Advanced Optimization Capabilities in SU2 for the Design of a Low-Boom Flight Demonstrator

Sonic Boom Activities IV – Low Sonic Boom Flight Demonstration
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Juan J. Alonso, Francisco Palacios, Trent Lukaczyk
Department of Aeronautics & Astronautics
Stanford University
Stanford, CA 94305, U.S.A.
Outline

• The challenge of low-boom design
• Regularizing the design process
• N+2 vehicle design efforts
• Low-Boom Flight Demonstrator ongoing efforts
• Conclusions & future work
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Classical Sonic Boom Theory

- Based on classical, linearized supersonic flow
- Parameterization of the F-function (near field pressure distribution) using 5 parameters
- Analytic optimization
- Drag impact of boom minimization not considered

But

- Tremendous physical insight
- Actual usable results:
  - Minimum pressure rise/overpressure/impulse
  - Target area distributions

\[ \Delta p \propto \frac{W_{\text{aircraft}}}{L^{3/2}} \]

From: Darden, C., AIAA J. Aircraft, vol. 14, no. 6, 1977
Why Is Low-Boom Design Difficult?

Coefficient of Drag, CD, vs. radii of two fuselage stations

$dv_1$, $dv_2$
Why Is Low-Boom Design Difficult? (2)

Ground boom loudness vs. radii of two fuselage stations (two different measures)

\[
dv_1, dv_2
\]
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Regularization: Equivalent Area Distributions

- CFD-based equivalent area inverse design

Note that multiple $A_e(x;\theta)$ need to be accounted for
### N+2 Supersonic Passenger Jet Concept

<table>
<thead>
<tr>
<th>Cruise:</th>
<th>Ma 1.6-1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic Boom:</td>
<td>65-70 PLdB</td>
</tr>
<tr>
<td>Fuel Efficiency:</td>
<td>baseline + 15%</td>
</tr>
<tr>
<td>Range:</td>
<td>4000 nmi</td>
</tr>
<tr>
<td>Payload:</td>
<td>35-70 pax</td>
</tr>
</tbody>
</table>

- Reduce Boom Noise, Reduce Drag, Maintain Lift, Structure, Propulsion Integration
Direct connection to gradient-based optimization

Baseline Mesh

Mesh Deformation

Direct Solver

Adjoint Solver

Signature Extraction

Gradient Module

From the optimizer

$\mathbf{f} \in \mathbb{R}^N$

$\mathbf{w}$ flow solution

$\Psi$ adjoint solution

$I$ design parameters

cost/constraint functions

To the optimizer

$\mathbf{w}$

$\Psi$

$I$

Gradient-Enhanced GPR Surrogate Models for Optimization

Objective Surface

+ Samples

Surrogate

Direct solver, adjoint solver, mesh deformation, grid adaptation, fluid/structure simulation, python wrappers...and much more

Under active development by the Aerospace Design Lab

http://su2.stanford.edu

SU² Ver. 3.2 will be released during the Aviation 2014 Conference, 10,000+ downloads to date (May 2014)
The fluid domain is typically bounded by a disconnected boundary that is divided into a “far-field” component, and a solid wall boundary.

We further subdivide the fluid domain into two subdomains separated by a ”near-field” boundary.

We are interested in **sensitivities of cost functions** of the kind

\[
J = \int_S \vec{d} \cdot (P \vec{n}_S) \, ds + \int_{\Gamma_{nf}} \, g(x, P) \, ds = \int_S j_S \, ds + \int_{\Gamma_{nf}} j_{nf} \, ds,
\]

where \( P \) is the value of the static pressure, and \( \vec{d} \) is an arbitrary constant vector to be defined later on.

Analysis / sensitivity procedure

Surface sensitivities using adjoint methods

The last step is to subtract the previous equations to obtain the complete variation of the functional

\[
\delta J = \int_S (\vec{d} \cdot \vec{n}_S) \delta P \, ds - \int_S (\vec{n}_S \cdot \vec{\varphi}) \delta P \, ds + \int_{\Gamma_{nf}} \frac{\partial g(x, P)}{\partial P} \delta P \, ds \\
- \int_{\Gamma_{nf}} \Delta \Psi \left( \vec{n}_{nf} \vec{A} \right) \delta U \, ds + \int_S \left( \vec{d} \cdot \vec{\nabla} P + (\partial_n \vec{v} \cdot \vec{n}_S) \vartheta + \nabla_s (\vec{v} \vartheta) \right) \delta S \, ds.
\]

And solving the adjoint equations subject to appropriate boundary conditions

\[
\begin{align*}
\vec{n}_S \cdot \vec{\varphi} &= \vec{d} \cdot \vec{n}_S \\
\vec{\nabla} \Psi \left( \vec{n}_{nf} \cdot \vec{A} \right) &= \frac{\partial g(x, P)}{\partial P} = h(x, P),
\end{align*}
\]

to obtain the sensitivity of the cost function with respect to the motion of each and every point on the surface of the mesh = surface shape sensitivities

\[
\delta J = \int_S \left( \vec{d} \cdot \vec{\nabla} P + (\partial_n \vec{v} \cdot \vec{n}_S) \vartheta + \nabla_s (\vec{v} \vartheta) \right) \delta S \, ds = \int_S \frac{\partial J}{\partial S} \delta S \, ds.
\]
Adj. formulation using equiv. area

Equivalent area adjoint derivation

The equivalent area is the Abel transform of the NF pressure distribution

\[ A_e(x; \theta) = \int_0^x C(P - P_\infty)(x - t)^{1/2} \, dt, \]

We are interested in the L-2 norm of the difference between the area and a target:

\[ J = \sum_{i=0}^{N-1} \omega_i \left[ A_e(x_i) - A_t(x_i) \right]^2 \]

A variation in this cost function can be written as

\[ \delta J = \sum_{i=0}^{N-1} 2\omega_i \left[ A_e(x_i) - A_t(x_i) \right] \delta A_e(x_i) \]

using the short-hand notation \( \delta A_e(x) = \int_0^x C(x - t)^{1/2} \delta P \, dt. \)

The key question is: can we handle this kind of cost function using the methodology described earlier?
Fortunately, the answer is YES. With some algebra...

\[
\delta J = \sum_{i=0}^{N-1} \left[ 2\omega_i \left[ A_e(x_i) - A_t(x_i) \right] \sum_{j=0}^{i-1} \int_{x_j}^{x_{j+1}} C(x_i - x)^{1/2} \delta P \, dx \right],
\]

where \( \Delta A_e(x_i) = 2\omega_i \left[ A_e(x_i) - A_t(x_i) \right] C. \)

And the variation of the objective function can be written as

\[
\delta J = \sum_{j=0}^{N-2} \int_{x_j}^{x_{j+1}} \sum_{i=j+1}^{N-1} \left( \Delta A_e(x_i)(x_i - x)^{1/2} \right) \delta P \, dx.
\]

The adjoint boundary conditions that eliminate the dependence on the fluid flow variation in the inverse equiv. area shape design problem is:

\[
\vec{\nabla} \Psi \left( \vec{n}_{nf} \cdot \vec{A} \right) = h(x, P)
\]

where

\[
h(x, P) = \begin{cases} 
0 & \text{if } -L < x < x_0, \\
\sum_{i=j+1}^{N-1} \Delta A_e(x_i)(x_i - x)^{1/2} & \text{if } x_0 \leq x \leq x_{N-1}, \\
0 & \text{if } x_{N-1} < x < L,
\end{cases}
\]
A_e Design Using Multiple Azimuthal Angles

2 Free-Form Def. boxes:
Fuselage FFD
- Degrees 4x1x1
- 20 control Points
Main wing FFD
- Degrees 3x4x1
- 40 control Points

Geometry: 1043
Cells: 4,819,934. Nodes: 1,192,791
Mach number: 1.7. Angle of attack: 2.1
Free-stream pressure: 15,473.81 Pa
Free-stream temperature: 216.65 K

Multi-objective minimization problem with constraints
(min C_L, min C_My).

\[ OF = \alpha C_D + (1.0 - \alpha) \sum_{\phi=0^\circ}^{\phi=60^\circ} (EA - EA_{baseline})^2 \]

~1.5% max difference between Final Design Equivalent Area and the baseline.

2.1% Objective Function reduction.
3.2% \( C_D \) reduction.
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Direct and Adjoint Simulations with Engines

MACH NUMBER = 1.7
AoA = 2.1
FREESTREAM PRESSURE = 11665.9 Pa
FREESTREAM TEMPERATURE = 216.65 K

Fan face Mach 0.515
Total nozzle temp 569.7 K
Total nozzle pressure 109764.5 Pa

DRAG OBJECTIVE FUNCTION

LIFT OBJECTIVE FUNCTION
Configuration Evolution

Configuration 1021
Phase I tri-jet

Configuration 1040
Refined tri-jet

Configuration 1043
Aft-deck

Configuration 1044
Aft-deck w/ prop effects

Configuration 1044-2
Stanford mod

Configuration 1044-3b
Unanalyzed mod rollup

Configuration 1044-x
Phase II going-fwd

LM3

LM4 and LTWT

Configuration Evolved Significantly During Phase 2 Effort
Recovering 1044-1 Ae
Starting from 1044-3b

It is possible to recover the boom performance after including the structurally-motivated and engine modifications to the baseline aerodynamic shape?

Original 1044-3b configuration with structurally-motivated modifications

Equivalent area computation at different azimuthal angles

Comparison with baseline 1044-1 configuration without structurally-motivated modifications

Optimization to Recover Equivalent Area with CL, CD, and CM constraints.
Comparison of 1044-1 and 1044-3b

• LM 1044-3b was modified to take advantage of better wing-body blending, and improved load paths through aft strut
• Engine nacelle/nozzle design also updated based on work by GE
Optimization Problem Description

Min. \( J(x) \)

\[ x \in \mathbb{R}^N \]

s.t. \( C_L(x) > 0.136 \)

- \( Ma = 1.7, \) AoA = 2.1deg, \( H = 50,000 \) ft
- Recover 1044-1 target equivalent area distribution
- Near-field at 2 body lengths
- Maintain minimum lift
- Free-Form Deformation (FFD) design variables

\[
J = \sum_{k=0}^{M} \sum_{i=0}^{N-1} \omega_{ik} \left[ A_e(x_i, \theta_k) - A_t(x_i, \theta_k) \right]^2
\]

- Multiple azimuth formulation maintains off-track performance
- Azimuth angle ranges: 0° to 60°, 2° increments
1044-3b Design Parameterization

- Total of 74 free-form deformation control points available
- Upper/Lower design variable bounds used to avoid non-physical geometry

- **Tail:** 12 Camber, 12 Thickness
- **Main Wing:** 16 Camber, 16 Thickness
- **Aft Deck:** 8 Camber
- **Fuselage:** 6 Z-Control Points, 4 Y-Control Points

* Mirrored half-body shown
12DV: Tail
24DV: Tail, Aft Deck
74DV: Tail, Aft Deck, Main Wing, Fuselage, scaled
74DV: Tail, Aft Deck, Main Wing, Fuselage, un-scaled

SLSQP Gradient-Based Optimization

Normally objective and constraint data is scaled before given to optimizer

In this study, un-scaled values found larger improvements
Baseline and Optimized Shape
( 74 DV un-scaled )

- Main wing dihedral increased, trailing edge de-cambered
- Tail angle of attack increased near root
- Fuselage volume increased
Optimization History

- 85.5% Reduction in Equivalent Area
- Objective
  - +1.8% CL, +1.1% CD
- Drag may be minimized by a second optimization with Ae and CL constraints or an optimization with multiple constraints

\[
\frac{\partial C_D}{\partial C_L} = 0.048
\]

0.8% of difference due to lift increase
Initial and Final Surface Contours
Mach Number

Baseline

Optimized

Baseline

Optimized

26
Equivalent Area Distribution Comparison

Nearfield Equivalent Area Distributions
Selected Azimuth Angles

- Target 1044-1
- Baseline 1044-3b
- Optimized 1044-3b

Psi=0deg
Psi=20deg
Psi=40deg
Psi=60deg
Comparison of Ground Boom signatures
LM 1044-1, -3b and -3b OPTIMIZED configurations

Sonic Boom @ ground
Flight conditions: Lift=268,900 lb; Alt=48,200 ft

Phi = 0 deg
Phi = 30 deg
Phi = 50 deg
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Conclusions

• A number of recent “firsts”
  – Full configuration (75 pax) with a shaped boom signature (front and back; all azimuthal angles)
  – Realizable vehicle (design continues as we speak) to be used as a low-boom flight demonstrator

• Designs enabled by:
  – Advanced CFD and adjoints
  – Better understanding of the design space variations
  – A completely integrated unstructured capability, SU²

• Next steps:
  – Finalize design of LBFD
  – Construct approaches to reduce the size of the design problem
“A low-dimensional subspace of the inputs that captures global trends of the objective”

- Works by finding eigenvectors of objective gradients
- Comparable to Principal Components Analysis
  - PCA: reduce output space dimension
  - Active Subspace: reduce input space dimension

N+2 Active Subspaces for Lift

Lift Active Variable 1.
N+2 Active Subspaces for Drag
N+2 Active Subspaces for Equiv Area
Thanks a lot for your attention!
Questions & Answers

More details in http://su2.stanford.edu/