Aerodynamic Shape Optimization of a Dual-Stream Supersonic Plug Nozzle

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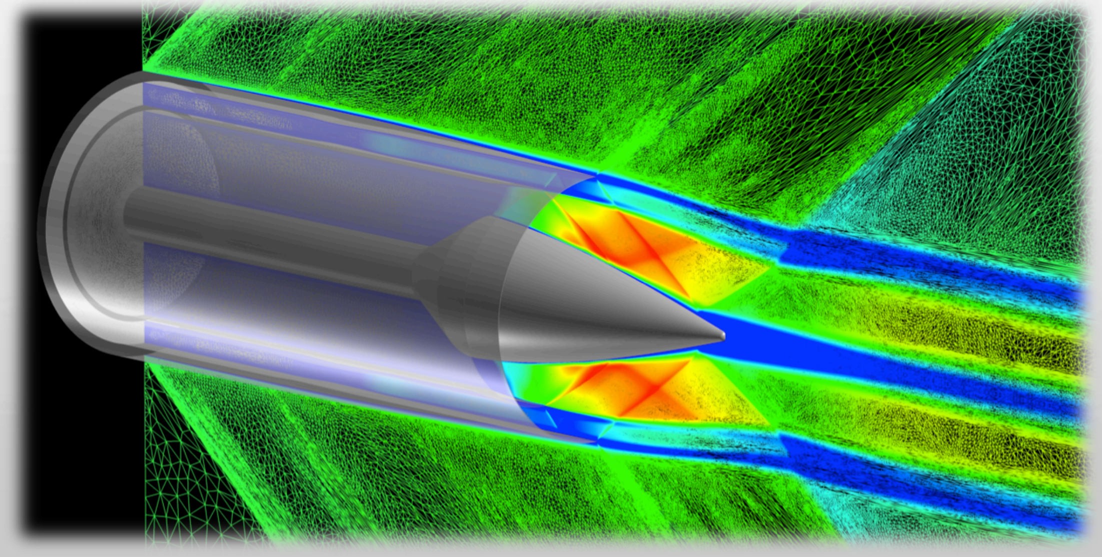

AIAAA SciTech Conference
Kissimmee, FL
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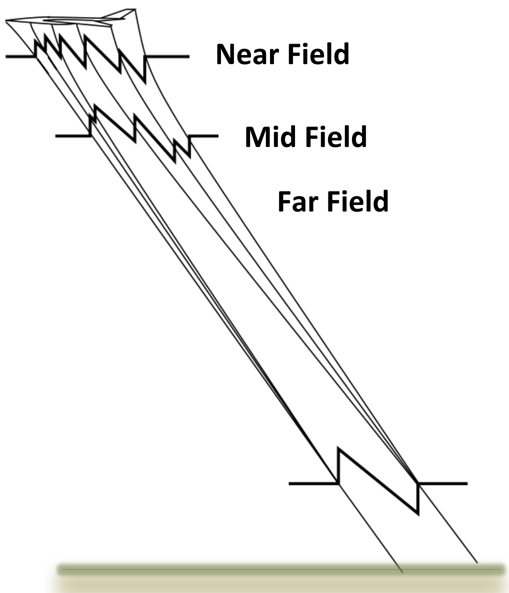
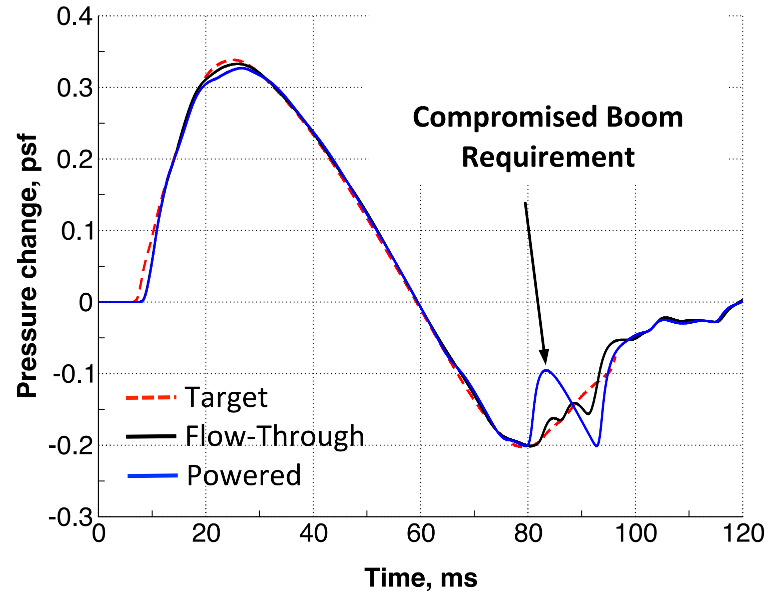
Research Motivation

<u>Overland sonic boom requirements</u> challenge supersonic aircraft viability



Propagated Ground Signature*



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 <u>propulsion effects</u> into an optimized airframe pressure signature can <u>compromise the low-boom requirement</u>

*Wintzer, M. et. al., "Aircraft-Nozzle-Plume Interactions in the Context of Low Sonic Boom Design," AIAA SciTech 2015.

Research Objectives

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

Current Approach:

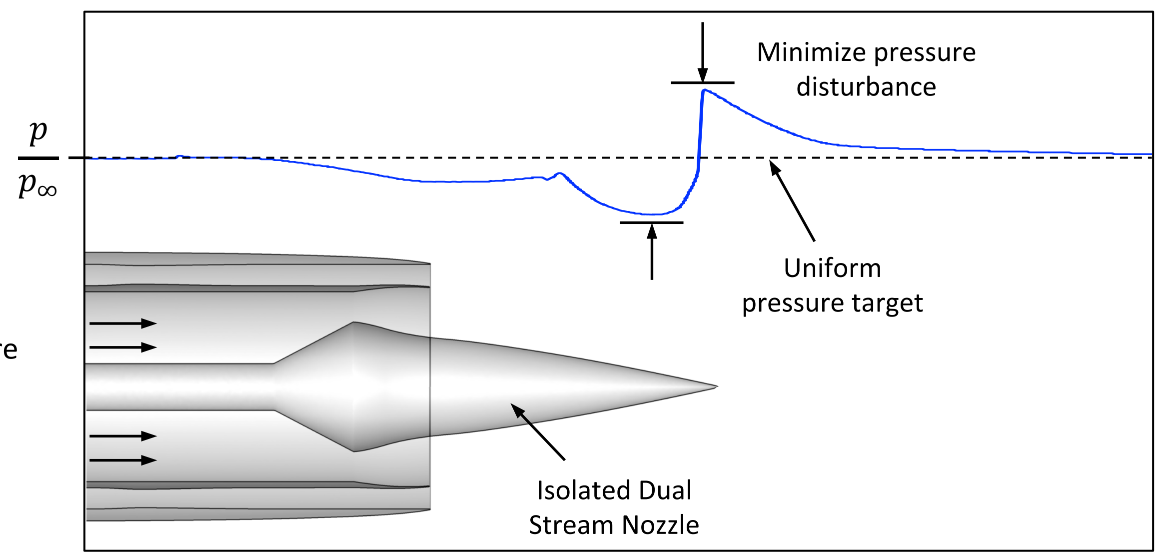
Aerodynamic tailoring of the powered propulsive streamtube to minimize all nearfield pressure contributions and simplify propulsion-airframe integration

Minimize:

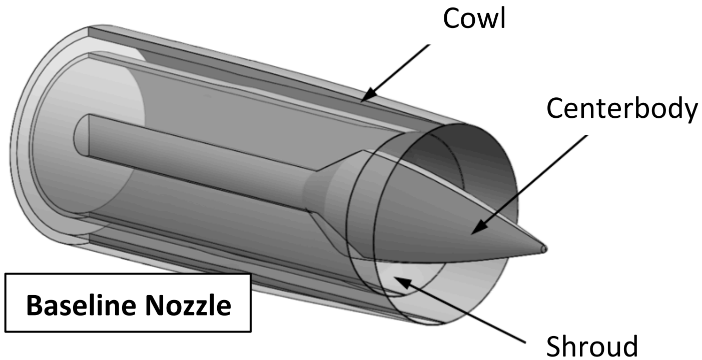
$$f = \sum_{i=1}^{N} \left(\left.\frac{p}{p_\infty}\right|_i - \left.\frac{p}{p_\infty}\right|_i^* \right)^2$$

Local pressure ratio

Target pressure ratio = 1

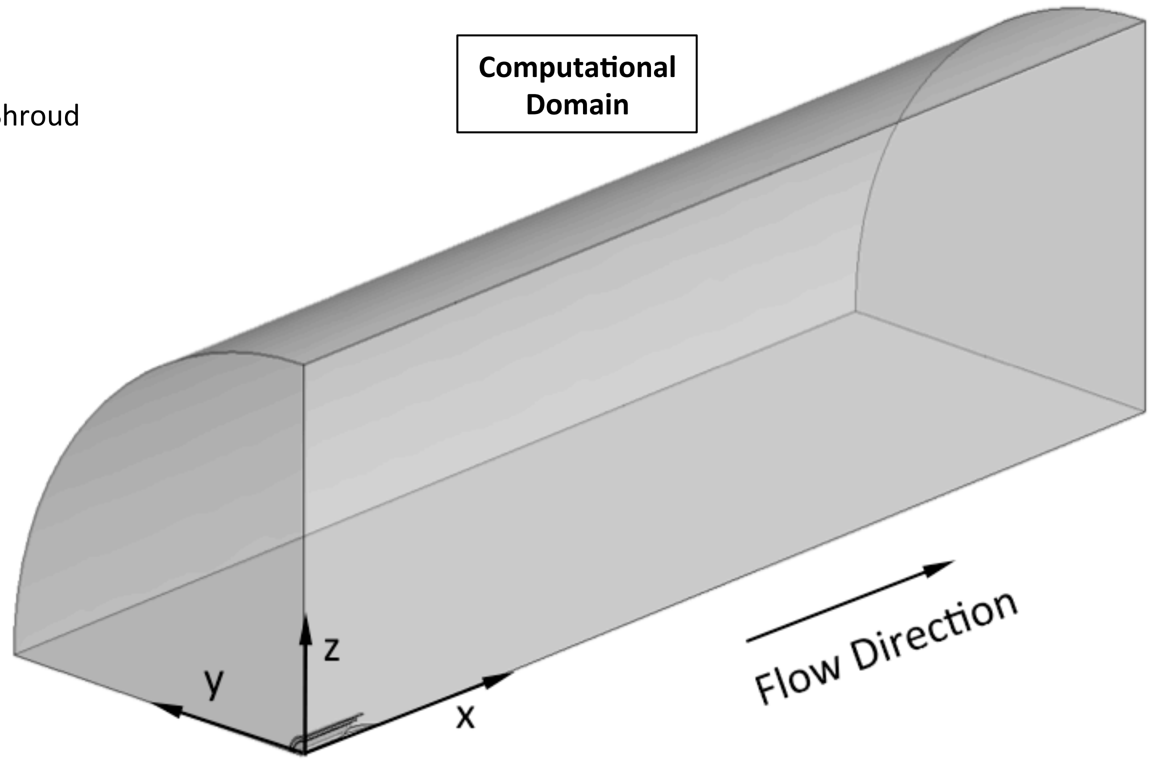


Problem Definition

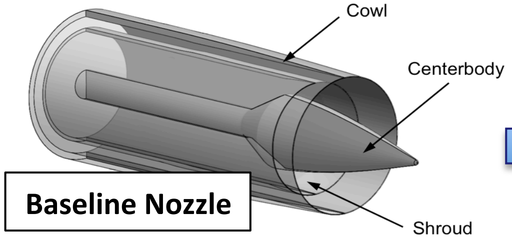


Optimized @ Design Pt.
45,000-ft std. day

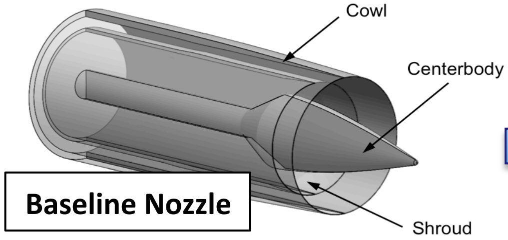
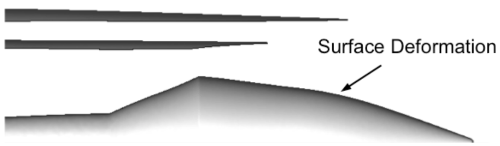
- Mach # = 1.6
- $NPR_{Core} = 6.19$
- $NPR_{Bypass} = 3.24$



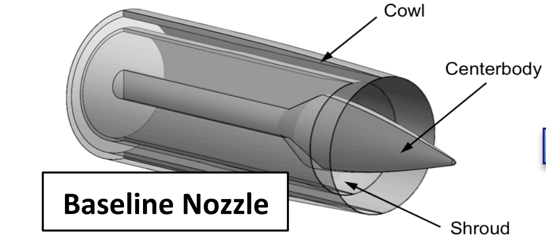
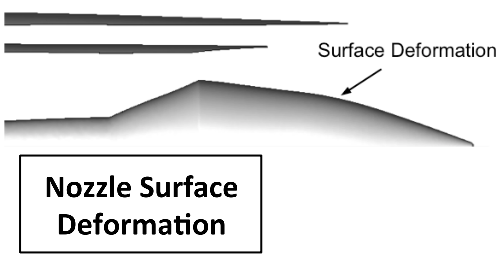
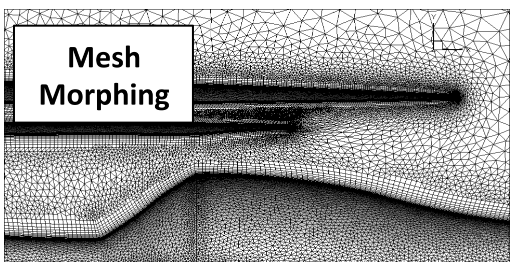
Solution Summary

	Need	Solution
	Accurate thrust and nearfield pressure signature prediction	Adjoint-adapted viscous RANS CFD (FUN3D)

Solution Summary

	Need	Solution
 **Baseline Nozzle**	Accurate thrust and nearfield pressure signature prediction	Adjoint-adapted viscous RANS CFD (FUN3D)
 **Nozzle Surface Deformation**	Flexible discrete surface geometry parameterization capability	Axisymmetric free-form deformation based on cubic B-spline interpolants

Solution Summary

	Need	**Solution**
	Accurate thrust and nearfield pressure signature prediction	Adjoint-adapted viscous RANS CFD (FUN3D)
	Flexible discrete surface geometry parameterization capability	Axisymmetric free-form deformation based on cubic B-spline interpolants
	Volume grid deformation capability	Solve analogous linear elasticity problem (FUN3D)

Solution Summary

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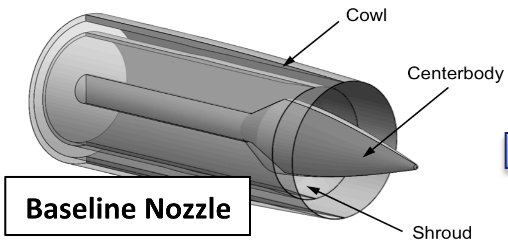
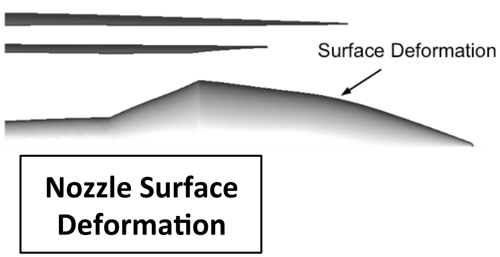
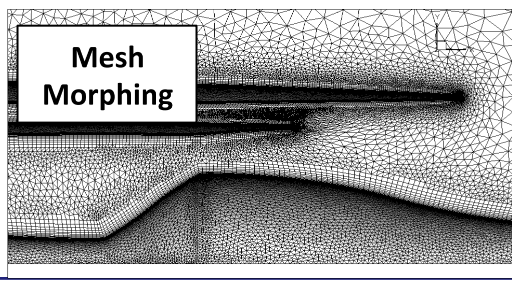
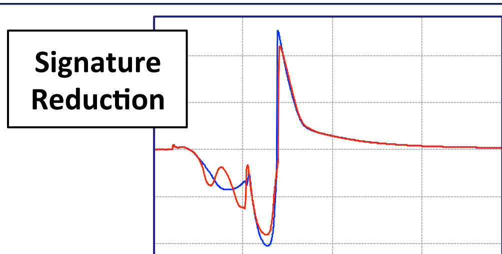
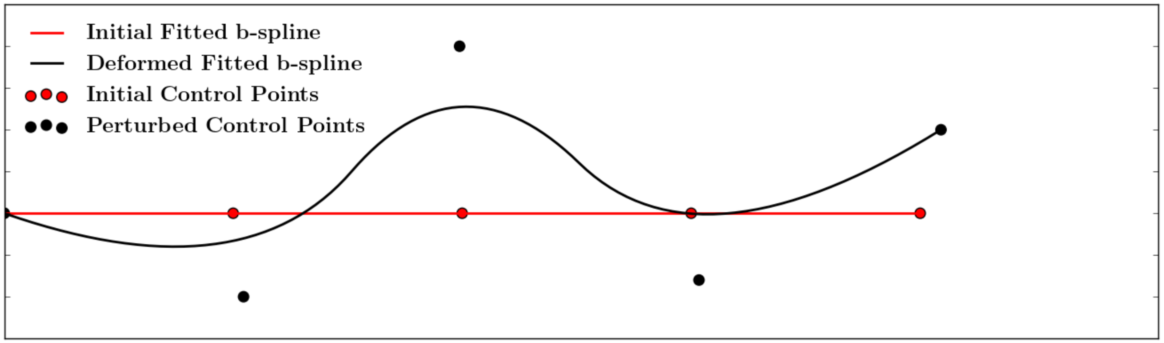
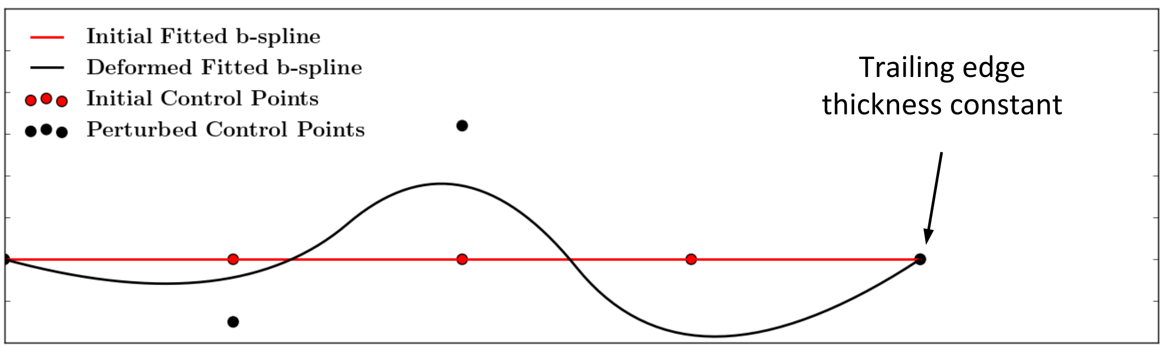
	Accurate thrust and nearfield pressure signature prediction	Adjoint-adapted viscous RANS CFD (FUN3D)
	Flexible discrete surface geometry parameterization capability	Axisymmetric free-form deformation based on cubic B-spline interpolants
	Volume grid deformation capability	Solve analogous linear elasticity problem (FUN3D)
	Minimize nozzle-induced nearfield pressure disturbances	Gradient-based aerodynamic shape optimization (SNOPT)

Cowl & Shroud Parameterization

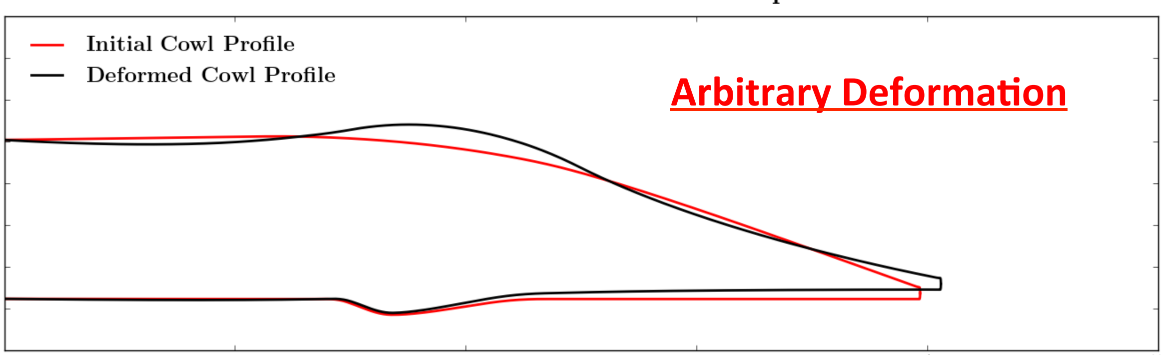
Cowl Centerline Control B-Spline



Cowl Thickness Control B-Spline



Initial and Deformed Cowl Shape

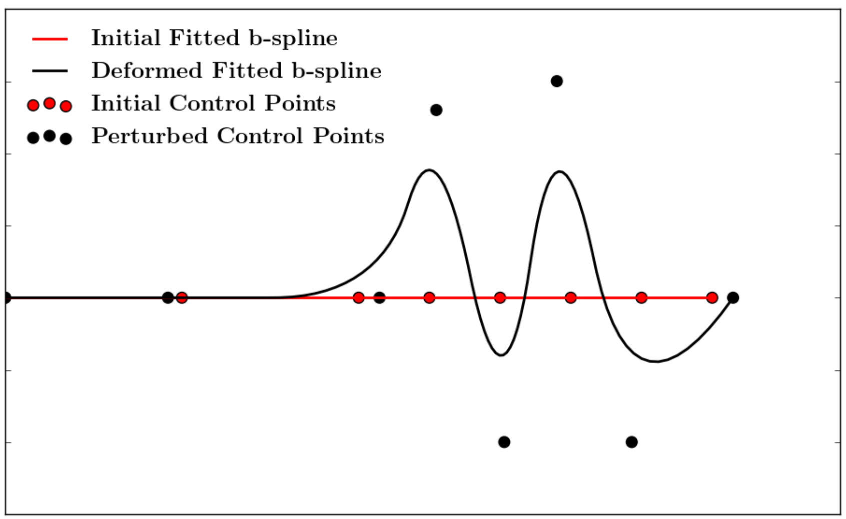


- Annular bodies of revolution
- Characterized by inner and outer surfaces
- Centerline spline (radial & axial DOF)
- Thickness spline (thickness DOF)

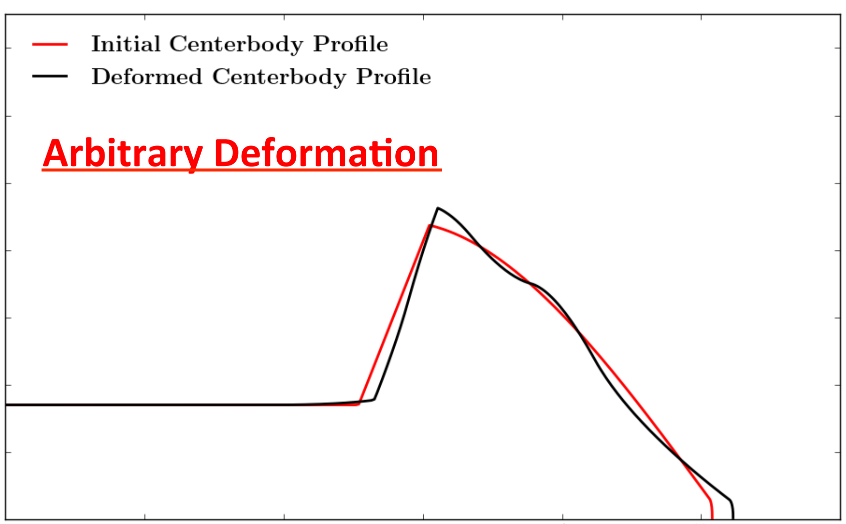
Core and bypass entrance flow areas held constant for engine integration

Centerbody Parameterization

Centerbody Control B-Spline

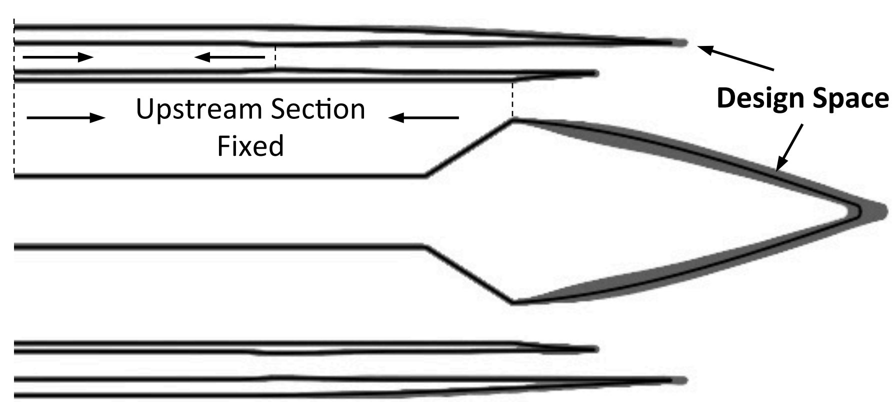


Initial and Deformed Centerbody Shape

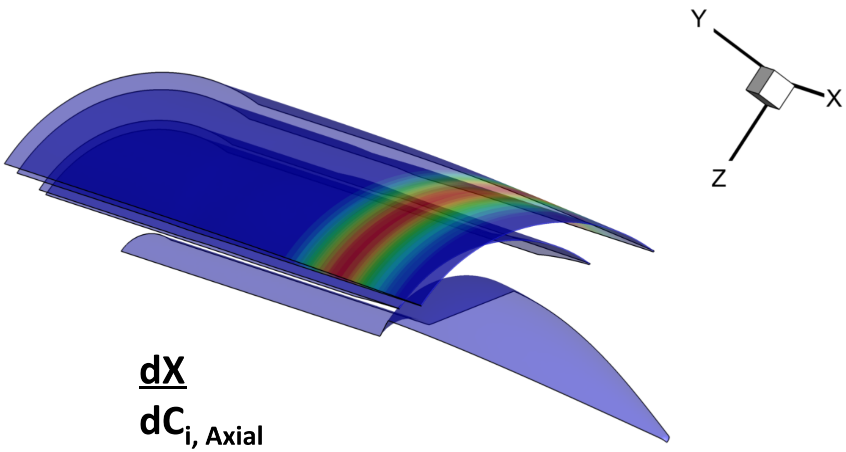


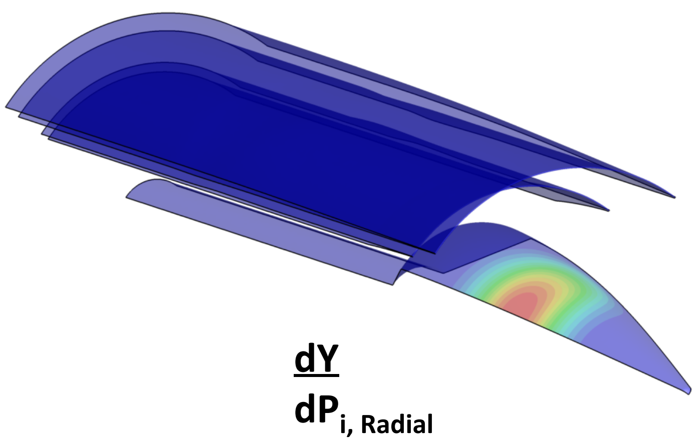
- Closed solid bodies of revolution
- Thickness spline (thickness and axial DOF)

Geometric variable bounds used to constrain core and bypass sections upstream of throats. Constant mass flow rate and thrust.



Direct Geometric and Surface Grid Sensitivities



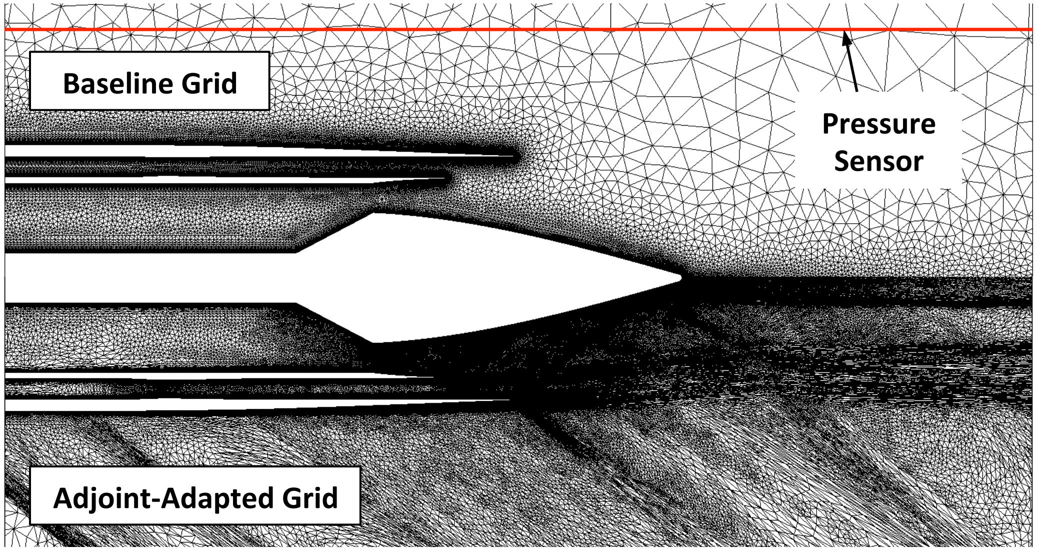


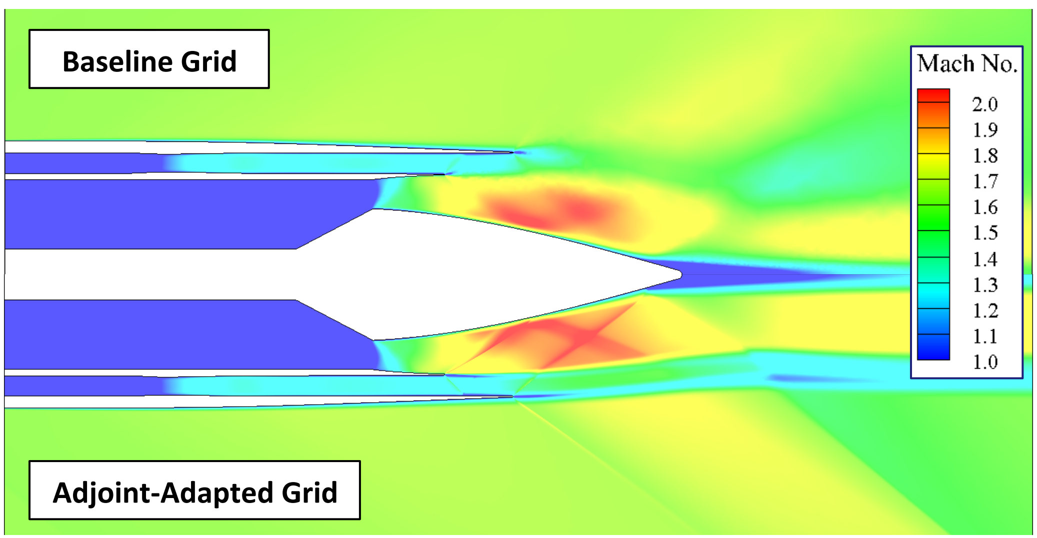
B-spline interpolants enabled the computation of native analytic derivatives. Continuous sensitivities mapped to the discrete grid coordinates and provided to Fun3D.

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

Adjoint-Based Grid Refinement





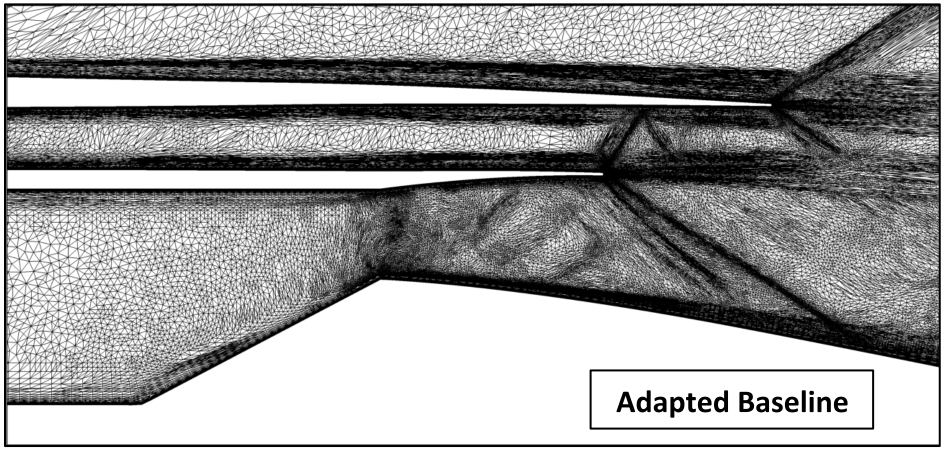
Baseline Grid:

- ~3.5 million nodes
- Fully unstructured 2-D and 3-D T-rex viscous grid transitioning to isotropic tets in farfield ($y^+<1$)

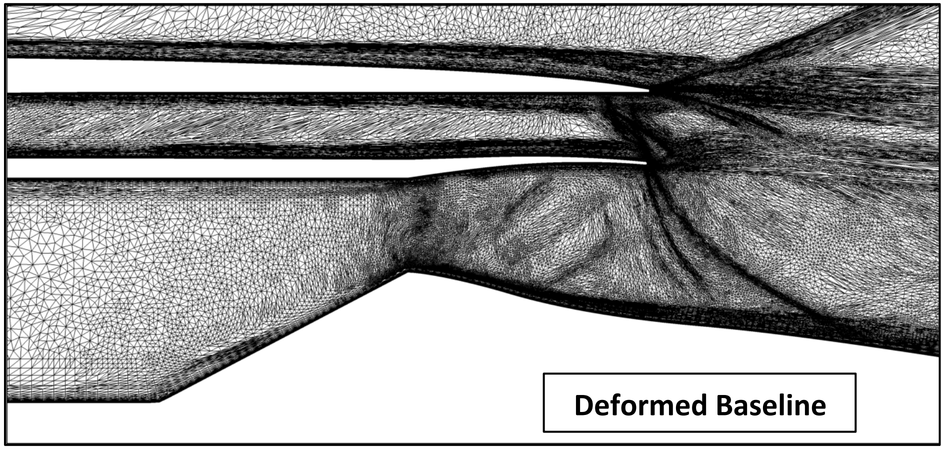
Adjoint-Adapted Grid:

- 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



Large Arbitrary Deformation



Large deformations compromise grid resolution of critical flow features and require re-adaptation

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.

Adjoint-Based Design Optimization

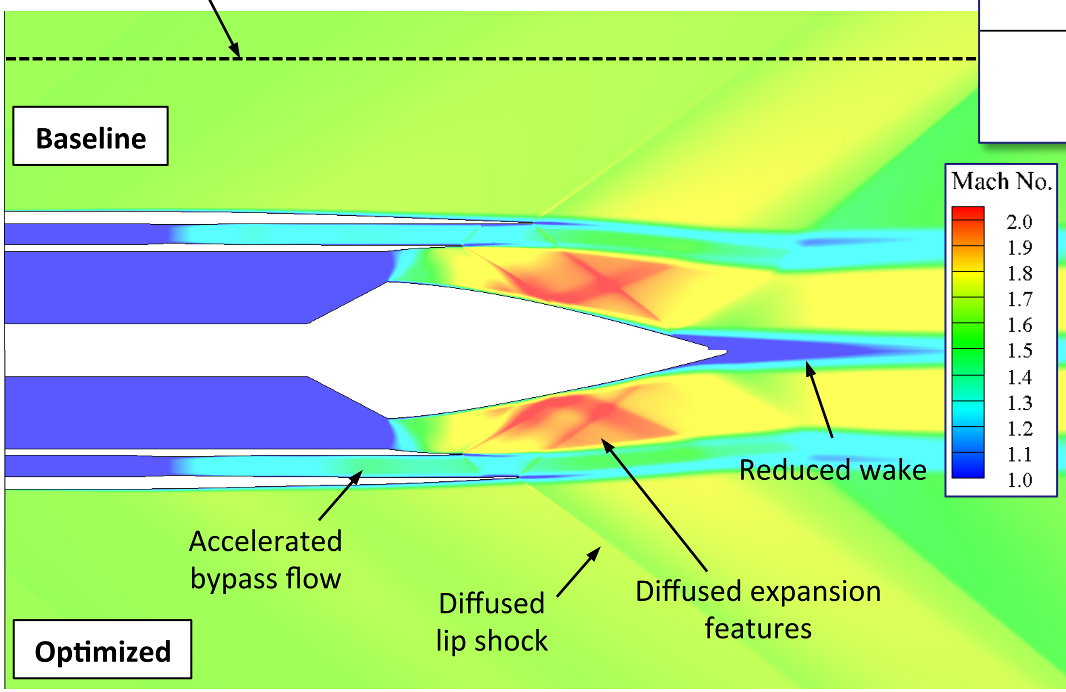
Minimize:

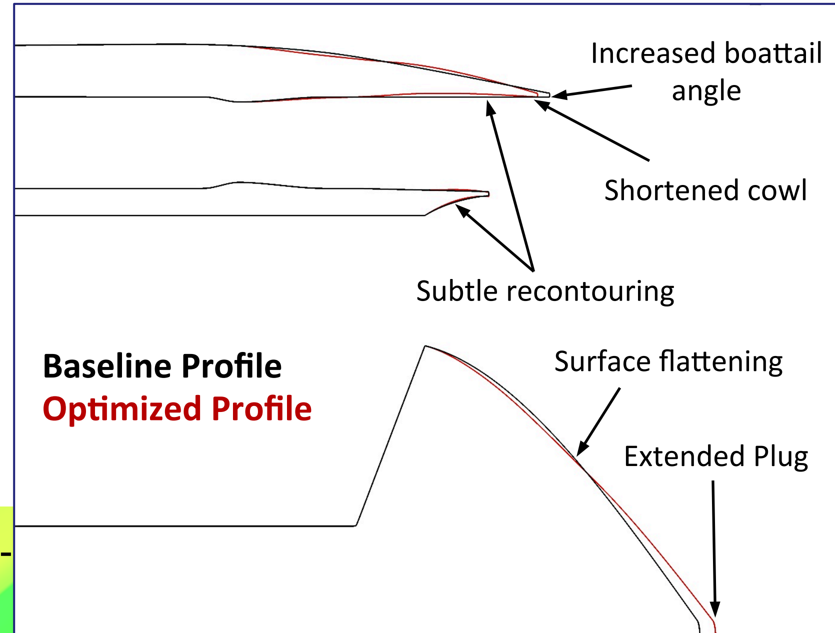
$$f = \sum_{i=1}^{N} \left(\frac{p}{p_\infty}\bigg|_i - \frac{p}{p_\infty}\bigg|_i^* \right)^2$$

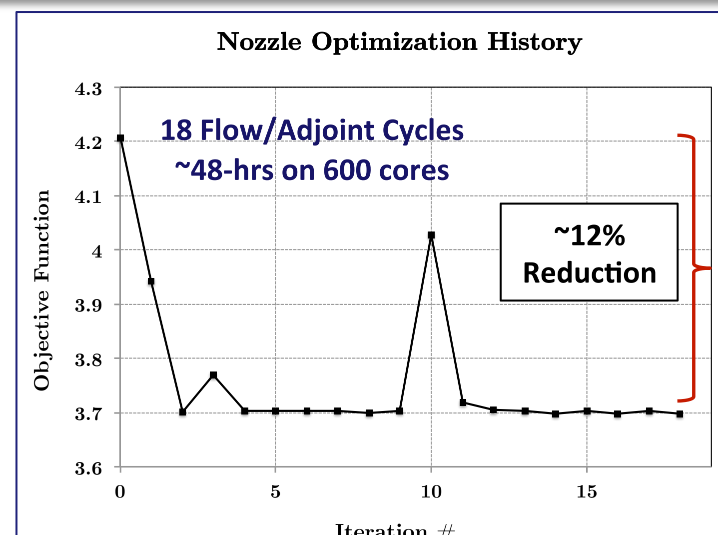
Local pressure ratio

Target pressure ratio

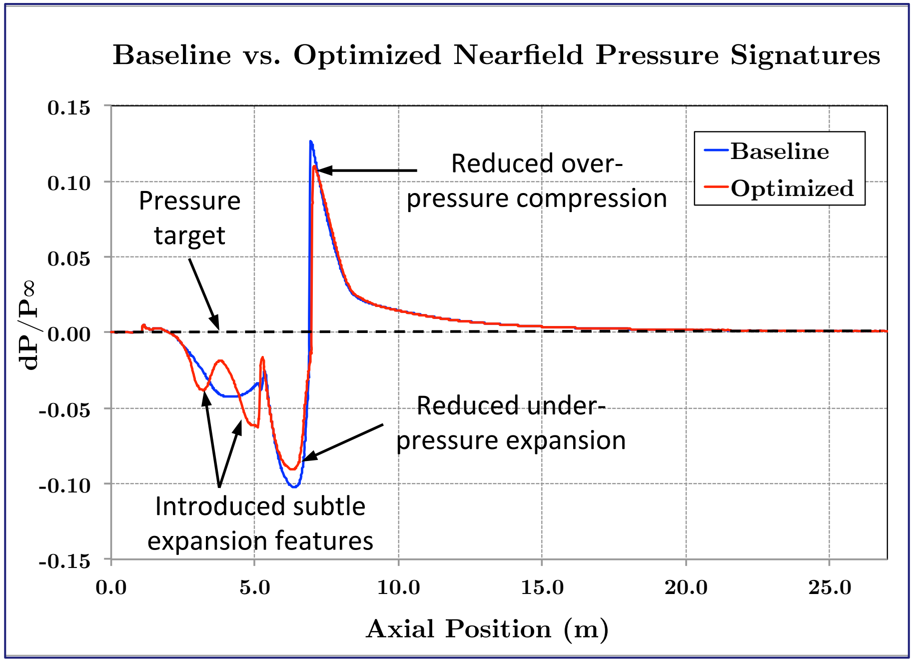
Pressure sensor location





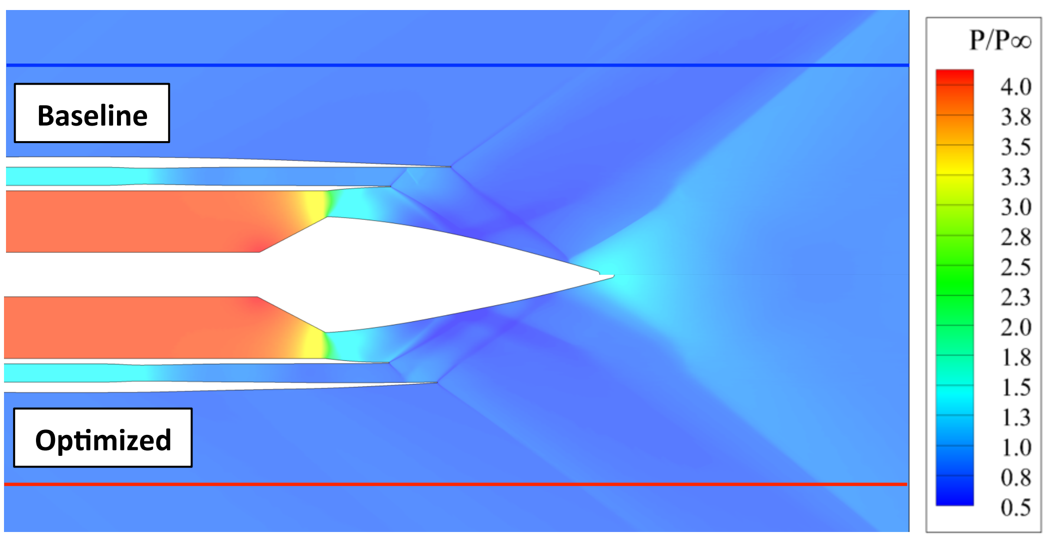


Adjoint-Based Design Optimization



Component	Thrust (N) Baseline	ΔThrust (N) Optimized
Bypass Inflow	26478	+5
Core Inflow	96228	-10
Inner Cowl	-1347	-10
Outer Cowl	-1525	-27
Inner Shroud	1505	+31
Outer Shroud	-1158	-32
Centerbody	-32121	+207
Total	88059	+175

~0.2% Thrust Increase



Conclusions

Aerodynamic shape optimization demonstrated for dual-stream supersonic plug nozzle to minimize nearfield pressure waveforms

Conclusions

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

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Jonathan Seidel, Raymond Castner and Nicholas Georgiadis

NASA