Aerospace Applications of Optimization under Uncertainty

Sharon Padula, Clyde Gumbert, and Wu Li
NASA Langley Research Center, Hampton VA

International Symposium on Uncertainty Modeling and Analysis

College Park, MD

September 22-24, 2003

More info: http://mdob.larc.nasa.gov/

Sharon Padula
NASA Langley Research Center

LaRC Aircraft in Front of Hangar, Building 1244
NASA Langley Research Center 6/27/1994 Image # EL-1996-00055

- Mathematician
- Multidisciplinary Optimization Branch
- Aerospace Systems, Concepts & Analysis Organization

Outline

1. Three examples of optimization under uncertainty
   – Impact Dynamics
   – Coupled Aerodynamics/Structures
   – Airfoil Shape Optimization
2. Lessons Learned
3. Enabling Technologies Identified

Three Examples of Optimization under Uncertainty
Characteristics of Test Problems

- Similarities
  - Computationally expensive simulations
  - Sensitive to uncertain input parameters
  - Continuous design variables
  - Nonlinear objectives
- Differences
  - Number of design variables from 3 - 50
  - Optimize expected value or limit probability of failure
  - Uncertainty quantification (UQ) either home grown or commercial codes
  - Types of uncertainty

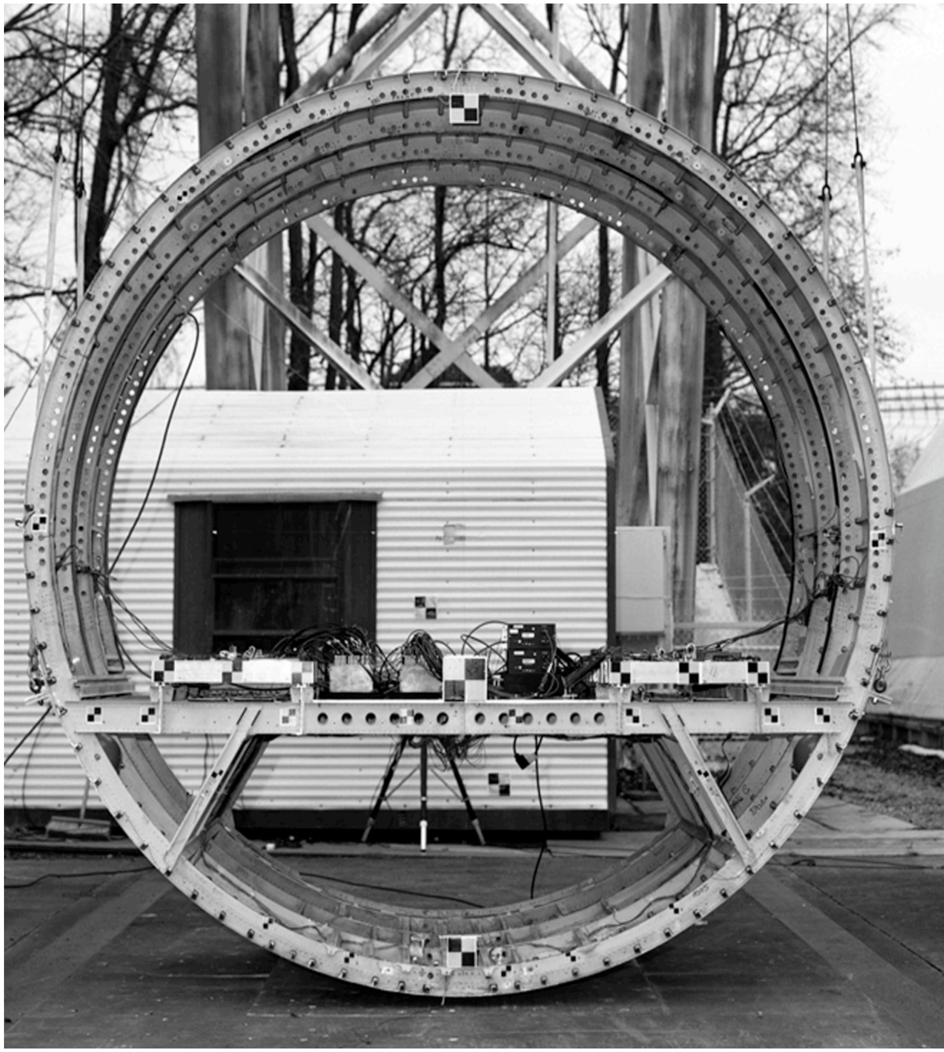
Outline

1. Three examples of optimization under uncertainty
   – Impact Dynamics
     • Lyle, Padula, Stockwell, "Applications of Probabilistic Analysis to Aircraft Impact Dynamics", AIAA-2003-1482.
   – Coupled Aerodynamics/Structures
   – Airfoil Shape Optimization
2. Lessons Learned
3. Enabling Technologies Identified

References available: http://mdob.larc.nasa.gov/

Impact Dynamics Example

Can we design a vehicle for crashworthiness?

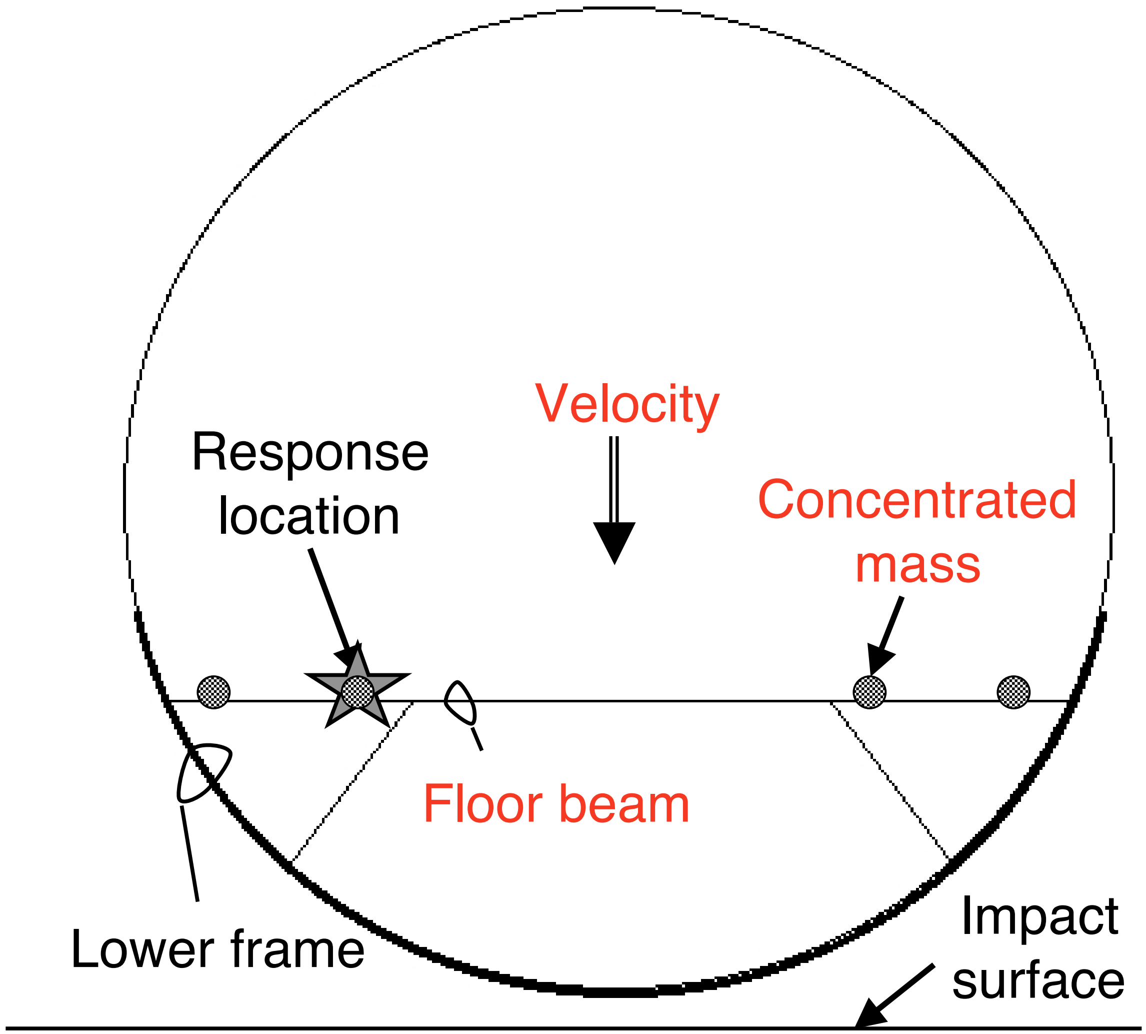


before

during

Notice floor beam and accelerometers

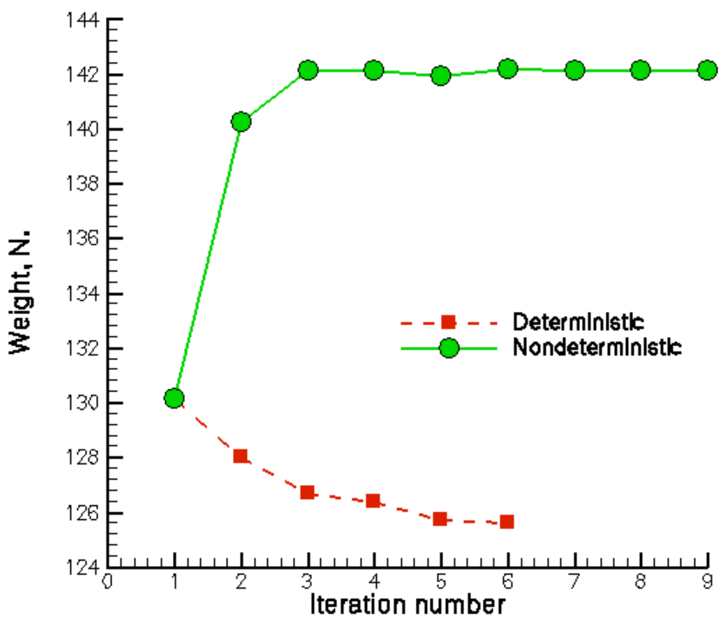
Schematic of Impact Dynamics Problem



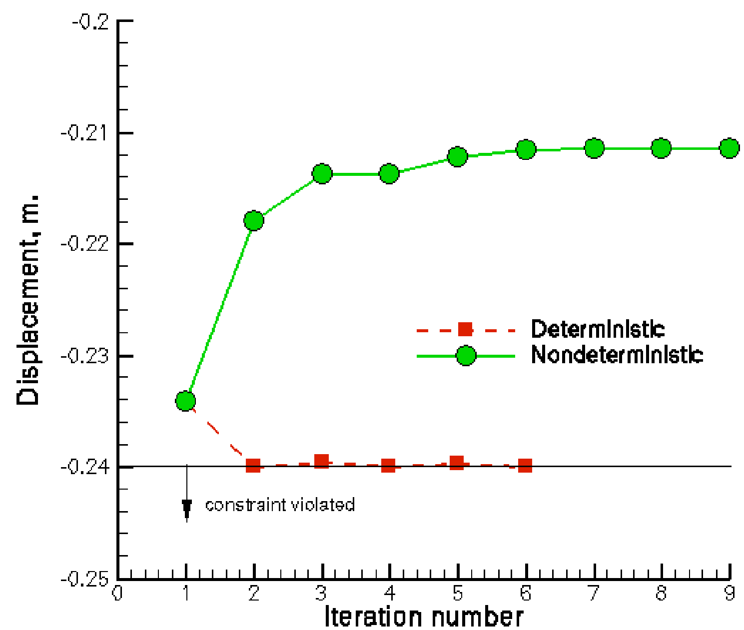
Note: Velocity and mass have normal distribution; floor beam has a maximum displacement

Design for Crashworthiness
A first attempt

Minimize:	vehicle weight
Subject to:	max acceleration < survivable
	probability (displacement < allowable) > 75%



Weight increases



Displacement physically possible

Lessons Learned

- Probabilistic constraints do steer optimizer away from troublesome regions of design space
- But, optimization under uncertainty is more difficult (e.g. more nonlinear problem) and expensive
- Approximate models (e.g. kriging) do reduce computational cost and provide credible solutions
- But, must rebuild approximate models as optimizer moves through design space

Enabling Technologies
In priority order

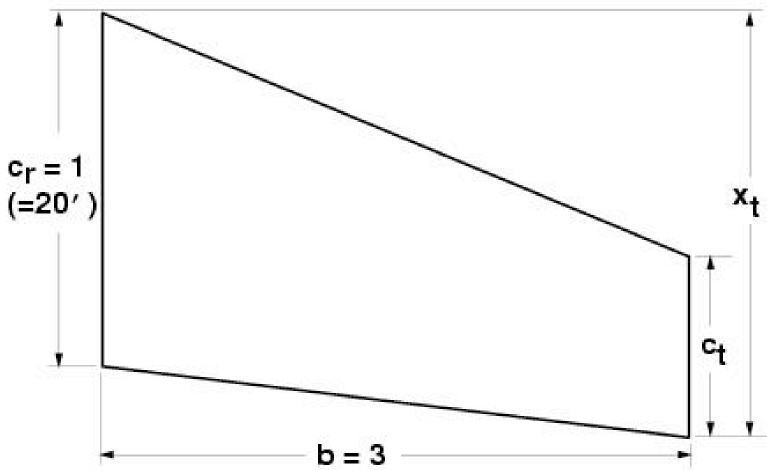
1. Approximate engineering analysis for UQ
2. Uncover designs with higher probability of success
3. Validate UBM for coupled multidisciplinary problems
4. Include physics-based UQ in conceptual design
5. Exploit variable-fidelity models to reduce expense
6. Enable UBM for time dependent analysis

Outline

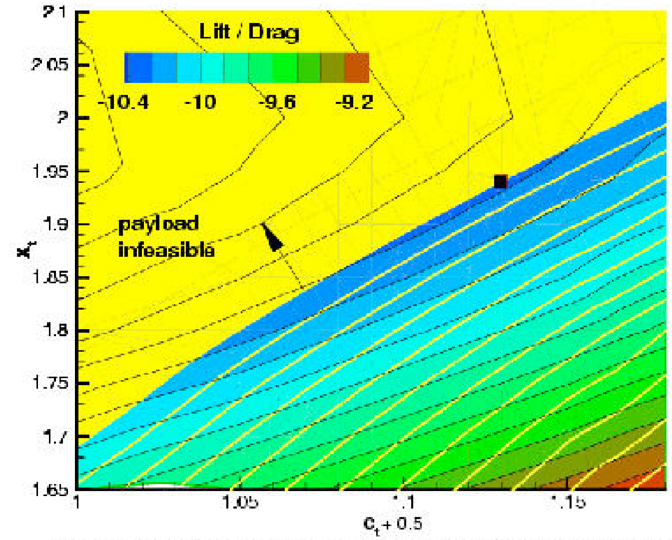
1. Three examples of optimization under uncertainty
   - Impact Dynamics
   - Coupled Aerodynamics/Structures
     - Gumbert, Newman, Hou, "Effect of Random Geometric Uncertainty on the Computational Design of a 3-D Flexible Wing", AIAA-2002-2806.
   - Airfoil Shape Optimization
2. Lessons Learned
3. Enabling Technologies Identified

References available: http://mdob.larc.nasa.gov/

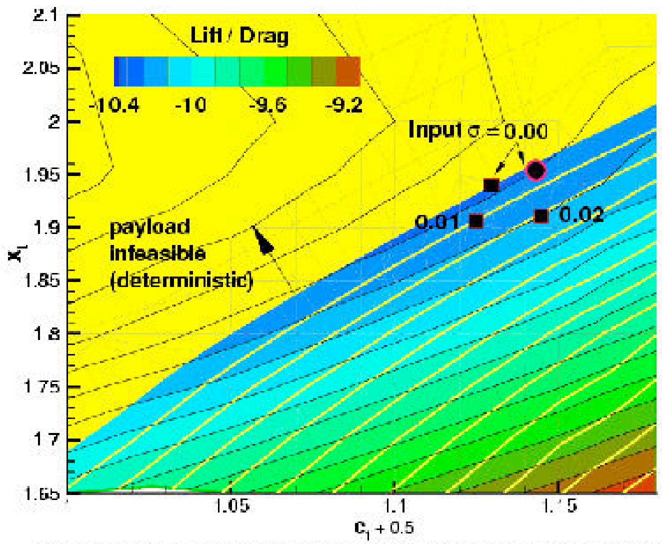
Robust Shape Optimization for Flexible Wing with Planform Uncertainty



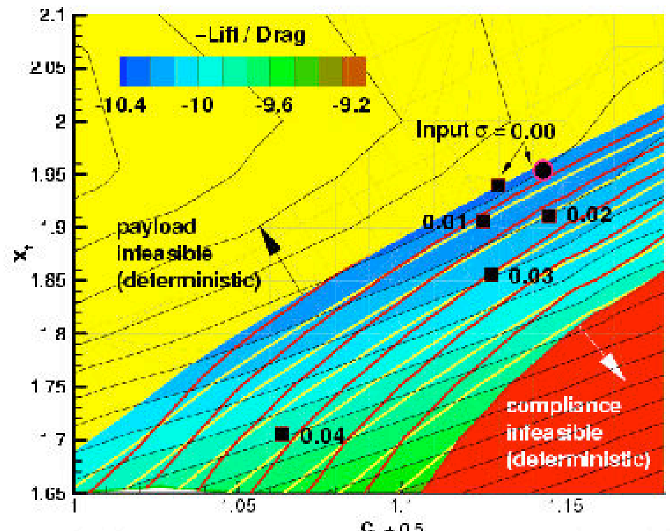
Wing planform variables c_t and x_t.



Conventional optimization result overlaid on level sets of deterministi objective and active constraint functions.

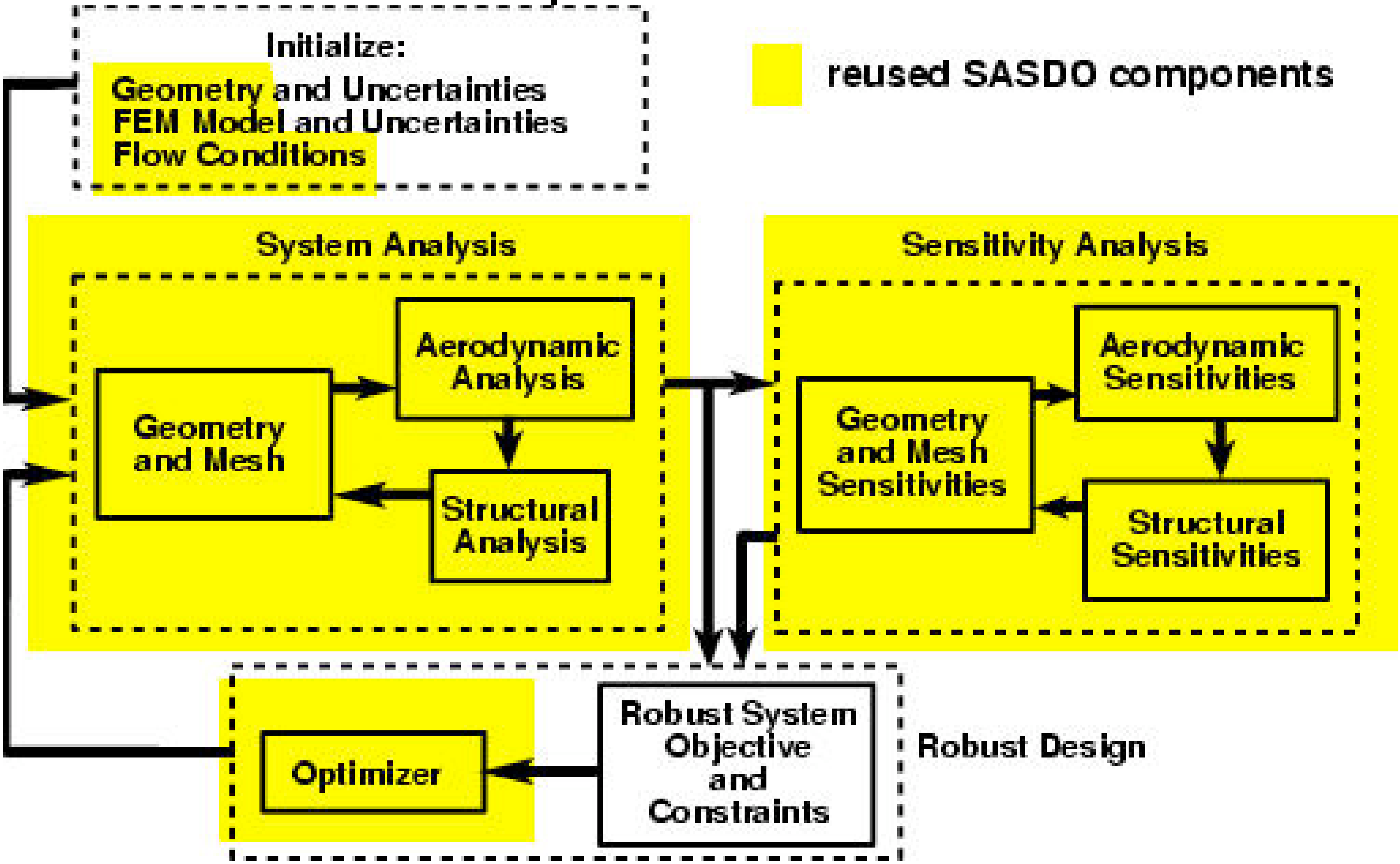


Probabilistic σ = 0.01 & 0.02 robust optimization results overlaid on deterministic level sets.



Probabilistic σ = 0.03 & 0.04 robust optimization results overlaid on deterministic level sets.

Coupled Aerodynamic-Structures Wing Optimization



Lessons Learned

- Adding uncertainty shrinks the design space
- Existence of deterministic solution does not guarantee a existence of non-deterministic solution
- Statistical First-order Second Moment Method was appropriate for this coupled multidisciplinary analysis

Enabling Technologies

1. Approximate engineering analysis for UQ
2. Uncover designs with highest probability of success
3. Validate UBM for coupled multidisciplinary problems
4. Include physics-based UQ in conceptual design
5. Exploit variable-fidelity models to reduce expense
6. Enable UBM for time dependent analysis

Outline

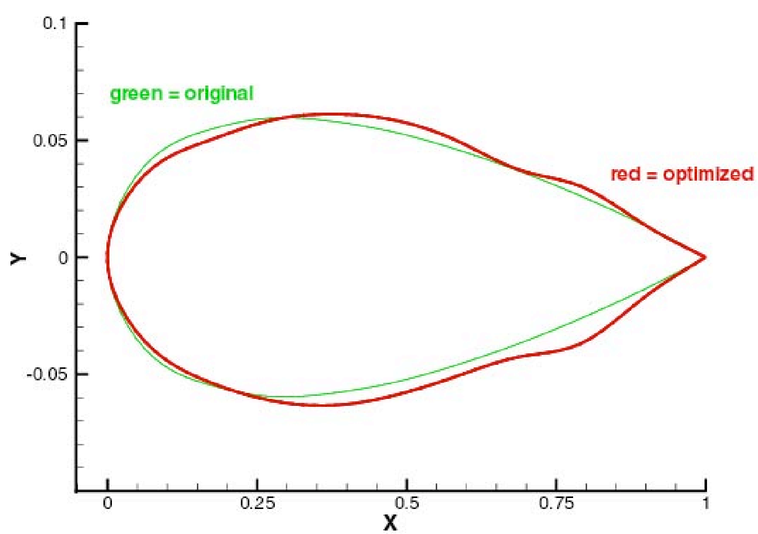
1. Three examples of optimization under uncertainty
   - Impact Dynamics
   - Coupled Aerodynamics/Structures
   - Airfoil Shape Optimization
     - Li and Padula,"Performance Trades Study for Robust Airfoil Shape Optimization", AIAA-2003-3790.
2. Lessons Learned
3. Enabling Technologies Identified

References available: http://mdob.larc.nasa.gov/

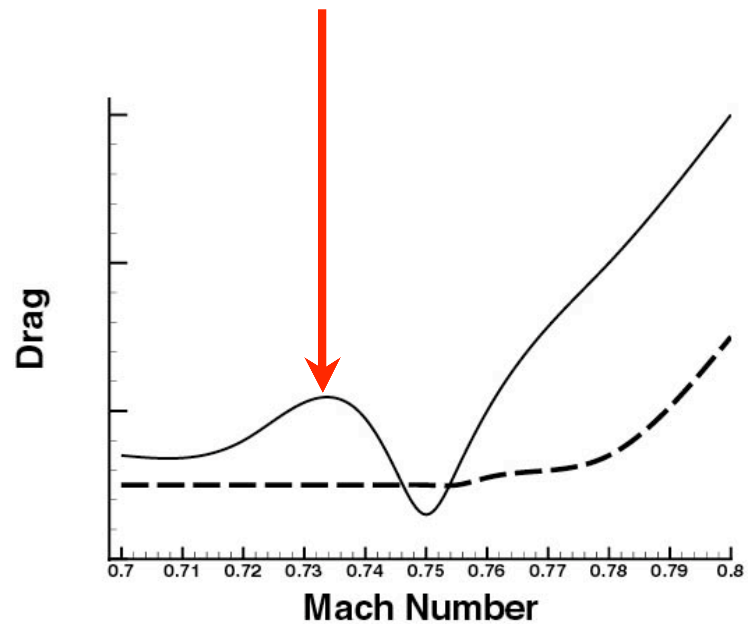
Two Known Problems Associated With Lift Constrained Drag Minimization

$$\min_{D,\alpha_1,\ldots,\alpha_r} \sum_{i=1}^{r} w_i\, c_d(D, M_i, \alpha_i) \text{ st } c_l(D, M_i, \alpha_i) \geq c_l^* \text{ for } 1 \leq i \leq r.$$

Noisy optimal airfoil

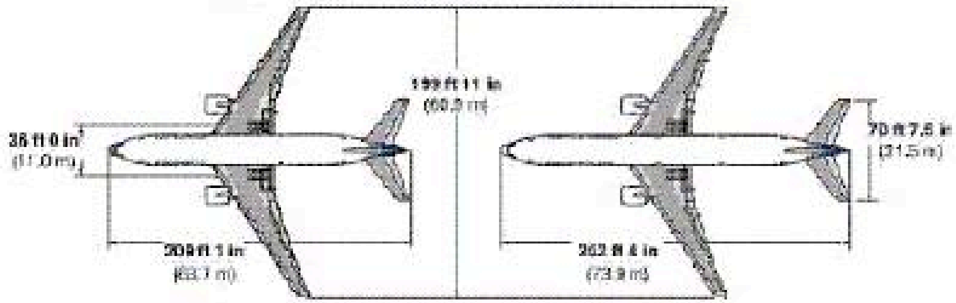


Off-design performance degradation

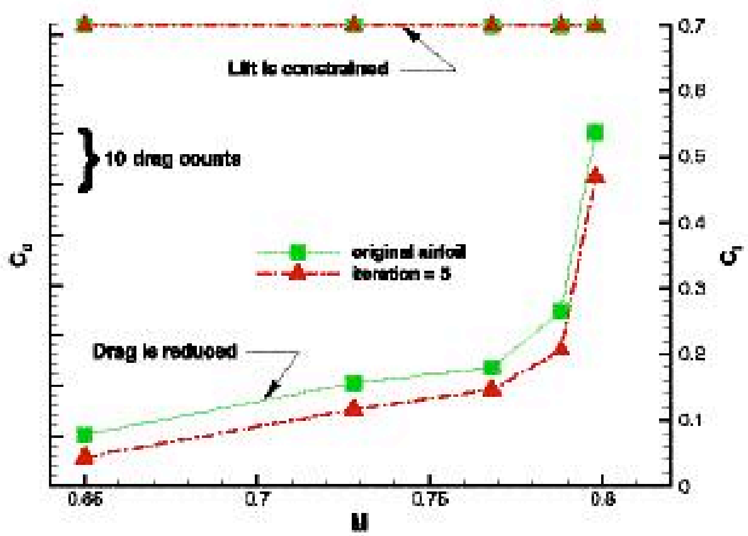


Airfoil Shape Optimization for Design Teams

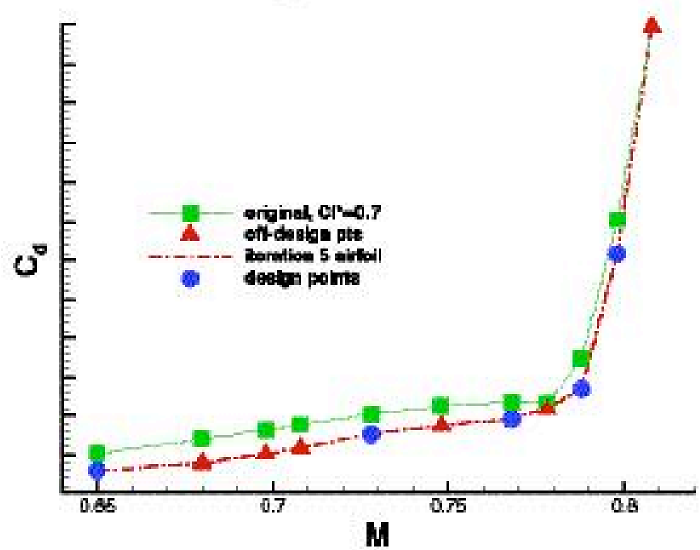
The baseline airplane with original airfoil → **A bigger and faster airplane with optimized airfoil**



Drag reduction at five specified design conditions

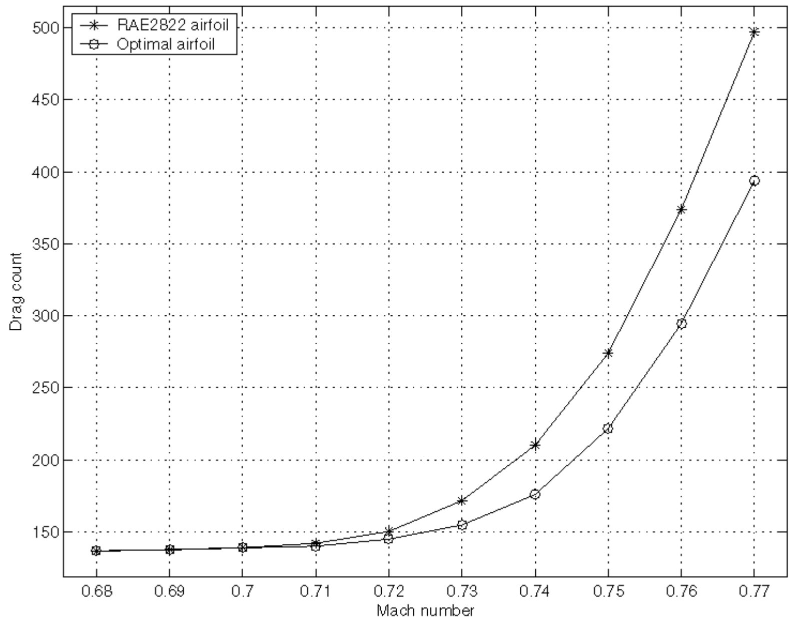


Post-optimization analysis at off-design conditions

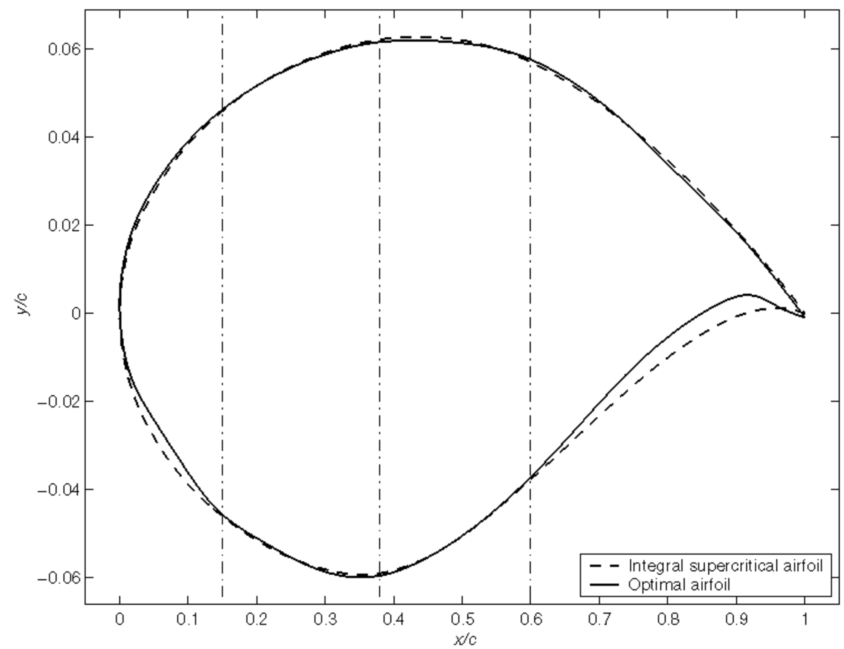


Airfoil Shape Optimization with uncertain operating conditions

4 RANS CFD solutions per iteration



Baseline & optimal airfoils



- What Has Been Accomplished?
  - Robust optimization directly minimizes wave drag for 0.7< Mach # <0.8
  - New airfoil is similar to baseline but has less drag and no off-design performance hit
  - Use a small number of function evaluations and a large number of design variables

Lessons Learned

- Relatively smooth optimum airfoils found even with 50-100 B-spline coefficients as design variables
- Success of optimization method depends on accurate gradient calculations (not available for all codes)
- Airfoils optimized including uncertainty are more acceptable to designers!!
- This work needs to be extended (e.g. 3-D wings)

Enabling Technologies

1. Approximate engineering analysis for UQ
2. Uncover designs with highest probability of success
3. Validate UBM for coupled multidisciplinary problems
4. Include physics-based UQ in early design stages
5. Exploit variable-fidelity models to reduce expense
6. Enable UBM for time dependent analysis

Concluding Remarks

- Optimization under uncertainty is a new concept for aerospace engineers at NASA Langley
- Impact dynamics and 3-D wing represent learning experiences for MDO branch
- Airfoil shape optimization pushes the state-of-the-art
- These studies uncover enabling technologies which require future investment