Aerodynamic Shape Optimization of a Dual-Stream Supersonic Plug Nozzle

Christopher M. Heath & Justin S. Gray
NASA GRC – Propulsion Systems Analysis Branch

Michael A. Park, Jan-Renee Carlson, & Eric J. Nielsen
NASA LARC – Computational AeroSciences Branch
Research Motivation

Overland sonic boom requirements challenge supersonic aircraft viability

Current State-of-the-Art:
Aerodynamic shape optimization demonstrated with airframe tailoring to meet low-boom perceived loudness goals

Drawbacks:
Recent experimental and computational research has shown introducing propulsion effects into an optimized airframe pressure signature can compromise the low-boom requirement

Research Objectives

Mitigate plume-induced near field pressure disturbances without compromising nozzle performance

Current Approach:
Aerodynamic tailoring of the powered propulsive streamtube to minimize all nearfield pressure contributions and simplify propulsion-airframe integration

Minimize:

\[ f = \sum_{i=1}^{N} \left( \frac{p_i}{p_{\infty}} - \frac{p_i^*}{p_{\infty}} \right)^2 \]

- Local pressure ratio
- Target pressure ratio = 1

Baseline vs. Optimized Nearfield Pressure Signatures

<table>
<thead>
<tr>
<th>Axial Position (m)</th>
<th>Uniform pressure target</th>
<th>Isolated Dual Stream Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
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<td>0.5</td>
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Minimize pressure disturbance

Uniform pressure target
Problem Definition

Optimized @ Design Pt. 45,000-ft std. day
- Mach # = 1.6
- NPR_{Core} = 6.19
- NPR_{Bypass} = 3.24
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| Nozzle Surface Deformation | Flexible discrete surface geometry parameterization capability | Axisymmetric free-form deformation based on cubic B-spline interpolants |
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**Baseline Nozzle**
- Cowl
- Centerbody
- Shroud

**Nozzle Surface Deformation**

**Mesh Morphing**
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<td>Minimize nozzle-induced nearfield pressure disturbances</td>
<td>Gradient-based aerodynamic shape optimization (SNOPT)</td>
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**Baseline Nozzle**

**Baseline vs. Optimized Nearfield Pressure Signatures**

![Baseline Nozzle Diagram](image)

![Nozzle Surface Deformation](image)

![Mesh Morphing](image)

![Signature Reduction](image)
Cowl & Shroud Parameterization

- Annular bodies of revolution
- Characterized by inner and outer surfaces
- Centerline spline (radial & axial DOF)
- Thickness spline (thickness DOF)

Core and bypass entrance flow areas held constant for engine integration
Centerbody Parameterization

- Closed solid bodies of revolution
- Thickness spline (thickness and axial DOF)

Geometric variable bounds used to constrain core and bypass sections upstream of throats. Constant mass flow rate and thrust.
B-spline interpolants enabled the computation of native analytic derivatives. Continuous sensitivities mapped to the discrete grid coordinates and provided to Fun3D.

Derivatives transformed to Cartesian coordinates and provided with respect to control point axial, radial, and thickness degrees of freedom.

Derivatives verified using finite difference and complex step.
**Baseline Grid:**
- ~3.5 million nodes
- Fully unstructured 2-D and 3-D T-rex viscous grid transitioning to isotropic tets in farfield \( (y^+<1) \)

**Adjoint-Adapted Grid:**
- Adapted to minimize discretization error of pressure integral extracted one nozzle diameter from centerline
- 8 flow/adjoint adaptation cycles
- ~11.5 million nodes
- Constraints used to control maximum anisotropy and grid size during adaptation
- Consumed ~36-hrs on 600 cores
Volume Mesh Morphing

Surface deformations transferred to the volume using a linear elastic approach

- Young’s Modulus inversely proportional to distance from nearest wall boundary.
- Poisson’s ratio set uniformly to 0.
- Relatively robust for surface-normal deformations on isotropic grids.
- Less effective for high shear deformations on adapted anisotropic grids.
- Frequent interruption of design optimization process with formation of negative volume cells during deformation step.
- Grid quality deterioration over subsequent deformation steps.

Large arbitrary deformation compromises grid resolution of critical flow features and require re-adaptation.
Adjoint-Based Design Optimization

Minimize:

\[ f = \sum_{i=1}^{N} \left( \frac{p|_i}{p_\infty|_i} - \frac{p^*_i}{p_\infty|_i} \right)^2 \]

- Local pressure ratio
- Target pressure ratio

Pressure sensor location

Baseline

Optimized

- Accelerated bypass flow
- Diffused lip shock
- Diffused expansion features
- Reduced wake

Baseline Profile

Optimized Profile

Increased boattail angle

Shortened cowl

Subtle recontouring

Surface flattening

Extended Plug

Flow/Adjoint Cycles

~48-hrs on 600 cores

~12% Reduction

Mach No.

- 2.0
- 1.9
- 1.8
- 1.7
- 1.6
- 1.5
- 1.4
- 1.3
- 1.2
- 1.1
- 1.0

Objectives Function

Nozzle Optimization History

18 Flow/Adjoint Cycles

~48-hrs on 600 cores

~12% Reduction
Adjoint-Based Design Optimization

Baseline vs. Optimized Nearfield Pressure Signatures

- **Baseline** vs. **Optimized**
  - **Baseline**
  - **Optimized**

- **Pressure target**
- **Reduced over-pressure compression**
- **Reduced under-pressure expansion**
- **Introduced subtle expansion features**

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<th>Component</th>
<th>Thrust (N) Baseline</th>
<th>ΔThrust (N) Optimized</th>
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<tr>
<td>Bypass Inflow</td>
<td>26478</td>
<td>+5</td>
</tr>
<tr>
<td>Core Inflow</td>
<td>96228</td>
<td>-10</td>
</tr>
<tr>
<td>Inner Cowl</td>
<td>-1347</td>
<td>-10</td>
</tr>
<tr>
<td>Outer Cowl</td>
<td>-1525</td>
<td>-27</td>
</tr>
<tr>
<td>Inner Shroud</td>
<td>1505</td>
<td>+31</td>
</tr>
<tr>
<td>Outer Shroud</td>
<td>-1158</td>
<td>-32</td>
</tr>
<tr>
<td>Centerbody</td>
<td>-32121</td>
<td>+207</td>
</tr>
<tr>
<td>Total</td>
<td>88059</td>
<td>+175</td>
</tr>
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~0.2% Thrust Increase

- Pressure target
- Reduced over-pressure compression
- Reduced under-pressure expansion
- Introduced subtle expansion features
Conclusions

Aerodynamic shape optimization demonstrated for dual-stream supersonic plug nozzle to minimize nearfield pressure waveforms
Intent is to optimize propulsive streamtube & reduce plume effects on overall aircraft pressure signature

Could be used in conjunction with airframe shape optimization
Conclusions

New axisymmetric geometry parameterization developed using 3rd order B-splines and integrated with FUN3D design optimization framework
Conclusions

Achieved notable reductions in over- and under-pressure disturbances measured one diameter from nozzle centerline.
Conclusions

No compromise to nozzle performance requirement on thrust during optimization
Future Work

- New adjoint thrust derivatives, allowing mass flow rates and thrust to be constrained at optimizer level
- Open geometric bounds on control points to enable greater geometric flexibility upstream of core & bypass throats (trade pressure & viscous forces)
- Consider propagated effects to ground observer
- Investigate alternate volume grid deformation approaches to minimize production of negative volume cells
- Consider B-spline surface-based parameterization for extension to non-axisymmetric engine components
- Opportunity for aggregate objective function including plug volume as a surrogate for nozzle weight
- Preliminary studies indicate ~30% reduction in nozzle pressure disturbance possible with ~4% thrust gain by varying BPR (engine cycle/nozzle coupling)
Acknowledgements

NASA High Speed Project

Jonathan Seidel, Raymond Castner and Nicholas Georgiadis