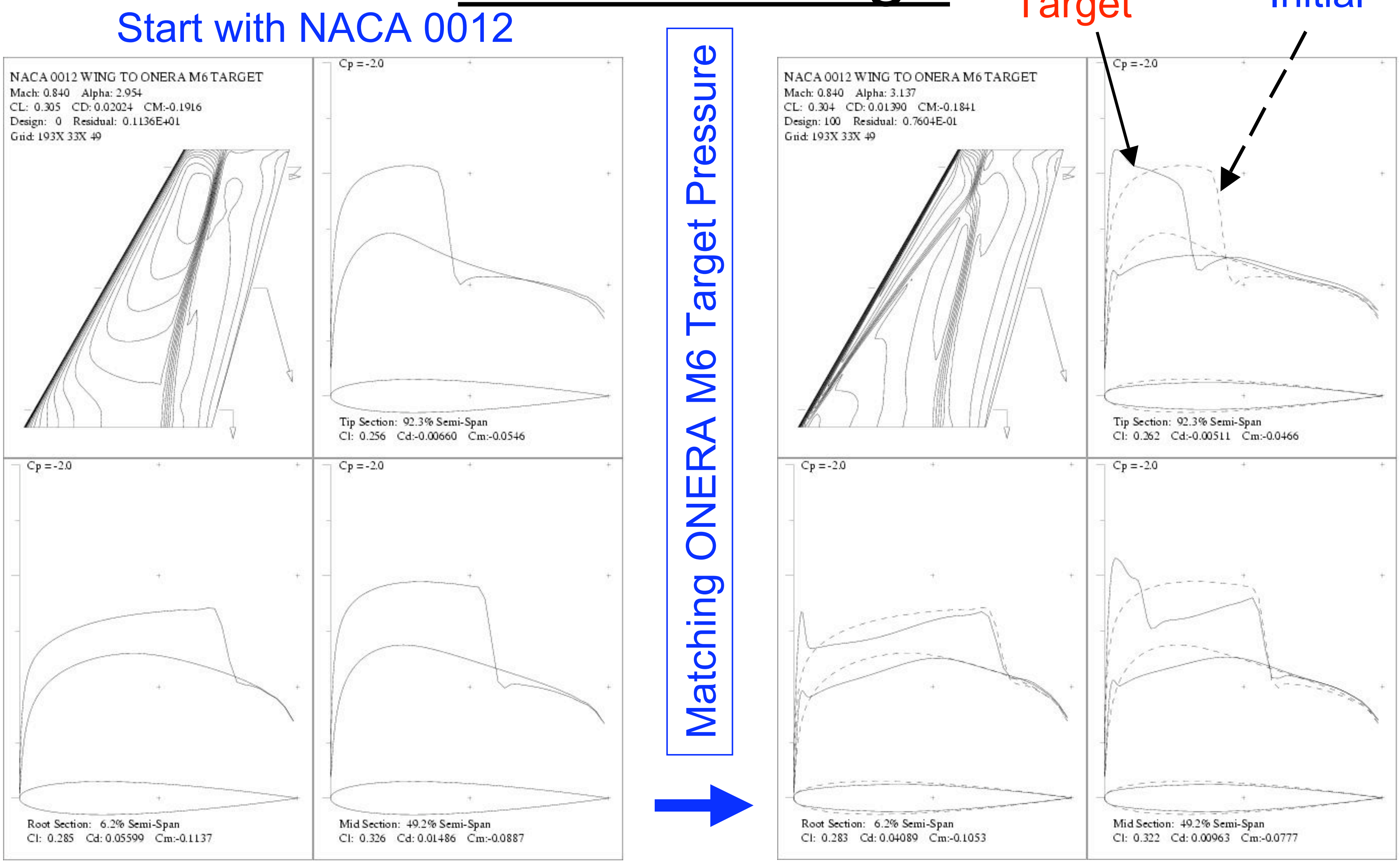
- A hard test :

  - ONERA M6 Wing target pressure
    Mach 0.84
    α 3.06 degree
    Lambda Shock

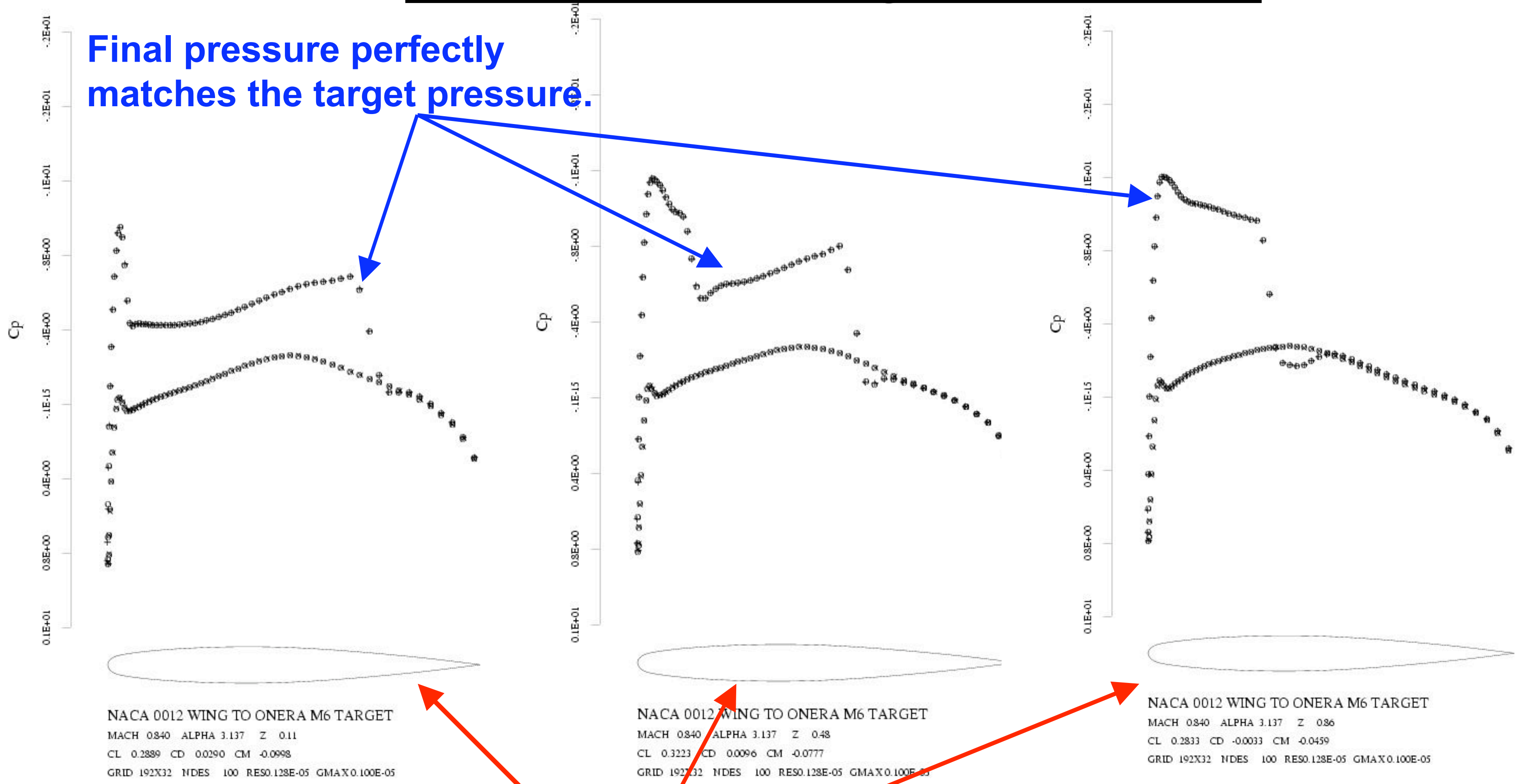
  - Starting from NACA0012 sections
    (single shock)

- Recovery of <u>smooth symmetric profile</u>
  from <u>discontinuous lifting pressure distribution</u>

Inverse Design

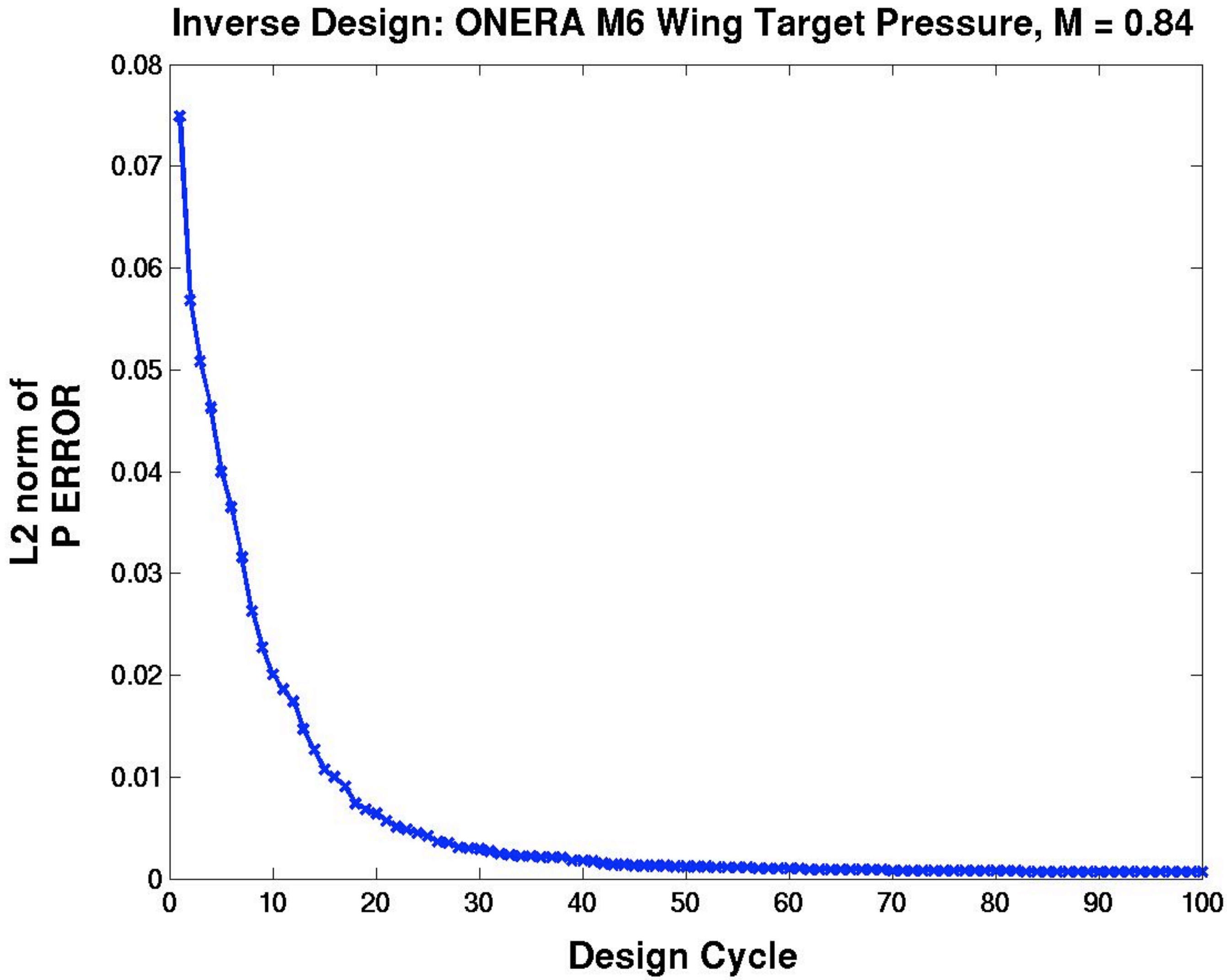


Inverse Design Results



Recover ONERA M6 Shape at all span stations

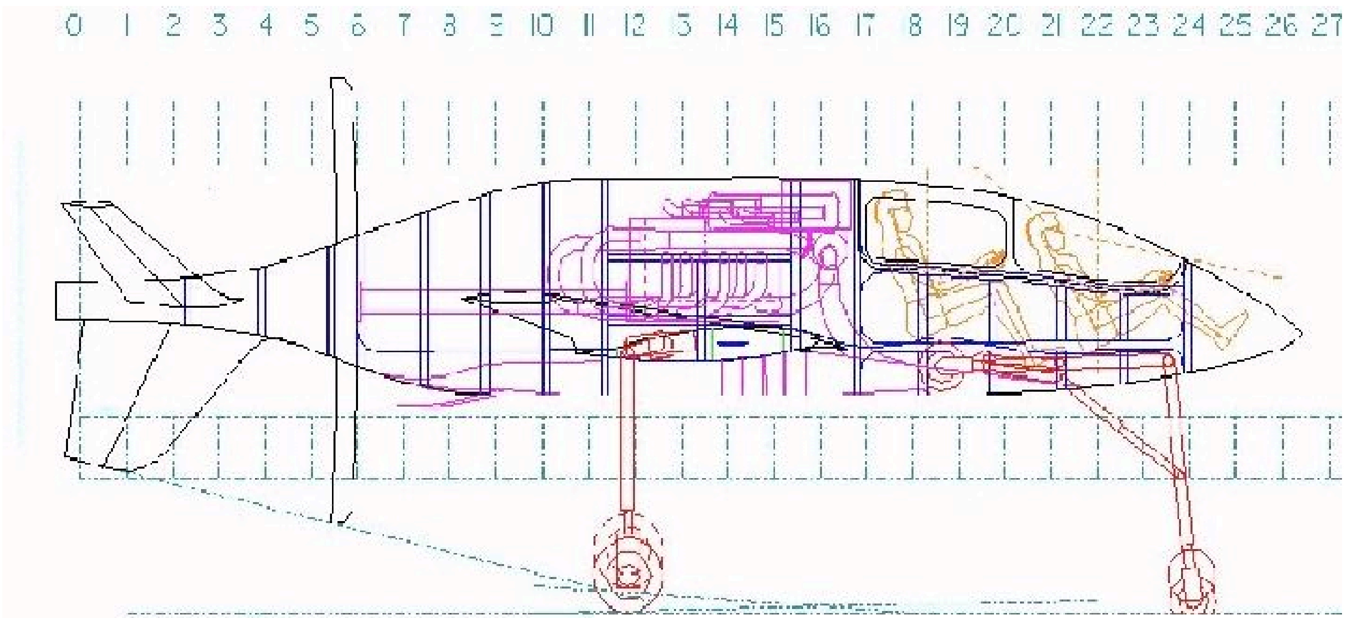
Convergence History of Inverse Design

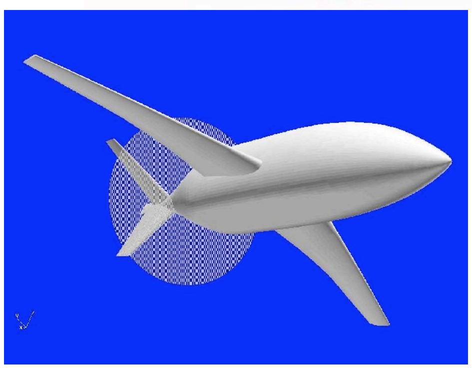


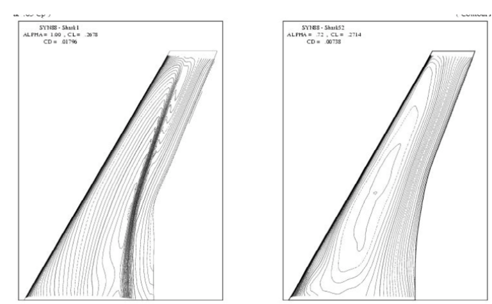
Applications to Unconventional Designs

Shark Reno Air Racer

(Ahlstrom, Gregg, Vassberg, Jameson, AIAA PAPER 2000-4341)







Original Redesign

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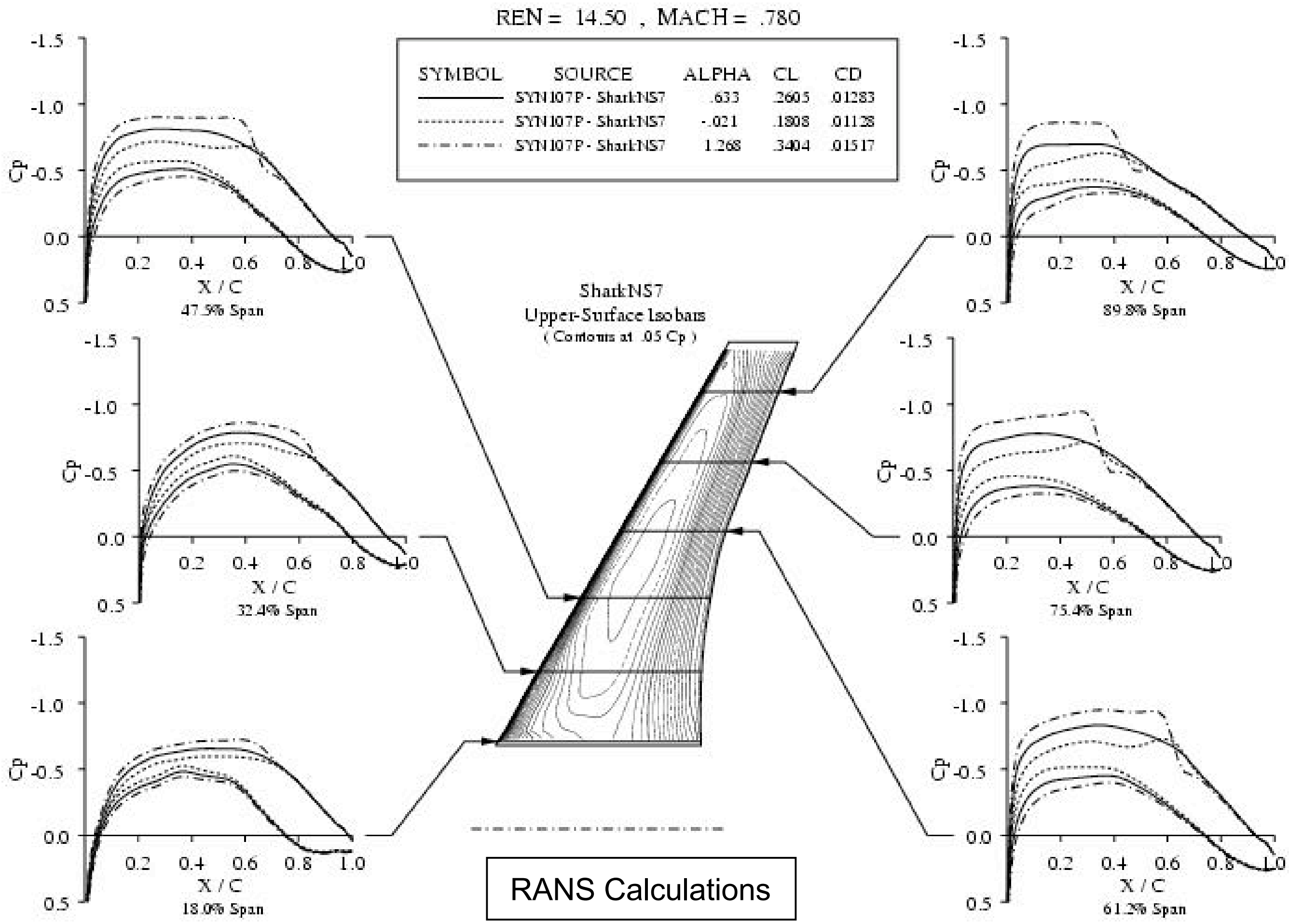
Shark Reno Air Racer



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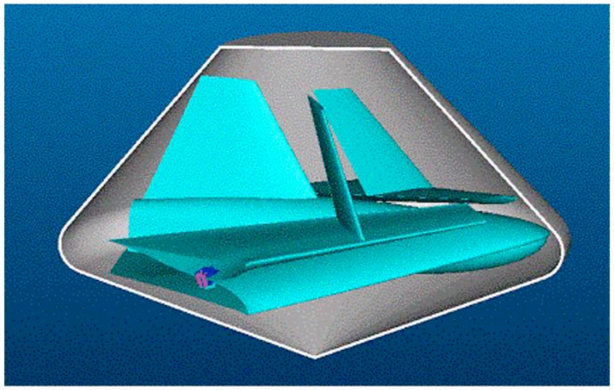
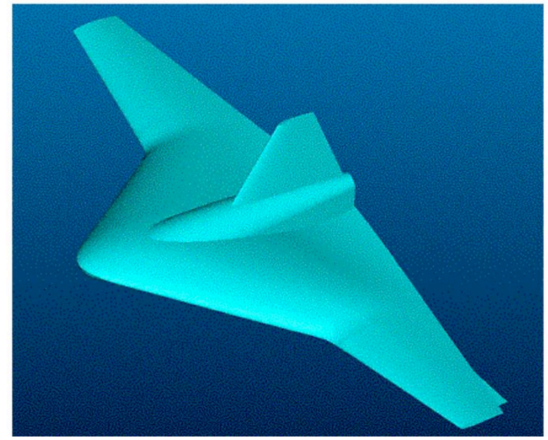
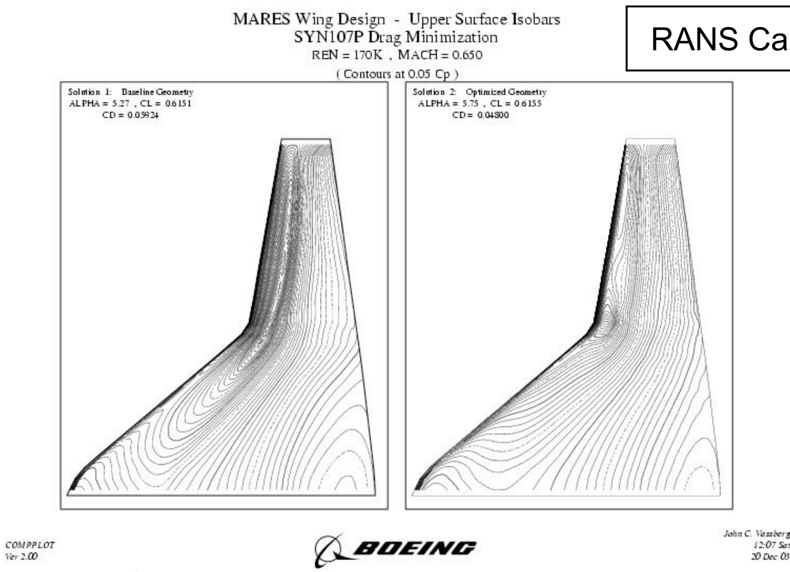
Mars Lander

(Vassberg, Jameson 2004)



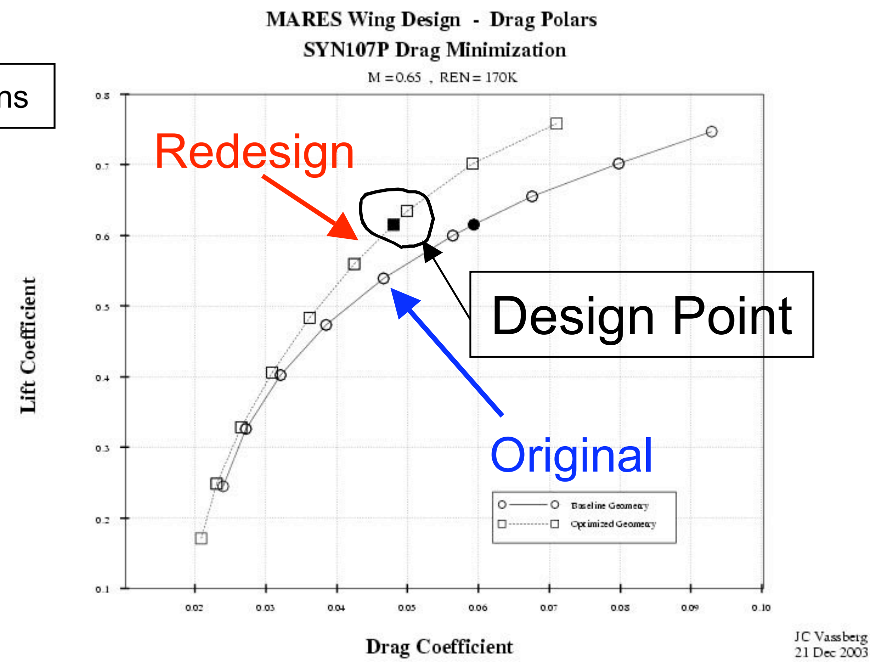




RANS Calculations

Original

Redesign



Drag reduced by 20 %

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Planform and Aero-Structural Optimization

(Leoviriyakit, Jameson 2003 - 2004)

- Design tradeoffs suggest an multi-disciplinary design and optimization

$$\text{Range} = \frac{VL}{D}\frac{1}{\text{sfc}}\log\frac{W_o + W_f}{W_o}$$

Maximize ($\frac{VL}{D}$) Minimize (W_o)

Planform variations can further maximize VL/D but affects W_o

Aerodynamic Design Tradeoffs

The drag coefficient can be split into

$$C_D = C_{DO} + \frac{C_L^{\ 2}}{\pi e AR}$$

$\frac{L}{D}$ is maximized if the two terms are equal.

Induced drag is half of the total drag.

If we want to have large drag reduction, we should target the induced drag.

$$D_i = \frac{2L^2}{\pi e \rho V^2 b^2}$$

Change span by changing planform

Design dilemma

Increase ***b*** → ***D_i*** decreases

→ ***W_o*** increases

Break Down of Drag

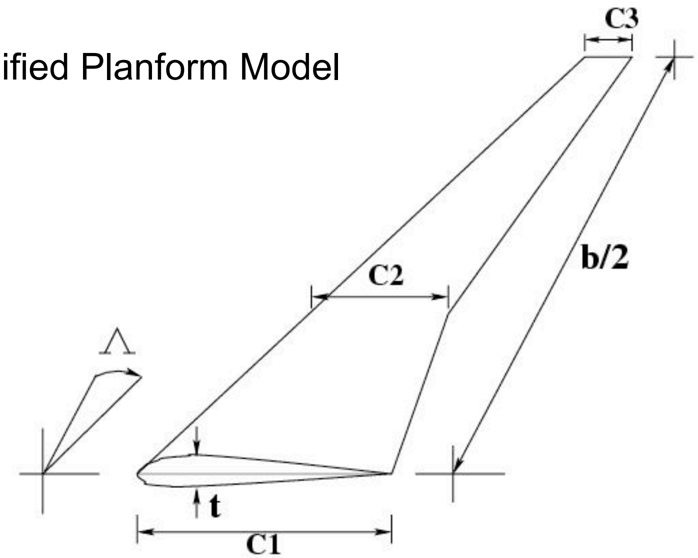
Boeing 747 at C_L ~ .47 (including fuselage lift ~ 15%)

Item	C_D	Cumulative C_D
Wing Pressure	120 counts	120 counts
	(15 shock, 105 induced)	
Wing friction	45	165
Fuselage	50	215
Tail	20	235
Nacelles	20	255
Other	15	270
Total	270	

Induced Drag is the largest component

Wing Planform Optimization

Simplified Planform Model



Wing planform modification can yield larger improvements BUT affects structural weight.

$$I = \alpha_1 C_D + \alpha_2 \frac{1}{2} \int (p - p_d)^2 \, dS + \alpha_3 C_W$$

where

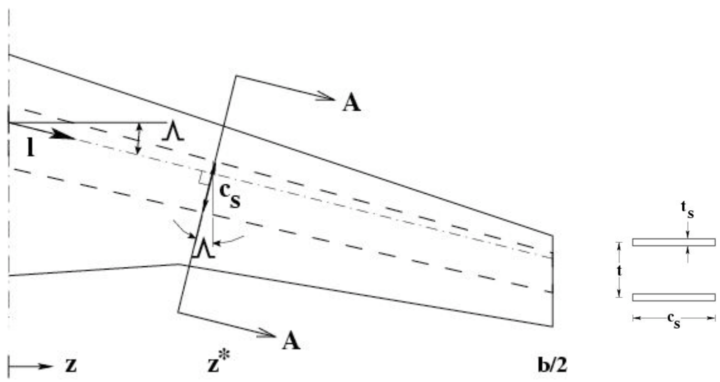
$$C_W = \frac{\text{Structural Weight}}{q \;\; S_{ref}}$$

Can be thought of as constraints

Additional Features Needed

- Structural Weight Estimation
- Large scale gradient : span, sweep, etc…
- Adjoint gradient formulation for dC_w/dx
- Choice of $\square_1$, $\square_2$, and $\square_3$

Use wing box to estimate the structural weight.



Large scale gradient

- Use summation of mapped gradients to be large scale gradient

Choice of Weighting Constants

Breguet range equation

$$R = \frac{VL}{D}\frac{1}{sfc}\log\frac{W_O + W_f}{W_O}$$

With fixed V, L, sfc, and $(W_O + W_f \equiv W_{TO})$, the variation of R can be stated as

$$\frac{\delta R}{R} = -\left(\frac{\delta C_D}{C_D} + \frac{1}{\log\frac{W_{TO}}{W_O}}\frac{\delta W_O}{W_O}\right) = -\left(\frac{\delta C_D}{C_D} + \frac{1}{\log\frac{C_{W_{TO}}}{C_{W_O}}}\frac{\delta C_{W_O}}{C_{W_O}}\right)$$

Maximizing Range $\equiv$ Minimizing

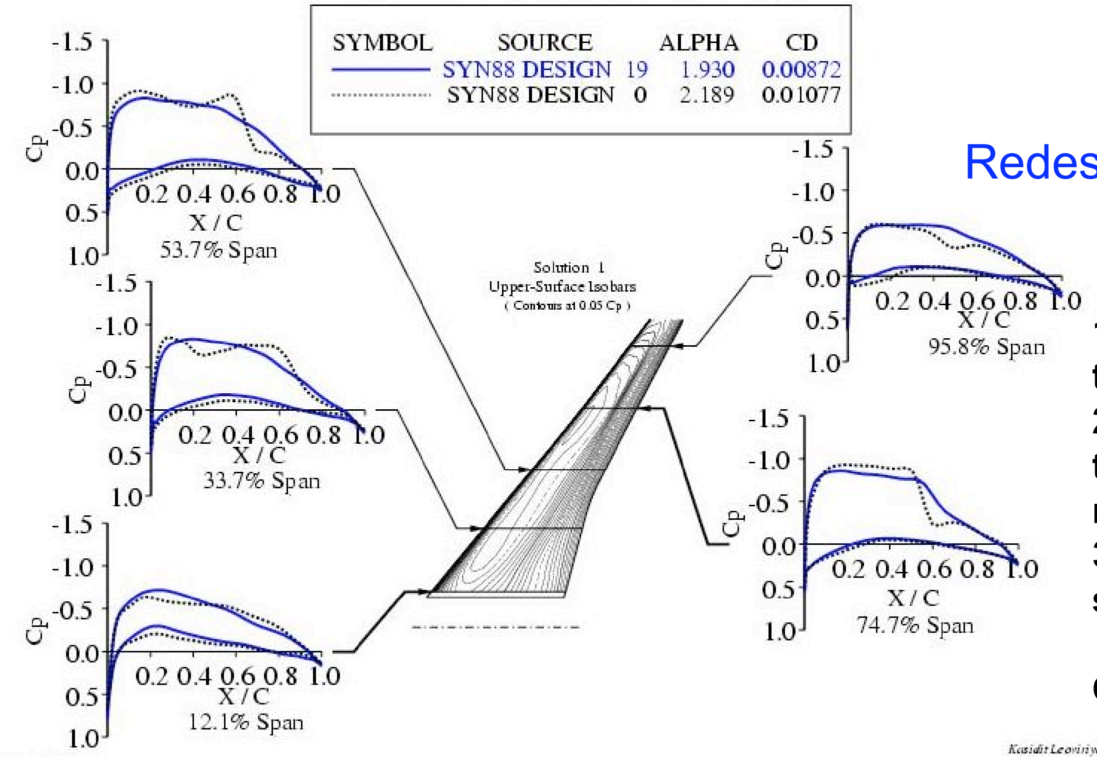
$$I = C_D + \frac{\beta_3}{\beta_1} C_W$$

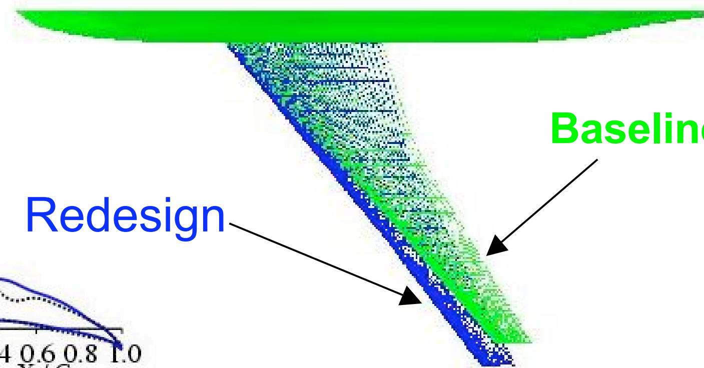
using

$$\frac{\beta_3}{\beta_1} = \frac{C_D}{C_{W_O}\log\frac{C_{W_{TO}}}{C_{W_O}}}$$

Planform Optimization of Boeing 747

Constraints : Fixed CL=0.42





1) Longer span reduces the induced drag
2) Less sweep and thicker wing sections reduces structure weight
3) Section modification keeps shock drag minimum

Overall: Drag and Weight Savings

	C_D	C_W
Baseline	108	455
Optimize Section at Fixed planform	94	455
Optimize both section and planform	87	450

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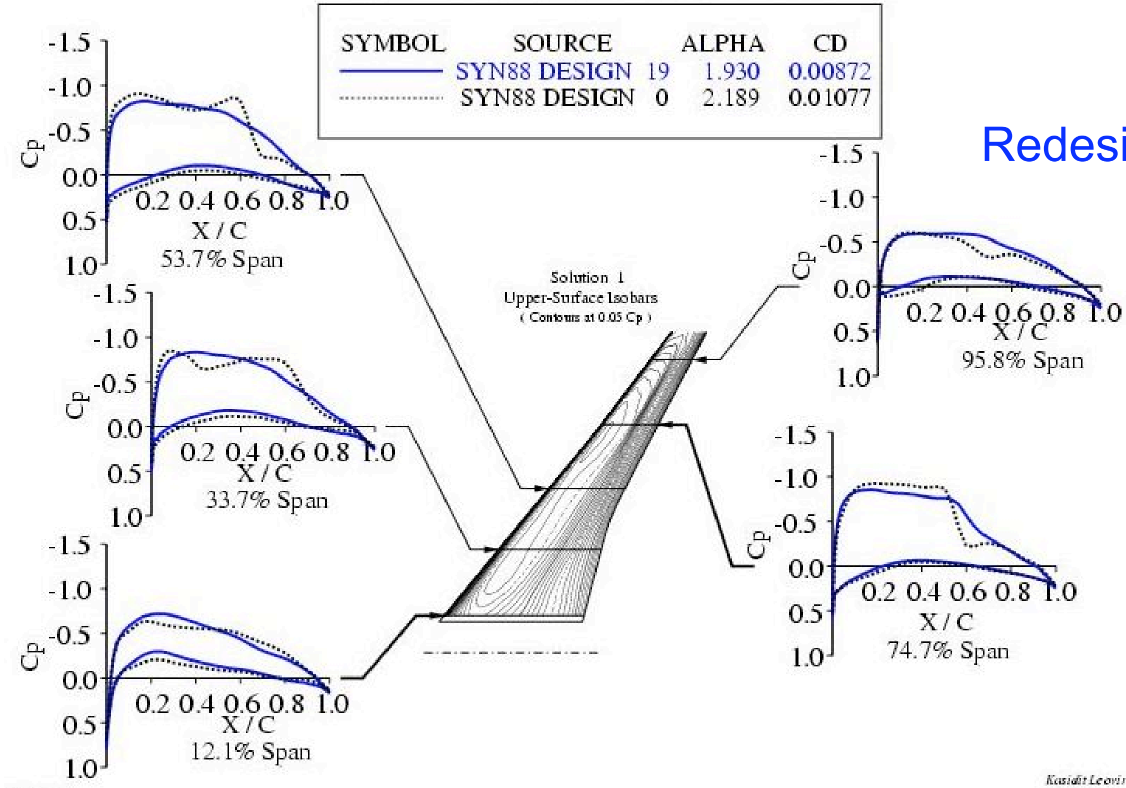
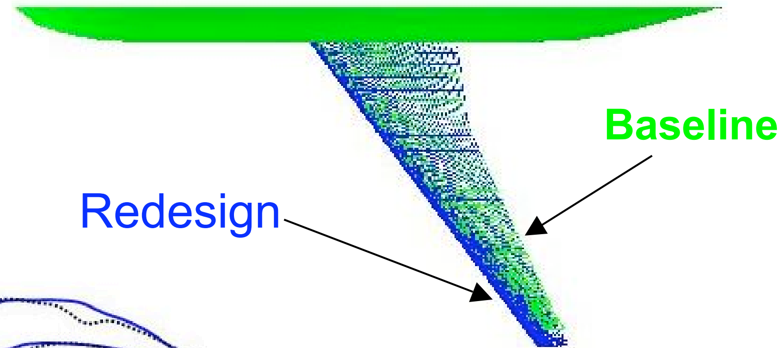
Aerospace Computing Laboratory

Planform Optimization of MD11

Constraints : Fixed CL=0.45

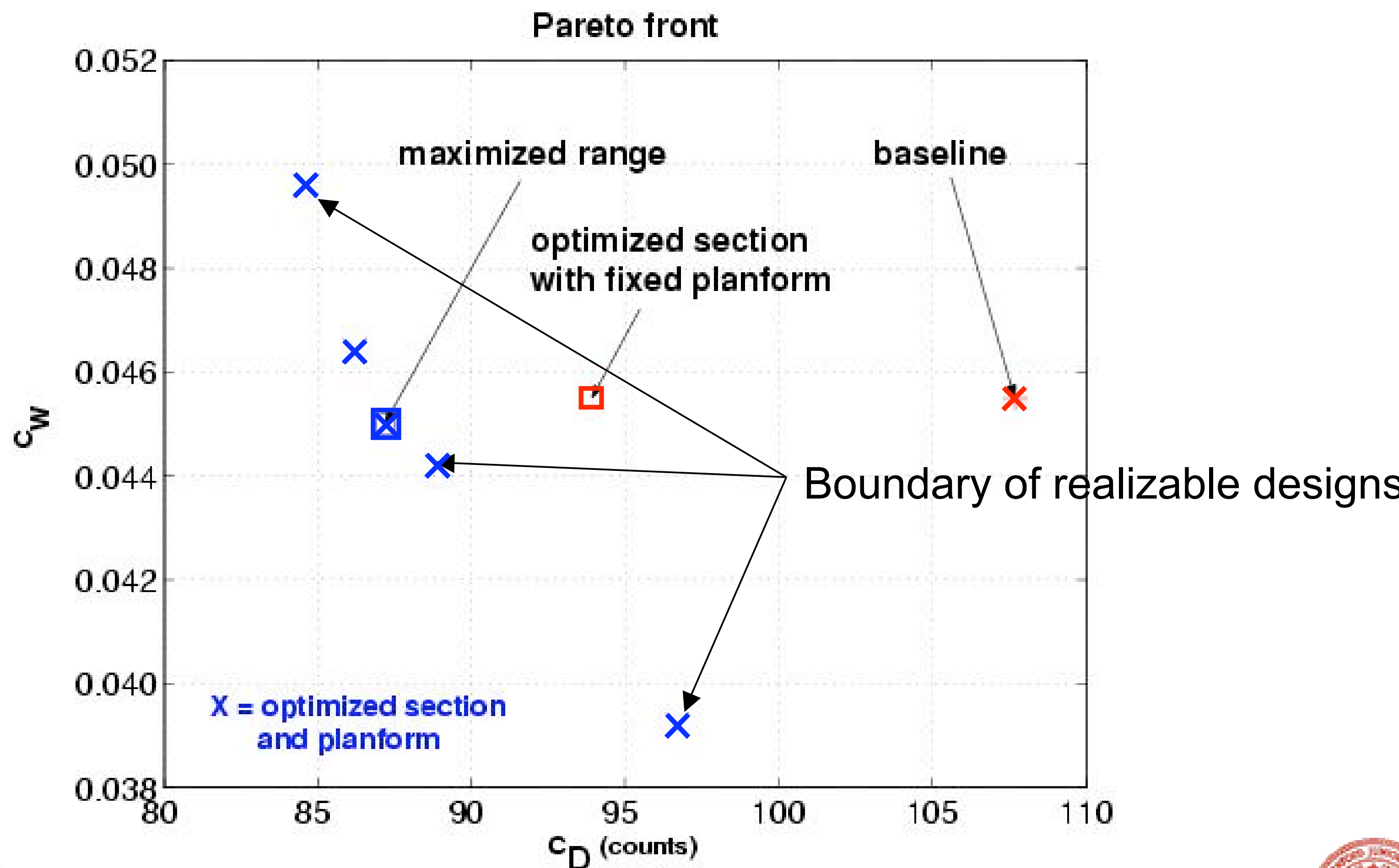




	C_D	C_W
Baseline	159	345
Optimize Section at Fixed planform	145	346
Optimize both section and planform	138	344

Pareto Front: "Expanding the Range of Designs"

Use multiple □3/□1 ==> Multiple Optimal Shapes



Automatic design for the Complete Aircraft Geometry on an Unstructured Mesh (SYNPLANE)

- Key step: reduce the gradient to a surface integral independent of the mesh perturbation

  (Jameson, A., and Kim, S., "Reduction of the Adjoint Gradient Formula in the Continuous Limit", 41 st AIAA Aerospace Sciences Meeting & Exhibit, AIAA Paper 2003-0040, Reno, NV, January 6-9, 2003.)

$$\delta I = -\iint_{B_w} \psi^T \left(\delta S_{2j} f_j + C_2 \delta w^*\right) d\xi_1 d\xi_3 - \iint_{B_w} \left(\delta S_{21}\psi_2 + \delta S_{22}\psi_3 + \delta S_{23}\psi_4\right) p \, d\xi_1 d\xi_3$$

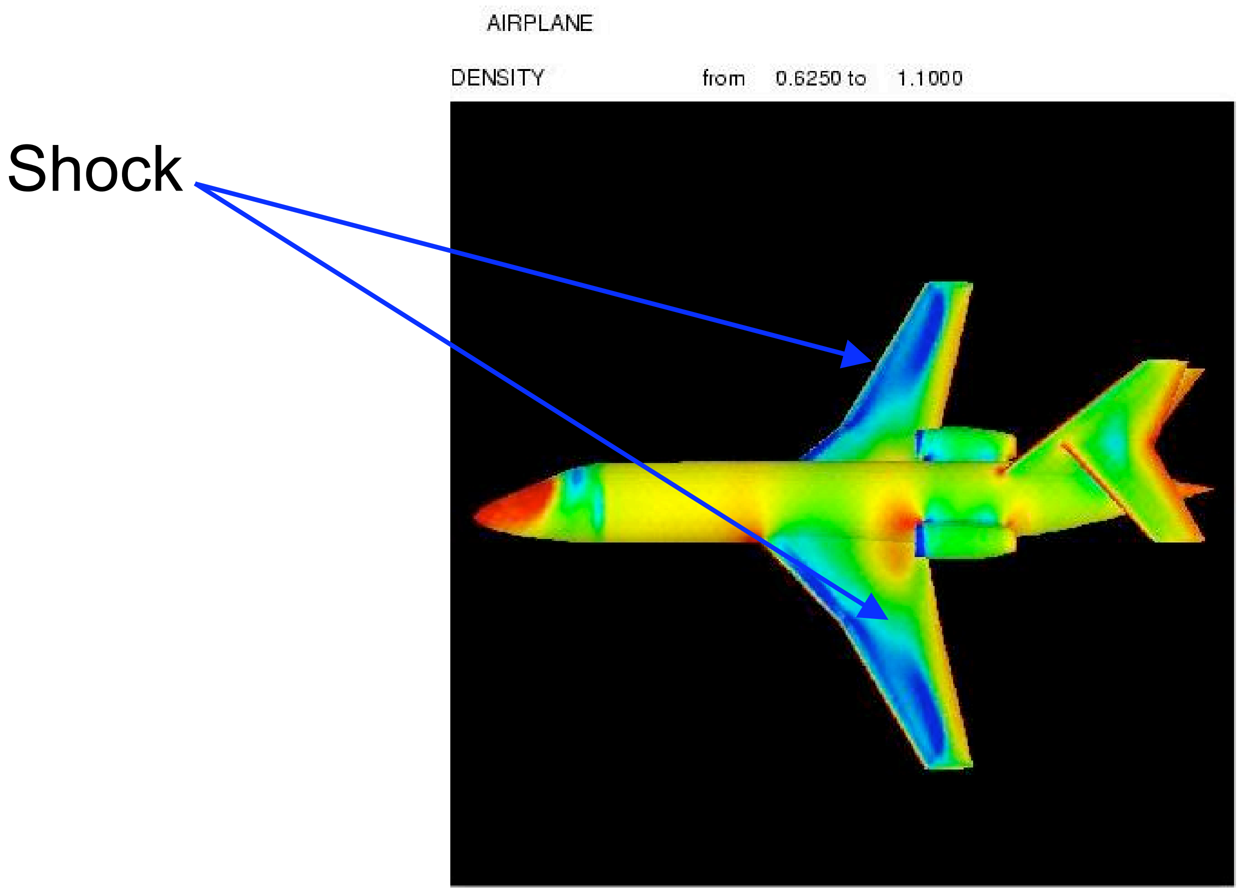
Compared to the previous formulation

$$\delta I = -\int_D \frac{\partial \psi^T}{\partial \xi_i} \delta S_{ij} f_j \, dD - \iint_{B_w} \left(\delta S_{21}\psi_2 + \delta S_{22}\psi_3 + \delta S_{23}\psi_4\right) p \, d\xi_1 d\xi_3$$

This field integral is converted to boundary integral

Redesign of Falcon

Complete aircraft calculation on Unstructured Mesh



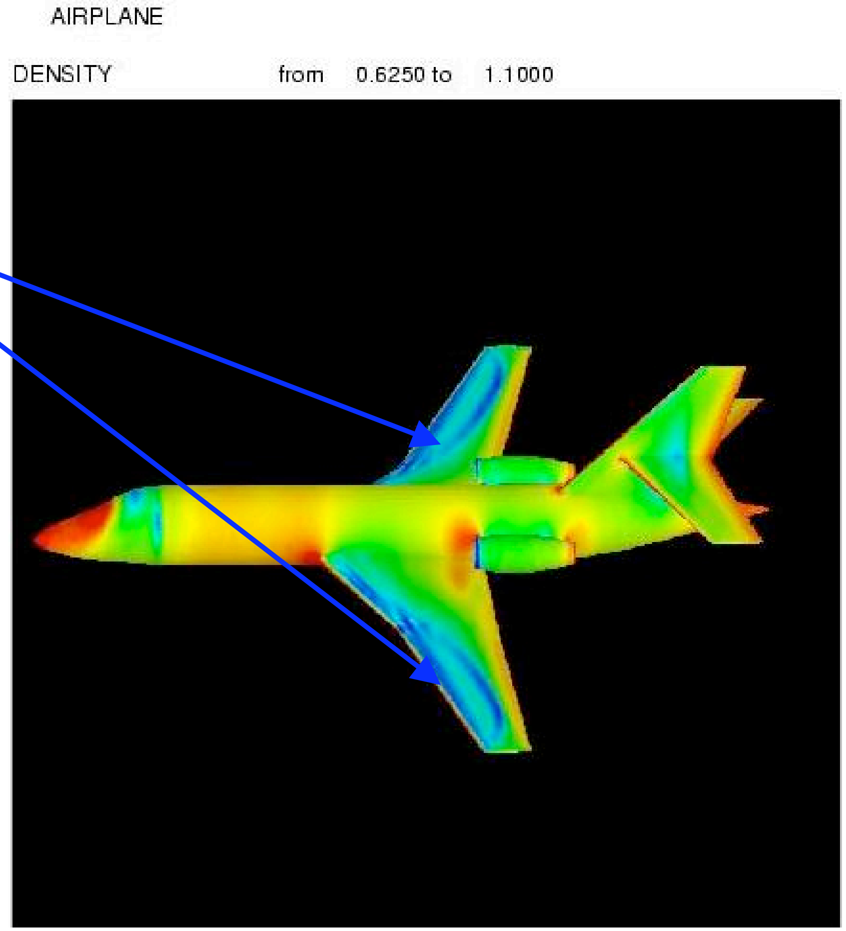
C_D = 234 counts

Redesign of Falcon

Using SYNPLANE

Drag reduction 18 counts at fixed $C_L = 0.4$

Weakened Shock



C_D = 216 counts

Aerodynamic Shape Optimization Payoffs

- Enables aerodynamic design by a small team of experts focusing on the true design issues (e.g. Reno Air Racer)
- Significant reduction in time and cost
- Potential for superior and unconventional designs
- Potential for "mid-course correction" during the development cycle

Other Potential Applications of Shape Optimization

- Combined shape and trajectory optimization for reentry vehicles to reduce thermal loads
- Reduction of acoustic signature (Take-Off and Landing noise, sonic boom reduction)
- Minimization of electro magnetic signature while meeting aerodynamic requirement
- Minimization of wave resistance of ship hulls (in process)

Other Applications of the Adjoint Method in CFD

- Automatic error estimation with computed error bounds

  (Barth and Deconinck, Lecture Noted in Computational Science and Engineering, Vol 25, Springer, 2002
  Giles and Pierce, SIAM Review, Vol 42, 2000, 247 - 64)

- Automatic mesh adaptation based on error estimation

  (Vendite and Darmofal, AIAA Paper 2003-3845)

Shape Optimization: Some Open Issues

- Embedding shape optimization in overall system optimization
- Multi-Disciplinary Optimization beyond aero-structural optimization
- Incomplete development for arbitrary grids
- Incomplete development for propulsion integration

Users of Intelligent Aerodynamics Design Software (SYN88, SYN107, SYNPLANE)

- ***Raytheon Beach***
- ***McDonnell Douglas***
- ***Lockheed Martin Skunk Works***
- ***Airbus UK***
- ***SAAB***
- ***IPTN***
- ***Embraer (via NLR)***
- ***Gulfstream***
- ***Bombardier Aerospace (in contract)***
- ***NASA Ames (HSCT, RLV)***

Proposal

- Collaborative development between Boeing, Intelligent Aerodynamics Inc., and Stanford University of the adjoint method to meet industrial requirements for a streamlined design process.
- Funding and distribution of intellectual property rights to be negotiated.
- Intelligent Aerodynamics has existing IP rights.
- Derivative codes might be co-owned and marketed.

Supplementary Data

Appendix 1

Further Data for Part 2

What do We Need For a Face-Based Data Structure?

The only Connectivity Information

List of faces

- **Pointer to the two cells separated by the face** .... $ncf(1,i)$ $ncf(2,i)$
- **Coordinates of face centroid** .... $x_f(:,i)$
- **Directed face area** .... $S_f(:,i)$

List of cells

- **Coordinates of cell centroid** .... $x_c(:,i)$
- **Volume** .... $Vol(i)$
- **Averaged values of solution variables** .... $W(:,i)$

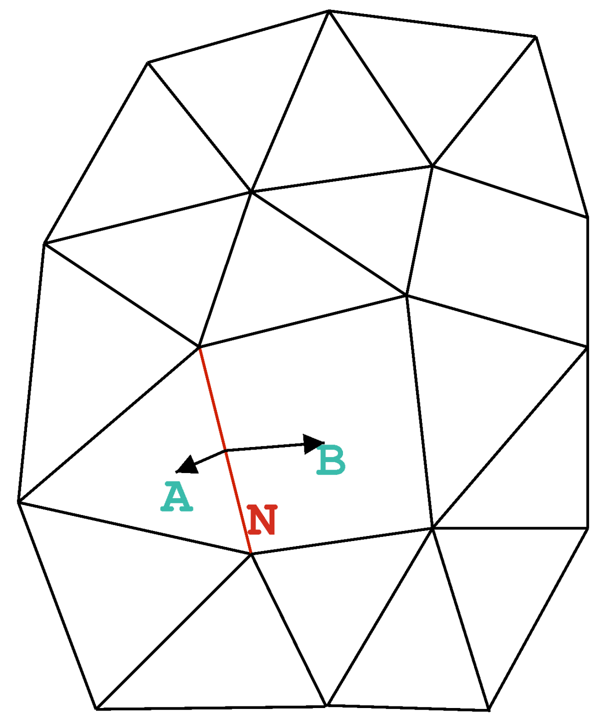
List of boundary faces and boundary conditions applied to each face

The Main Algorithm

```
do i=ncell1,ncell2
   set residual(i) to zero
end do
```

```
do n=nface1,nface2
   A = ncf(1,n)
   B = ncf(2,n)
   flux(N) = f(solution(A),solution(B))
   residual(B) = residual(B) + flux(N)
   residual(A) = residual(A) - flux(N)
end do
```

```
do i=ncell1,ncell2
   solution(i) = solution(i) - residual(i)
end do
```



Constructing the Fluxes

$$f(\vec{x},\vec{u},t,\xi) = \int_0^t g(\vec{x}-\vec{u}(t-t'),\vec{u},t',\xi)\, e^{-\frac{(t-t')}{\tau}}\, dt' + e^{-\frac{t}{\tau}} f_0(\vec{x}-\vec{u}t,\vec{u},\xi)$$

- The initial nonequilibrium distribution at a face can be approximated from an approximate distribution in the neighboring cells A and B

$$f_0 = \begin{cases} g^A\left(1+a^A s\right), & s<0 \\ g^B\left(1+a^B s\right), & s\geq 0 \end{cases} \qquad s = (\vec{x}-\vec{x}_f)\bullet\vec{n}_f$$

- Similarly, the time dependent equilibrium distribution *g* at the cell interface is obtained as

$$g = g_0\left\{1+\left(1-H(s)\right)\tilde{a}^A s + H(s)\tilde{a}^B s + \overline{A}t\right\}, \qquad H(x) = \begin{cases} 0, & x<0 \\ 1, & x\geq 0 \end{cases}$$

Constructing the Fluxes

- The Fluxes, in *x* say, are computed as

$$F = \begin{bmatrix} F_\rho \\ F_u \\ F_v \\ F_w \\ F_E \end{bmatrix} = \int u \begin{bmatrix} 1 \\ u \\ v \\ w \\ \frac{1}{2}(u^2 + v^2 + w^2 + \xi^2) \end{bmatrix} f(x_f, t, u, v, w, \xi)\, du\, dv\, dw\, d\xi$$

- Compute the fluxes in y and z (*G*,*H)* in similar fashion
- Update the solution according to

$$\vec{W}^{n+1} = \vec{W}^{n} - \frac{1}{V} \int_0^{\Delta t} \oint \vec{F} \bullet d\vec{A}\, dt \qquad \vec{F} = (F, G, H)^T$$

Appendix 2

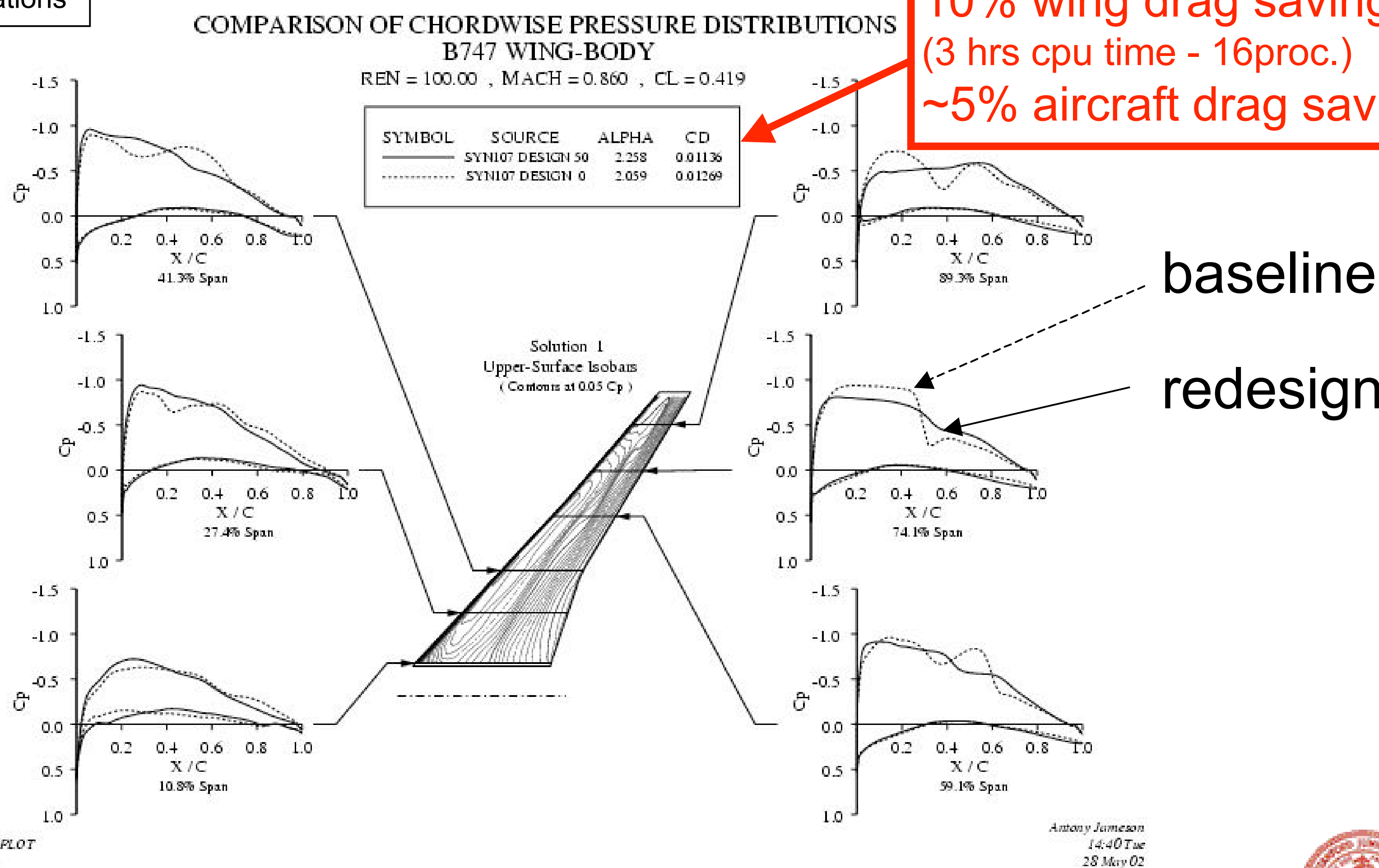
Shape Optimization Results via Control Theory

Redesign of the Boeing 747 Wing at its Cruise Mach Number

Constraints : Fixed $C_L = 0.42$
: Fixed span-load distribution
: Fixed thickness

RANS Calculations

10% wing drag saving
(3 hrs cpu time - 16proc.)
~5% aircraft drag saving



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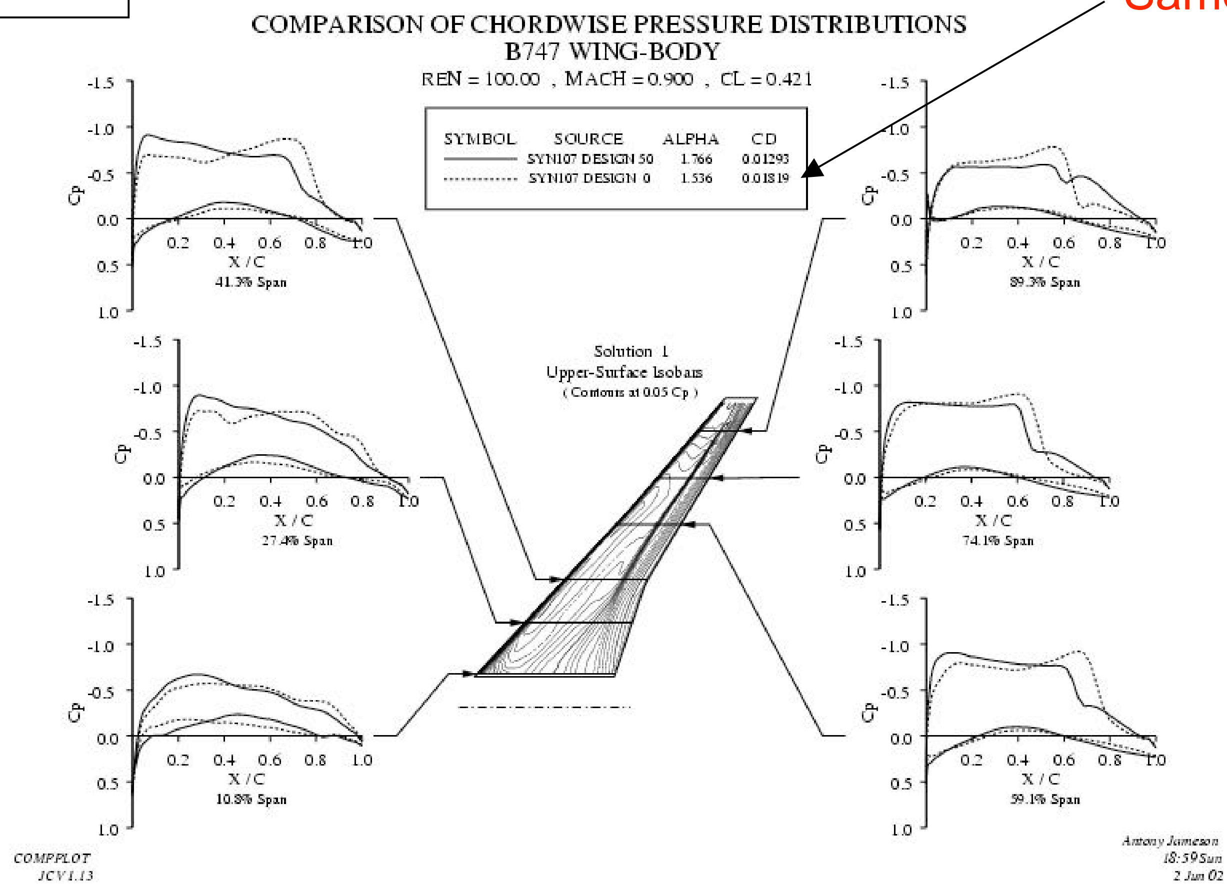
Redesign of the Boeing 747 Wing at Mach 0.9 “Sonic Cruiser”

Constraints : Fixed C_L = 0.42
: Fixed span-load distribution
: Fixed thickness

RANS Calculations

Same C_D @Cruise



We can fly faster at the same drag.

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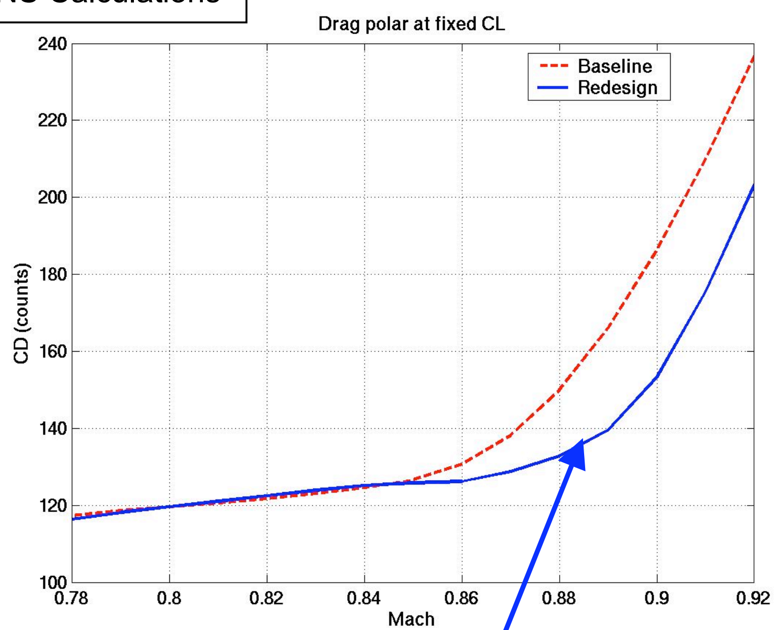
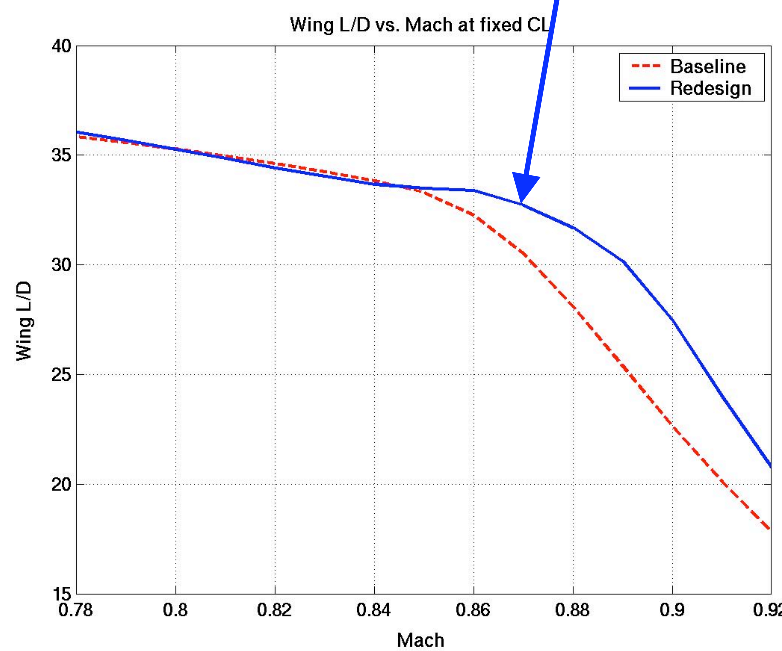
Redesign of the Boeing 747: Drag Rise
(Three-Point Design)

Constraints : Fixed $C_L = 0.42$
: Fixed span-load distribution
: Fixed thickness

Improved Wing L/D

RANS Calculations





Improved M_{DD}

benefit → Lower drag at the same Mach Number

benefit → Fly faster with the same drag

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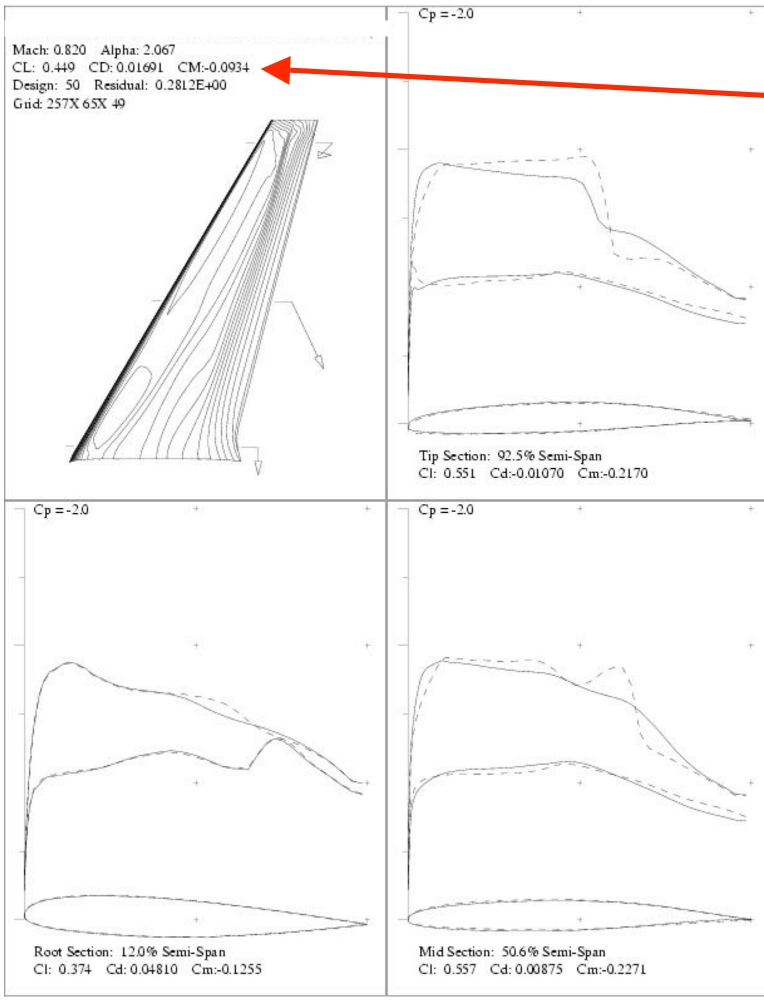
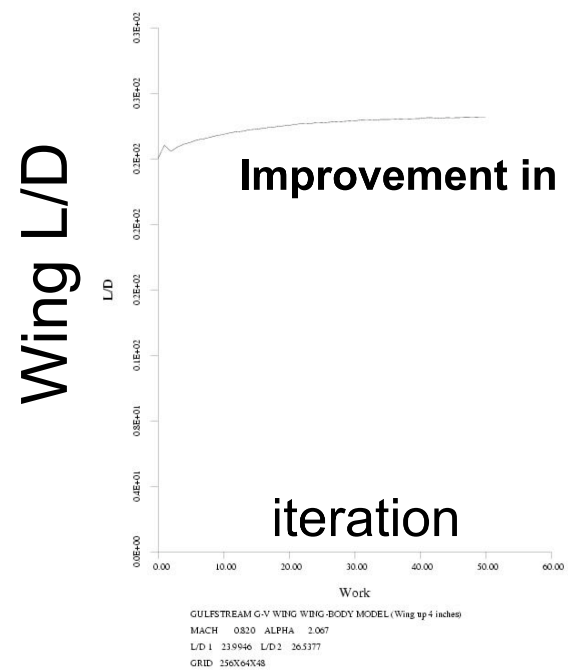
Redesign of an Executive Jet

Constraints : Fixed C_L = 0.45
: Fixed span-load distribution
: Fixed thickness

RANS Calculations



Drag saving:
189 counts to 169 counts



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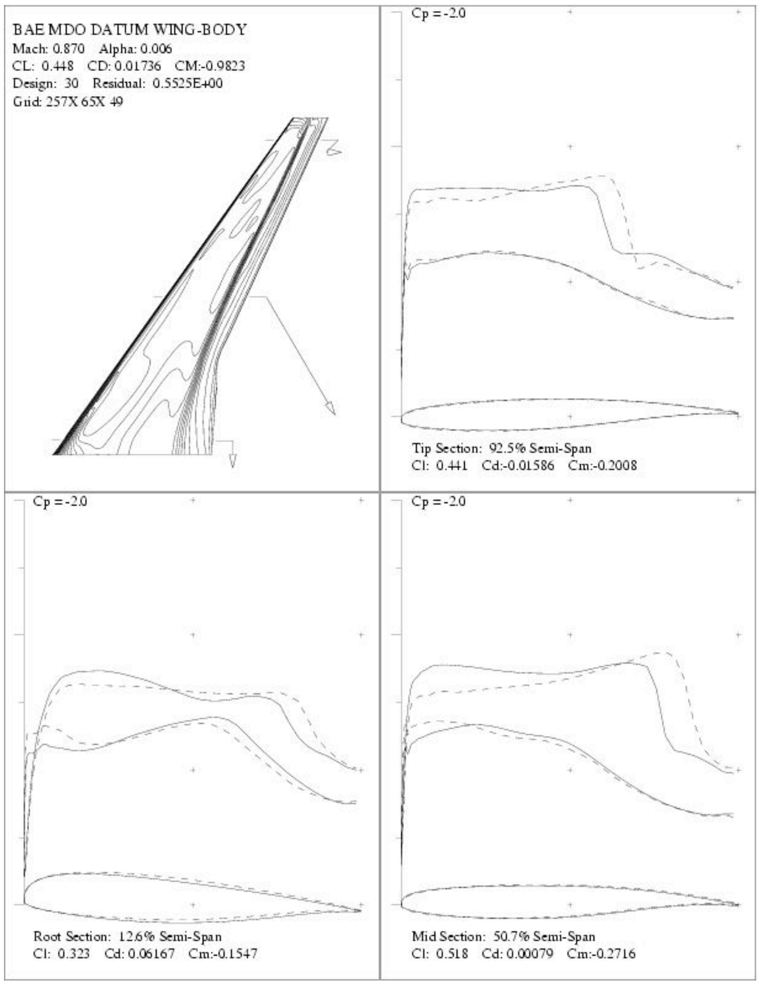
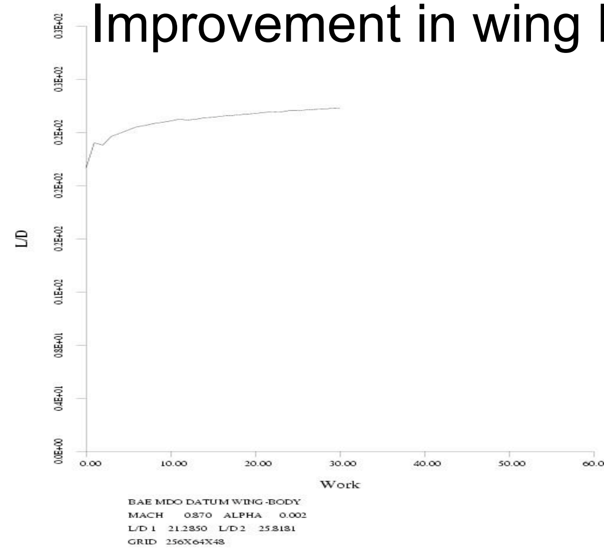
Redesign of the BAE MDO Datum Wing-Body

Constraints : Fixed $C_L = .454$
: Fixed span-load distribution
: Fixed thickness

RANS Calculations



Improvement in wing L/D



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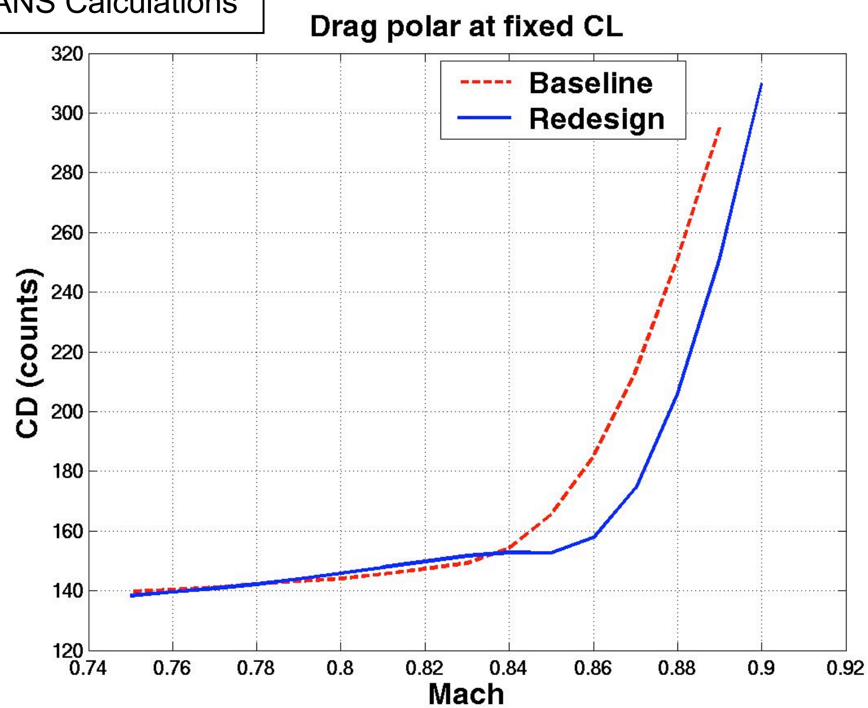
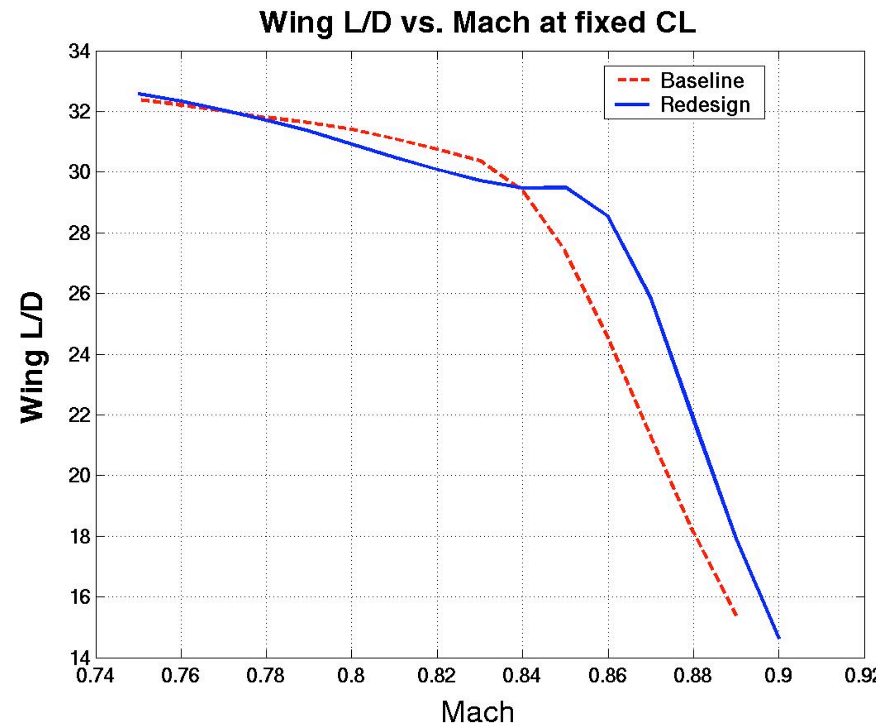
Redesign of the BAE MDO Datum Wing-Body : Drag Rise

Constraints : Fixed C_L = 0.454
: Fixed span-load distribution
: Fixed thickness

RANS Calculations





ML/D improved by 3 %

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Theses on BGK Method

- ***Chongam Kim***
- ***Yee Feng Ruan***
- ***Balaji Srinivasan***
- ***Georg May***

Theses on Dual Time-Stepping and Time-Spectral Method

- ***Juan Alonso***
- ***Andre Belov***
- ***Bing Ham Liou***
- ***Paul Lin***
- ***Sriram Shankaran***
- ***Mathew McMullen***
- ***Arathi Gopinath***

Theses on Shape Optimization

- ***James Reuther***
- ***Sangho Kim***
- ***Siva Nadarajah***
- ***Sriram Shankaran***
- ***Kasidit Leoviriyakit***

(At Princeton under Luigi Martinelli)

- ***James Dreyer***

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Bio
Antony Jameson

Position

1997 - Present	*Thomas V. Jones Professor of Engineering* , Stanford University
1982 - 1997	*James S. McDonnell Distinguished University Professor of Aerospace Engineering* , Princeton University
1980 - 1982	*Director, Program in Applied and Computational Mathematics,* Princeton University

Honors

2002	Docteur Honoris Causa, Uppsala University
2001	Docteur Honoris Causa , Université Pierre et Marie Curie, Paris VI
1997	Foreign Associate, National Academy of Engineering
1995	ASME Spirit of St. Louis Medal
1995	Fellow of the Royal Society of London
1993	American Institute of Aeronautics and Astronautics Fluid Dynamics Award
1990	Fellow of the American Institute of Aeronautics and Astronautics
1988	Gold Medal of the Royal Aeronautical Society
1980	NASA Medal for Exeptional Scientific Achievement

Bio
Antony Jameson

Biography

1953 - 1955	2nd Lieutenant British Army in Malaysia
1955	Bristol Siddeley Jet Engines
1955 - 1963	Cambridge university
	BA, MA Mechanical Sciences
	PhD Magneto-Hydrodynamics
1964 - 1965	Economist London
1965 - 1966	Chief Mathematician
1966 - 1972	Grumman Aerospace Aerodynamics Department
1972 - 1980	Courant Institute of Mathematics
	Professor of Computer Science 1974-80
1980 - 1997	Princeton University
	James S. McDonnell Distinguished University Professor of Aerospace Engineering 1982-97
1997 - present	Stanford university
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Relationship to the Boeing Company

- Antony Jameson has had a long standing relationship with both McDonnell Douglas and Boeing
- Flo22, provided to Douglas in 1976, was a principal design tool for the C17 wing design. It is still used by Phantom Works.
- Flo27 was incorporated as the flow solver in the Boeing A488 software, which was used in the wing design of the Boeing 757, 767, and 777.
- Flo27 was incorporated in the McDonnell Douglas DACTRAN 10, 20 and 30 codes
- The AIRPLANE code was used in the MD11 CPIP, HSR and C17 winglet studies