Conceptual Design and CFD

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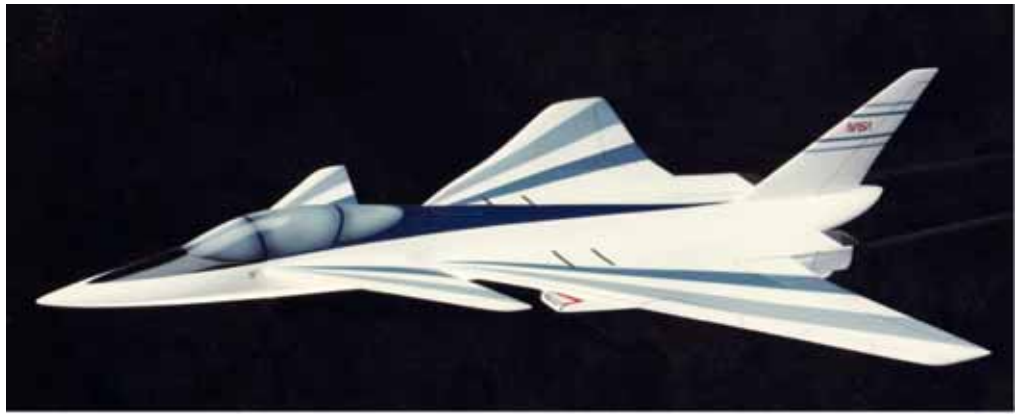

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Update from AIAA 98-2513

Things to think about If you want to do conceptual design

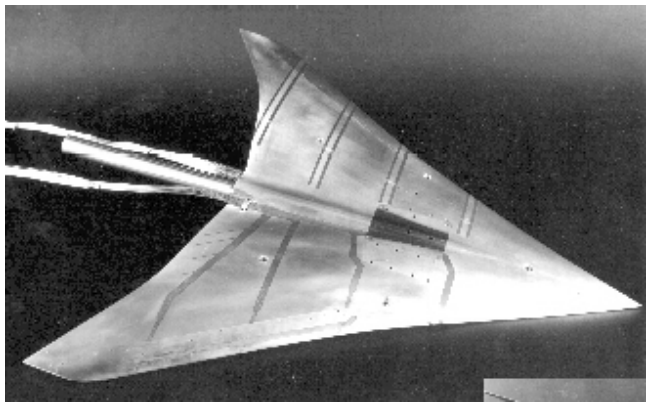
- "Quick" answers
- Truly arbitrary geometry
- Force and moment focus

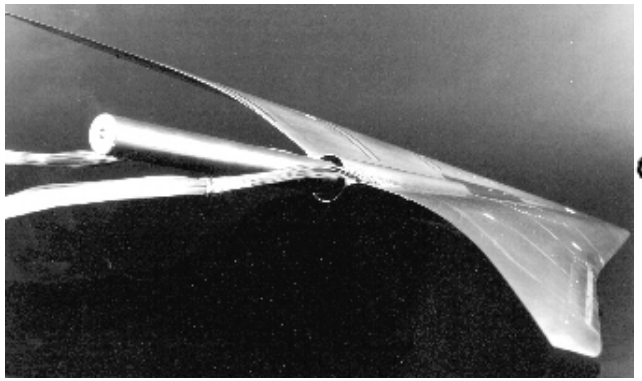
  - including trim
- *Analysis* of a geometry is of little value

  - What performance could you get after a detailed design/optimization?
- "Organization"
- One example of what we do

“Typical” advanced concepts

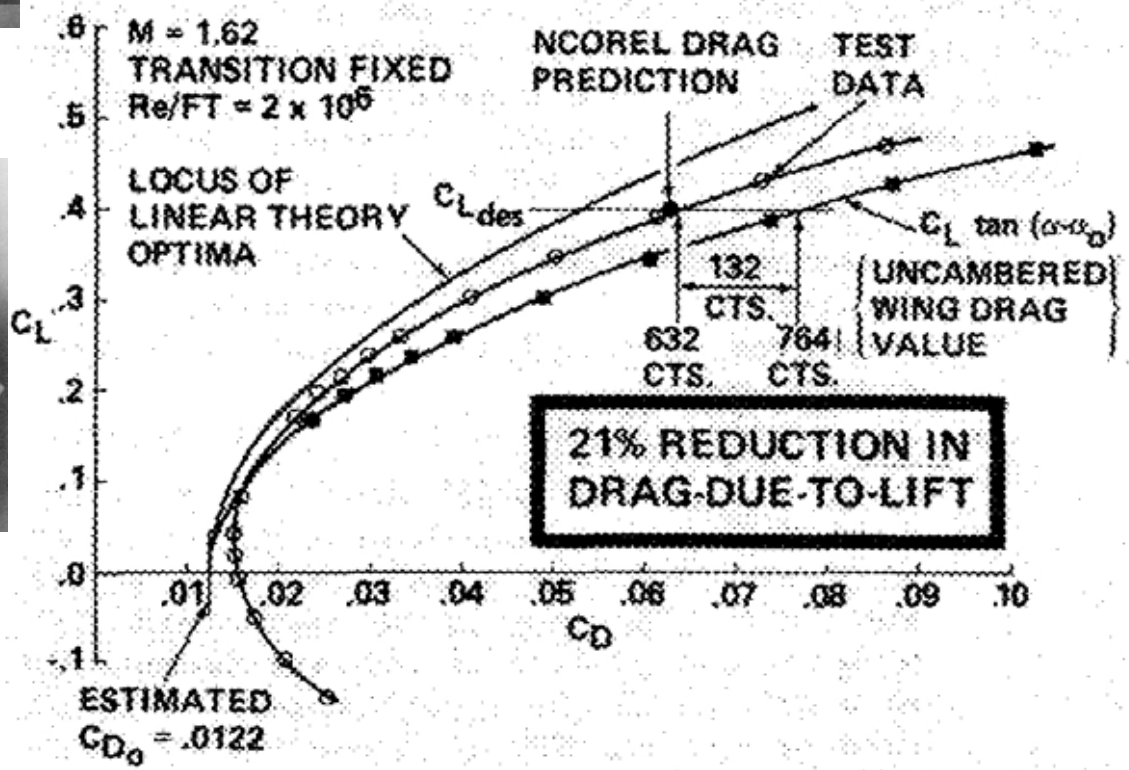
What performance level can you get?





Supercritical Conical Camber, SC^3

Need to project expected % LES, early - before WT Test!



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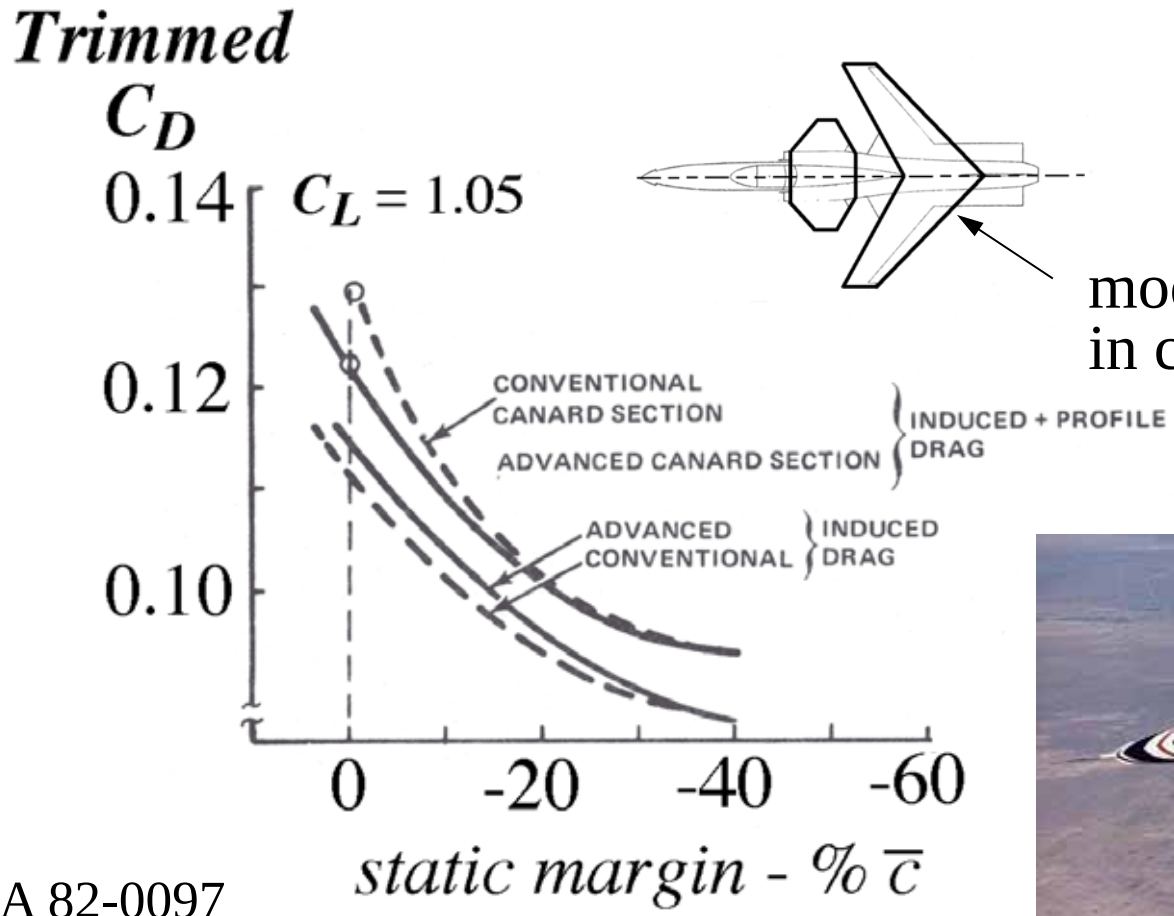
NASA CR 3763/AIAA 83-1858

You must trim for minimum trimmed drag

- **Performance strongly related to design static stability**



model used
in calculation

AIAA 82-0097

The Goal of Our Group's Work
- for over a decade -

- How to use high-fidelity analysis early in the design process
  - Putting high-quality information into the design process is a key to successful design, especially for hard problems, *i.e.*, the HSCT
  - Once sweep, *t/c*, etc are picked and detailed design begins, they're hard (expensive) to change

Tools and Considerations

- *Optimization methods*
  - design variables, objective function, constraints
  - gradient based and global approaches
- *Variable Complexity* (now called - variable fidelity)
- *Design of Experiments Theory*
  - from statistics, to create a *database*
- *Surrogates for High Fidelity Analysis*
  - Response surface models or Kriging
    - » to “interpolate” our database, also from statistics
- *Parallel computing*
  - the key to generating the database
- *Design Space Visualization*
- *Uncertainty in analysis and optimization*

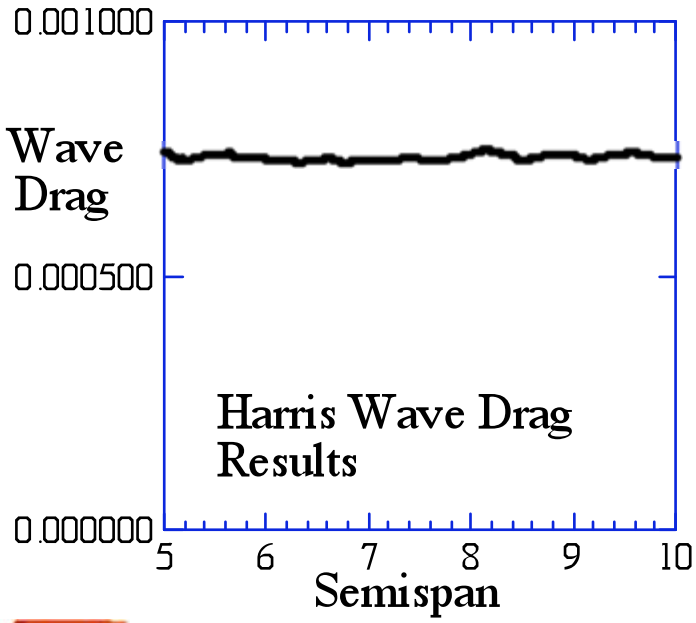
Problems to Anticipate

- Formal optimization methods are expensive and time consuming if you work in more than a few design variables
  - Local optima in high-dimensional space
- A CFD analysis of a wing that is not aerodynamically designed (optimized) is not relevant
- CFD codes, like all discrete approximation methods, produce noisy results as the geometry varies
  - sub iterations, shocks jumping from one grid line to another, etc.
- In conceptual design, optimization is not done just once
- Software development - the problem of the monster code
- There *is* no single discipline design at this level

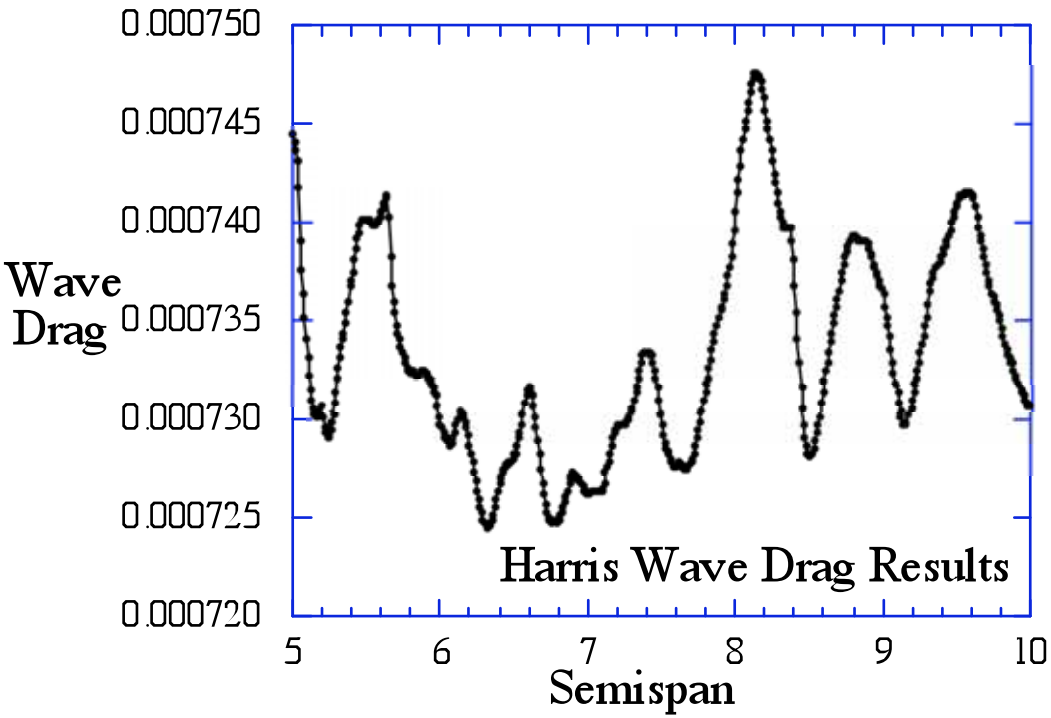
The Noise Problem, One Example of Many

- Analysis predictions aren't "smooth" with geometric changes:
- Wing example: change the span and examine the wave drag
- Trap: fixing a code to produce smooth results

Plotted at "engineer" scale



Plotted at "optimizer" scale



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Aerodynamics at the Conceptual Design Level

- Usually algebraic approximations or very simple computations
- Aerodynamicists need to use CFD in Conceptual Design
  - *this is where CFD provides the biggest benefit*
- The span, thickness and sweep are all changing
  - this is MDO, not the "normal" aerodynamic design problem where planform, *t/c*, etc are specified.
- We want to present the optimizer with a modern-day version of a design handbook, tailored for a concept.

The Navier-Stokes Nightmare

Someone hooks up a RANS code to an optimizer, and runs optimizations over and over. Each time 100s of solutions are required, and almost all of them are computing and recomputing solutions over nearly identical geometries. The entire computing resources of the US are consumed.

There must be a saner way!

Multidiscipline Design – 10,000 – 100,00 analysis required

Early Work: Response Surfaces

- Sid Powers used response surfaces in the early 1960s,
  - Powers, S. A., "Drag Minimization Using Exact Methods," *AIAA Journal*, Vol.2, pp. 941-943, May 1964.
- Methods were developed at Boeing using design of experiments and response surface models in the 1970s, but we haven't seen papers recently:
  - Healy, M.J., Kowalik, J.S., and Ramsay, J.W., "Airplane Engine Selection by Optimization on Surface Fit Approximations," *Journal of Aircraft*, Vol. 12, No. 7, July 1975, pp. 593-599.

Overview of Our Approach

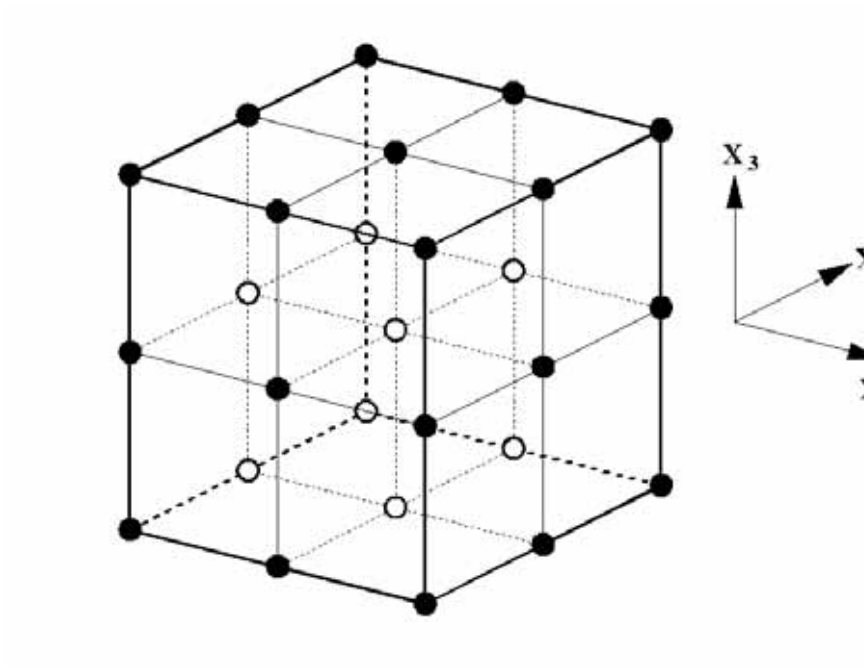
- Represent expensive computations by a *database*
  - computing cost is moved out of the optimization step
  - the database can be continually updated
  - eliminates software problems with huge MDO codes
- "Interpolate" the database
  - use 2nd order polynomials of *functions* of the CFD results
  - the algebraic models are computationally instantaneous
  - noise is filtered out before optimizing
  - today people often use Kriging models

Detailed approach to using CFD (in 10 steps)

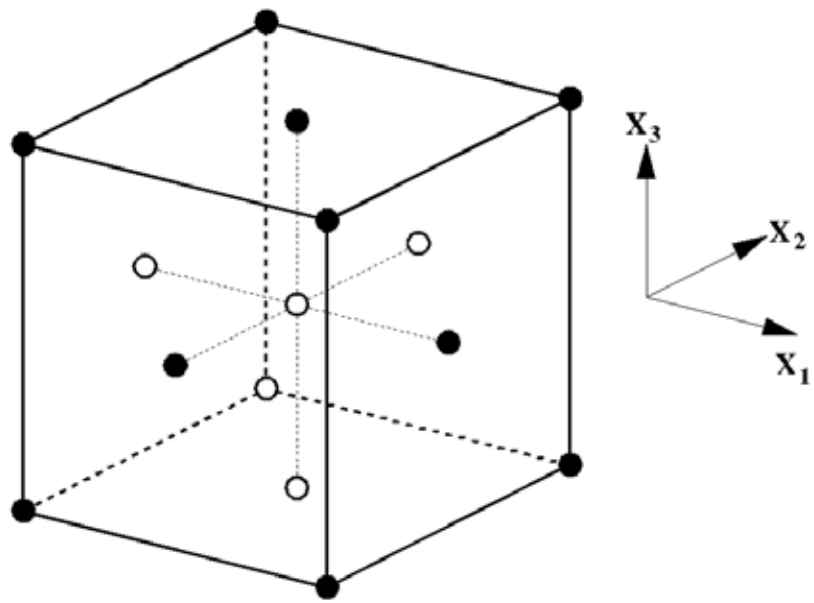
- *Step 1:* Represent the design parametrically with design variables (our HSCT work had up to 29 DVs)
- *Step 2:* Generate combinations of these variables (designs) using Design of Experiments (DOE) methods
  - full factorial is one example, too many combinations (designs)
  - central composite design produces fewer designs

Design of Experiments Boxes

A full factorial design

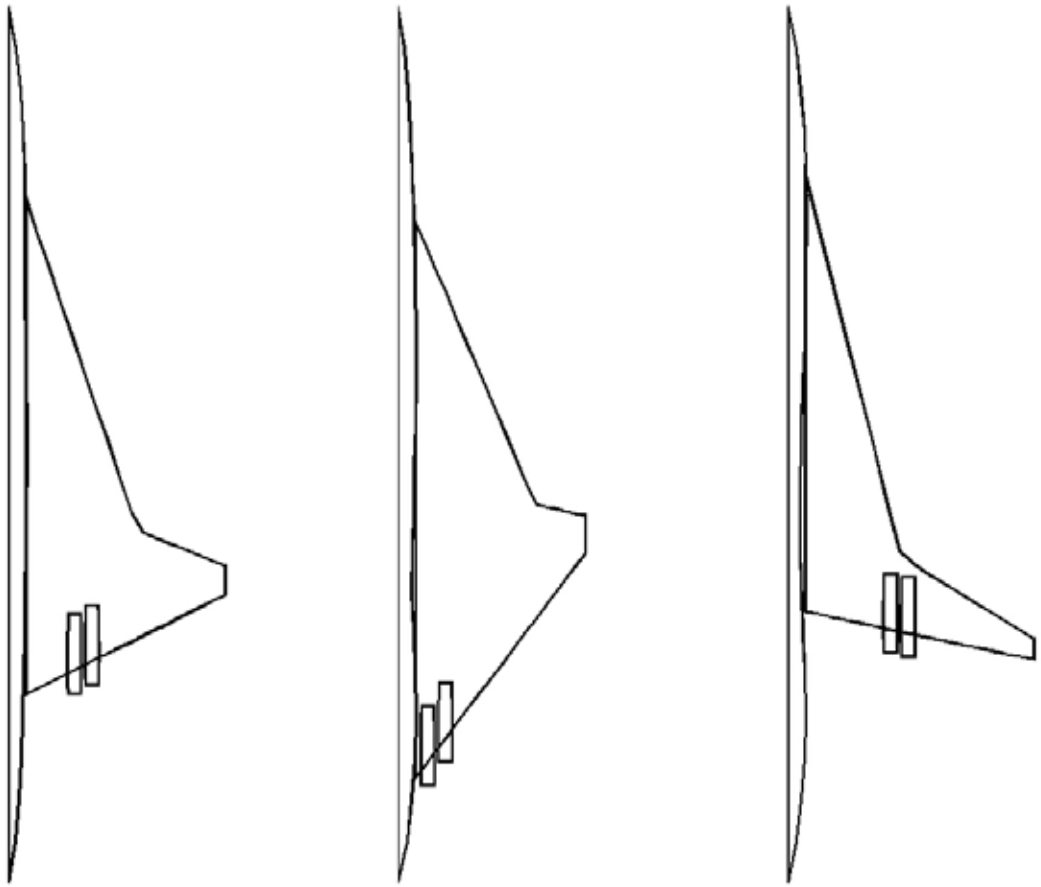


A central composite design



For n DVs, 2^n candidate designs, 25 DVs = 335,000,000 vertices?

Planforms corresponding to our DOE Boxes



Design Space Reduction

- *Step 3:*
  - eliminate ridiculous geometries (automatic screening)
  - do a constraint analysis
    - » *e.g.*, throw out design that grossly violate the range constraint using very simple models
  - Select a subset of the designs using the D-optimal method (or others)
    - » pick several times the number of coefficients in the polynomial response model

Adding Aerodynamic Intelligence

- *Step 4:* Think about what we are going to do with information we gather.
  - If we need a polar. We fit the form of the polar, either

$$C_D = C_{D_0} + KC_L^2$$

or

$$C_D = C_{D_m} + K(C_L - C_{L_m})^2$$

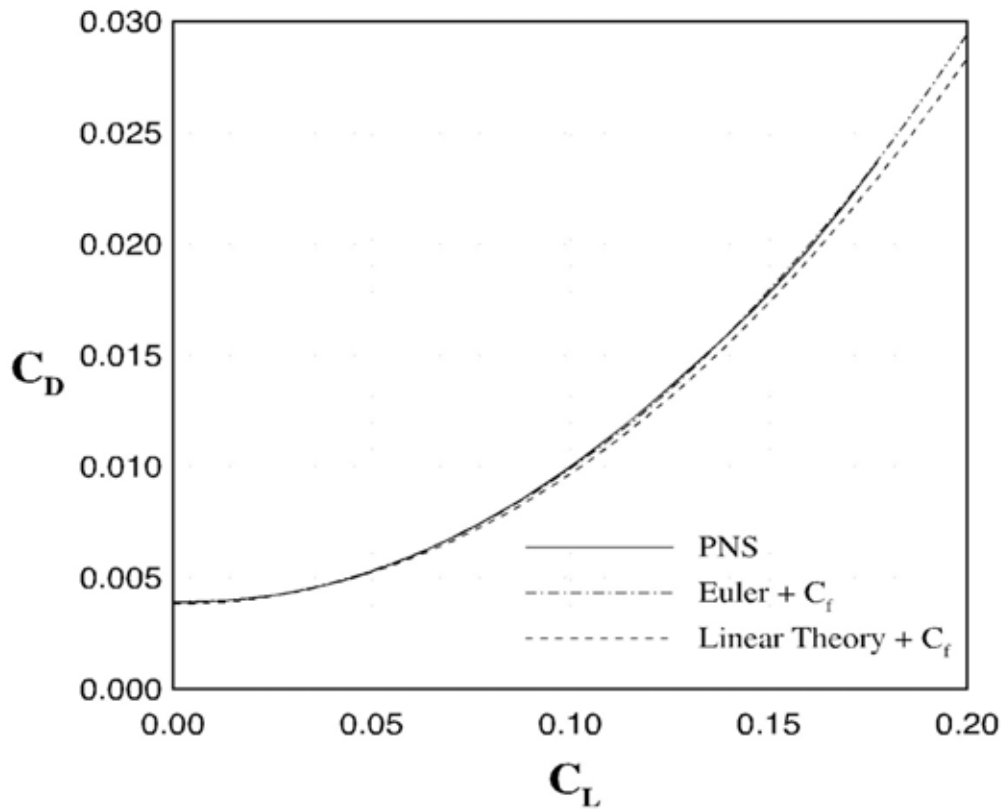
Do two or three runs for each design to define the parameters.

The polar *parameters* are then fit with an RS model,

$$C_{D_0}(\mathbf{X}),\ K(\mathbf{X})$$

Drag Prediction and Aircraft Performance

- Linear theory induced drag consistently low
- Harris wave drag estimates within 2 counts of CFD value
- Skin friction estimate larger than PNS value (within 1 count)
- Addition / Cancellation of zero-lift drag and induced drag errors at cruise C_L
- Linear theory drag prediction typically 1-2 counts lower than PNS values
- 2 count drag underprediction results in 120 *n.mi.* overestimate of the range



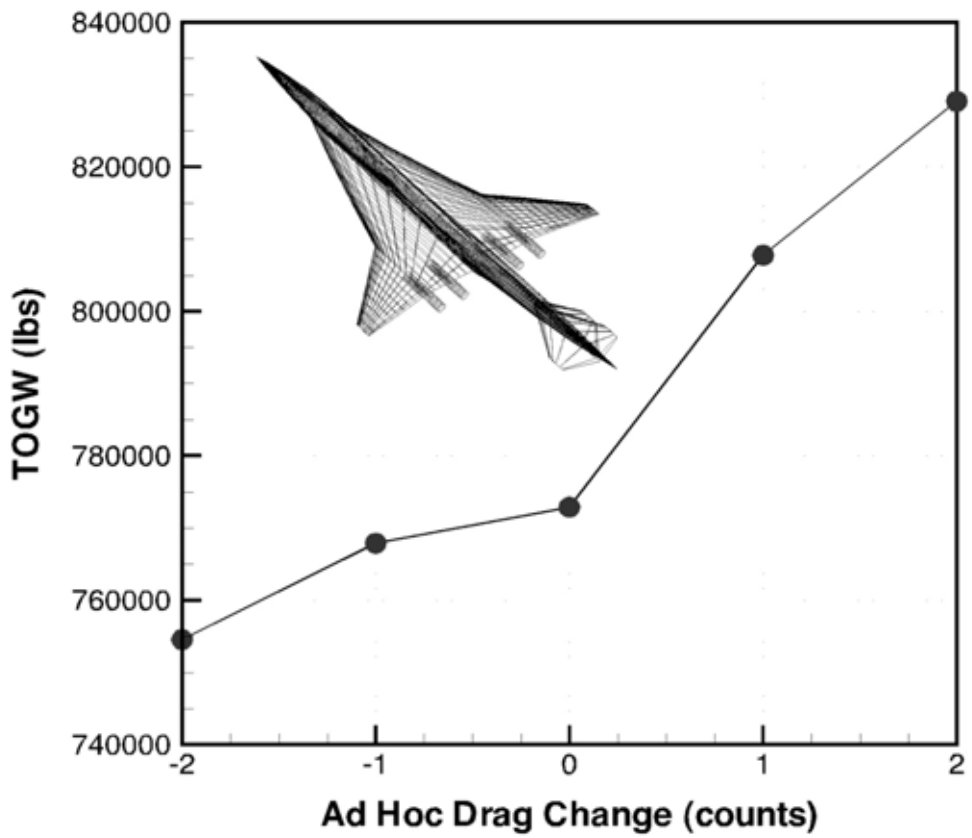
at $C_L = 0.082$

C_D (PNS) = 0.00792
C_D (Euler + C_f) = 0.00789
C_D (L.T. + C_f) = 0.00771

Sensitivity of Optimization to Drag

- Oleg Golovidov
- Examine sensitivity of optimization to *ad hoc* changes in the drag
- 56,000 lb increase in TOGW when 2 counts of drag are added over entire mission
  - 37,000 *lb* added fuel
  - 9000 *lb* propulsion
  - 6000 *lb* wing weight
  - 4000 *lb* other components

  Increase outboard wing sweep



* *Reference: AIAA 97-0098*

Starting to create the data base

- *Step 5:* Evaluate the D-optimal designs selected in Step 3 using a cheap method, typically linear theory. Create a response surface in the form selected in Step 4
  - Note: use the "almost lineary theory" of Harry Carlson to get the minimum drag camber shapes of each design (attainable LES)
- *Step 6:* Do a regression analysis. Which terms are important? Define the reduced term model.

Note: 25 DVs mean 351 coefficients in a quadratic polynomial, requires at least 2x351 to fit the surface

Obtain Euler Equation solutions, build and check the model

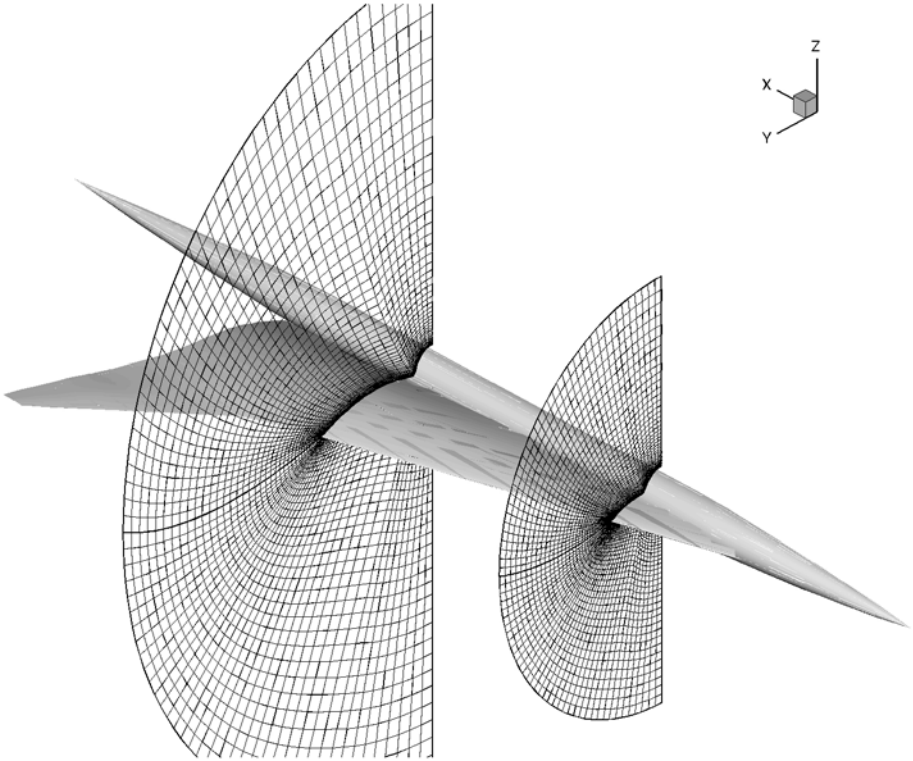
- *Step 7:* Assume that the important terms from the linear theory analysis are also the important ones in higher fidelity, and run Euler cases to make the reduced term model (GASP space-marched)
  - use coarse grain parallel computing, run desigsn on different processors (got 100s of cases a day)
- *Step 8:* Check the model. How accurate is it compared to the Euler results used to create it and other Euler calculations (you have many designs available from the complete set used for the linear theory work)?

Lucky Break in Grid Generation

Grid generator for space marching calculations originally developed by Ray Barger at NASA Langley

Features of code

- Uses as input the aircraft configuration written in Craidon format
- Robust for large planform changes
- Measures are employed to reduce grid skewness
- Hands-off grid generation

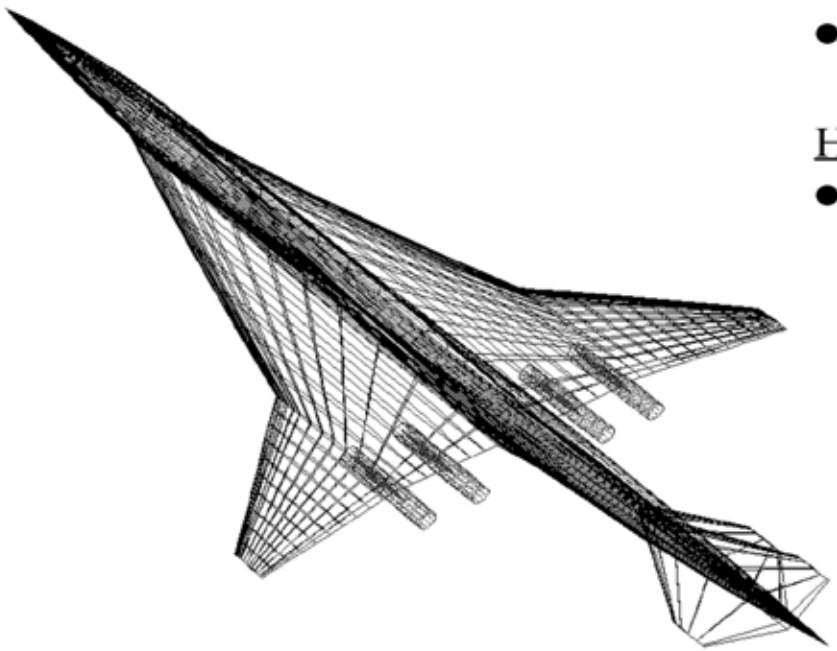


Finally, do Optimization!

- *Step 9:* Do the optimization!
  - *with the response surface models available, this can be done many times at little additional cost*
- *Step 10:* Last step, check at the design point by doing an Euler Calculation

Using 73 of 210 terms for a 20 DV case, saved 255 out of 392 CPU hours on an SGI Power Challenge.

HSCT Optimization Problem



Design Requirements

- $\text{Mach}_{\text{cruise}} = 2.4$, Range = 5500 n.mi., Payload = 250 passengers
- Objective: minimize takeoff gross weight (TOGW)

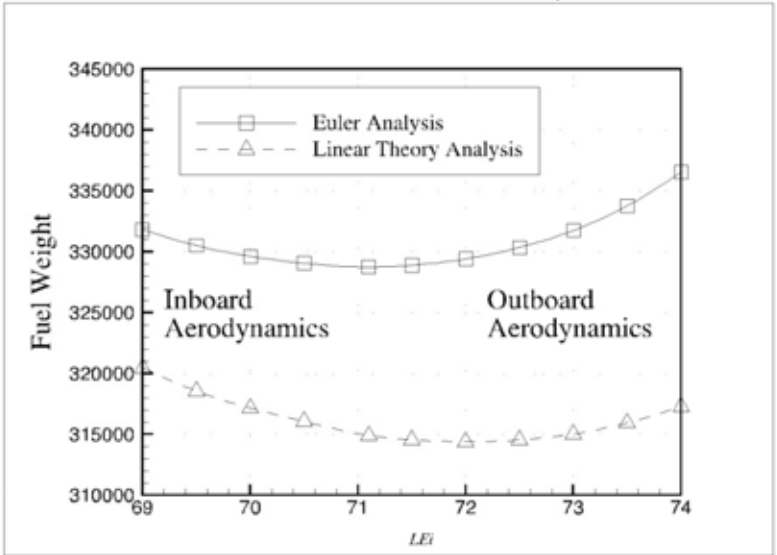
HSCT Model Parameterization

- 29 variables:
  - 8 - wing planform
  - 8 - fuselage
  - 5 - airfoil section
  - 2 - nacelle location
  - 2 - vertical and horizontal tail areas
  - 1 - engine thrust
  - 3 - mission variables: fuel weight, initial cruise altitude, rate of climb

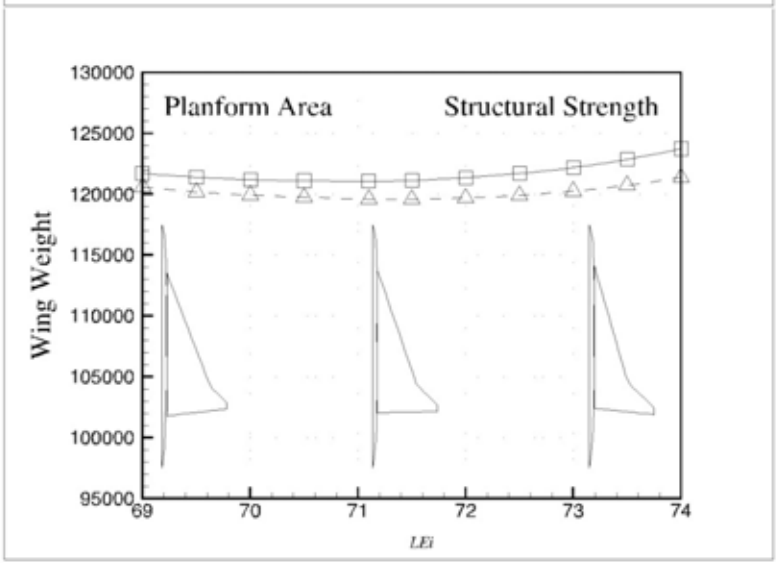
Optimization Problem

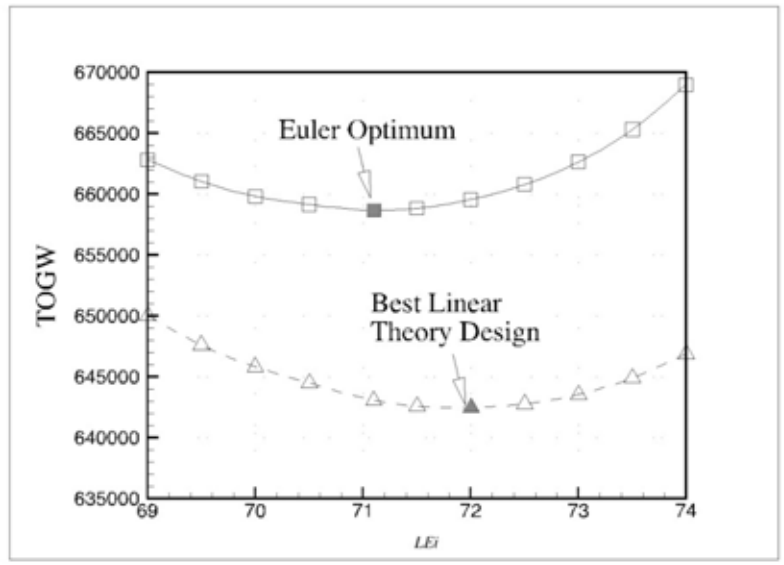
$$\underset{x \varepsilon R^{29}}{\text{minimize}}\ TOGW(\boldsymbol{x}), \quad \text{subject to} \quad g_i(\boldsymbol{x}) \leq 0,\ i = 1,\ldots,70$$

Design Trade-Off Information (Inboard LE Sweep)

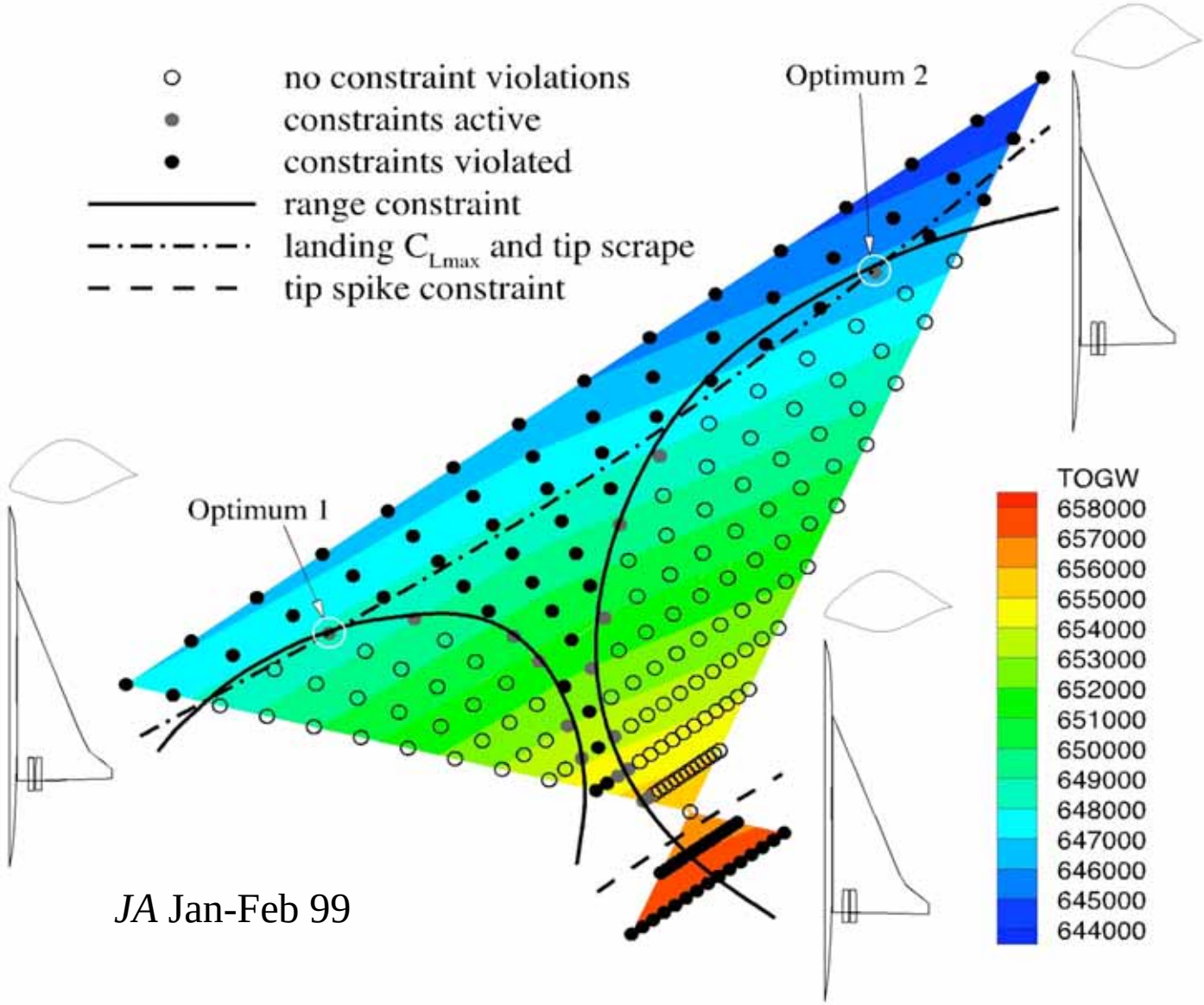


- Compromise of aerodynamic influences
- With span fixed, any increase in wing sweep has corresponding undesirable increase in outboard section size
- Euler has larger penalty for the outboard aerodynamics compared to linear theory, thereby shifting optimal Λ_{LE_I} forward





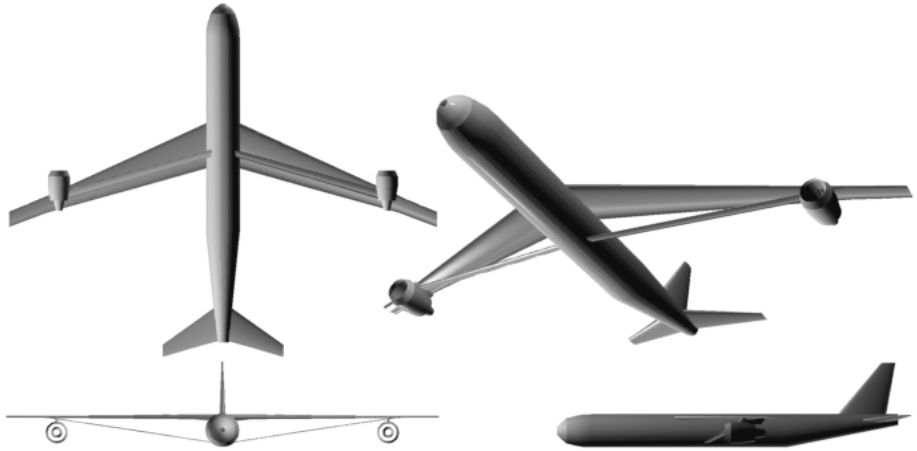
Visualization of the Design Space



JA Jan-Feb 99

Other Response Surface Examples

- Included HSCT pitchup constraints
- Structural optimization for wing weight for the HSCT
- Wing-strut interference drag for a strut-braced wing concept



- Number of containers (in ship MDO)

What We Didn't Talk About: Sensitivity Methods (Jameson) AIAA 2008-0326 for discussion and Refs.

Questions?

See also: Giunta, A.A., Golovidov, O., Knill, D.L., Grossman, B., Mason, W.H., Watson, L.T., and Haftka, R.T., "Multidisciplinary Design Optimization of Advanced Aircraft Configurations," *Fifteenth International Conference on Numerical Methods in Fluid Dynamics*, P. Kutler, J. Flores, J.-J. Chattot, Eds., in Lecture Notes in Physics, Vol. 490, Springer-Verlag, Berlin, 1997, pp. 14-34.