Industrial Applications of Aerodynamic Shape Optimization

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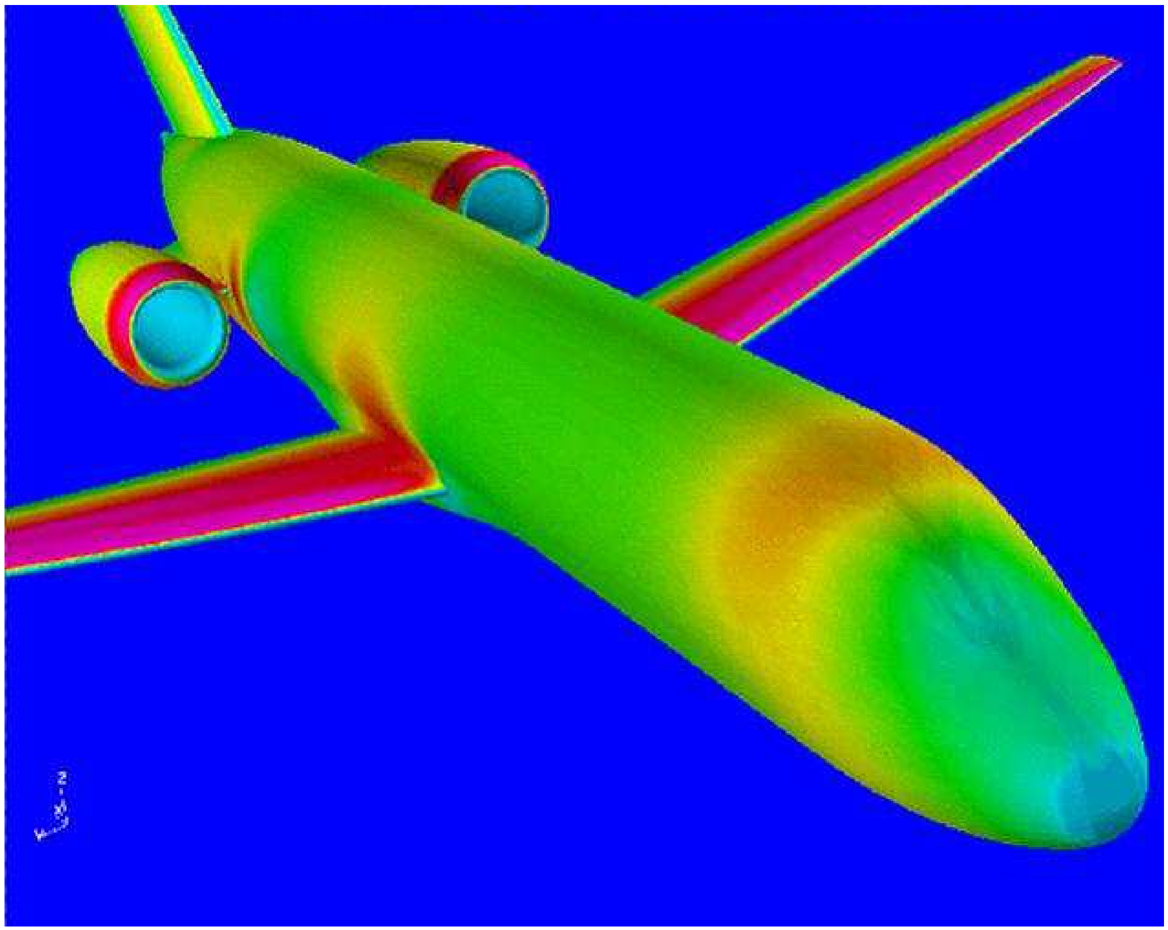
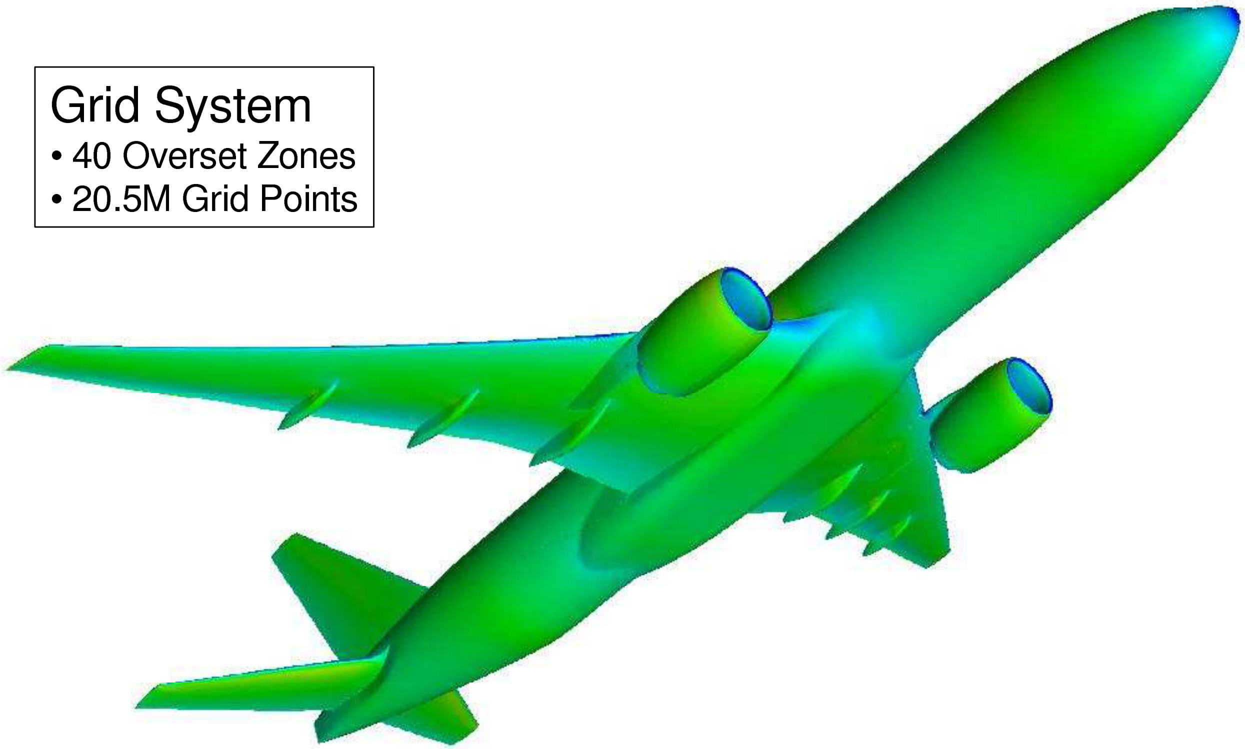
LECTURE OUTLINE

- **INTRODUCTION**
- **THEORETICAL BACKGROUND**
  - SPIDER & FLY
  - BRACHISTOCHRONE
- **SAMPLE APPLICATIONS**
  - MARS AIRCRAFT
  - RENO RACER
  - GENERIC 747 WING/BODY
- **DESIGN-SPACE INFLUENCE**

COMMERCIAL AIRCRAFT DESIGN



COMMERCIAL AIRCRAFT DESIGN



AERODYNAMIC OPTIMIZATION

- PROCESS OVERVIEW
- GRADIENT CALCULATION
- COMPUTATIONAL COSTS
- SYN107P CAPABILITIES

PROCESS OVERVIEW

1. Solve the flow equations for w.
2. Solve the adjoint equations for ψ.
3. Evaluate $\mathcal{G}$, and precondition to get $\bar{\mathcal{G}}$.
4. Project $\bar{\mathcal{G}}$ into an allowable subspace.
5. Update the shape.
6. Return to 1 until convergence is reached.

Practical implementation of the viscous design method relies heavily upon fast and accurate solvers for both the state (w) and co-state (ψ) systems. Steps 1-2 can be semi-converged during trajectory. Step 4 is only necessary for the final design. Step 5 can be Krylov subspace accelerated. Steps 1-5 can be accelerated with multigrid.

GRADIENT CALCULATION

For flow about an arbitrary body, the cost function, I, depends on the flowfield variables, w, and the shape of the body, $\mathcal{F}$.

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

A change in $\mathcal{F}$ results in a change of the cost function

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

The governing equation, R, expresses the dependence of w and $\mathcal{F}$ within the flowfield domain D.

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

GRADIENT CALCULATION

Then δw is determined from

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

Introducing a Lagrange multiplier, ψ,

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

With some rearrangement

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

GRADIENT CALCULATION

Choose ψ to satisfy the adjoint equation

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

Now, δw can be eliminated in the variation of the cost function to give

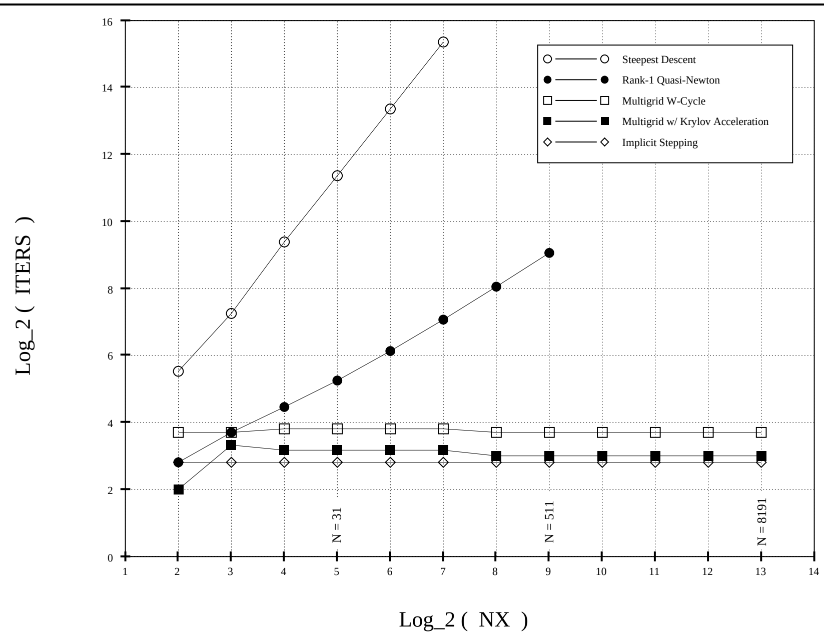
$$\delta I = \mathcal{G}^T \delta \mathcal{F},$$

where

$$\mathcal{G}^T = \frac{\partial I^T}{\partial \mathcal{F}} - \psi^T \left[\frac{\partial R}{\partial \mathcal{F}}\right].$$

COMPUTATIONAL COSTS

Cost of Search Algorithm.	
Steepest Descent	$\mathcal{O}(N^2)$ steps
Quasi-Newton	$\mathcal{O}(N)$ steps
Smoothed Gradient	$\mathcal{O}(K)$ steps



COMPUTATIONAL COSTS

Total Computational Cost of Design.	
Finite Difference Gradients + Steepest Descent	$\mathcal{O}(N^3)$
Finite Difference Gradients + Quasi-Newton Search	$\mathcal{O}(N^2)$
Adjoint Gradients + Quasi-Newton Search	$\mathcal{O}(N)$
Adjoint Gradients + Smoothed Gradient Search (Note: K is independent of N)	$\mathcal{O}(K)$

SYN107P CAPABILITIES

- **GENERALIZED ATTRIBUTES**
  - Design Space Is Automatically Defined
  - Design Space Is Not Artificially Constrained
  - Thickness Constraints Automatically Set-Up
  - Fast Turn-Around Times (Wall Clock)
    - NS Analysis $\leq$ 30 minutes on 8 processors
    - NS Optimization $\leq$ 5 hours on 8 processors
    - NS Optimization $\leq$ 27 hours on a Notebook
- **SPECIFIC ATTRIBUTES**
  - Automatic Euler & NS Grid Generation
  - Can Constrain Spanload Distribution
  - Can Specify Lifting Condition

CASE 1: MARS AIRCRAFT

- **MARES BACKGROUND**
- **MARES GENERAL DESIGN**
- **MARES DETAILED DEVELOPMENT**
- **SUMMARY**

MARES: Mars Airborne Remote Exploration Scout

MARES BACKGROUND

- **AERIAL-BASED GEOLOGIC SURVEYING**
  - Better Resolution Than Orbiting Platforms
  - Faster Than Land Based Rovers
  - More Controlable Than Balloon Systems
  - Can Enhance NASA's Exploration Capabilities
    - Provides Access To Entire Planet Surface
    - Can Survey In Close Proximity To Terrain
    - Precision Landing With Hazard Avoidance
  - However, Not All Planets Have An Atmosphere

MARES BACKGROUND

- **EXTRA-TERRESTRIAL MISSIONS**
  - Aircraft Packaged In An Aero-Shell Capsule
  - Atmospheric Entry & Hypersonic Deceleration
  - Capsule Decent On A Parachute
  - Free-Fall Deployment & Pull-Out Maneuver
  - Transition To Steady-State Flight Path
  - Landing On Austere Terrain
- **RAREFIED MARTIAN ATMOSPHERE**
  - Similar To Earth's At About 100K feet Altitude

MARES GENERAL DESIGN

- GENERAL SYSTEMS
- AERO-SHELL PACKAGING
- IN-FLIGHT CONFIGURATION
- PLANFORM CHARACTERISTICS
- REFERENCE QUANTITIES
- CRUISE DESIGN POINT

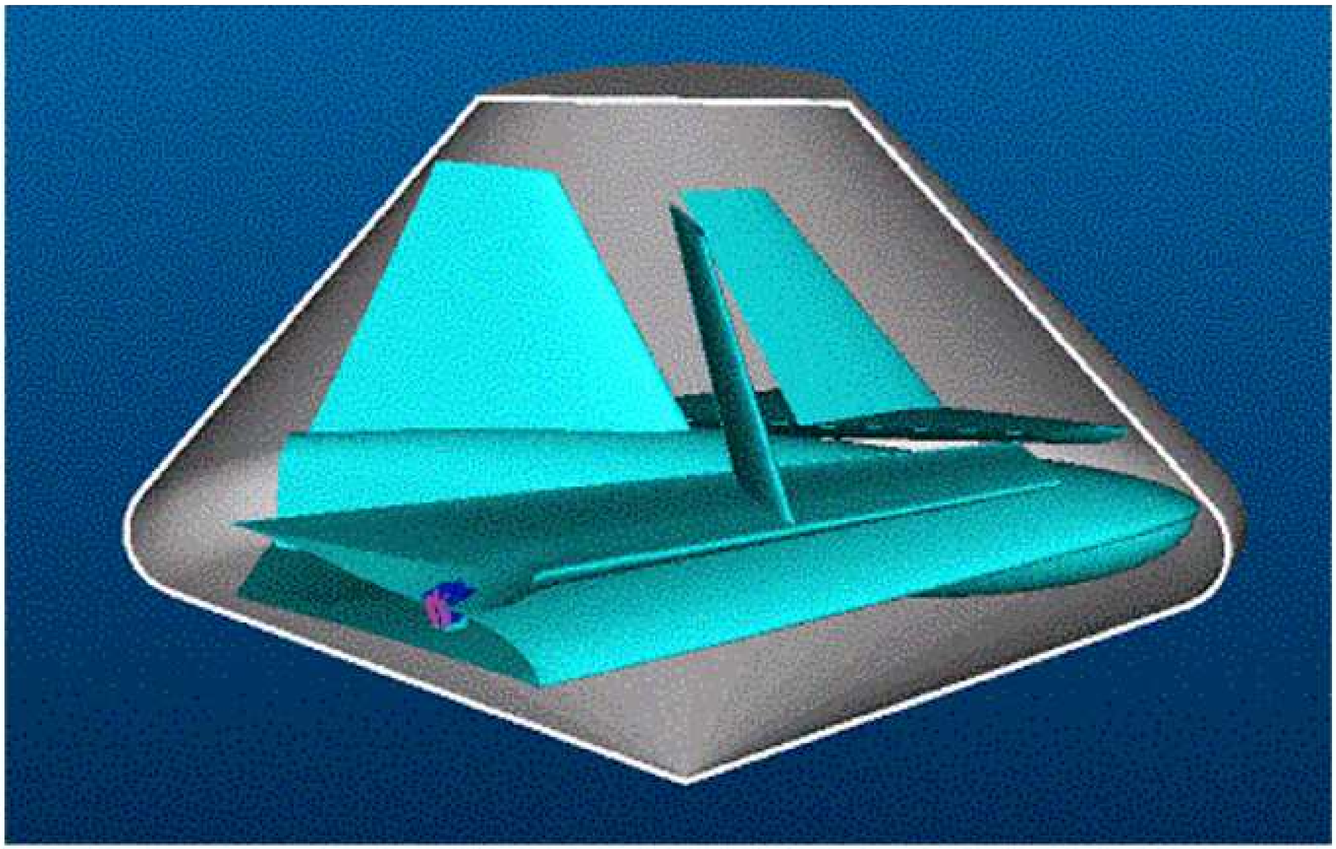
MARES GENERAL DESIGN

- **GENERAL SYSTEMS**
  - Flying Wing Configuration
    * Inboard Delta Wing, Low-Sweep Outboard Wing
    * Centerline Vertical, Outboard Ventral Fins
    * No Horizontal Stabilizer
    * Autonomous Deployment Uses Aerodynamic Unfolding
  - Solid Rocket Motor For Reliability
  - Reaction Control System
    * Used During Free Fall And Landing
    * Provides Zero Axial Velocity Control
  - Steady-State Flight
    * Uses Conventional Aerodyanmic Control Systems

MARES GENERAL DESIGN

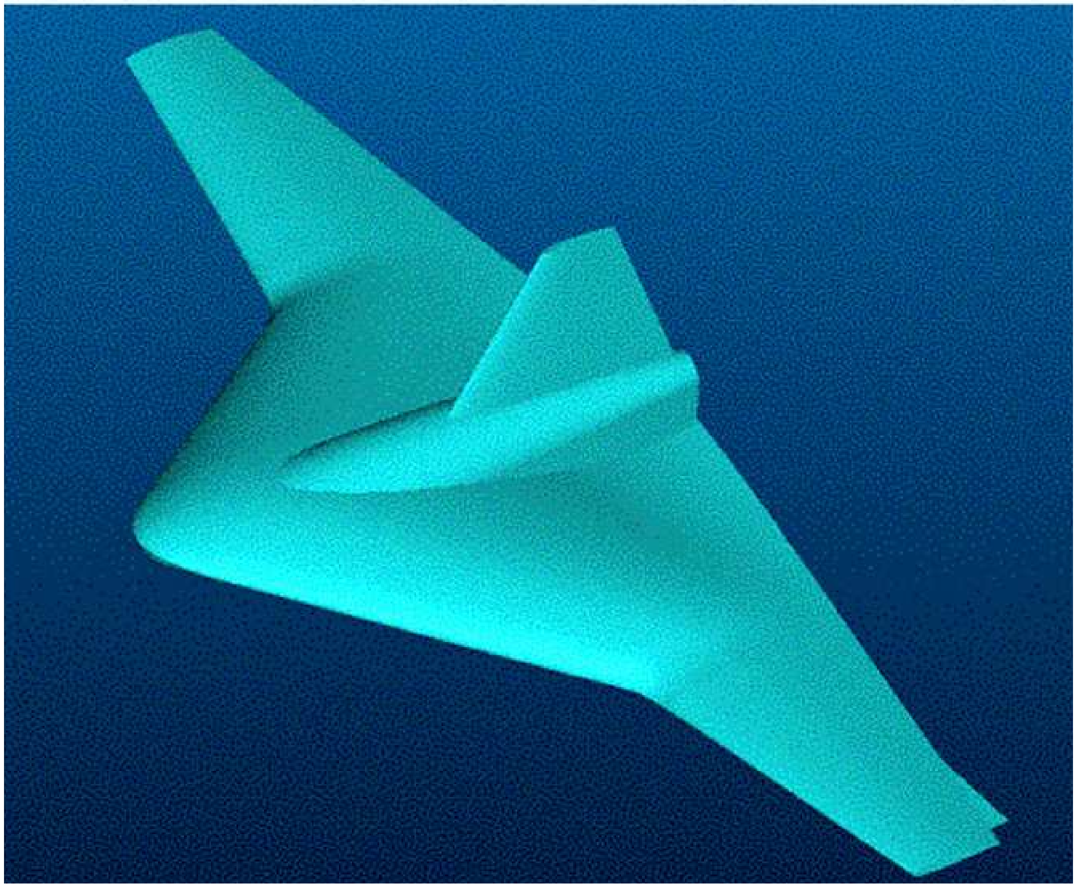
- **GENERAL SYSTEMS**
  - Landing Mode
    * Deep-Stall, Nose-Up Attitude
    * Z-Axis Thruster
    * Energy-Absorbing Ventral Fins
  - Data Collection During Flight
  - Data Transmission After Landing
    * Reduces Bandwidth Requirements
  - Flight Duration Is About 20 Minutes

MARES GENERAL DESIGN



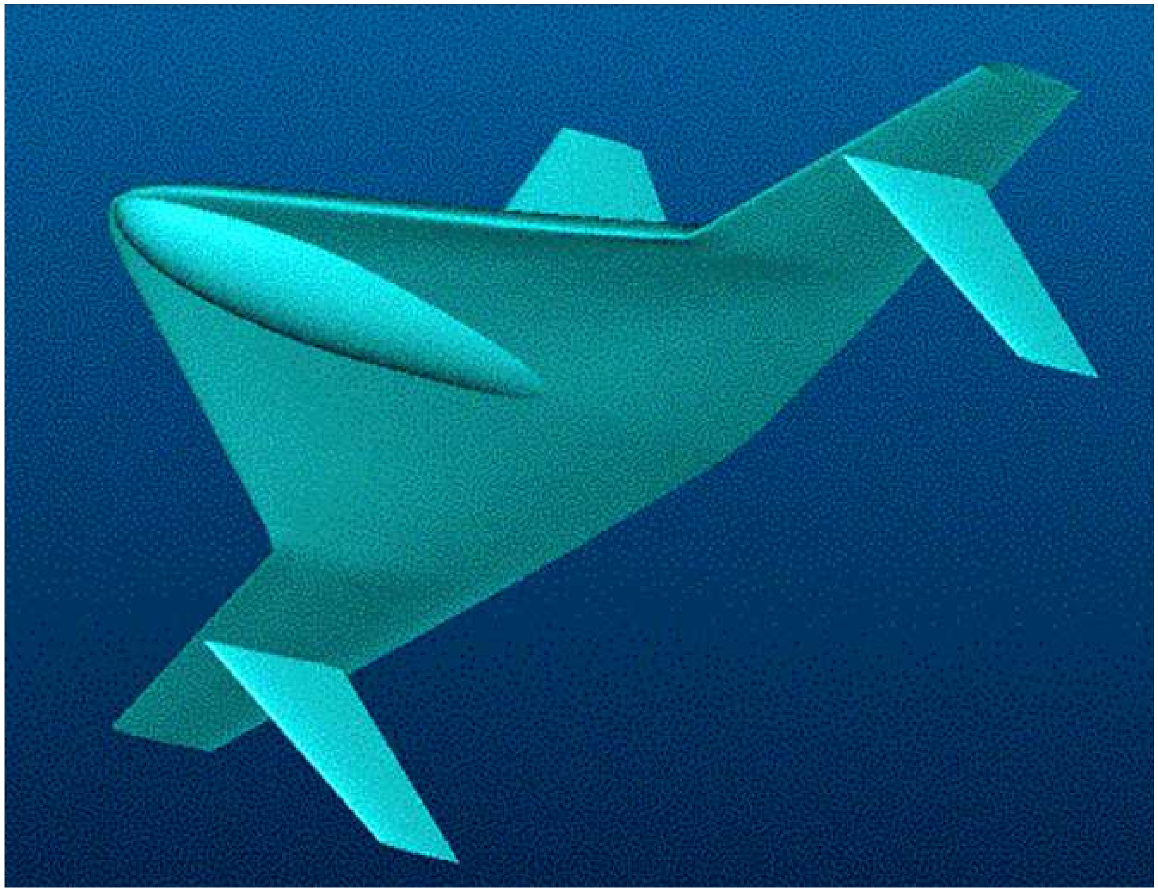
MARES Packaging in the Aerodynamic-Shell Capsule.

MARES GENERAL DESIGN



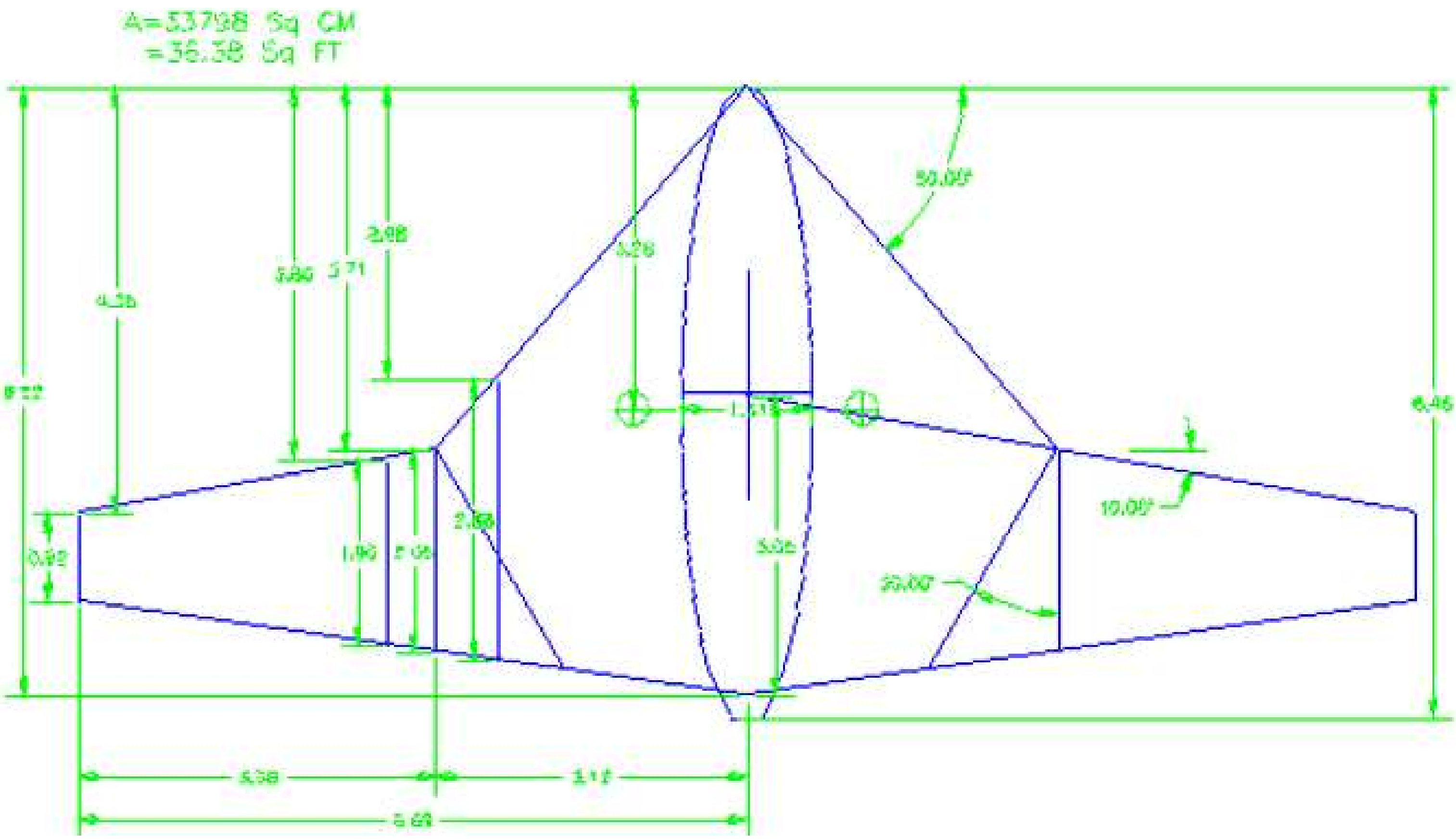
MARES Configuration in Flight, Top-View Rendering.

MARES GENERAL DESIGN



MARES Configuration in Flight, Bottom-View Rendering.

MARES GENERAL DESIGN



MARES General Planform Layout.

MARES GENERAL DESIGN

- **REFERENCE QUANTITIES**

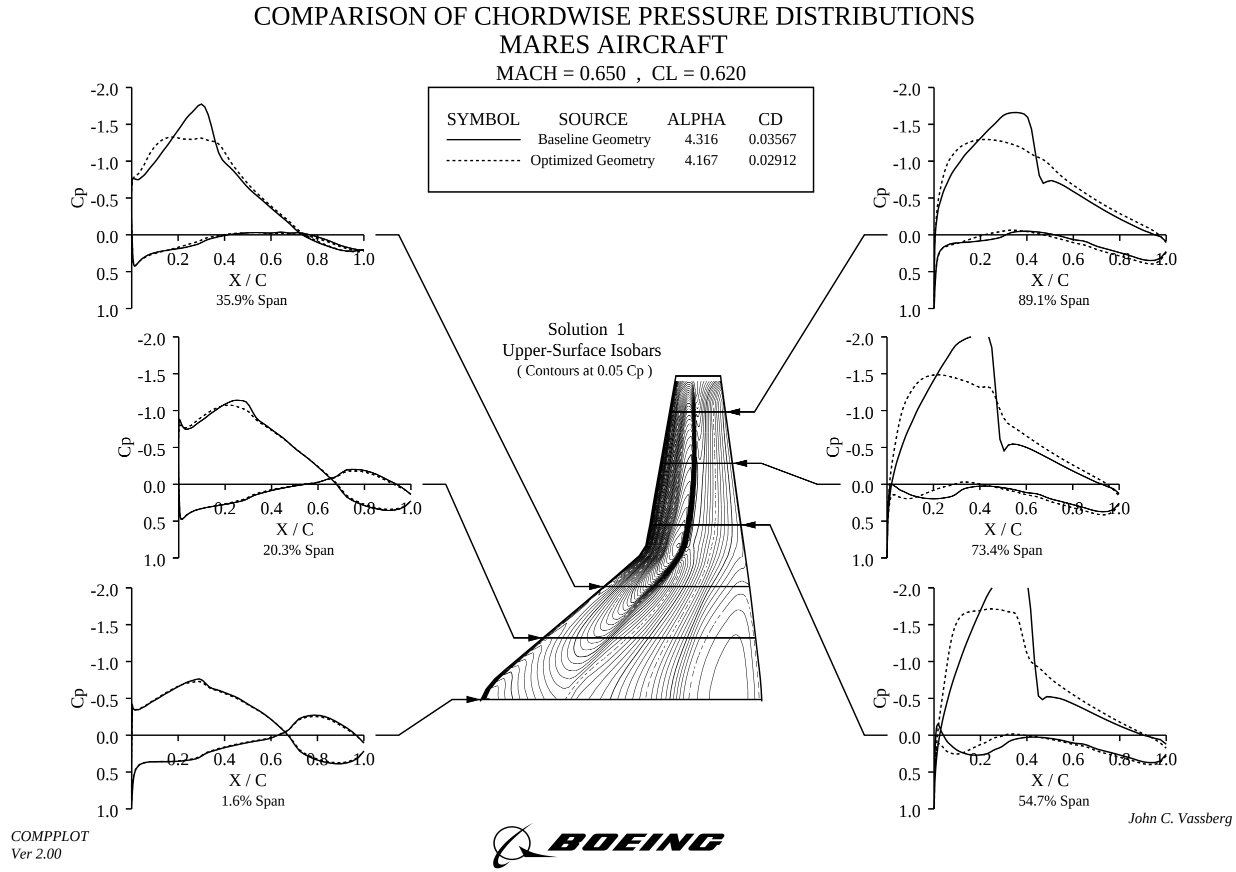
$Sref$	$36.38\ ft^2$	AR	4.9
b	$13.38\ ft$	λ	0.3
$Cref$	$3.28\ ft$	$\Lambda_{c/4}$	5.5°
$Xref$	$3.28\ ft$	Λ_{LE}	10.0°
$Yref$	$1.51\ ft$	$\Lambda_{LE.\Delta}$	50.0°

- **CRUISE DESIGN POINT**
  - $M = 0.65,\ C_L = 0.62,\ Re = 170K$
  - $\rho = 2.356 * 10^{-5}\ slugs/ft^3$
  - $\nu = 2.2517 * 10^{-7}\ slugs/ft/sec$

MARES DETAILED DEVELOPMENT

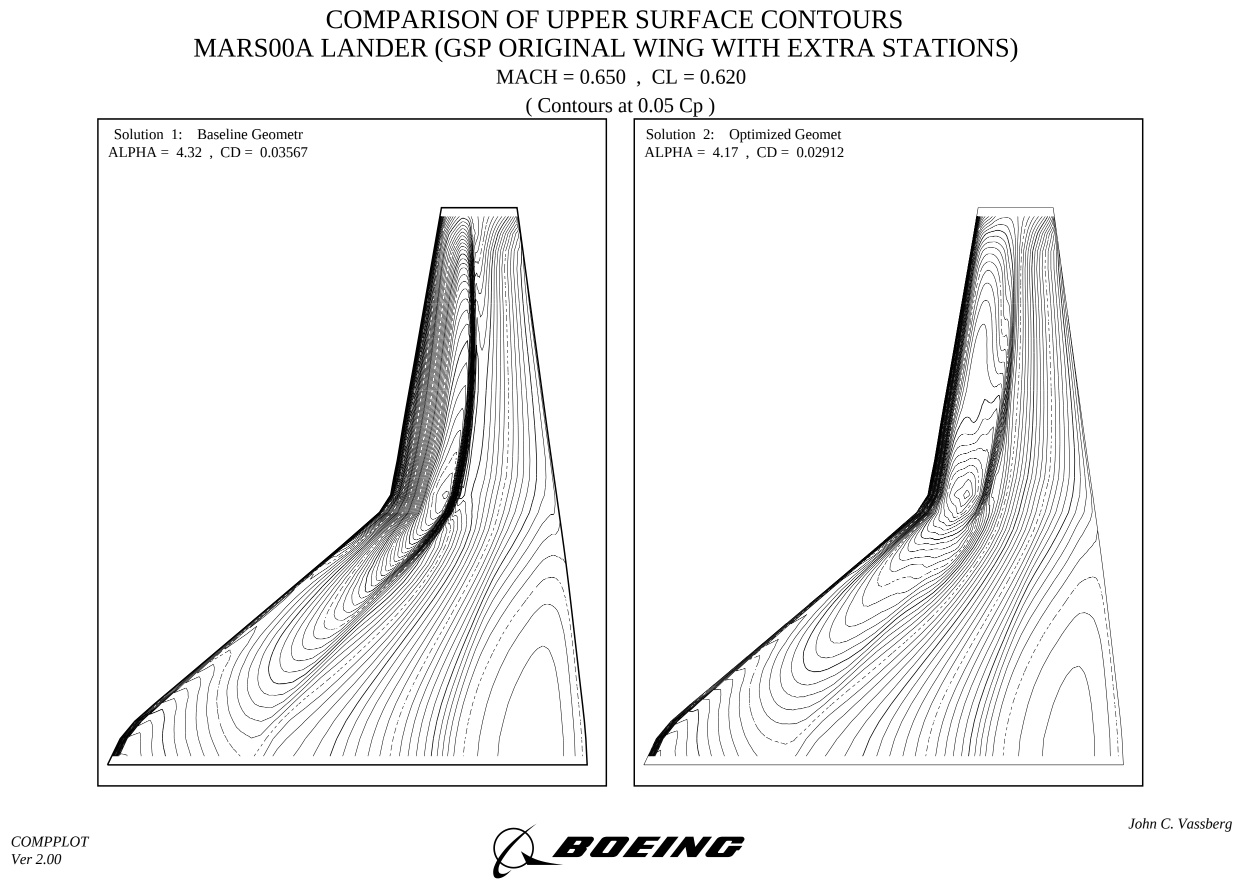
- **EULER OPTIMIZATION**
  - Runs Within 30 Minutes On A Notebook
  - Input Deck Check-Out
- **NAVIER-STOKES OPTIMIZATION**
  - Drag Minimization
  - Single-Point Design
  - Specified Lifting Condition
  - Matched Baseline's Spanload
  - Matched Baseline's Thickness Or Thicker

MARES DETAILED DEVELOPMENT



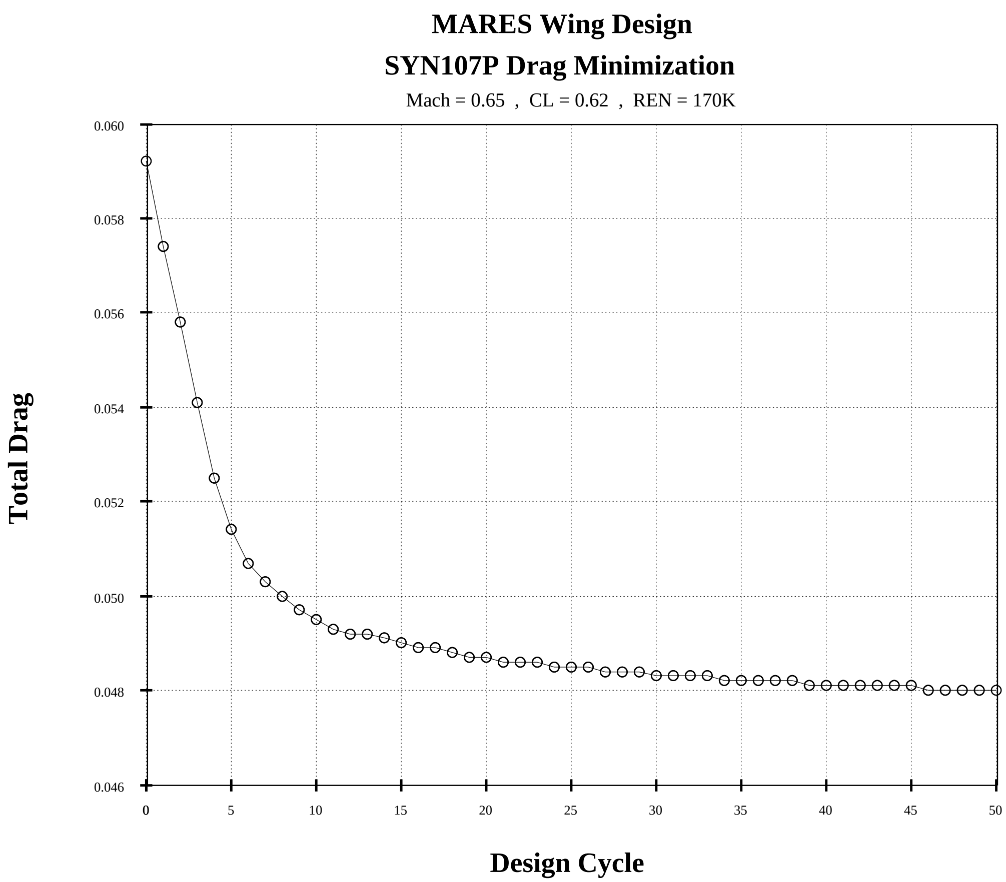
Baseline and Euler Optimized Wing Pressure Distributions.

MARES DETAILED DEVELOPMENT



Baseline and Euler Optimized Wing Pressure Contours.

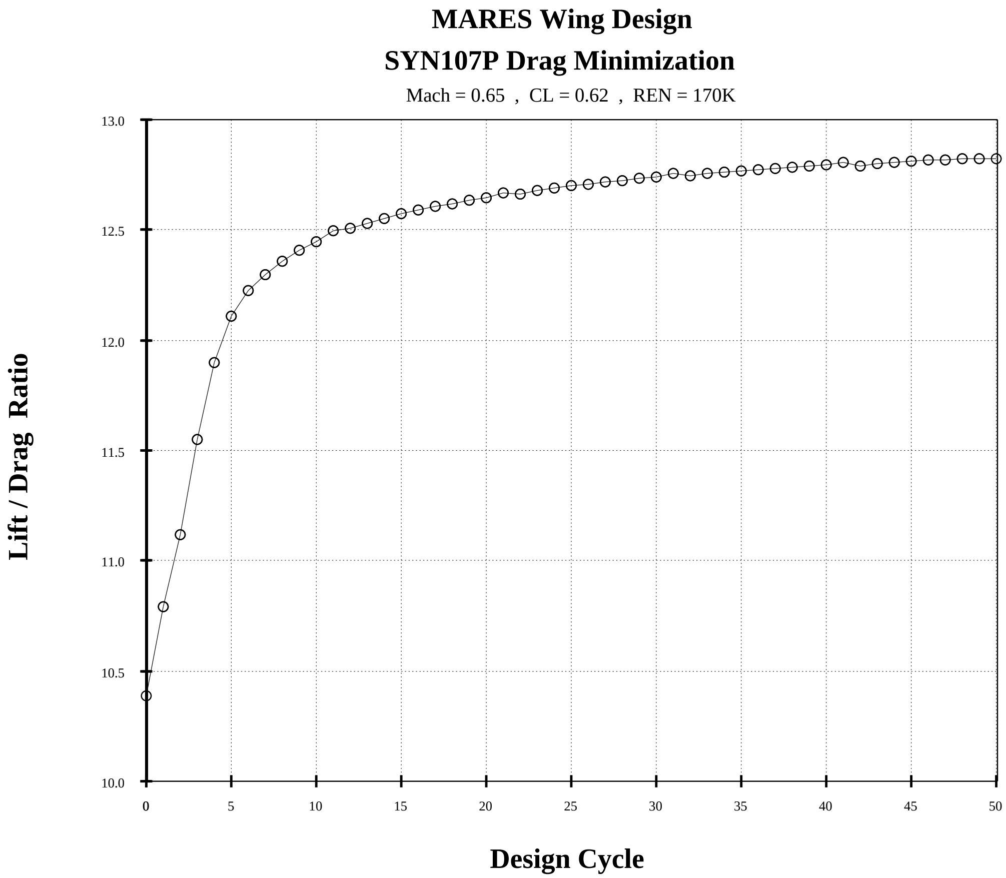
MARES DETAILED DEVELOPMENT



Baseline:	592.4 counts
Optimized:	480.0 counts
ΔDrag:	-112.4 counts

History of Drag Minimization during Navier-Stokes Optimization.

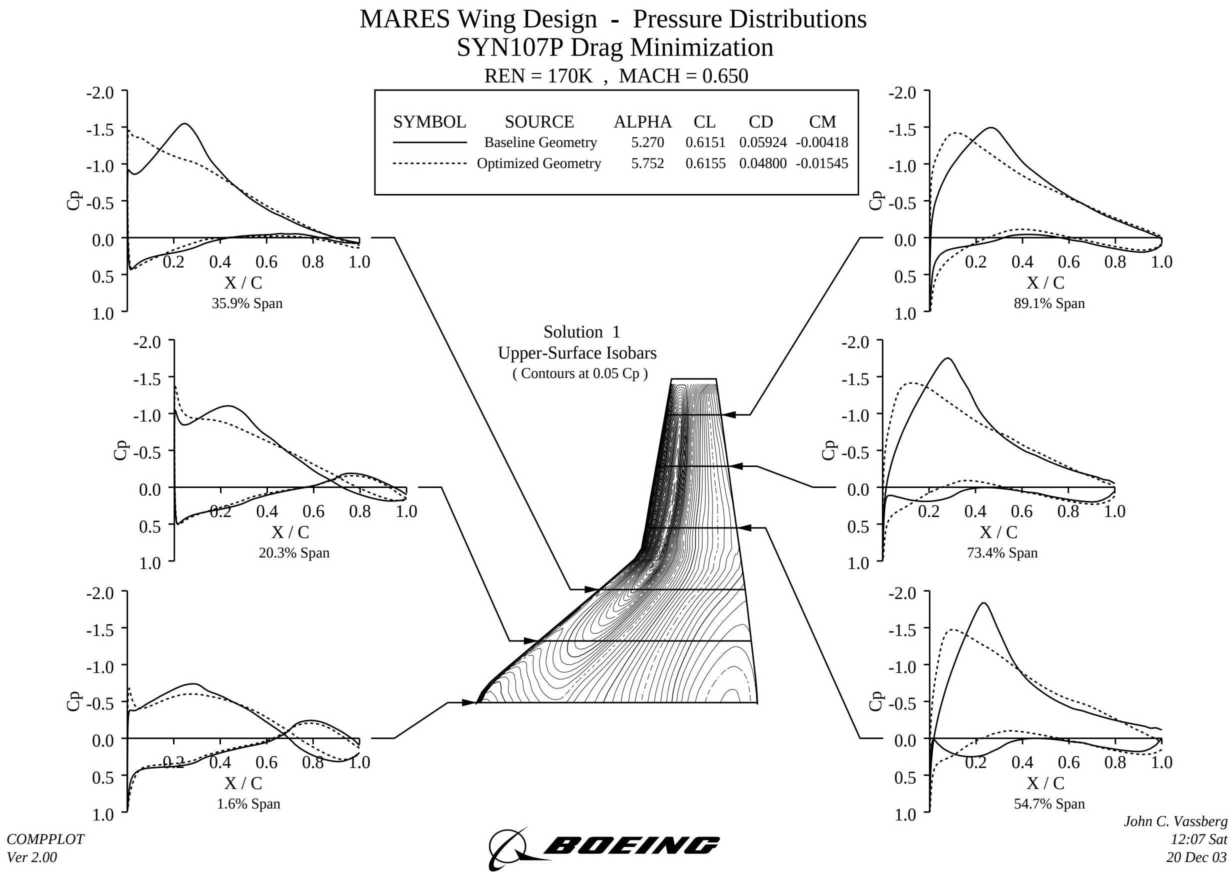
MARES DETAILED DEVELOPMENT



Baseline:	10.4
Optimized:	12.8
ΔL/D:	+23.4%

History of Lift-to-Drag Ratio during Navier-Stokes Optimization.

MARES DETAILED DEVELOPMENT



Upper Surface

. LE Peak Reduced

. LE Peak Moved Forward

. Cp Gradient Reduced

. BL Health Improved

Lower Surface

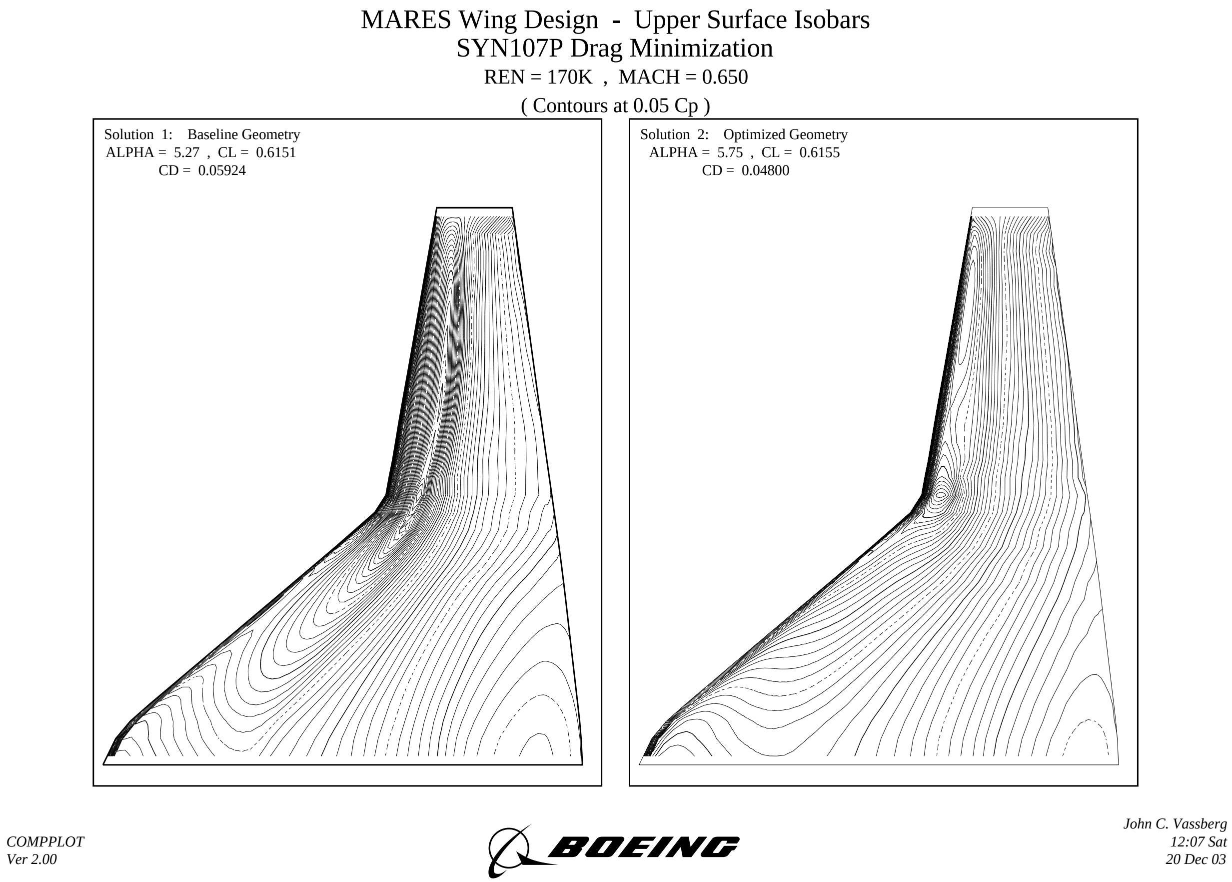
. LE Peak Removed

. Favorable Cp Gradient

. BL Health Improved

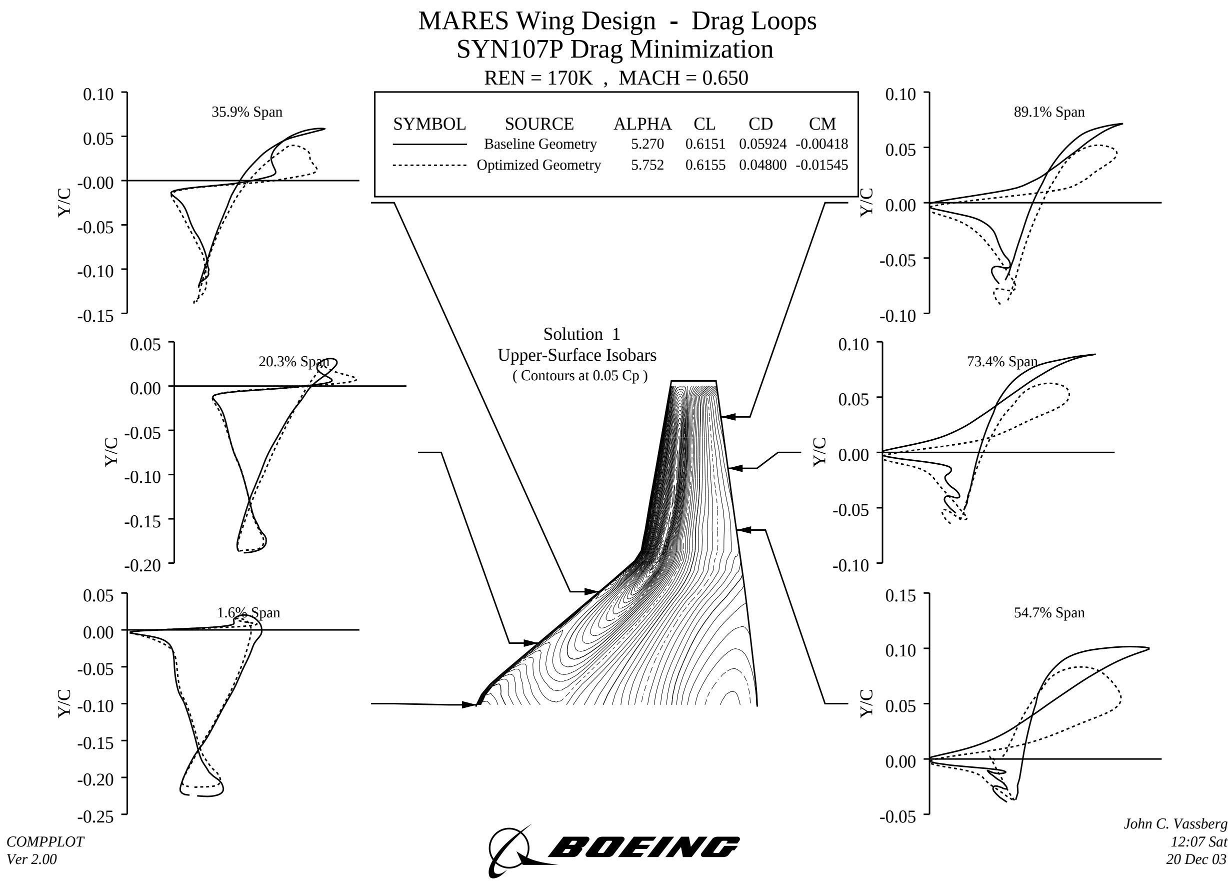
Baseline and Navier-Stokes Optimized Wing Pressure Distributions.

MARES DETAILED DEVELOPMENT



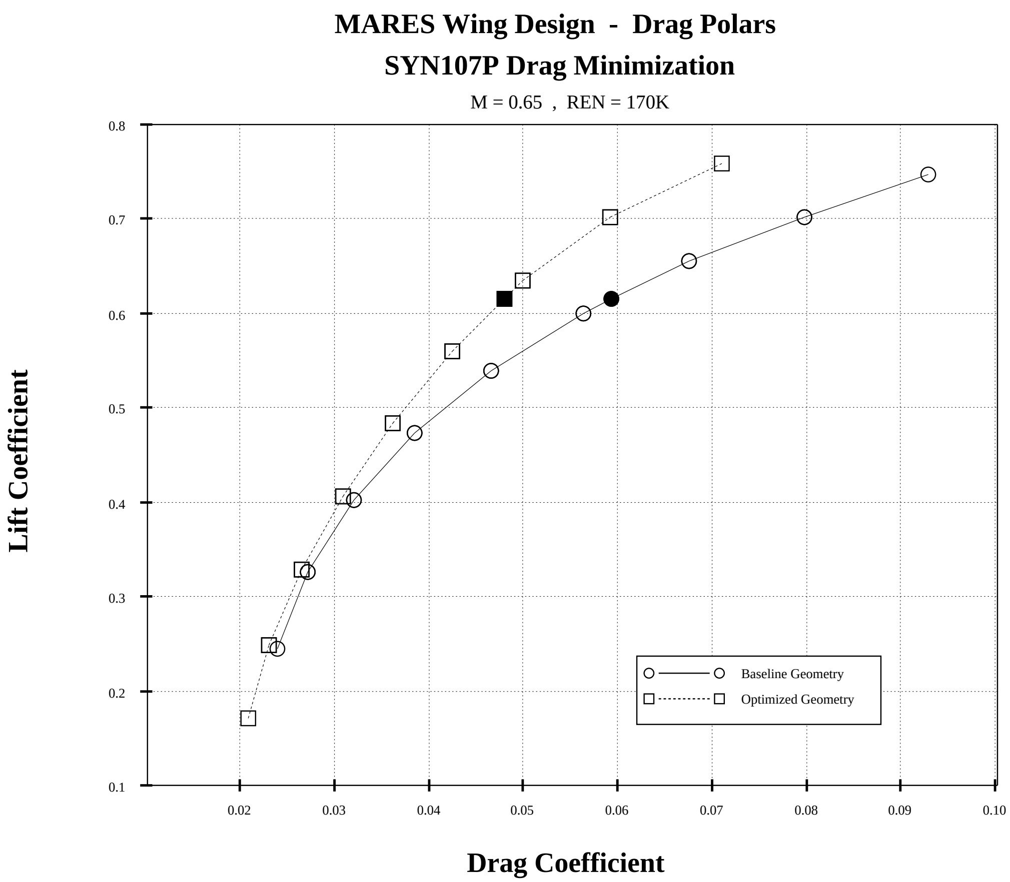
Baseline and Navier-Stokes Optimized Wing Upper-Surface Isobars.

MARES DETAILED DEVELOPMENT



Baseline and Navier-Stokes Optimized Wing Drag Loops.

MARES DETAILED DEVELOPMENT

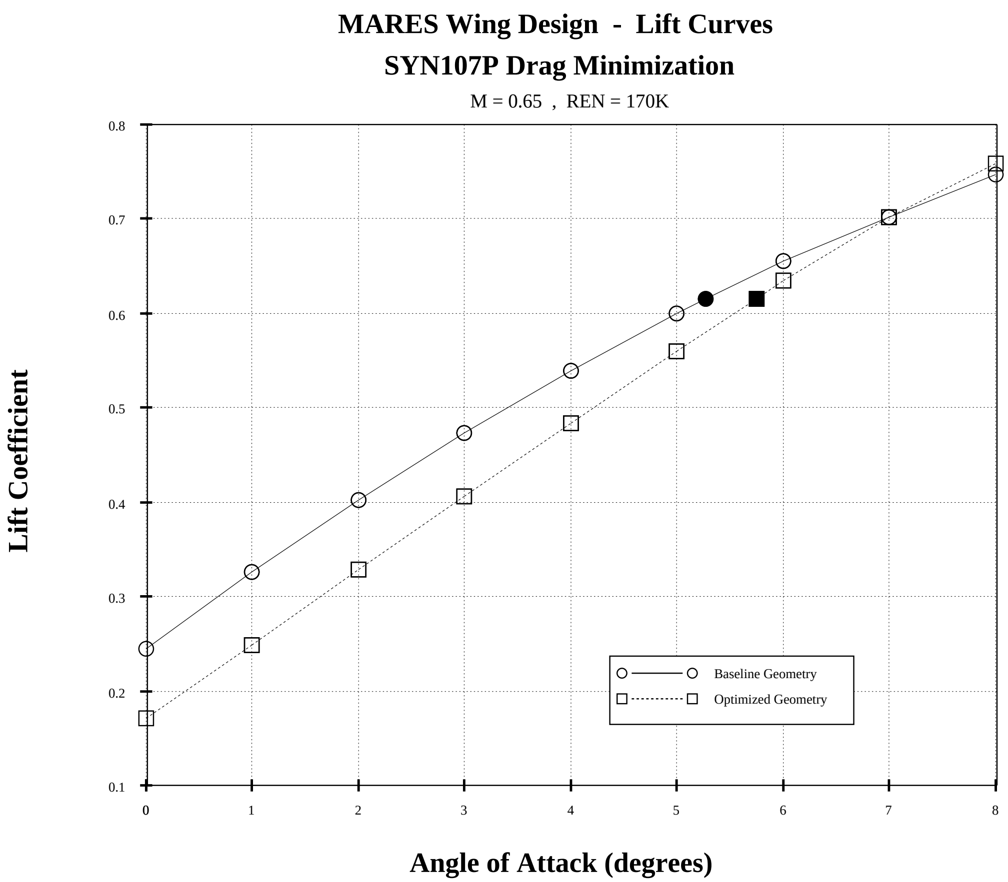


Off-Design Characteristics Are Well Behaved

Improvements Are Realized At All Lifting Conditions

Baseline and Navier-Stokes Optimized Wing Drag Polars.

MARES DETAILED DEVELOPMENT

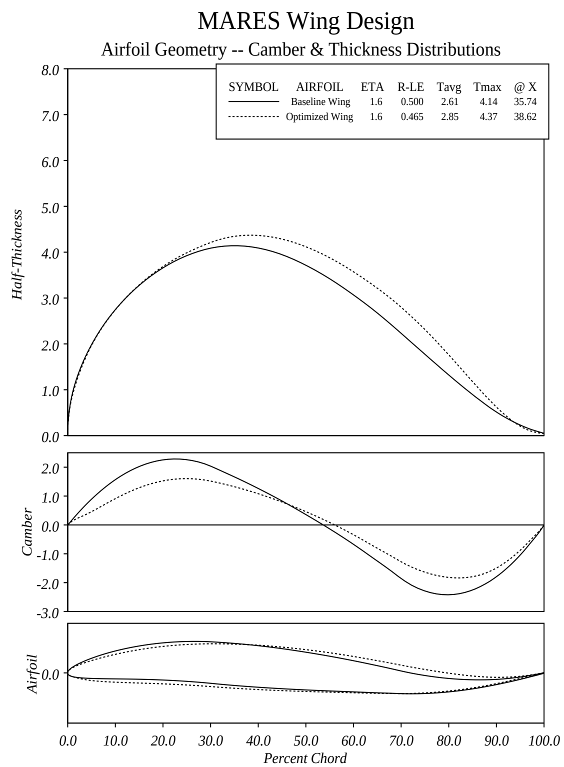


Baseline Lift-Curve Slope Diminishes At The Higher Lifting Conditions

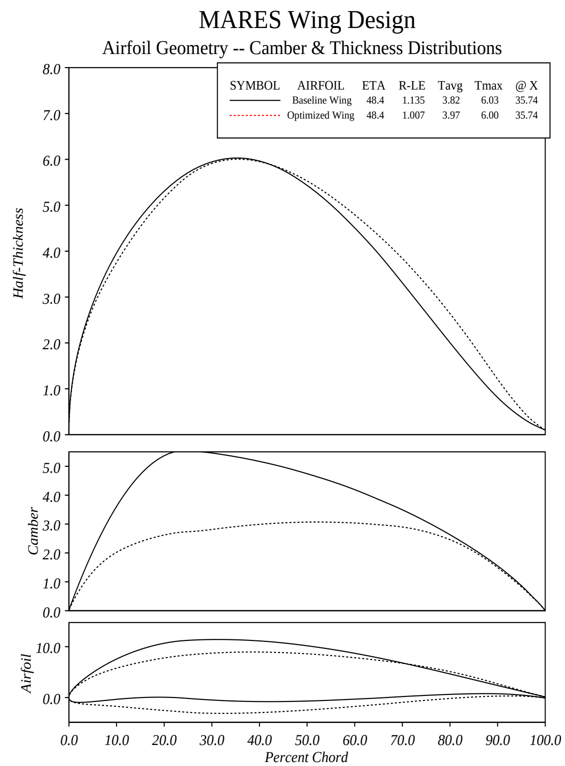
Optimized Lift-Curve Slope Remains Strong, Indicating That Its BL Health Is Improved Relative To Baseline

Baseline and Navier-Stokes Optimized Wing Lift Curves.

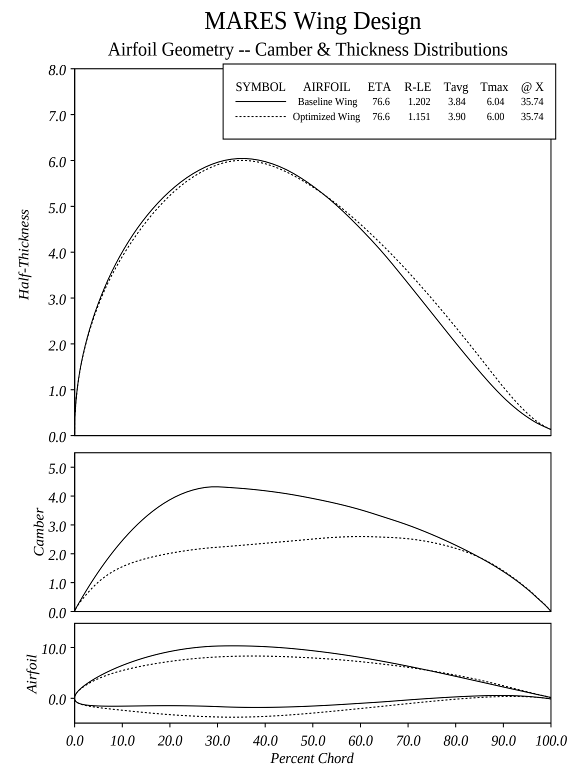
MARES DETAILED DEVELOPMENT



Root



Mid-Span



Outboard

Baseline and Navier-Stokes Optimized Wing Airfoil Sections.

MARES SUMMARY

- **MARES PERFORMANCE IMPROVEMENTS**
  - Drag Reduced 112 Counts At Design Point
  - L/D Improved 23% From 10.4 To 12.8
  - Improvements Made At All Lifting Conditions
  - Off-Design Characteristics Are Well Behaved
- **SYN107P UTILITY DEMONSTRATED**
  - Ease Of Use
  - Fast Turn-Around Times
  - Affordable Computers
  - Significant Performance Improvements Realized

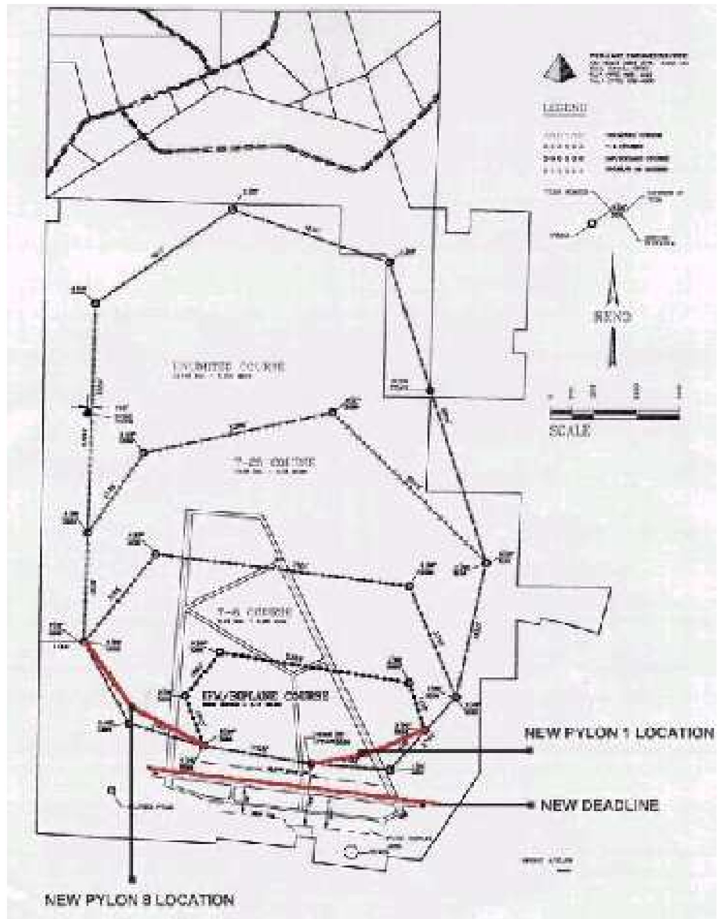
CASE 2: RENO RACER

- RENO AIR RACES
- DESIGN OVERVIEW
- WING DESIGN
- SUMMARY

RENO AIR RACES

Miss Ashley II and Rare Bear en Route.

RENO AIR RACES

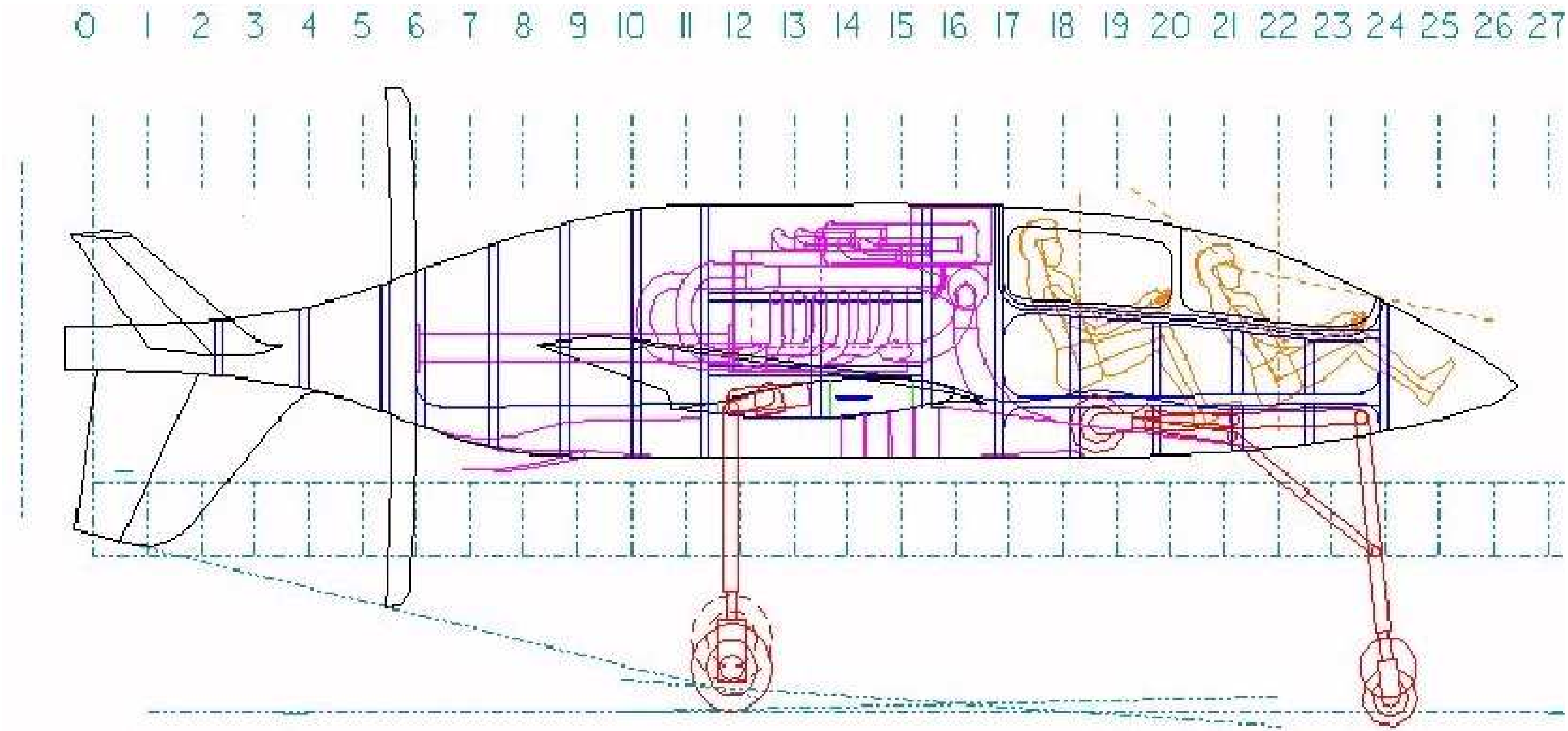


DESIGN OVERVIEW

- **CONSTRAINTS - UNLIMITED CLASS**
  - Piston Engine
  - Propellor Driven

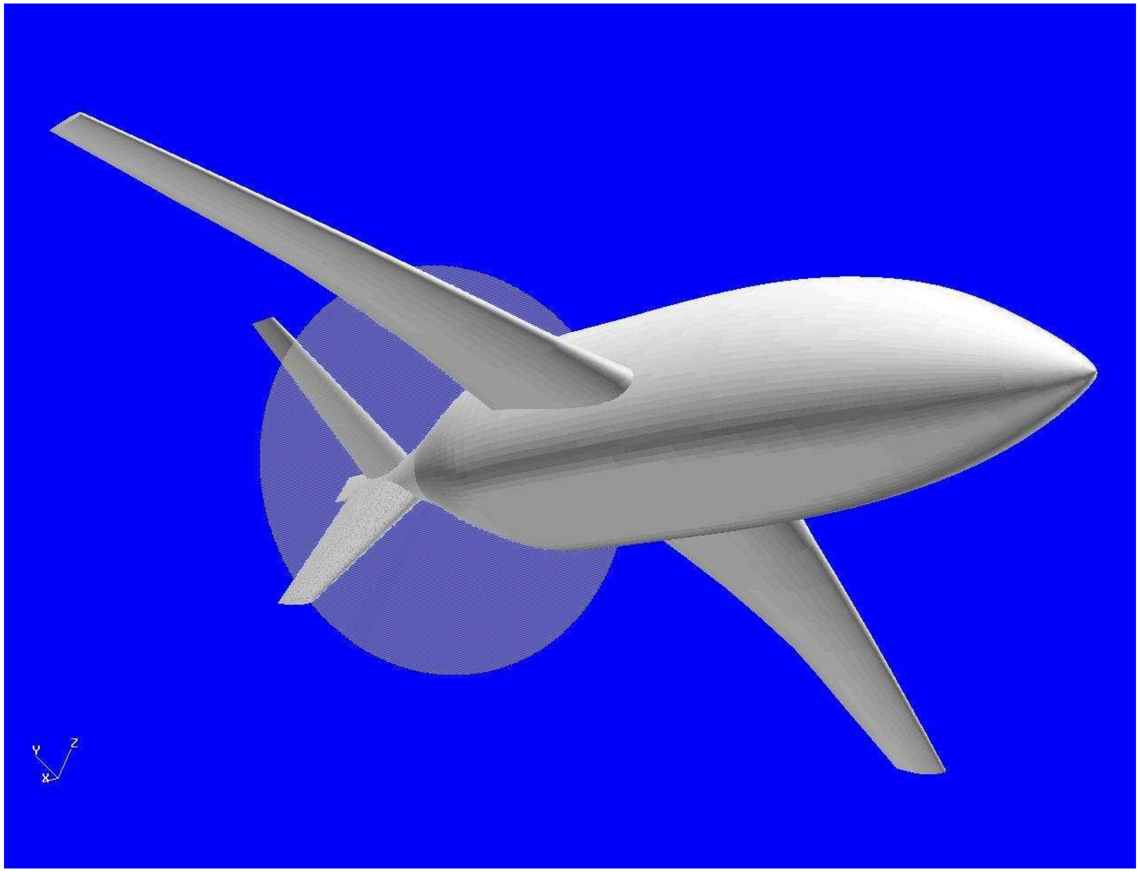
- **DESIGN OBJECTIVES**
  - 600 MPH TAS, Level Flight
  - 550 MPH TAS, Average Lap Speed
  - Stall Speed $\leq$ 90 KEAS
  - 9G Maneuver $+$ 5G Gust $=$ 14G Total

DESIGN OVERVIEW



Side View of Body-Prop Design.

DESIGN OVERVIEW



Rendering of Body-Prop Design in Flight.

WING DESIGN

- CONCEPTUAL LAYOUT
- ROUGH DETAILED DESIGN
- AERODYNAMIC OPTIMIZATION
- LAMINAR FLOW
- FINAL TOUCHES

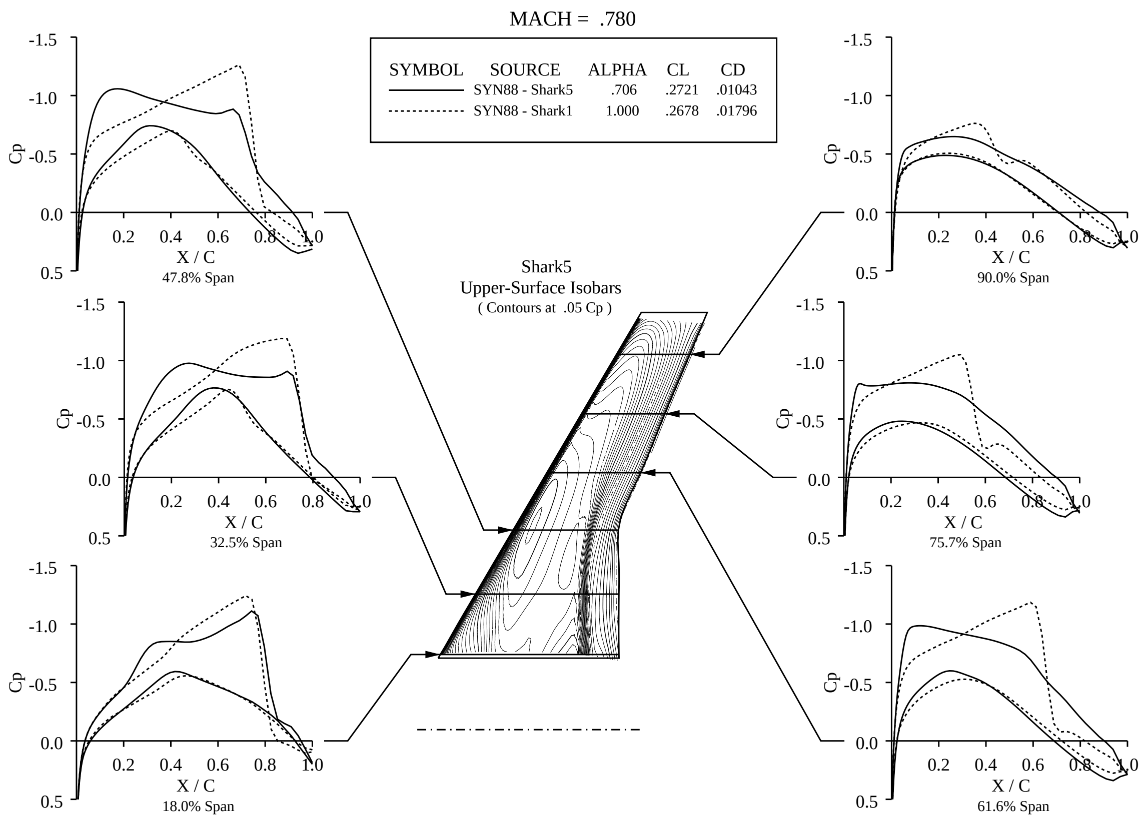
CONCEPTUAL LAYOUT

- **WING PLANFORM**
  - $S_{ref} = 75ft^2$, $\Lambda_{c/4} = 28^\circ$, $\lambda = 0.45$
  - $AR = 8.3$, $\frac{t}{c} = 12\%$
- **CRUISE DESIGN**
  - $M = 0.72$, $CL_{Total} = 0.32$, $Ren = 14.5M$
- **OFF DESIGN**
  - $CL_{maxCW} = 1.60$ at $M = 0.20$
  - $CL_{Buffet} = 0.64$ at $M = 0.72$
  - $M_{dd} = 0.80$ at $CL_{Total} = 0.1$
  - $M_{dd} = 0.77$ at $CL_{Total} = 0.3$

ROUGH DETAILED DESIGN

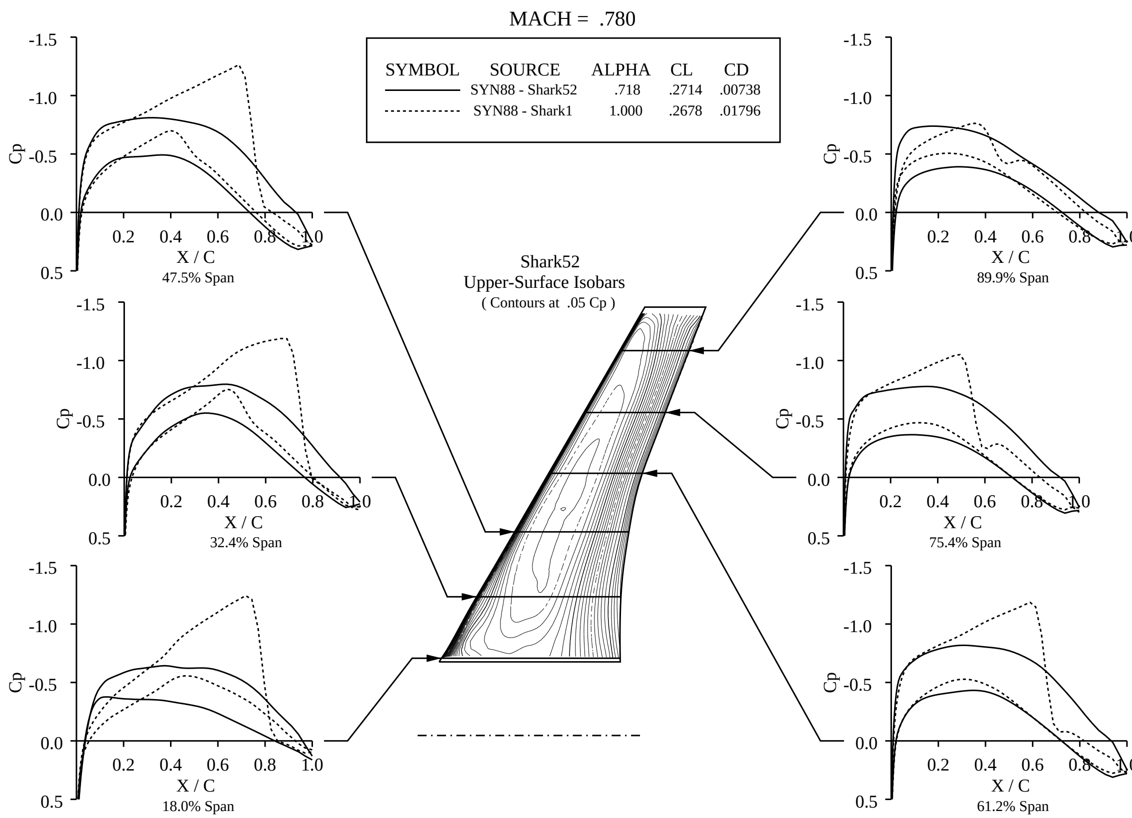
- **AIRFOIL SECTIONS**
  - NACA SC(2) Sections
  - 2D Optimizations using SYN103
  - Simple Sweep Theory
- **FLO22 FULL-POTENTIAL METHOD**
  - Pseudo-Body Effects
  - Coupled w/ 2D Integral BL Method
- **RESULTS**
  - $M_{dd} = 0.775$ at $CL_{Total} = 0.3$
  - Basic Wing Planform was Appropriate
  - Concerned about Contoured Fuselage Effects

AERODYNAMIC OPTIMIZATION



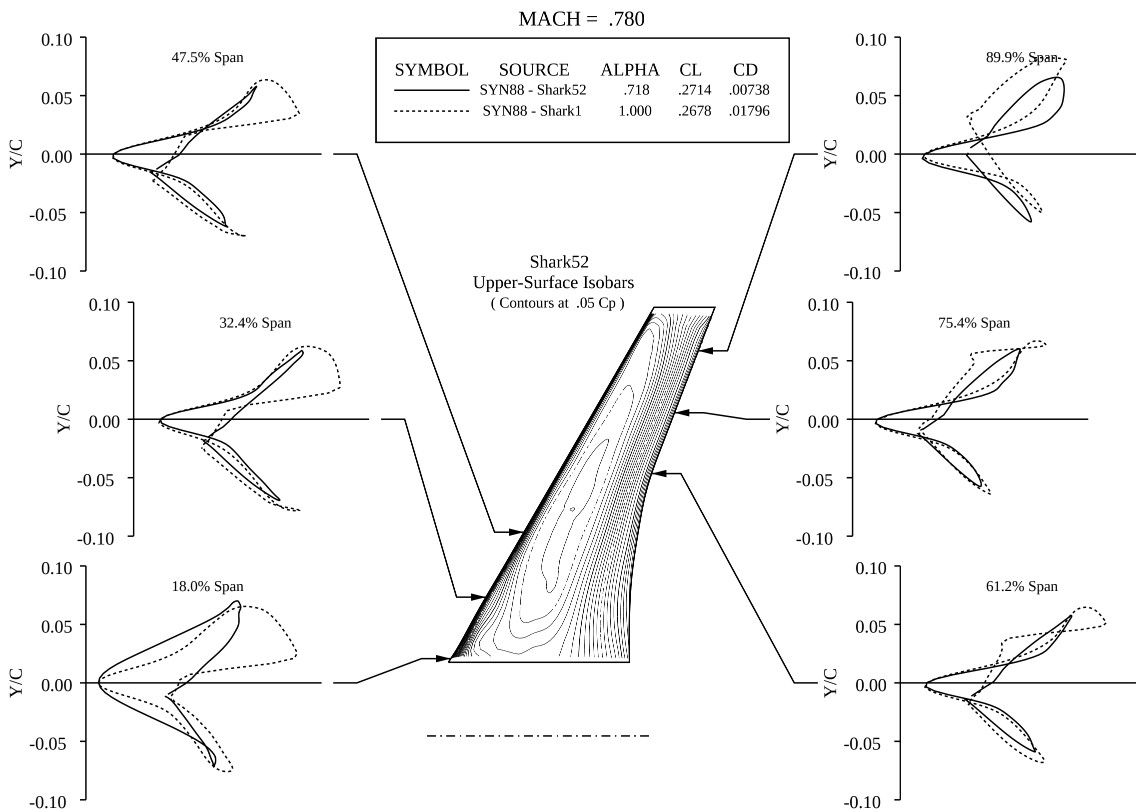
Shark5 and Shark1 Wings on Baseline Fuselage.

AERODYNAMIC OPTIMIZATION



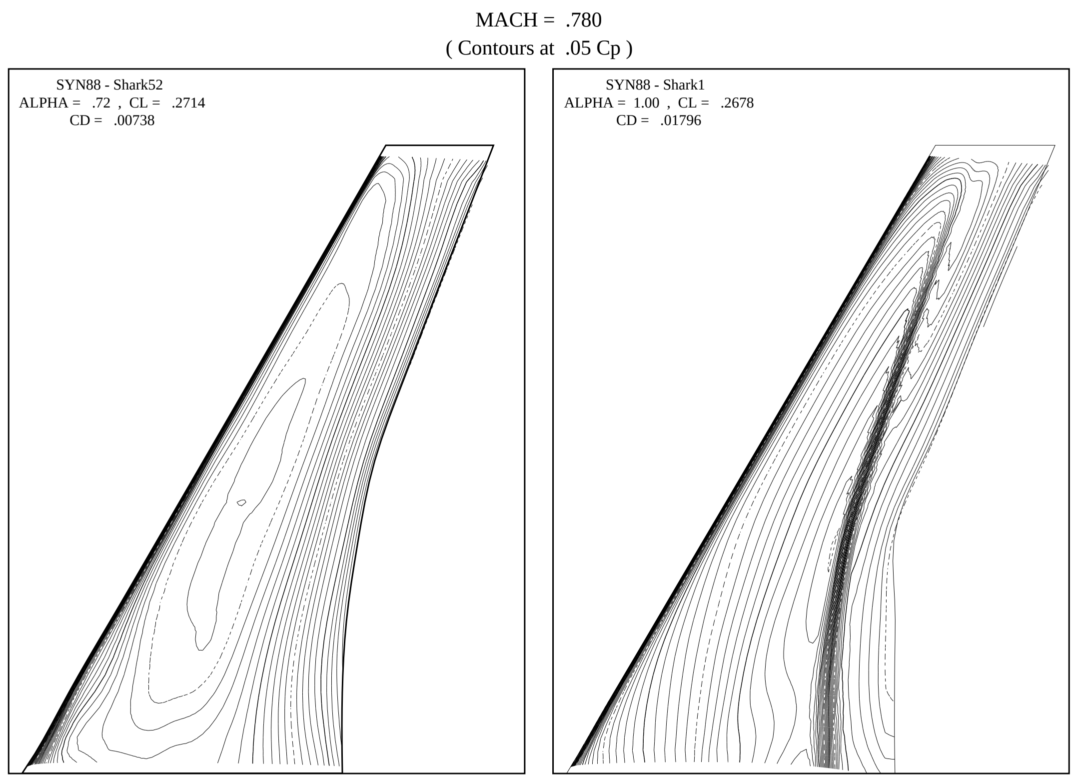
Shark52 and Shark1 Wings on Stretched Fuselage.

AERODYNAMIC OPTIMIZATION



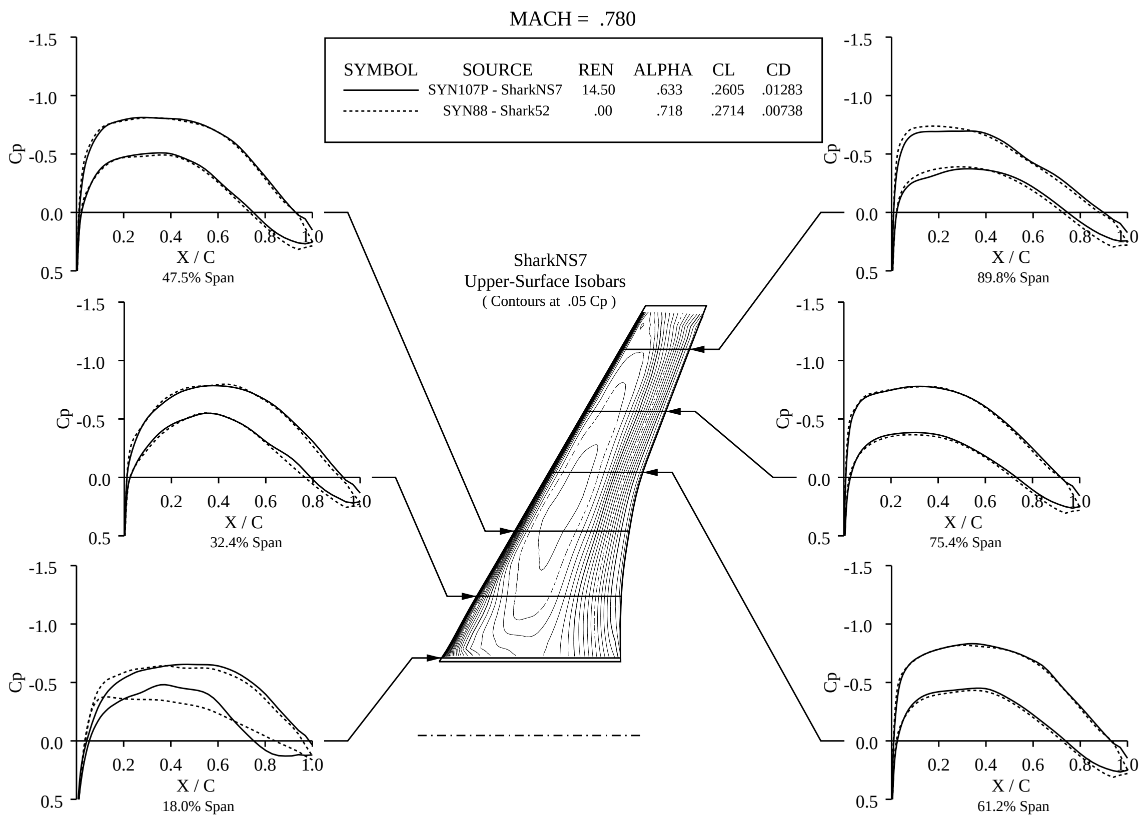
Shark52 and Shark1 Wing Drag Loops.

AERODYNAMIC OPTIMIZATION



Shark52 and Shark1 Wing Pressure Contours.

LAMINAR FLOW

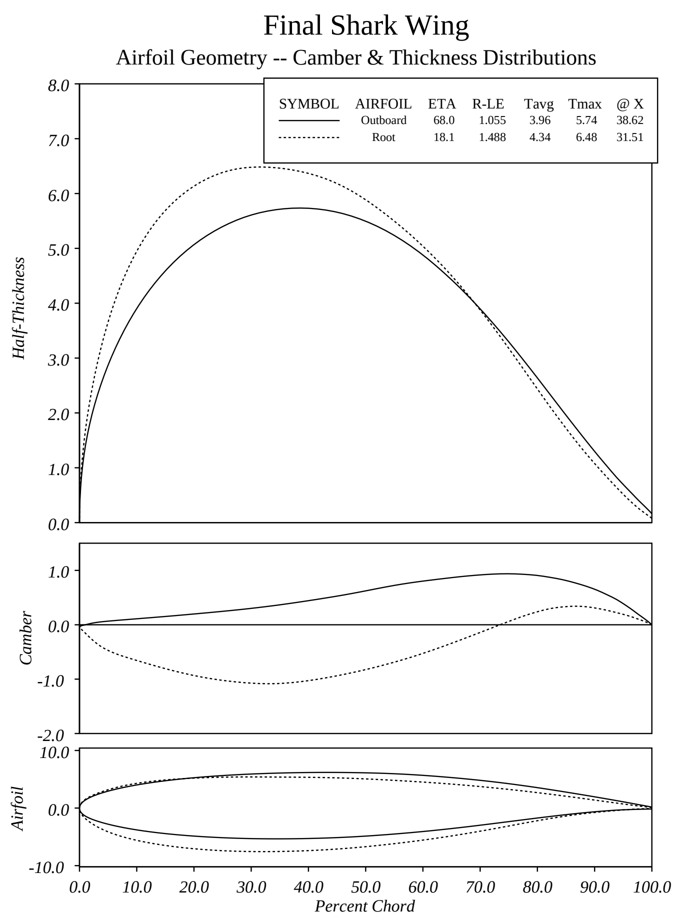


Result of Navier-Stokes Inverse Design.

FINAL TOUCHES

- **LOW SPEED CHARACTERISTICS**
  - Tailored Leading-Edge Radius Distribution
  - $CL_{maxCW} = 1.64$ at $M = 0.20$
- **MANUFACTURING**
  - Re-Tailored Thickness Distribution

FINAL TOUCHES



RENO RACER SUMMARY

- **SUCCESSFUL AERO OPTIMIZATIONS**
  - Significant Improvements
  - Very Compressed Time
- **ACCURATE CONCEPTUAL METHODS**
- **GLOBAL EVOLUTION**
  - Planform TE Changes for Landing Gear
  - Fuselage Stretch
  - No Impact on Cost or Schedule

CASE 3: GENERIC 747

- STRUCTURAL MODEL
- STRUCTURAL WEIGHT
- PLANFORM DESIGN VARIABLES
- AERO-STRUCTURAL OPTIMIZATION
- PARETO FRONTS
- SUMMARY

COST FUNCTION

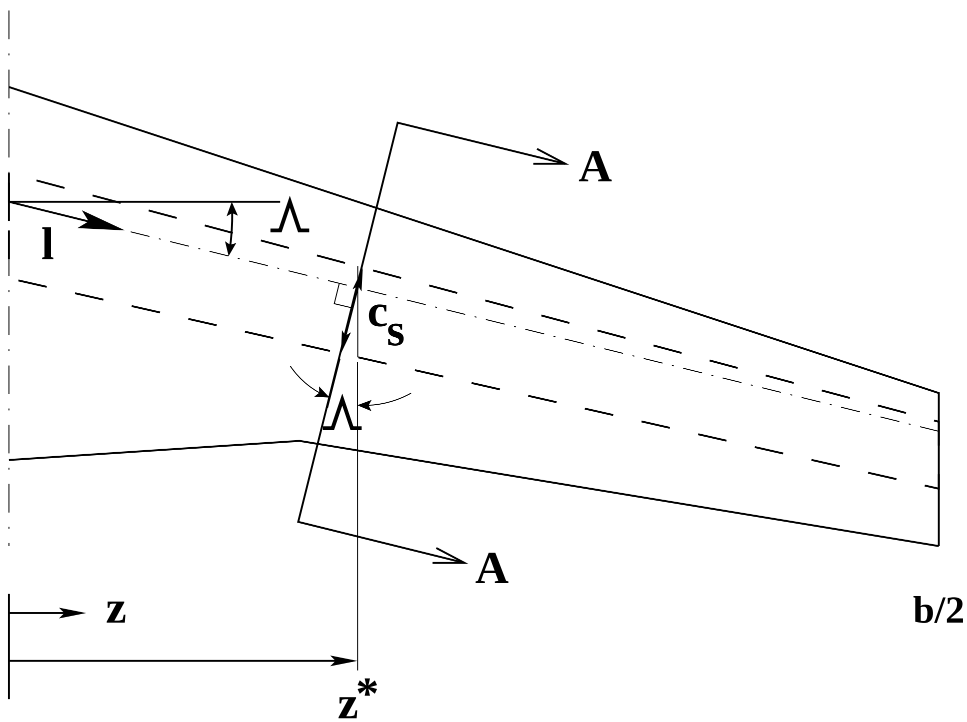
$$I = \alpha_1 C_D + \alpha_2 C_W.$$

Here α_1 and α_2 are properly chosen weighting constants, and C_W is a non-dimensional weight coefficient:

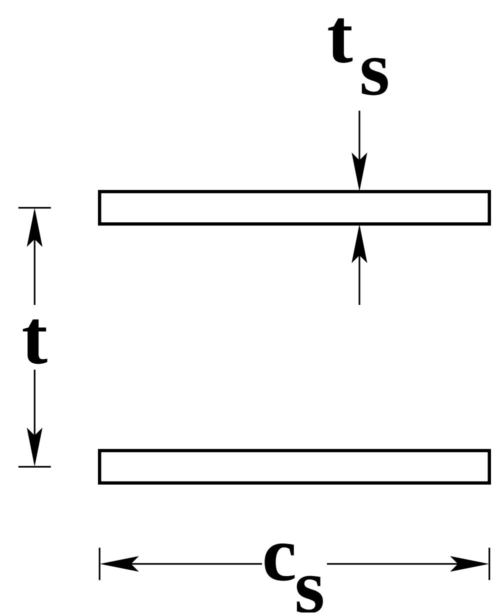
$$C_W = \frac{weight}{q_\infty S_{ref}}.$$

Emphasizes Trade-Off between Aerodynamics and Structures.

STRUCTURAL MODEL



(a) swept wing planform



(b) section A-A

Structural Model for a Swept Wing.

STRUCTURAL MODEL

Bending Stress at Section z^* is:

$$\sigma = \frac{M(z^*)}{t\ t_s c_s}.$$

Structural Box-Beam Weight is:

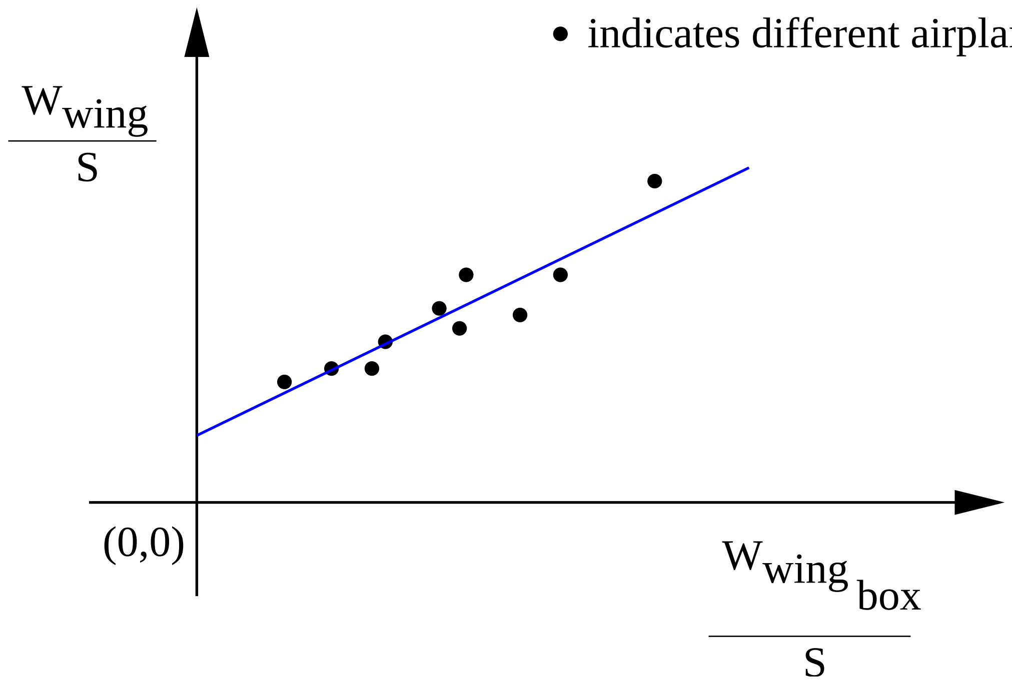
$$W_{\text{wing}_{\text{box}}} = 4\frac{\rho_{\text{mat}} g}{\sigma cos(\Lambda)} \int_0^{\frac{b}{2}} \frac{M(z^*)}{t(z^*)} dz^*,$$

and

$$C_{W_b} = \frac{\beta}{cos(\Lambda)} \int_0^{\frac{b}{2}} \frac{M(z^*)}{t(z^*)} dz^*, \quad \beta = \frac{4\rho_{\text{mat}} g}{\sigma q_\infty S_{ref}},$$

where ρ_{mat} is the material density.

STRUCTURAL WEIGHT

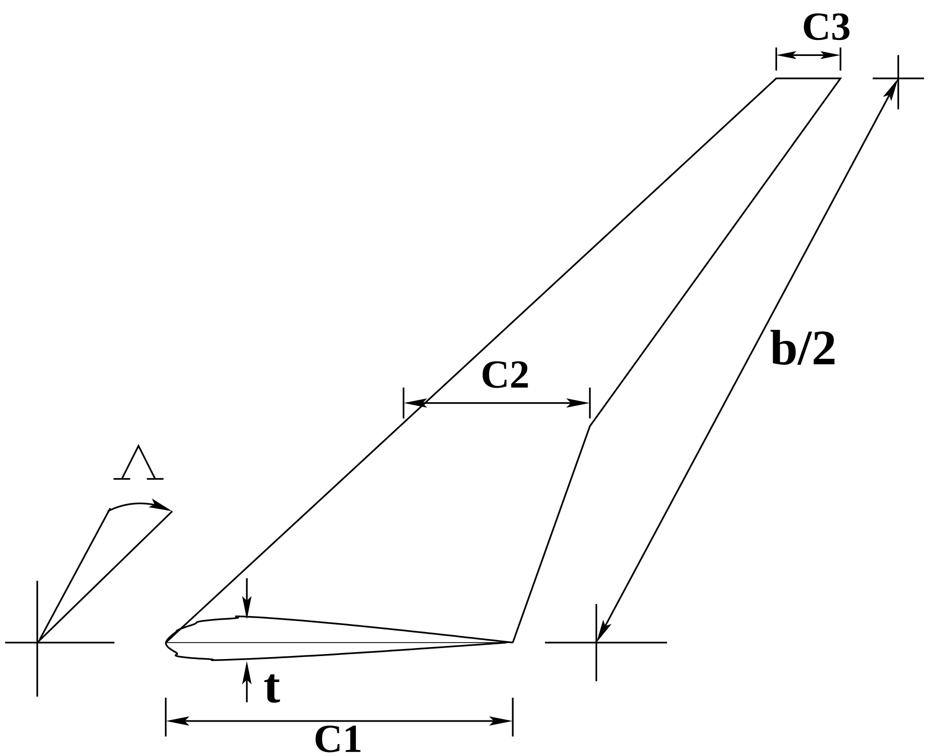


$$\frac{W_{\mathrm{wing}}}{S} = \alpha_1 \frac{W_{\mathrm{b}}}{S} + \alpha_2$$

$$\alpha_1 = 1.30,$$
$$\alpha_2 = 6.03 \ (lb/ft^2).$$

Statistical Correlation of Total Wing Weight and Box Weight.

PLANFORM DESIGN VARIABLES



General Design Criteria:

- Wing Shape
- Area
- Span
- Sweep
- Taper Ratio
- Airfoil Sections
- Airfoil Thickness
- Aspect Ratio

Wing Planform Design Variables.

MAXIMIZING RANGE

Maximizing Range → Intuitive Choice of α_1 and α_2.

Consider the Breguet-Range Equation:

$$R = \frac{V}{C}\frac{L}{D} ln\left(\frac{W_e + W_f}{W_e}\right)$$

Where

W_e is Airplane Gross Weight without Fuel, and

W_f is Weight of Fuel Burnt.

MAXIMIZING RANGE

$$
\begin{aligned}
W_1 &= W_e + W_f = \text{Fixed} \\
W_2 &= W_e
\end{aligned}
$$

With Fixed $\frac{V}{C}$, W_1, and L, Variation of R is:

$$
\delta R = -\frac{V}{C}\frac{L}{D} ln \frac{W_1}{W_2} \left(\frac{\delta D}{D} + \frac{1}{ln \frac{W_1}{W_2}} \frac{\delta W_2}{W_2} \right)
$$

$$
\frac{\delta R}{R} = - \left(\frac{\delta C_D}{C_D} + \frac{1}{ln \frac{C_{W_1}}{C_{W_2}}} \frac{\delta C_{W_2}}{C_{W_2}} \right).
$$

MAXIMIZING RANGE

Minimize the Cost Function defined as:

$$I = C_D + \alpha C_W.$$

Where

$$\alpha \;=\; \frac{C_D}{C_{W_2} ln \frac{C_{W_1}}{C_{W_2}}}$$

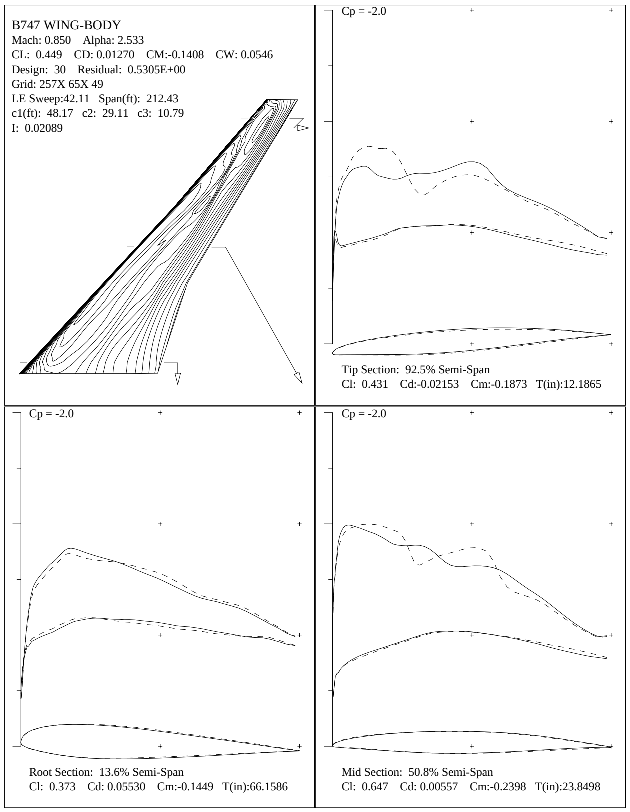
Corresponds to Maximizing Range of Aircraft.

AERO-STRUCTURAL OPTIMIZATION

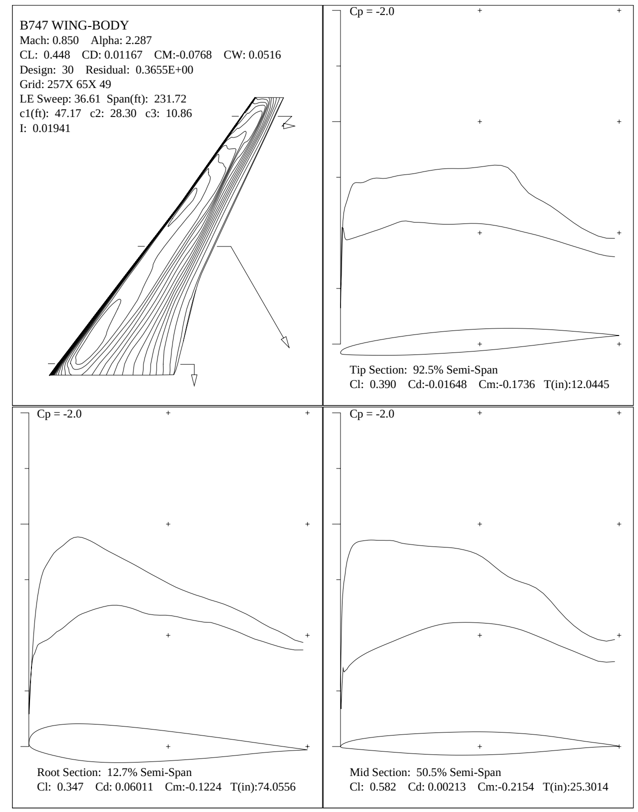
- **NOMINAL CRUISE CONDITIONS**
  - Mach = 0.85, $C_L = 0.45$
- **DESIGN SPACE**
  - $4,224$ Surface-Point Design Variables
  - 6 Planform Design Variables
- **NAVIER-STOKES SOLUTION**
  - Grid Dimension: (256x64x48)

Configuration	C_D	C_W	SPAN	WEIGHT
Baseline	137	546	212.4	88,202
Fixed Planform	127	546	212.4	88,202
Variable Planform	117	516	231.7	83,356

AERO-STRUCTURAL OPTIMIZATION

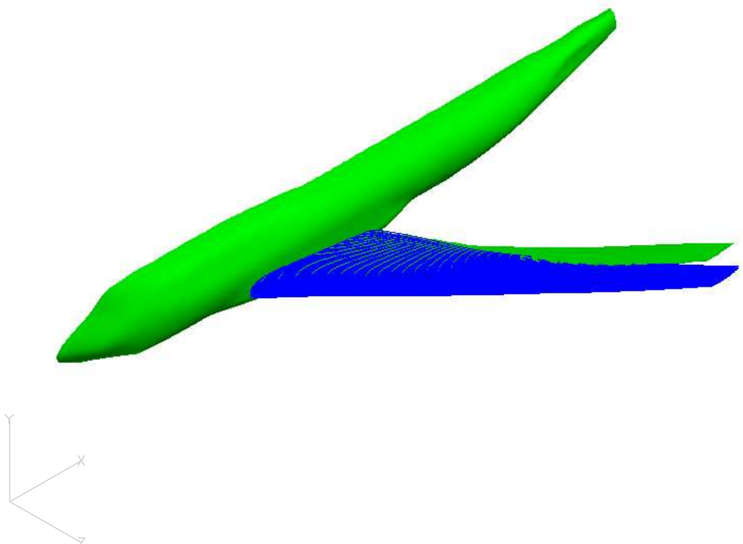


Fixed Planform



Variable Planform

VARIABLE-PLANFORM OPTIMIZATION

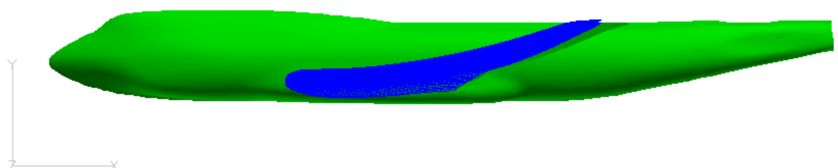


(a) Isometric

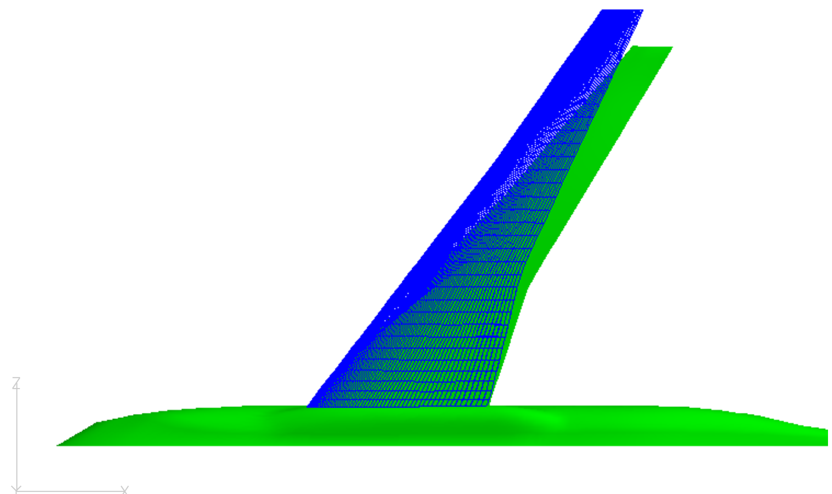
(b) Front View

Baseline (Green) / Redesigned (Blue).

VARIABLE-PLANFORM OPTIMIZATION



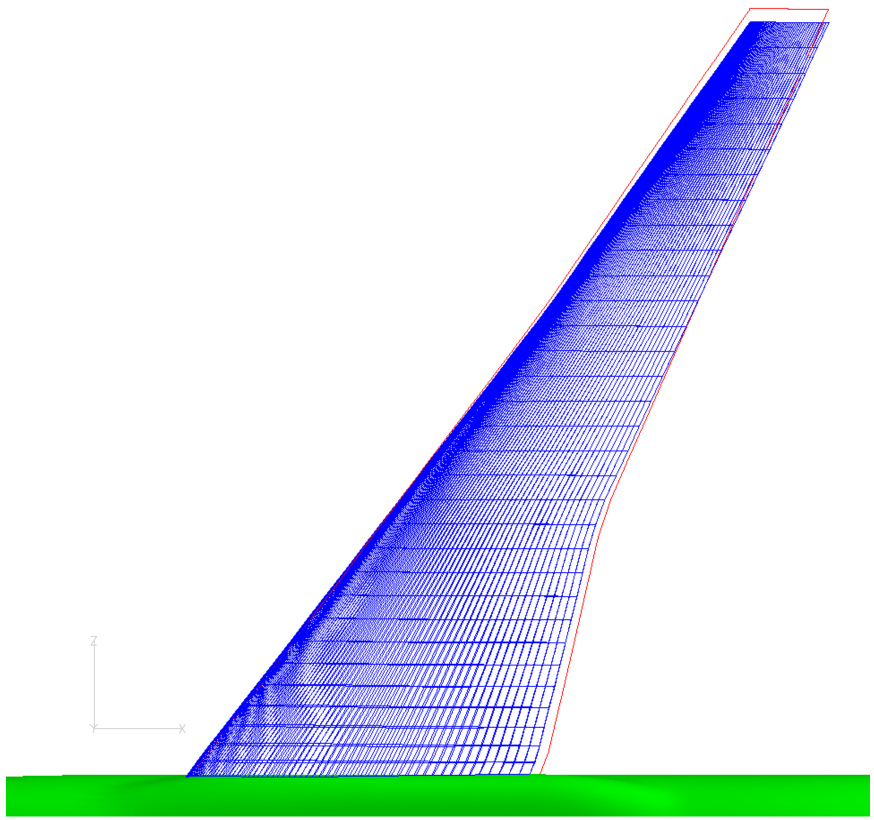
(c) Side View



(d) Top View

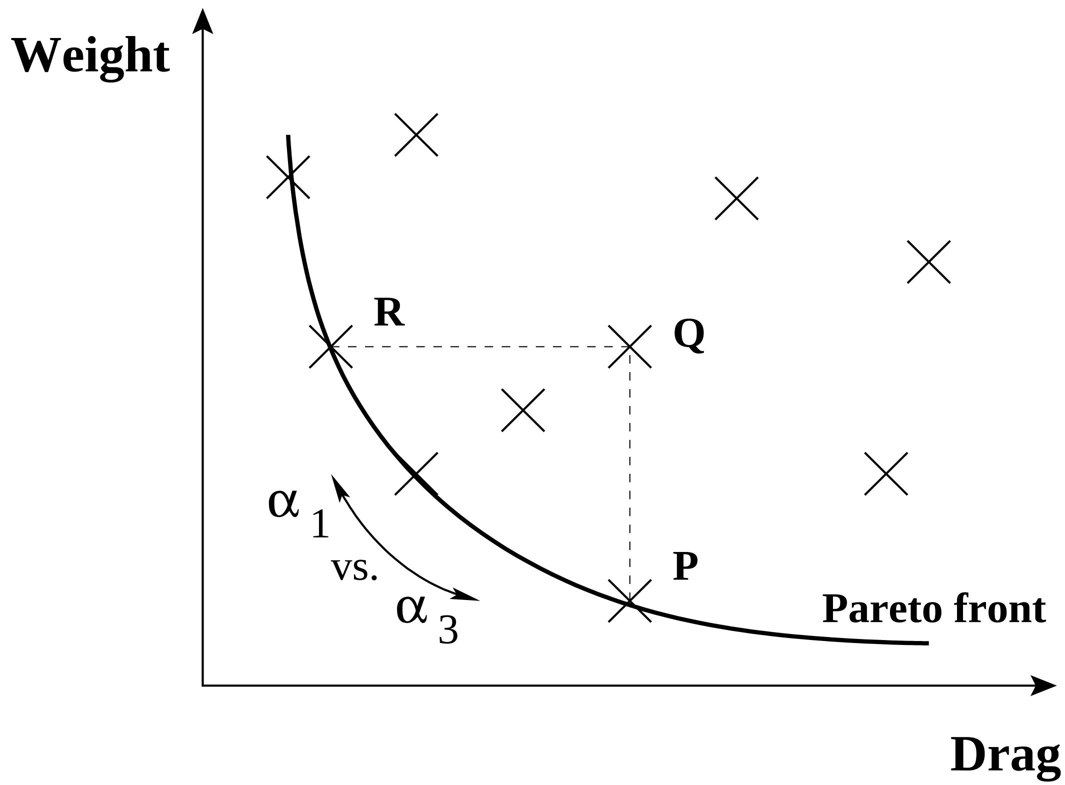
Baseline (Green) / Redesigned (Blue).

VARIABLE-PLANFORM OPTIMIZATION



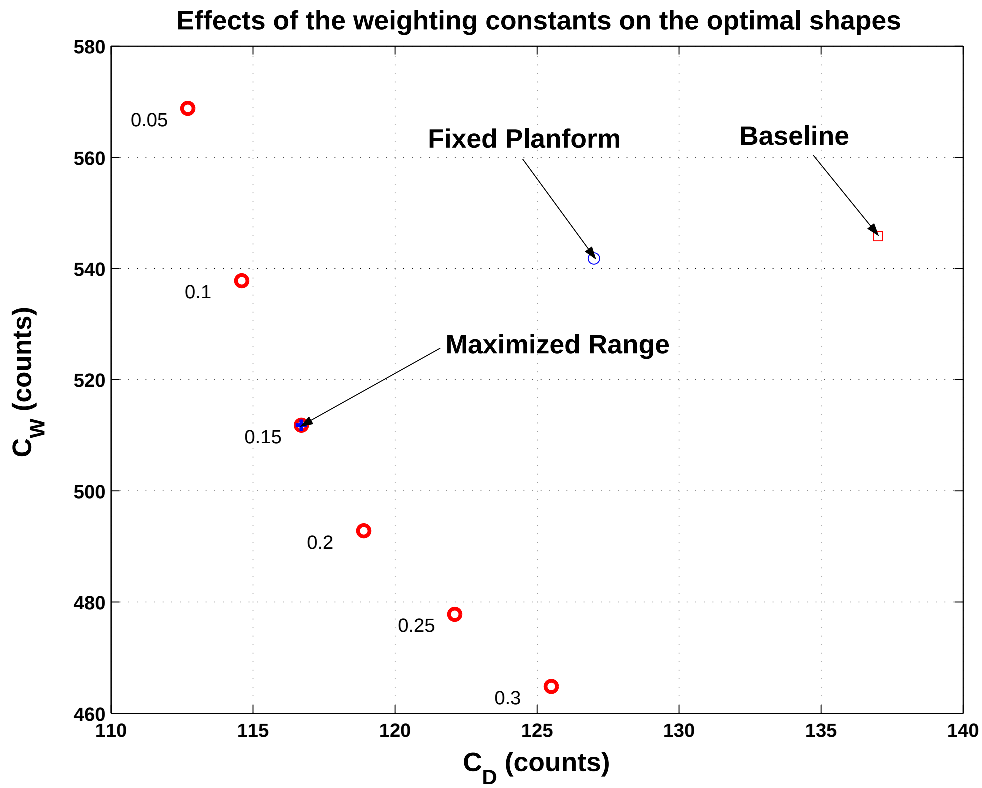
Comparison of Euler-Redesigned (Red)
and NS-Redesigned (Blue) Planforms.

PARETO FRONT



Cooperative Game Strategy with Drag and Weight as Players.

PARETO FRONT



Pareto Front; Ratios of $\frac{\alpha_2}{\alpha_1}$ Indicated.

GENERIC 747 SUMMARY

- STRUCTURAL MODEL
- STRUCTURAL WEIGHT
- PLANFORM DESIGN VARIABLES
- AERO-STRUCTURAL OPTIMIZATION
- PARETO FRONTS

POST SCRIPT

- **SUCCESSFUL AERO OPTIMIZATIONS**
  - McDonnell-Douglas MDXX
  - NASA High-Speed Civil Transport
  - Boeing Blended Wing Body
  - Beech Premier
- **IMPACT OF AERO OPTIMIZATIONS**
  - Achieving Designs Close To Theoretical Bound
  - Designers Focus on Creative Aspects
  - Does Not Replace The Designers

POST SCRIPT

- **KEYS TO SUCCESSFUL OPTIMIZATIONS**
  - Over-Night Turn-Around – Preferably Faster
  - Multi-Point & Multi-Objective Optimizations
  - Usability of Methods
  - Design Space Not Artificially Constrained
  - Affordable Parallel Computers
  - Variety of Cost Functions
    - Drag Minimization, Inverse Design, . . .
  - Flexible Set of Constraints
    - Geometric: Curvature, Thickness, . . .
    - Aerodynamic: Lift, Moments, Spanload, . . .

Industrial Applications of Aerodynamic Shape Optimization

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QUESTIONS