Summary of MDO experience

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The challenges of MDO

- Computational
  - Analysis models are expensive
  - Optimization is difficult for a single discipline
  - MDO increases the cost significantly
- Human
  - Collaboration across department and disciplinary boundary is difficult
  - Collaboration between designers and disciplinary specialists is also a challenge

MDO teams

- Creating an MDO team is a challenge
- Therefore I have continued collaboration with Virginia Tech team
  - Bernard Grossman – CFD
  - William Mason – aircraft design
  - Layne Watson – numerical analysis and computer science
- Also
  - Joseph Schetz – CFD and propulsion
  - Rakesh Kapania – structures and aeroelasticity

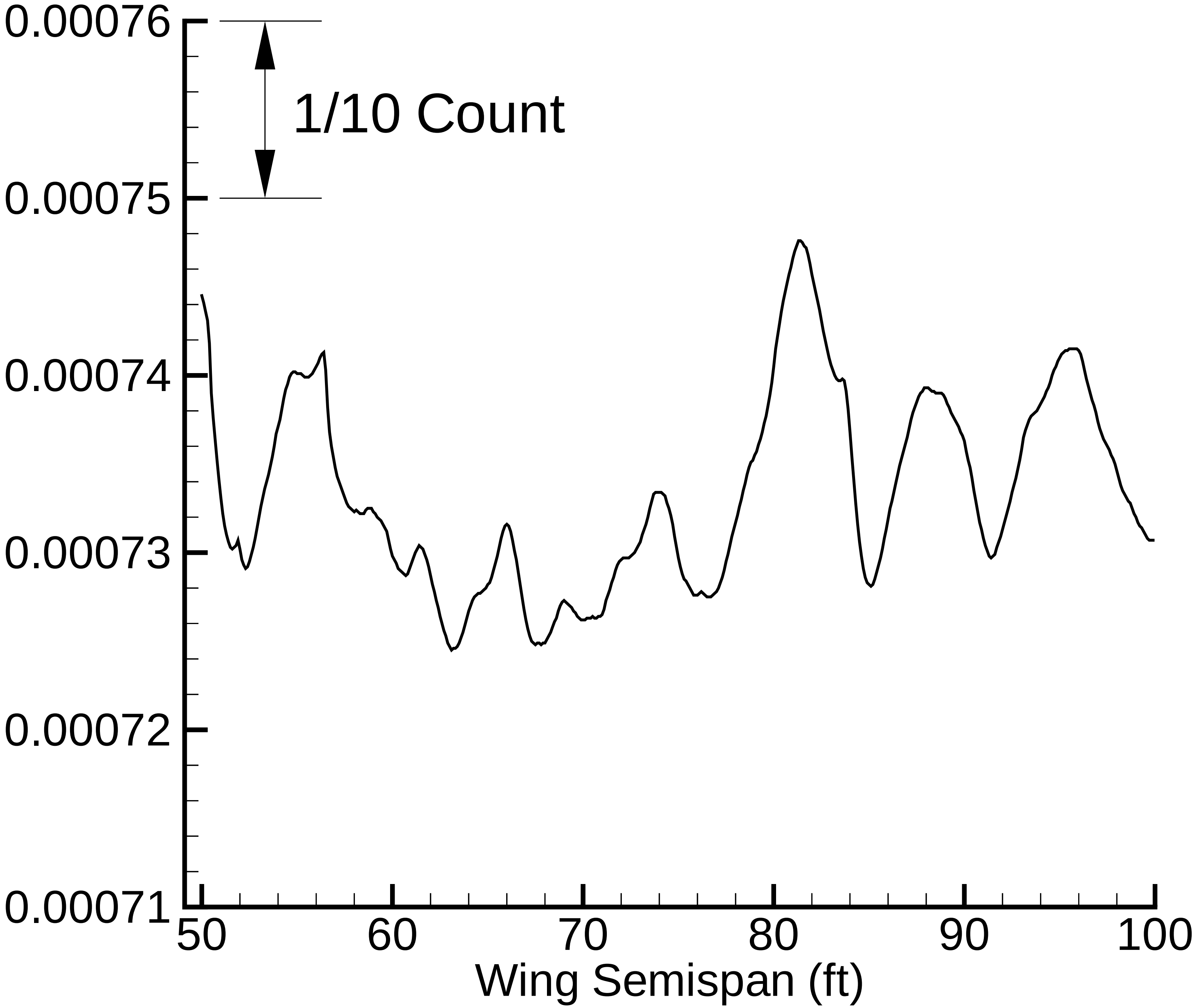
Algorithmic challenges

- Decomposition versus approximation
  - Approximation is the traditional approach, control remains with project manager
- Multi-fidelity approximations
  - Parkinson's law dictates that a single "acceptable analysis" takes about one day of computation
  - Must use simpler models for MDO
- Overall versus local design
  - Decomposition easier here

Approximation vs. Decomposition

- Decomposition algorithms, such as Collaborative Optimization allow disciplinary optimization, but present theoretical and numerical difficulties
- Response surface approximations imitate the traditional approach, such as weight equations in programs like FLOPS
- Each discipline responsible for its response surface
- Giunta, AA, Balabanov, V, Haim, D, Grossman, B, Mason, WH, Watson, LT, and Haftka, RT, ``Aircraft Multi-disciplinary Design Optimisation Using Design of Experiments Theory and Response Surface Modelling," Aeronautical Journal, Vol. 101, No. 1008, 1997, 347-356.

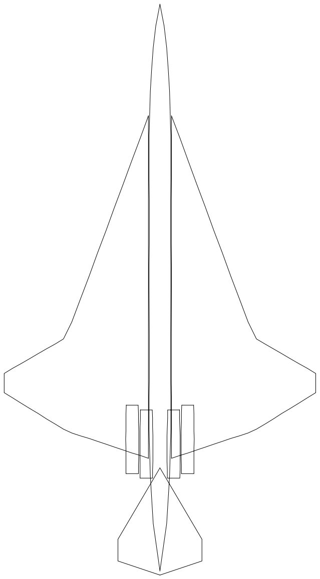
Noisy Analysis Example



Response Surface Model Generation Process

- Selection of a Baseline Design
- Design Space Sizing
- Data Set Generation, Design of Experiments
- Removal of Unreasonable Designs
- Analyses of Design Points
- RS Model Generation

Starting Points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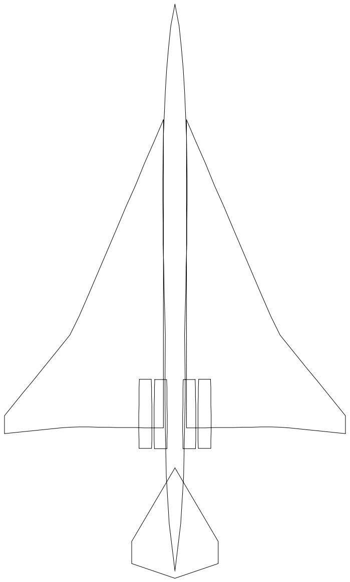
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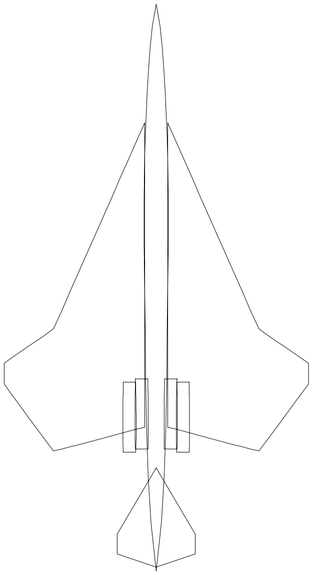
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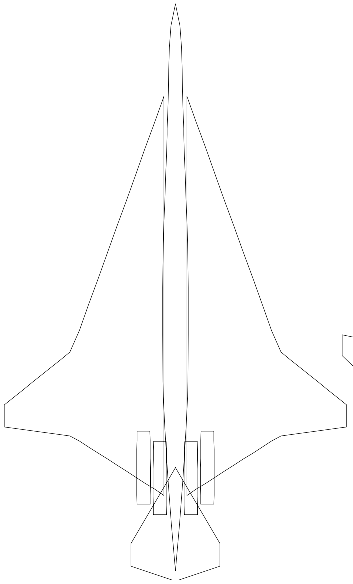
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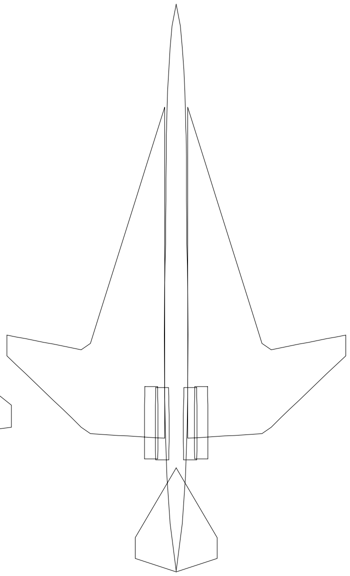
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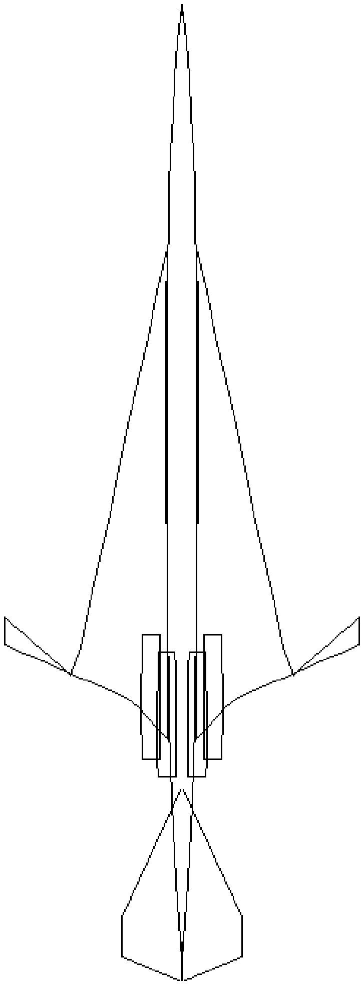
- **Starting Points Within ±15% Bounds**
- **Starting Point Set was Manually Selected to Represent the Variety of Designs Available in the Design *Box***

Removal of Unreasonable Designs



- **Designs Removed from Design Sets Using Geometric Criteria, i.e.:**
  - Wing/Tail Overlap
  - Negative Chords

Orthogonal Array Set

3 designs removed, **2206** points remain

SCD-Based Set

512 designs removed, **1593** points remain

- Supplementary 1024 point SCD created for box with ±7.5% variables bounds

no designs removed, **2617** points remain

Multifidelity Approximations

- Correction response surface
- Trust region – approximation frameworks (John Dennis, Natalia Alexandrov)
- Identification of less important terms
- Identification of intervening variables and functions

Combining low fidelity and high fidelity models

- Derivative-based local approximation: Haftka, R.T., “Combining Global and Local Approximations,” AIAA Journal, Vol. 29, No. 9, pp. 1523-1525, 1991.
- Unger, E.R., Hutchison, M.G., Rais-Rohani, M., Haftka, R.T., and Grossman, B., “Variable-Complexity Multidisciplinary Design of a Transport Wing,” International Journal of System Automation: Research and Applications (SARA), 2(2), pp. 87--113, 1992.
- Correction response surface of ratio or differences of two models
- Kaufman, M., Balabanov, V., Burgee, S.L., Giunta, A.A., Grossman, B., Mason, W.H., Watson, L.T., and Haftka, R.T., ``Variable-Complexity Response Surface Approximations for Wing Structural Weight in HSCT Design,” 34th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper No. 96-0089, Reno, Nevada, January 15-18, 1996.

Learning from low fidelity models

- Identifying intervening functions and variables
- Identifying important and less important terms
- Knill, D.L., Giunta, A.A., Baker, C.A., Grossman, B., Mason, W.H., Haftka, R.T., and Watson, L.T., ``Response Surface Methods Combining Linear and Euler Aerodynamics for Supersonic Transport Design," Journal of Aircraft, 36(1), pp. 75-86, 1999.

Response Surface Approximation to Euler Drag

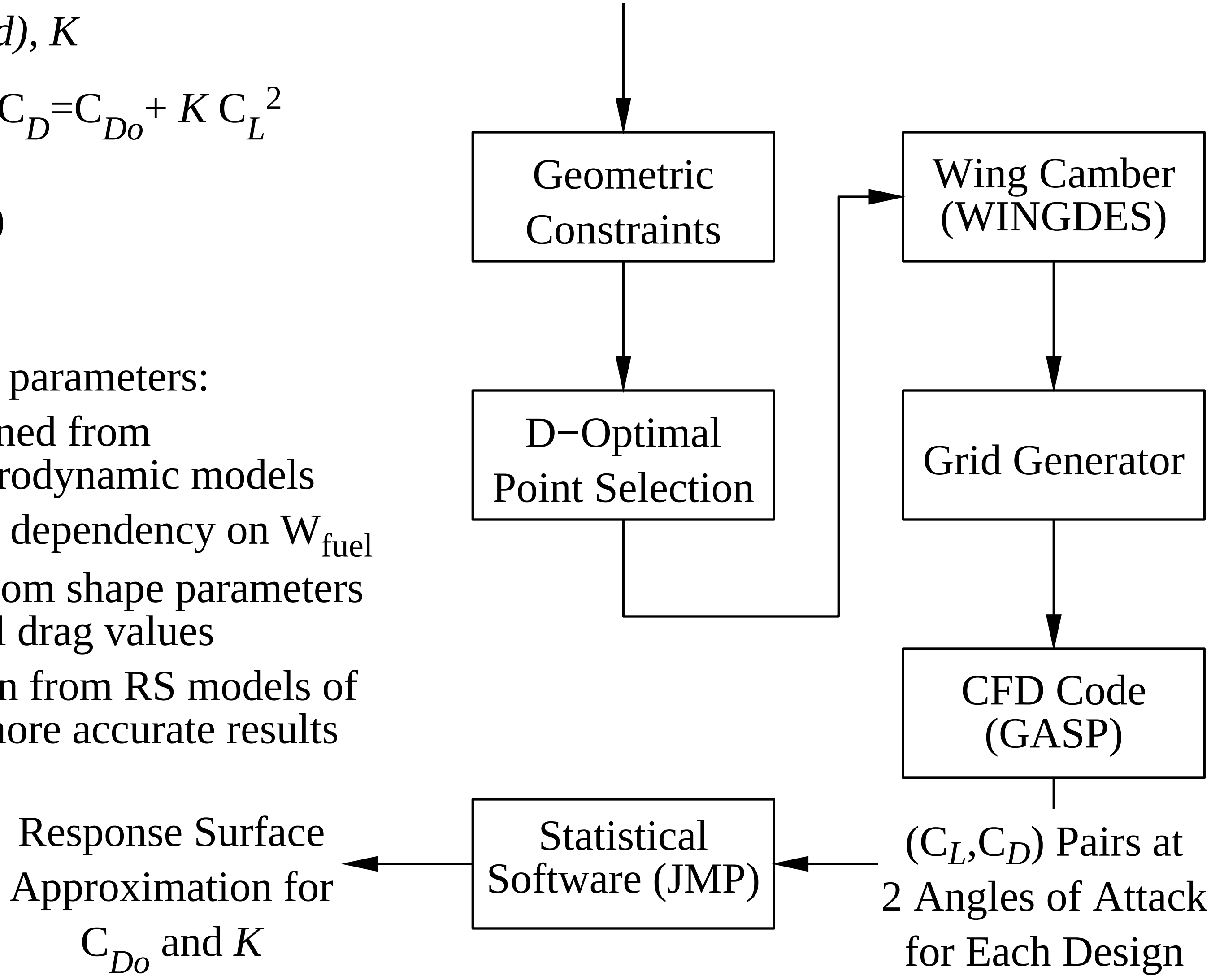
2 RS Models: C_{D_o}*(inviscid), K*

Compute Inviscid Drag as $C_D = C_{D_o} + K\,C_L^{\,2}$
where

$C_{D_o} = C_{D_o}(x_1, x_2, \ldots, x_n)$
$K = K(x_1, x_2, \ldots, x_n)$

Advantages of using shape parameters:

1. Use information gained from conceptual−level aerodynamic models
2. Eliminate RS model dependency on W_{fuel}
3. Gain more insight from shape parameters than from individual drag values
4. Building the function from RS models of components gives more accurate results



Geometric Constraints

D−Optimal Point Selection

Wing Camber (WINGDES)

Grid Generator

CFD Code (GASP)

(C_L, C_D) Pairs at 2 Angles of Attack for Each Design

Statistical Software (JMP)

Response Surface Approximation for C_{D_o} and K

Incremental RS Models

- Create RS models for the difference between the linear theory and Euler solutions
- 2 RS Models: ΔC_{Do}, ΔK

Compute inviscid drag as $C_D = C_{Do} + K\, C_L^2$

where

$$C_{Do} = \overline{C}_{Do}(x_1, x_2, \ldots, x_n) + \Delta C_{Do}(x_1, x_2, \ldots, x_n)$$

$$K = \overline{K}(x_1, x_2, \ldots, x_n) + \Delta K(x_1, x_2, \ldots, x_n)$$

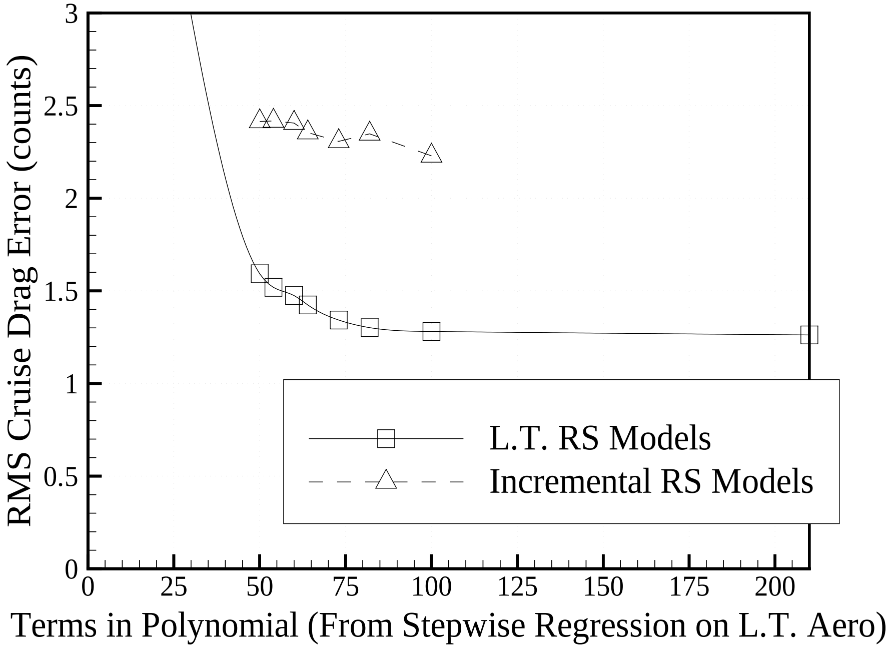
Linear Theory RS Model	Correction Term

Regression Analysis (Twenty−Variable HSCT Design)

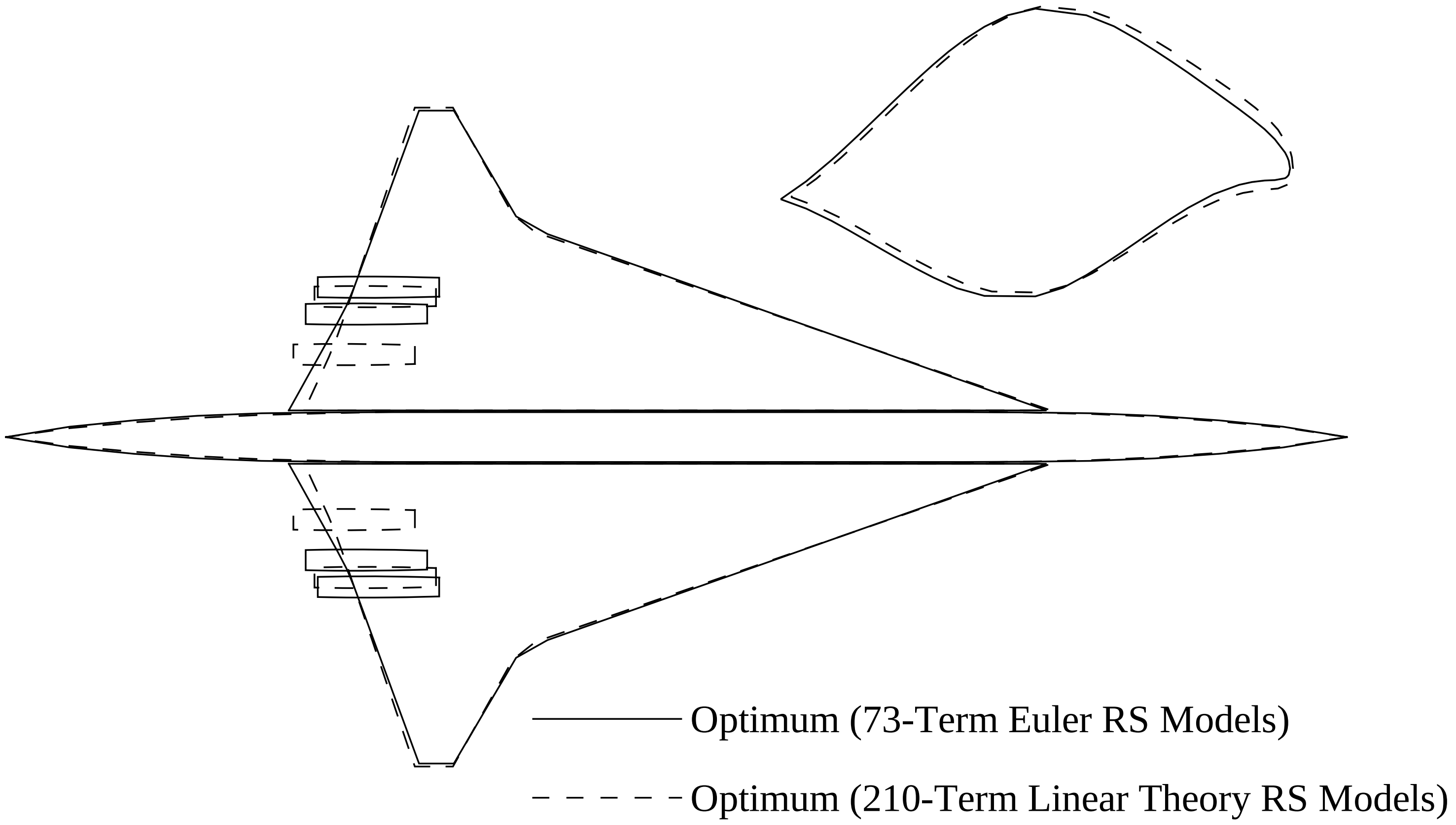
- Able to use 73−term incremental models instead of 210−term Euler models

- Computational savings

210−Term L.T.	50 minutes
210−Term Euler	392 hours
73−Term Euler	137 hours



Optimization Results: Incremental RS Models



Drag coefficient from reduced−term incremental RS model
is 0.8 count lower than that from Euler analysis

System-level and Component Optimization

- Rigorous decomposition algorithms possible
  - Quasi-separable systems
  - R. T. Haftka and L. T. Watson, “Multidisciplinary design optimization with quasiseparable subsystems”, *Optim.Engrg.* to appear, 2004.
- Response surfaces of component optima useful in system level design
  - Liu, B., Haftka, R.T., and Akgün M.A., "Two-Level Composite Wing Structural Optimization Using Response Surfaces," Structural Optimization, 20(2), pp. 87-96, 2000.

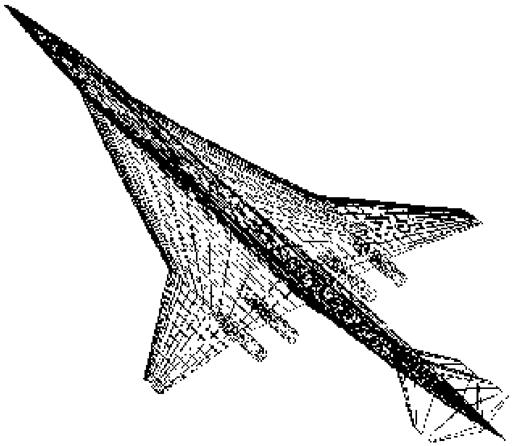
Recent MDO Studies

- High speed Civil Transport
  - Flying fuel tank
  - Classical aero-structure interaction
- Truss (strut) braced wing
  - Learning from general aviation airplanes
- Blended wing body
  - Official Boeing project, we are looking at distributed propulstion and noise

High-Speed Civil Transport (HSCT) Test bed

Mach 2.4 aircraft

Modify:
- wing shape
- fuselage shape
- nacelle placement
- horizontal and
- vertical tails
- engine thrust
- wing structural sizing



Requirements:
- 250 passengers
- range 5,500 naut. miles
- trim and control
- T/O & landing
- geometry
- stress, strain, buckling

Objective:
- Minimize Take-Off Gross Weight (TOGW)

Baseline Configuration

Geometry Parametrization

- Small number of design variables for research code, 20–100.
  - Adequate resolution of baseline geometry
  - Sufficiently general for design improvements
  - Not intended for conceptual design
  - Not tied directly to analysis codes

HSCT Test bed Design Variables

25 Configuration

8 wing planform
5 wing thickness
8 fuselage
2 nacelle location
2 horiz. & vert. tail areas

40 Wing Structure

26 skin panel thicknesses
12 spar cap areas
2 rib cap areas

4 Performance

1 mission fuel weight
1 initial cruise altitude
1 cruise-climb rate
1 maximum thrust per engine

HSCT Configuration Optimization Problem

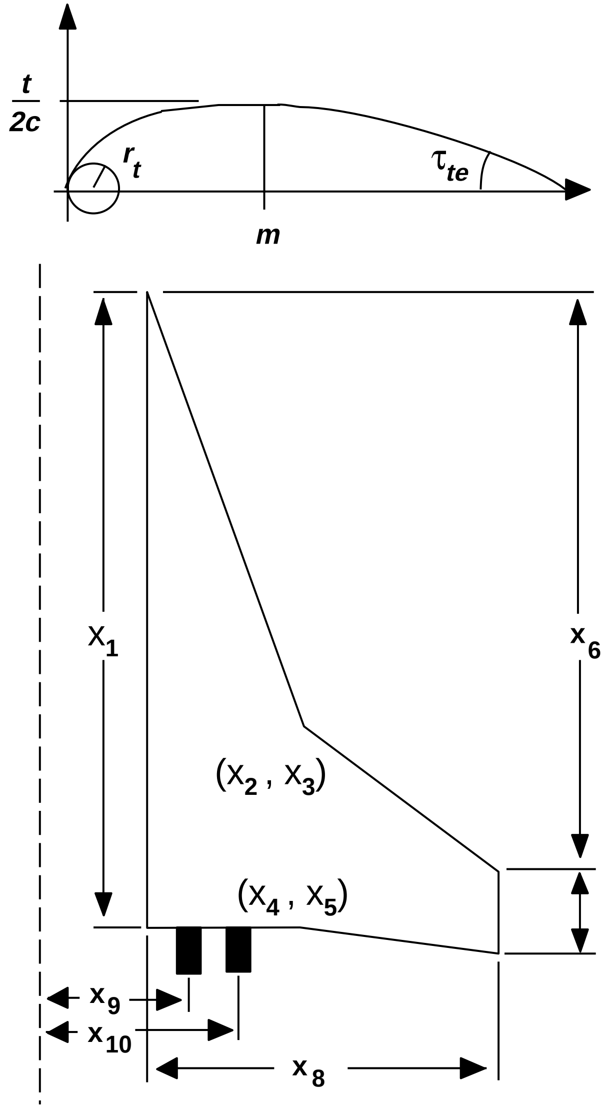
Mission requirements: Mach 2.4, 251 passenger, 5,500 n.mi. range

Described by 29 design variables

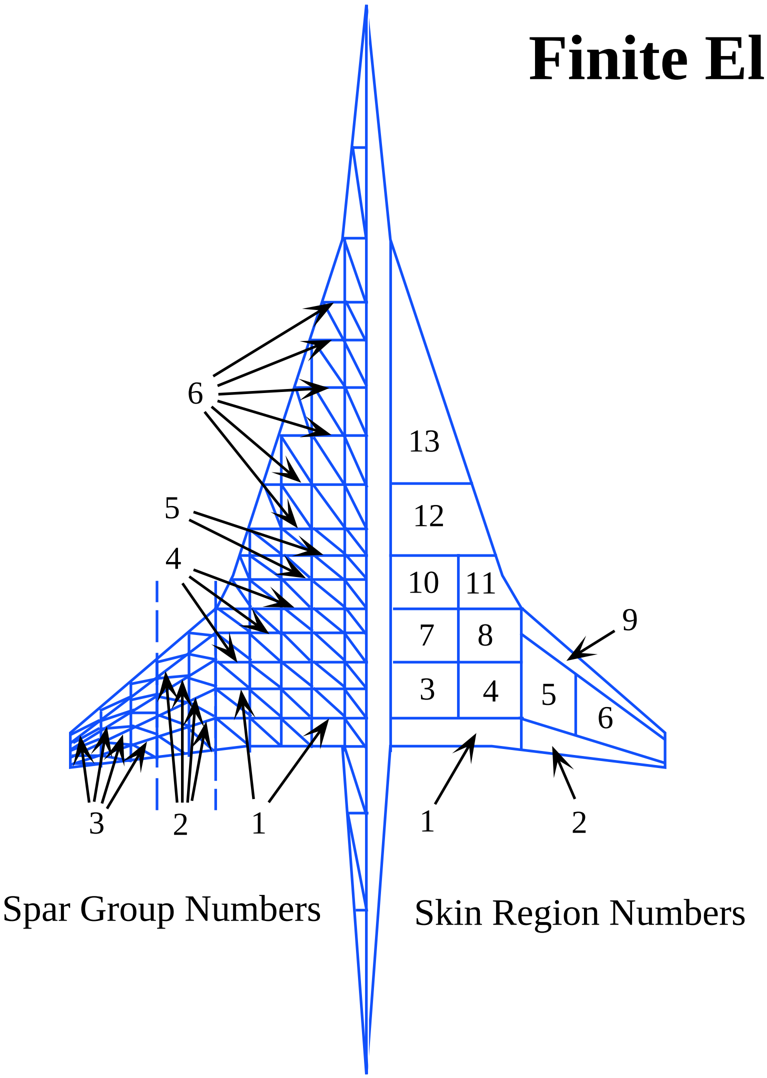
- Wing Planform
- Airfoil Shape
- Tail Areas
- Nacelle Placement
- Fuselage Shape
- Mission Profile

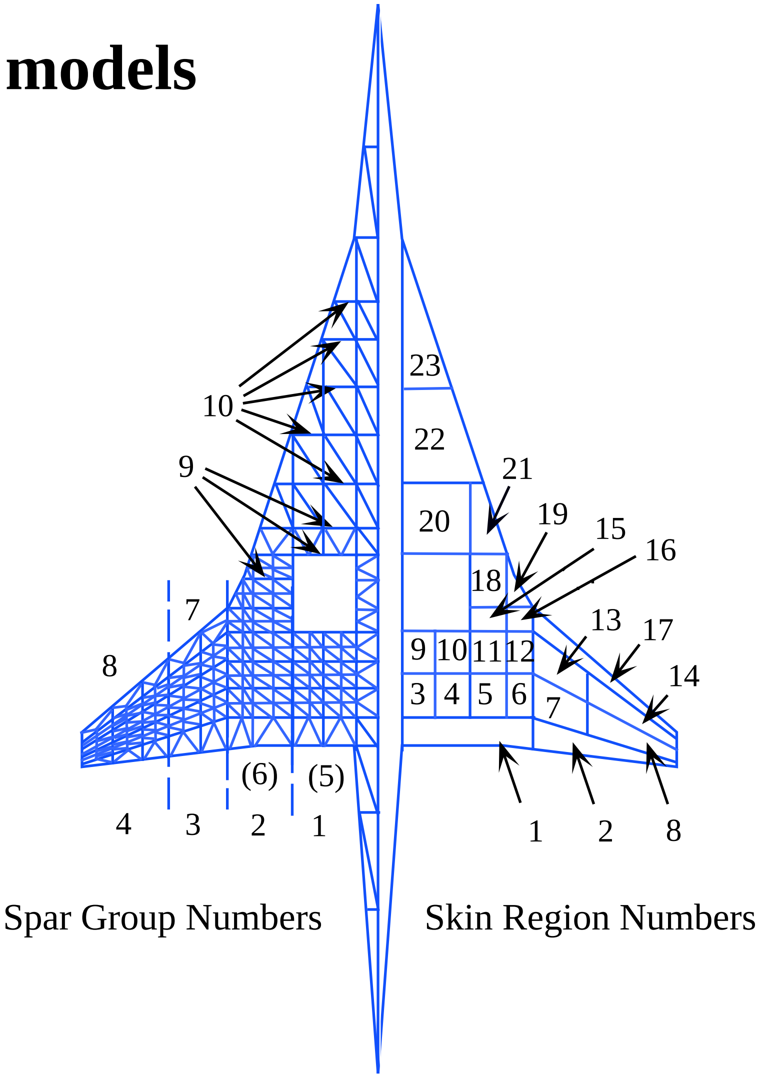
68 geometry, performance, aerodynamic constraints

Baseline configuration from previous work



Finite Element models





baseline model

1242 dof, 1127 elmnts, 226 nodes

40 design variables

refined model

3216 dof, 2214 elmnts, 555 nodes

74 design variables

Design Constraints

70 aerodynamic constraints implemented.

- Range $\geq$ 5500 *nm*. Drag estimates throughout flight envelope.
- 250 passengers. Fuselage geometry and volume constraints.
- Wing volume adequate to carry fuel. Wing geometry constraints.
- Balanced field length $\leq$ 10,000 *ft*.
- Engine Out Condition: Trimmed flight with 2 engines inoperative.
- Cross-Wind Landing Condition: Landing with 20 knot crosswind. Rudder deflection and bank angle constraints.
- Nacelle, Wing, Tail Strike Constraints: Requires bank angle, landing incidence, landing gear location and length and planform geometry.
- Take-Off Rotation Requirement: Rotating to take-off pitch attitude at $0.9V_{min}$. Requires center of gravity and inertia estimates. Also landing gear details.
- Powered Approach Trim Consideration: Trimmed flight at landing attitude. Horizontal tail deflection below 75% maximum.

Simplified Aerodynamic-Structural Coupling

Objective: minimize take-off gross weight (TOGW)

$$TOGW = W_{fuel} + W_{structural} + W_{non-structural} + W_{payload}$$

W_{fuel}: design variable

$W_{non-structural}$: weight equation

$W_{structural}$: $\mathcal{F}$(configuration variables)
weight equation (simple)
structural optimization (detailed)

Problem: existing weight equations do not have large supersonic data base

HSCT Analysis and Optimization

Simple Analysis Methods

- Subsonic Aerodynamics: Algebraic C_{L_α}; DATCOM stability derivatives.
- Supersonic Aerodynamics: Linear theory; approx. wave drag; strip boundary layer.
- Weight Estimation: FLOPS (algebraic).

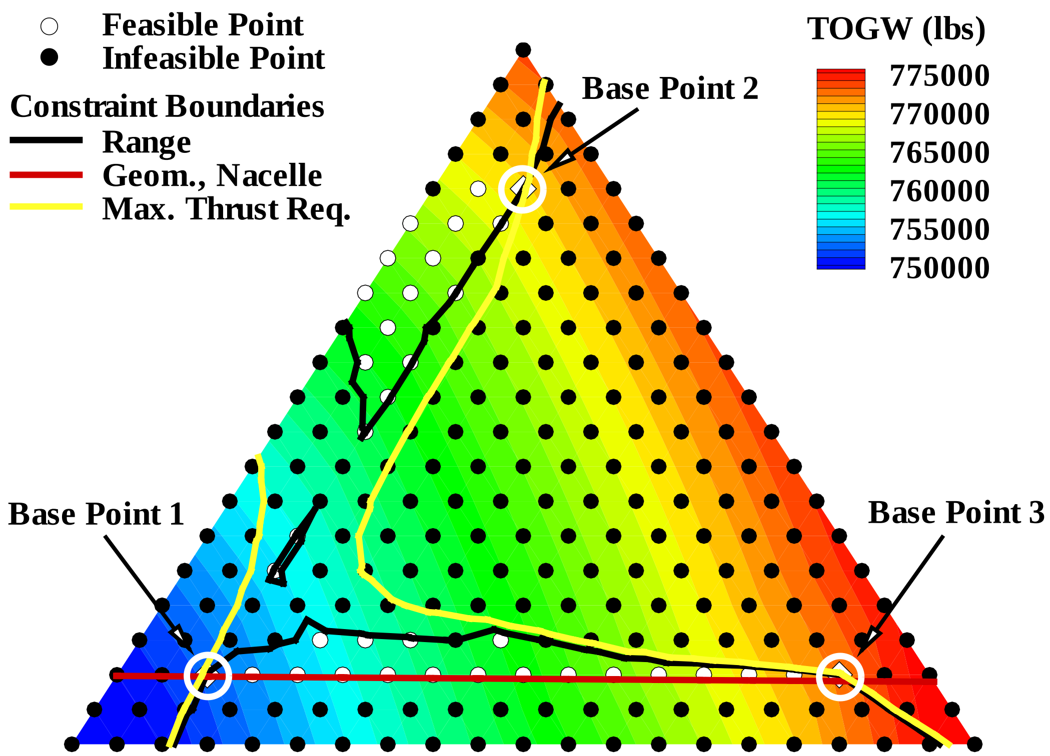
Detailed Analysis Methods

- Subsonic Aerodynamics: Vortex lattice Method.
- Supersonic Aerodynamics: Harris wave drag; panel code.
- Transonic and Supersonic Loads: Euler and Navier-Stokes code GASP.
- Structural Weight: GENESIS (finite-element structural optimization).

Optimization Methods

- NEWSUMT-A, DOT (Method of Feasible Directions, SQP)

The Design Space



Visualization Plot

- Choose 3 Feasible *Base Points*
- Connect *Base Points* to get Plane in 28-Dimensional Space
- Create Grid in Plane
- Evaluate Objective Fn. and Constraints at Grid Points (with RS models)

Infeasible Points outside Constraint Boundaries on plot violate Side Constraints

- Even in Simplified Plot, Design Space appears Complicated, Nonconvex
- Range Constraint is Multiply Connected even with Quadratic Drag RS Models

Selected References

Response surface methodology:

- Giunta, A. A., Balabanov, V., Haim, D., Grossman, B., Mason, W. H., Watson, L. T., and Haftka, R. T., "Multidisciplinary Optimisation of a Supersonic Transport Using Design of Experiments Theory and Response Surface Modelling," *Aeronautical Journal,* **101**, No. 1008, 1997, pp. 347-356.

Using detailed CFD in design:

- Knill, D. L., Giunta, A. A., Baker, C. A., Grossman, B., Mason, W. H., Haftka, R. T. and Watson, L. T., "Response Surface Models Combining Linear and Euler Aerodynamics for Supersonic Transport Design," *J. Aircraft,* **36**, No. 1, Jan.–Feb. 1999, pp. 75–86.

Using detailed structural analysis in design:

- Balabanov, V., Giunta, A. A., Golividov, O., Grossman, B., Mason, W. H., Watson, L. T. and Haftka, R. T., "Reasonable Design Space Approach to Response Surface Approximation", *J. Aircraft*, **36**, No. 1, Jan.–Feb. 1999, pp. 308–315.

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Parallel computing:

- Burgee, S., Giunta, A. A., Balabanov, V., Grossman, B., Mason, W. H., Narducci, R., Haftka, R. T., and Watson, L. T., "A Coarse Grained Variable-Complexity Multidisciplinary Optimization Paradigm," *Intl. J. Supercomputing Applications and High Performance Computing*, **10,** No. 4, 1996, pp. 269-299.
- Krasteva, D. T., Watson, L. T., Baker, C., Grossman, B., Mason, W. H. and Haftka, R. T., "Distributed control parallelism in multidisciplinary aircraft design", *Concurrency, Practice Experience*, Vol. **11**(8), 1999, pp. 435–459.

Design space exploration:

- Baker, C., Grossman, B., Mason, W. H., Watson, L. T. and Haftka, R. T., "HSCT Configuration Design Space Exploration Using Aerodynamic Response Surface Approximations", Proceedings of the 7th AIAA/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Paper No. 98–4803–CP, St. Louis, MO, Sept. 1998, pp. 769–777.

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- Cox, S.E., Haftka, R.T., Baker, C.A., Grossman, B., Mason, W.H., and Watson, L.T., “ A Compariosn of Global Optimization Methods for the Design of a High-speed Civil Transport,” J. of Global Optimization, **21,** pp. 415-433, 2001.
- Baker, C.A., Watson, L. T., Grossman, B., Mason, W. H. and Haftka, R. T., “Parallel global aircraft configuration design space exploration", *Internat. J. Compuer. Research*, **10** (4) 2001, 501-515.
- Kim, H, Papila, M., Mason, W. H., Haftka, R. T., Watson, L. T., and Grossman, B., "Detection and Repair of Poorly Converged Optimization Runs," AIAA J., **39**(12), December 2001, pp. 2242-2249.
- Hosder, S., Watson, L.T., Grossman, B., Mason, W.H., and Kim, H., “ Polynomial Response Surface Approximations for Multidisciplinary Design Optimization of a High Speed Civil Transport,” Optimization and Engineering, **2,** 431-452, 2001.

NASA

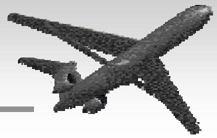
LOCKHEED MARTIN

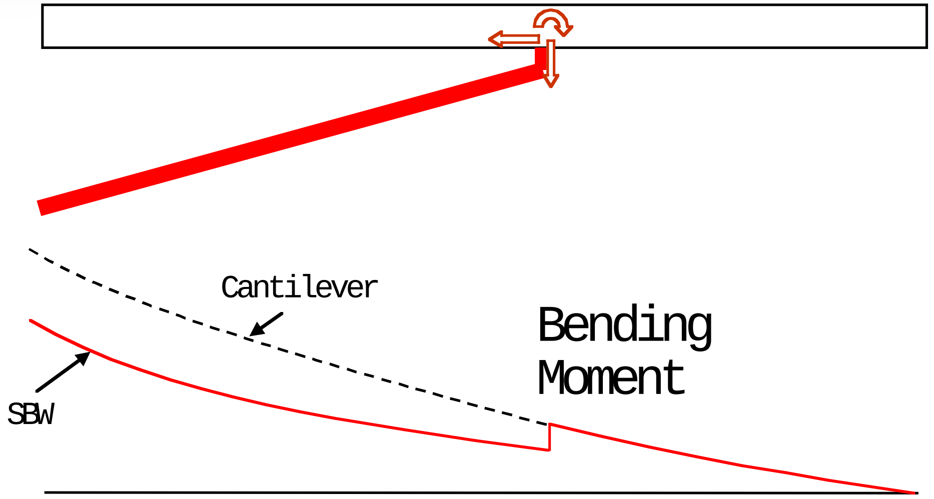
Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

NASA Langley
Research Center
October 16, 1998

A Structural and Aerodynamic Investigation of a Strut-Braced Wing Transport Aircraft Concept

Why a Strut-Braced Wing?



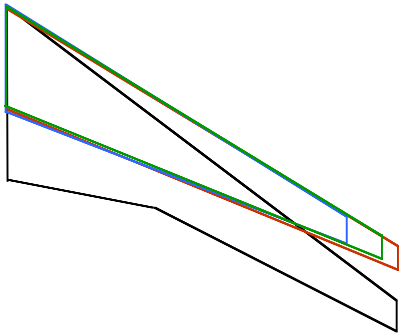


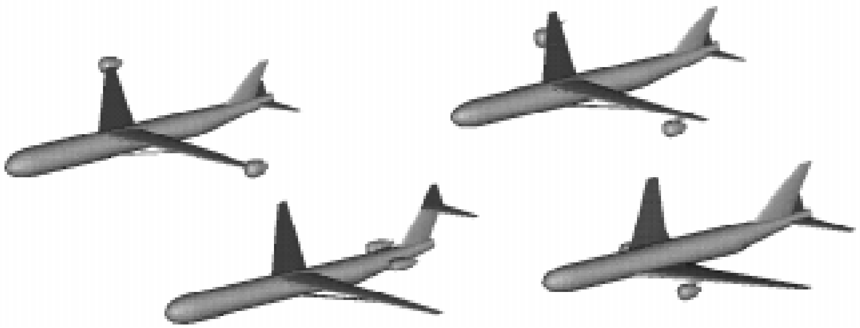
- Strut Allows Span Increase, t/c Reduction and/or Wing Bending Material Weight Reduction
- Small t/c Allows Wing to Unsweep for Same Transonic Wave Drag
- Reduced Sweep Permits More Natural Laminar Flow
  - Fuel Savings
  - Causes Additional Weight Savings

2010 Minimum-TOGW Optima

- Thrust Reduction of 21.5-31.6%
  - Lower Noise Pollution at Urban Airports
- Large SBW Sweep Reduction
- Less Wing Area

- SBW %TOGW Improvement = 9.2-17.4%
- SBW %Fuel Improvement = 14.3-21.8%
- Similar Wingspans Except for Wingtip-Engine Case
- Wingtip Deflection Constraint





Truss braced wing references

- Gundlach, J.F., Tetrault, P-A., Gern, F.H., Naghshineh-Pour, A.H., Ko, A., Schetz, J.A., Mason, W.H., Kapania, R.K., Grossman, B., and Haftka, R.T., "Conceptual Design Studies of a Strut-Braced Wing Transonic Transport," Journal of Aircraft, Vol. 37, No. 6, Nov-Dec 2000, pp. 976-983.
- Gern, F.H., Ko, A., Sulaeman, E., Gundlach, J.F., Kapania, R.K., and Haftka, R.T., “ Multidisciplinary Design Optimization of a Transonic Commercial Transport with Strut-Braced Wing,” J. Aircraft, **38(6),** November-December, 2001, pp. 1006-1014.
- Sulaeman, E., Kapania, R.K., and Haftka, R.T., "Effect of Compressive Force on Strut-Braced Wing Response," AIAA Paper 2001-1611, Proceedings 42nd AIAA/ASME-/ASCE/AHS/ASC Structures, Structural Dynamics and Material Conference, Seattle, WA, April, 2001.

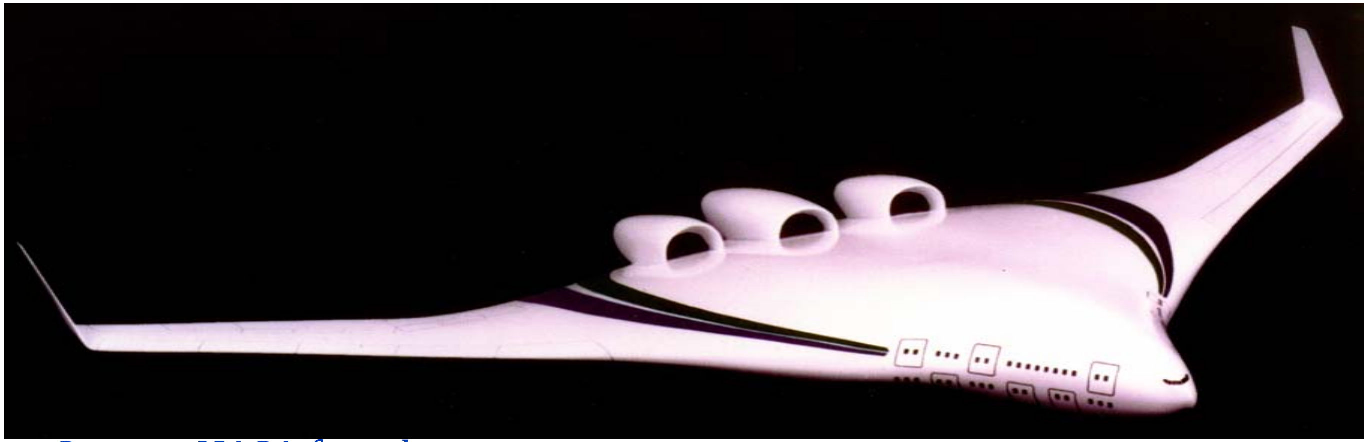
MDO of a Blended-Wing-Body Transport Aircraft with Distributed Propulsion

Andy Ko, Leifur T. Leifsson, W.H. Mason,
J.A. Schetz, and Bernard Grossman
Virginia Tech
and
R.T. Haftka, *University of Florida*

Work sponsored by NASA Langley Research Center

AIAA 3rd Annual ATIO Technical Forum, Denver
November 17, 2003

Conventional Propulsion BWB



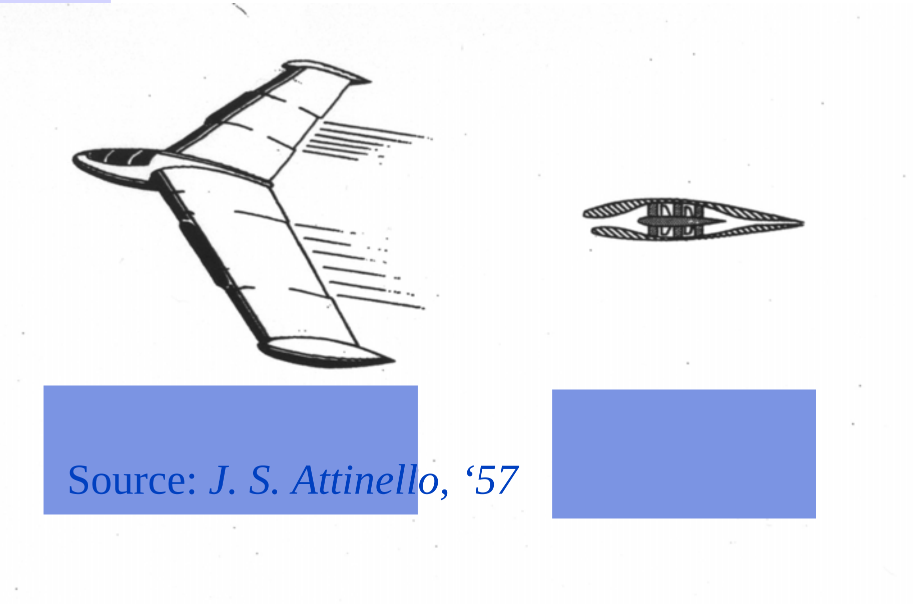
Source: *NASA fact sheet*

- Concept originated by McDonnell-Douglas
- A small number of large engines
- Elevons used for longitudinal control

Distributed Propulsion Concepts

Vehicle propulsion

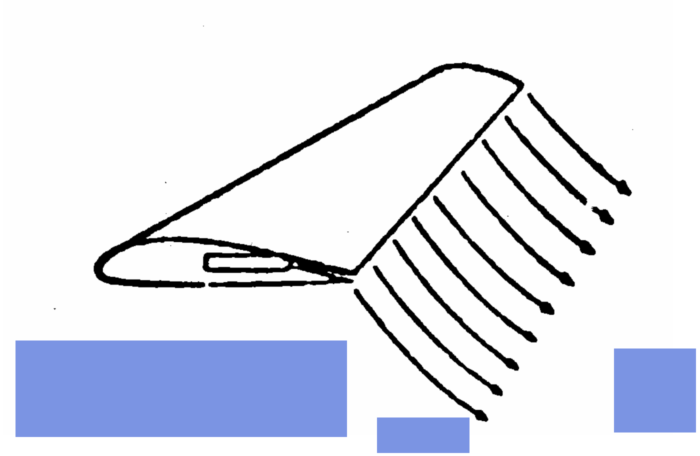
Kuchemann's Jet Wing



Source: *J. S. Attinello*, '57

Generation of high lift

Pure Jet Flap



Source: *C. J. Woan*, '83

Publicite

- University of Florida is francophone with a French interdisciplinary center and a center in Paris
- Our department has five faculty members with some French educational background
- We are interested in joint PhD programs
- I am interested in the possibility of working with you on MDO