

High-Fidelity Aeropropulsive Assesssment of Distributed Electric Propulsion and Boundary Layer Ingestion for the SUSAN Electrofan

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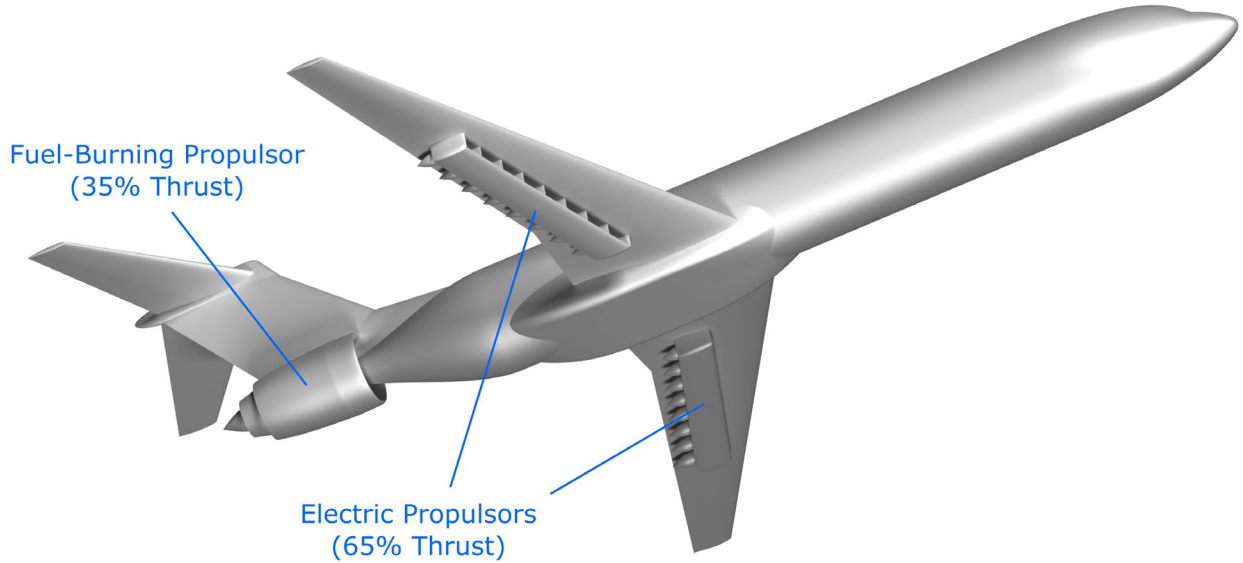
Special Session: Updates to the NASA SUSAN Electrofan Trade Study I

AIAA SciTech Forum and Exposition

January 8, 2025, Orlando, FL

The SUbsonic Single Aft eNgine (SUSAN) Electrofan

- SUSAN Electrofan is a hybrid-electric transport aircraft incorporating advanced **electrified aircraft propulsion (EAP)** and **propulsion-airframe integration (PAI)** technologies to significantly reduce aviation energy usage and emissions, targeting the 2035–2040 timeframe
  - Retains size, speed, and range of a large regional jet
  - Remains compatible with existing airport infrastructure and operations
- Previously demonstrated that a **closed aircraft concept** can be achieved with a **net aircraft level benefit**
  - Higher aircraft weight from EAP systems (power, thermal, and battery systems)
  - Improved TSFC from propulsive and thermal efficiency
  - Based on low-fidelity aircraft sizing and mission analysis



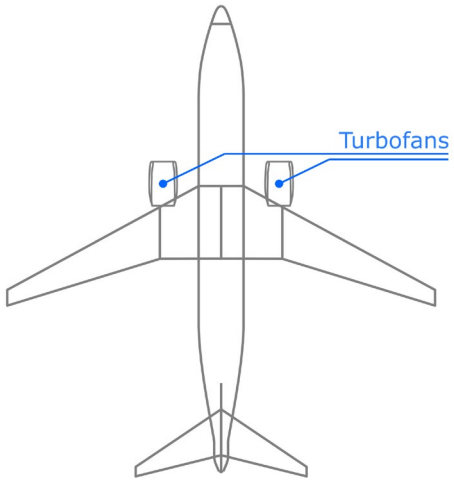
Can we improve our understanding of the aeropropulsive benefits of the SUSAN Electrofan's **DEP and BLI turbofan systems** and how they impact aircraft system performance through the application of computational tools for high-fidelity design and analysis?

*Chau and Duensing, AIAA 2024-1326.

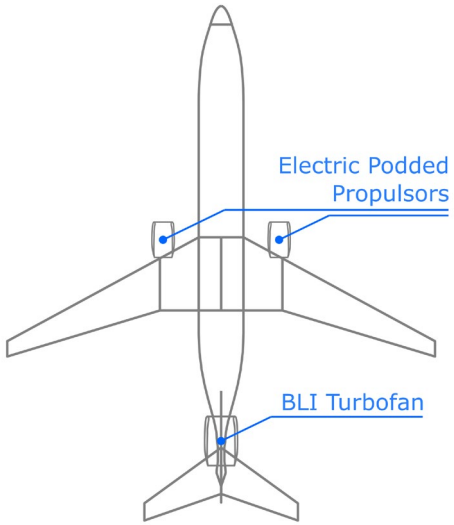
Technology Assessment Method

Assessments are based on cruise performance of **representative aircraft models** developed through the application of **aerodynamic and aeropropulsive shape optimization** based on the Reynolds-averaged Navier-Stokes (RANS) equations.

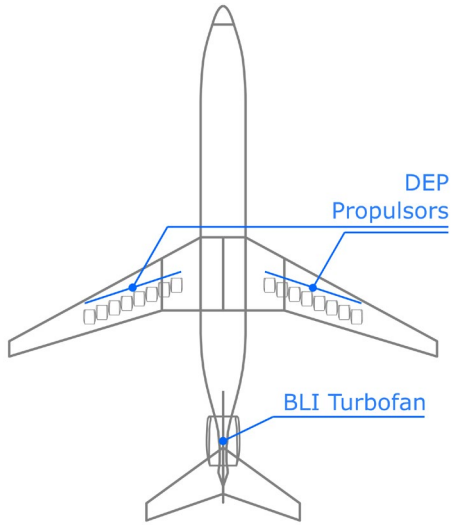
- **Drag:** Aerodynamic performance at cruise, which accounts for differences in airframe and propulsion system aerodynamic performance
- **Shaft Power:** Mechanical power required to maintain steady, level flight based on required propulsive power, adiabatic fan efficiency, and electrical transmission efficiency
- **Range Parameter:** Product of aerodynamic (M*L/D) and propulsion system (1/TSFC) efficiency at cruise



B737-8



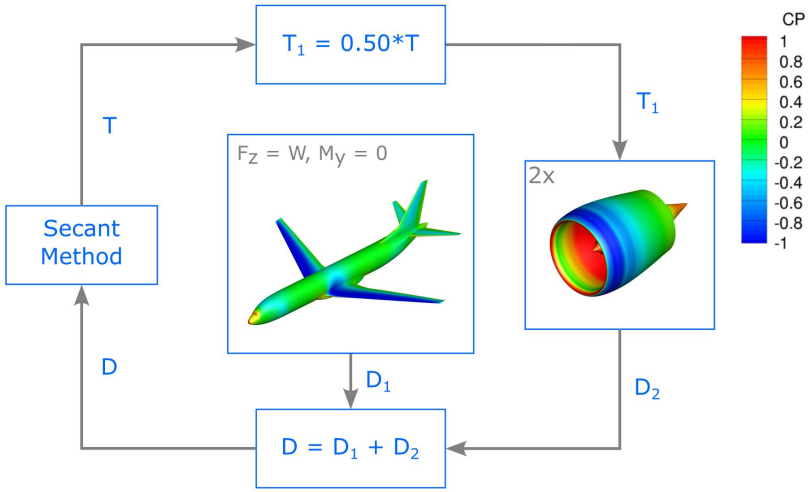
SUSAN-Pod



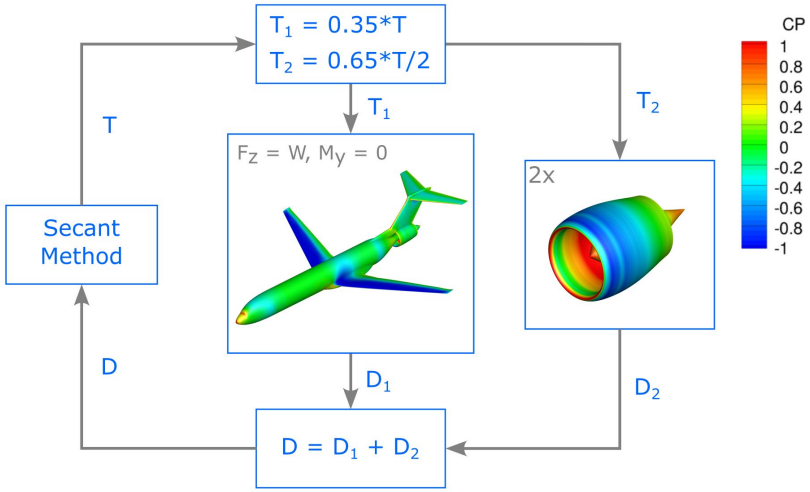
SUSAN-DEP

Power Balance Method

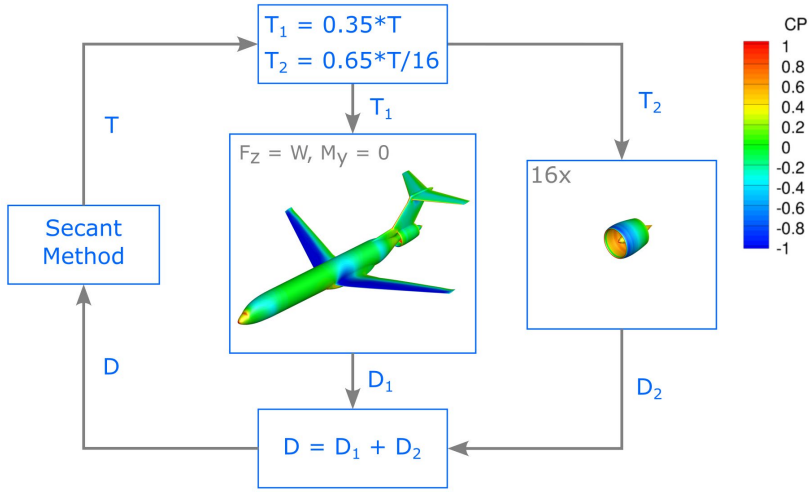
- **Decoupled airframe and wing propulsor** CFD simulations
  - Airframes include BLI turbofan from Machado et al. 2022 (where applicable) – **captures BLI benefit of aft fuselage turbofan**
  - Wing propulsors modeled as simple podded propulsors – **captures ultra-high effective bypass ratio benefits of DEP**
- Performance evaluations are based on CFD analysis of optimized designs at cruise
  - Trim/power balance achieved through iterative methods
  - DOFs: i.) angle of attack, ii.) horizontal tail incidence angle, and iii.) thrust inputs
  - **Accounts for differences in airframe/propulsor aerodynamic performance**, including “snowball effects”



B737-8



SUSAN-Pod



SUSAN-DEP

Aerodynamic/Aeropropulsive Shape Optimization Frameworks

Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework – NASA	MACH-Aero Framework[4] – UM MDO Lab
Purpose: Aerodynamic shape optimization	**Purpose:** Aeropropulsive shape optimization
Flow solver: LAVA Curvilinear with structured overset meshes • Reynolds-averaged Navier-Stokes (RANS) equations with Spalart-Allmaras turbulence model (SA-RC-QCR2000) • 2nd-order finite-difference method • Parallel implicit approximate Newton-Krylov method • Actuator zone method for modeling propulsor thrust	**Flow solver:** ADFlow with structured multiblock meshes • RANS equations with SA-QCR2000 • 2nd-order finite-difference method • Parallel implicit approximate Newton-Krylov method • Actuator zone method for modeling propulsor thrust
Geometry control: Free-form deformation (FFD) method • Implemented via pyGeo[1]	**Geometry control:** OpenVSP[5]
Mesh deformation: Inverse distance weighted method[2]	**Mesh deformation:** IDWarp[2]
Optimization: SNOPT[3] • Gradient-based optimization • Discrete-adjoint method for flow-based gradient evaluation	**Optimization:** SNOPT[3] • Gradient-based optimization • Discrete-adjoint method for flow-based gradient evaluation

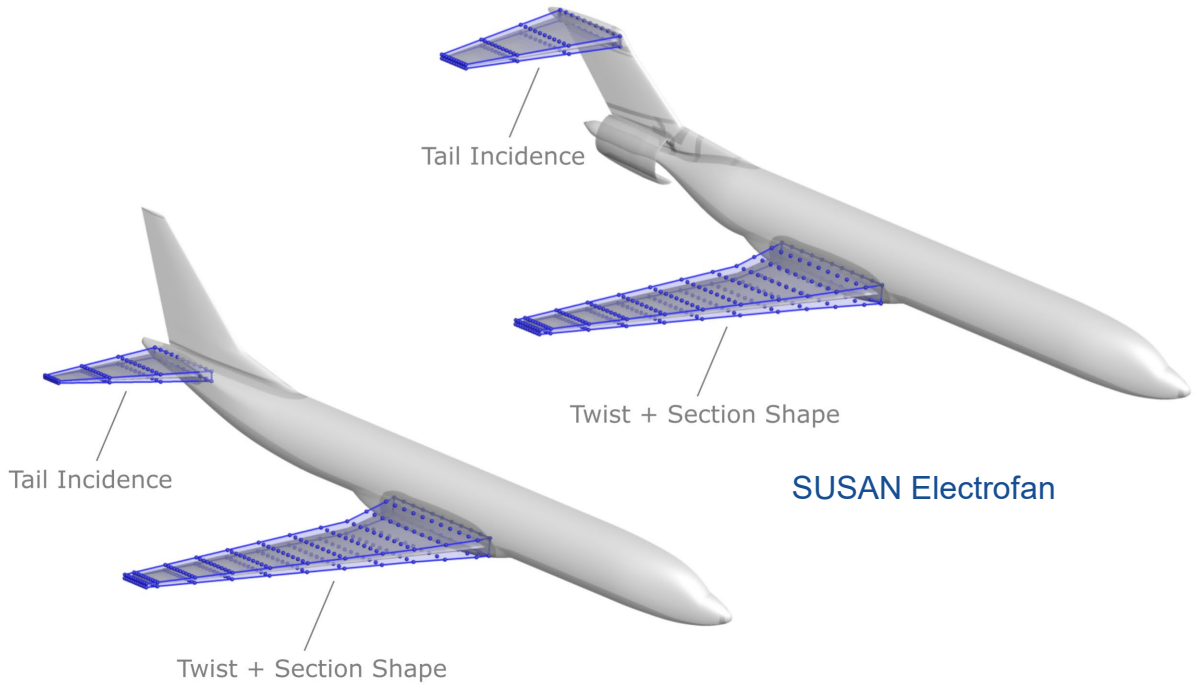
The LAVA Framework is used to develop representative airframe models. The MACH-Aero Framework is used to develop representative wing propulsor models. Post-optimization grid-convergence studies are performed with the LAVA curvilinear flow solver for all geometries.

[1]pyGeo: github.com/mdolab/pygeo. [2]Secco et al., AIAA Journal 2021. [3]Gill et al., SIAM Review 2005. [4]MACH-Aero: github.com/mdolab/MACH-Aero. [5]OpenVSP: openvsp.org

Representative Airframe Design Optimizations

Objective (1)	Minimize C_D (1)
Design Variables* (281)	Angle of attack (1)
	Twist (12)
	Section shape (268)
Nonlin. Constraints (15)	Constant lift (1)
	Zero pitching moment (1)
	Minimum wing volume (1)
	Minimum $(t/c)_{max}$ (12)

Geometric design variables are defined through the free-form deformation (FFD) volume method



SUSAN Electrofan

B737-8

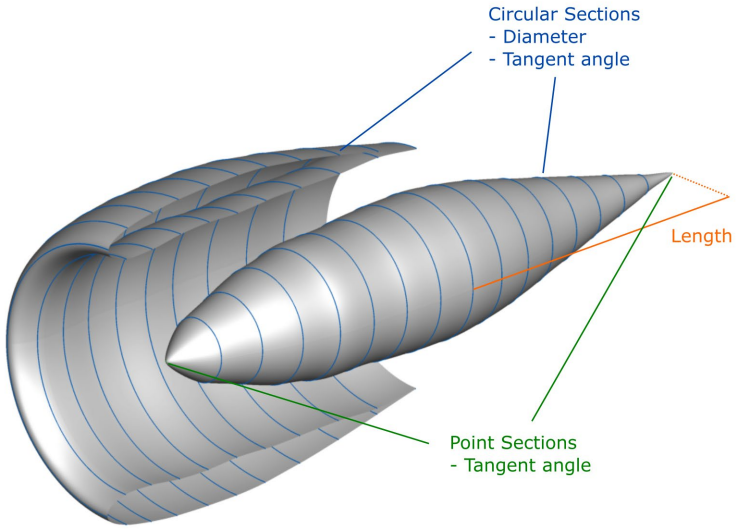
Airframe designs optimized for minimum cruise drag at constant lift and zero pitching moment.

*Planform DVs (chord, sweep, span, and dihedral) not included to reduce impact on non-aerodynamics disciplines and off-design performance

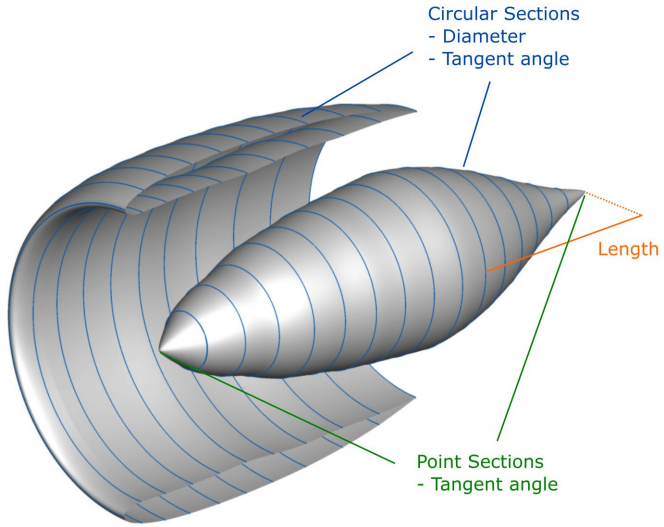
Representative Wing Propulsor Design Optimizations

Objective (1)	Minimize P_{shaft} (1)
Design Variables (74)	Thrust (1)
	Diameter (35)
	Tangent angle (37)
	Length (1)
Nonlin. Constraints (23)	Constant net thrust (1)
	Maximum fan Mach (1)
	Minimum t/c (20)
	Minimum LE radius (1)

Geometric design variables are defined through OpenVSP's geometry parameterization



Turbofan-147 and Pod-147 Baseline



DEP-125 Baseline

Wing propulsor designs are optimized for minimum shaft power at constant net thrust based on top of climb requirements.

Optimized Airframe: B737-8

Flow Conditions

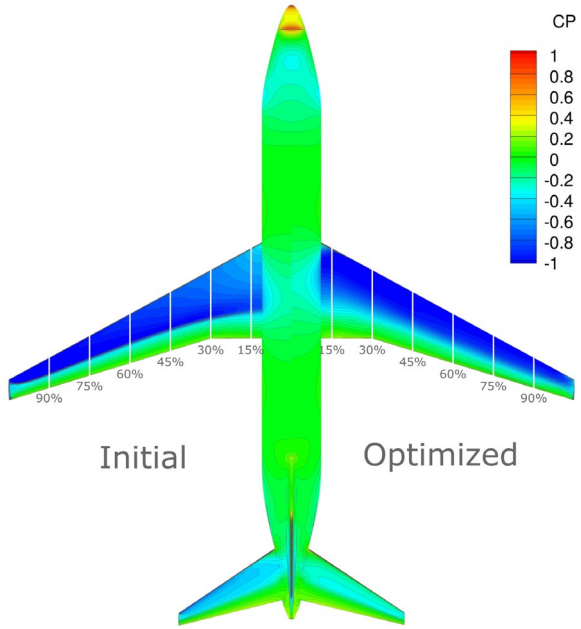
M = 0.785
Re = 24.14 M

Optimized Aerodynamic Performance

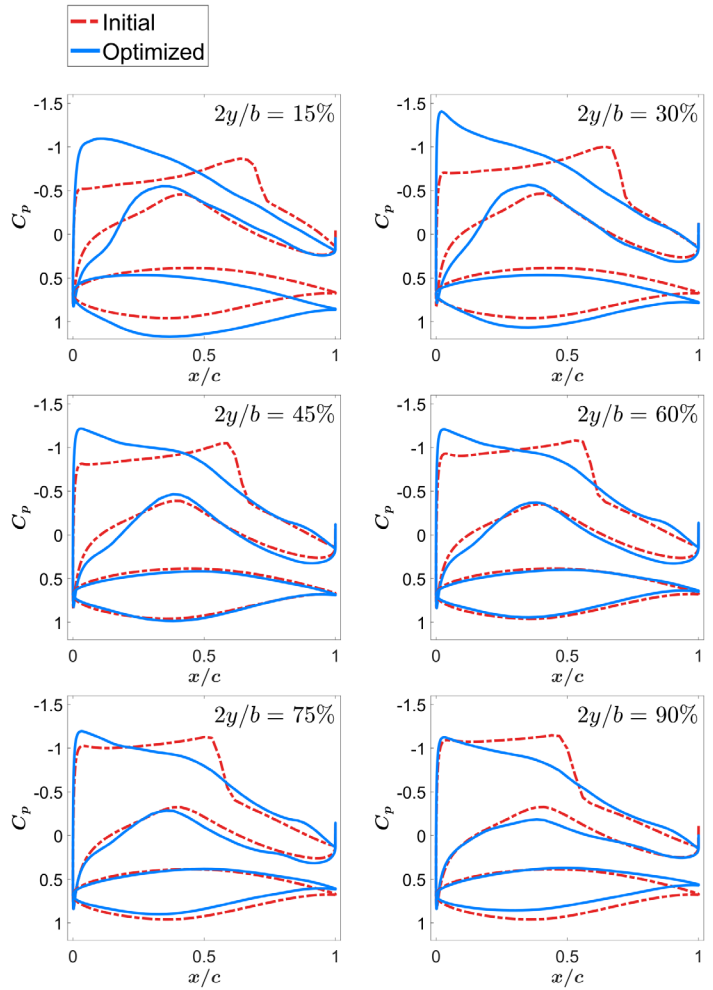
C_L = 0.556
C_D = 0.0279
C_M = 0.000



Shock surfaces



Surface pressure contours



Airfoil profiles and pressure distributions

Optimized B737-8 geometry has reasonable design and flow features and is considered a good representation of the airframe at transonic conditions.

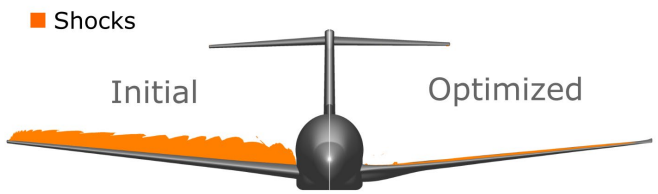
Optimized Airframe: SUSAN-Pod and SUSAN-DEP

Flow Conditions

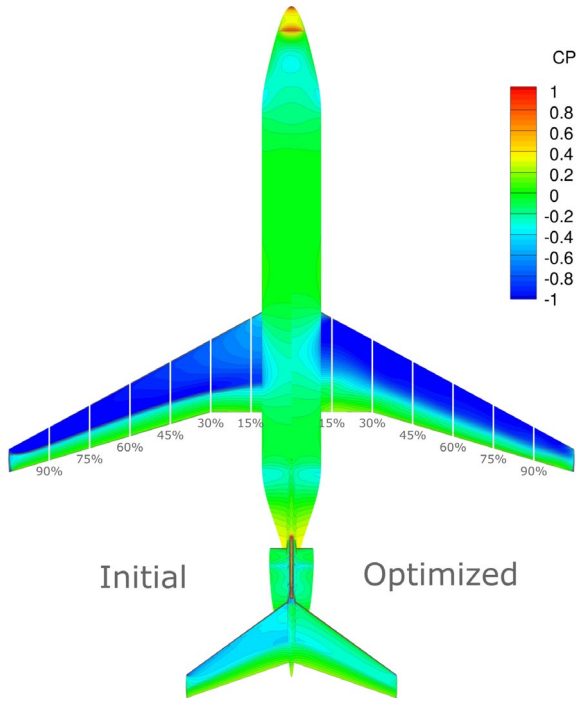
M = 0.785
Re = 25.07 M

Optimized Aerodynamic Performance

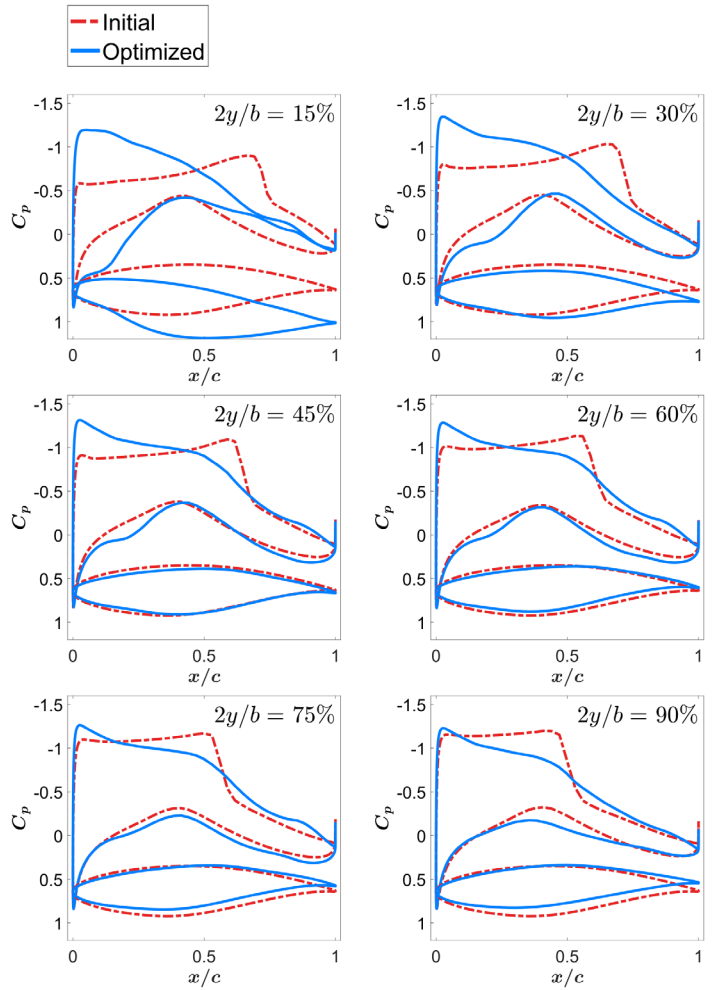
C_L = 0.589
C_D = 0.0318
C_M = 0.000



Shock surfaces



Surface pressure contours

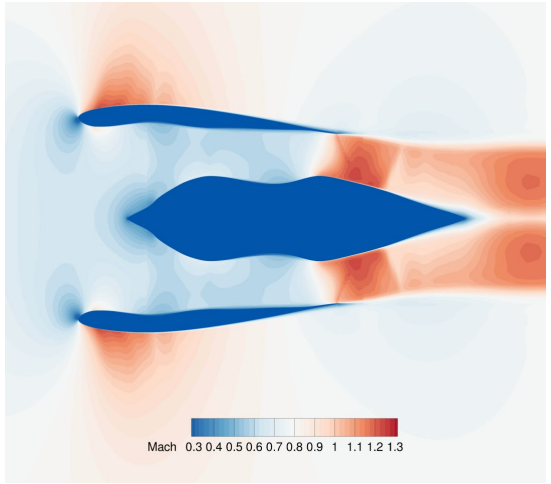


Airfoil profiles and pressure distributions

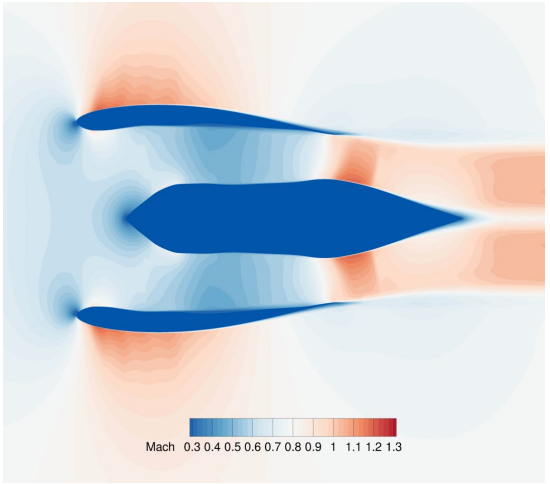
Optimized SUSAN Electrofan geometry has reasonable design and flow features and is considered a good representation of the airframe at transonic conditions.

Optimized Wing Propulsors

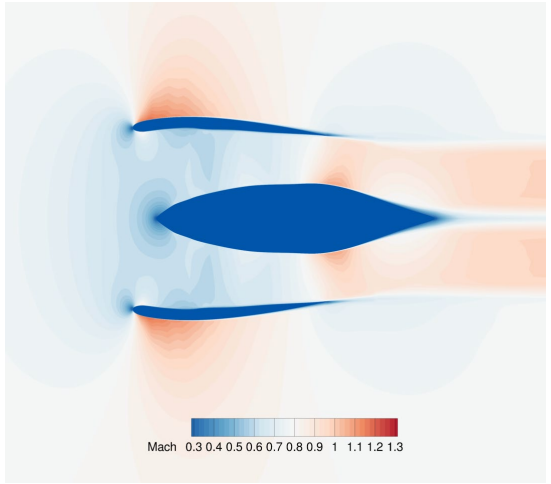
Sized based on a Top of Climb (TOC) thrust of 11,500 lb at Mach 0.800 and 35,000 ft



Turbofan-147



Pod-147



DEP-125

Parameter	Turbofan-147	Pod-147	Delta	DEP-125	Delta
Thrust share (%)	50.0	32.5	-35.0%	4.0625	-91.9%
Adiabatic fan efficiency* (%)	93.5	95.0	+1.6%	96.1	+2.8%
Power / thrust* (hp/lb)	1.94	1.85	-4.6%	1.70	-12.4%

Optimized propulsor geometries satisfy design requirements and show improved aeropropulsive performance as thrust output per propulsor and design fan pressure ratio is reduced.

*Values based on coarse grid level analysis

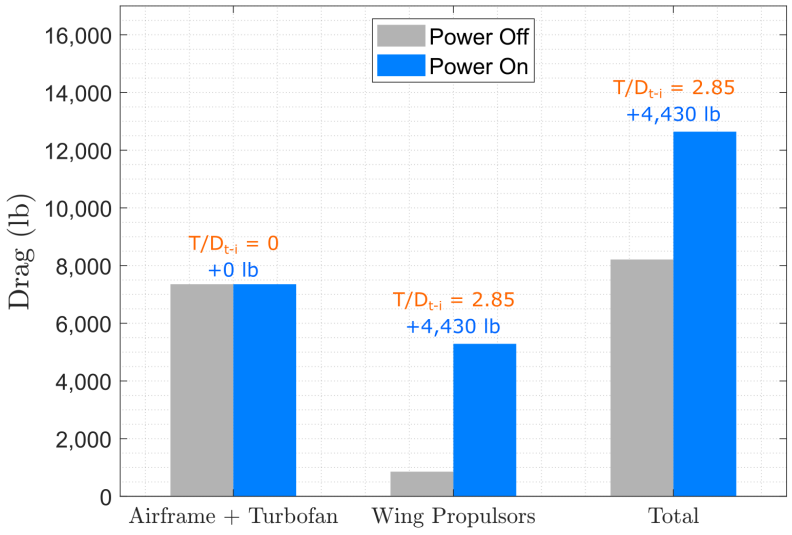
Power Balance Results*

Parameter	B737-8	SUSAN-Pod	Delta	SUSAN-DEP	Delta
Lift coefficient	0.556	0.589	---	0.589	---
Drag coefficient	0.0458	0.0518	---	0.0468	---
Lift (lb)	152,480	169,130	+10.9%	169,130	+10.9%
Drag** (lb)	12,640	15,010	+18.8%	13,570	+7.4%
Lift-to-drag ratio***	15.4	14.9	-3.2%	14.9	-3.2%
Thrust, gross (lb)	12,640	15,010	+18.8%	13,570	+7.4%
Shaft power (hp)	13,480	15,010	+11.4%	14,310	+6.2%
Normalized range parameter	1.000	1.133	+13.3%	1.189	+18.9%

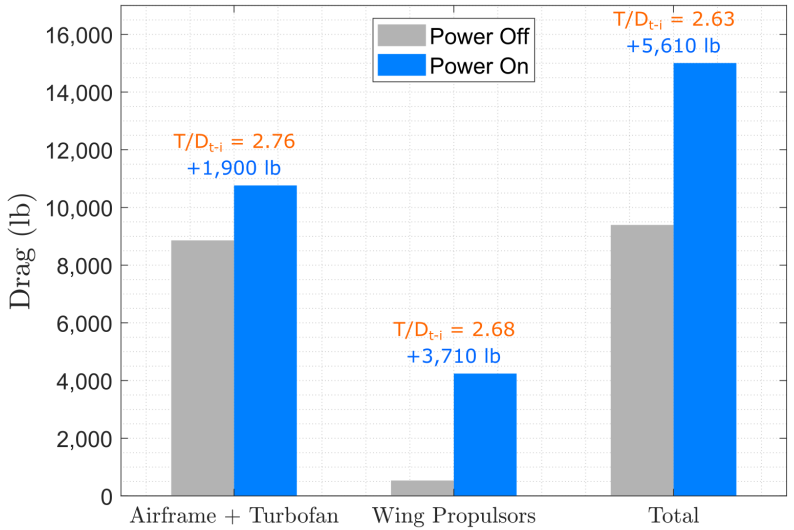
SUSAN Electrofan configurations experience more drag due to higher weight, larger airframe components, and integrated tail design. They also requires more shaft power when accounting for 10% electrical transmission losses, despite the higher fan efficiency of their wing propulsors. However, they maintain range efficiency improvements of 13.3% and 18.9% when accounting for TSFC.

*Values based on Richardson extrapolation, **No special thrust-drag bookkeeping, ***Conventional thrust-drag bookkeeping

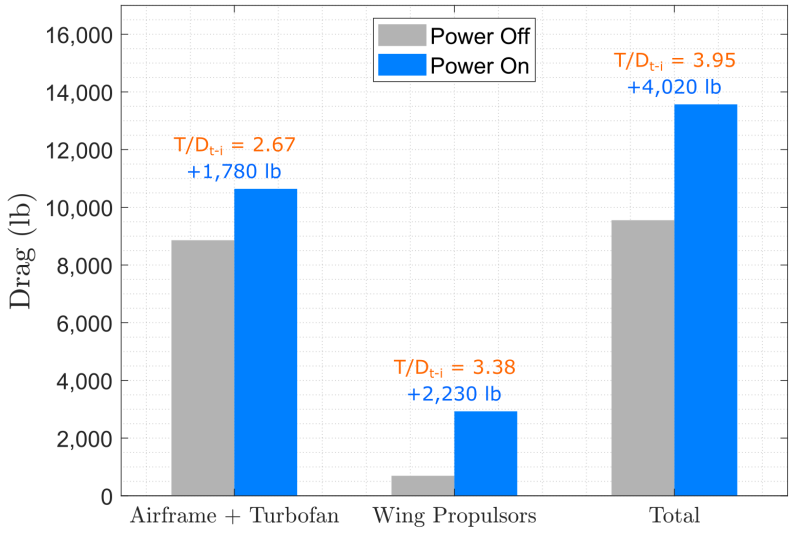
Thrust-Induced Drag, $D_{t\text{-}i}$ (Power off vs. Power on Drag)



B737-8



SUSAN-Pod



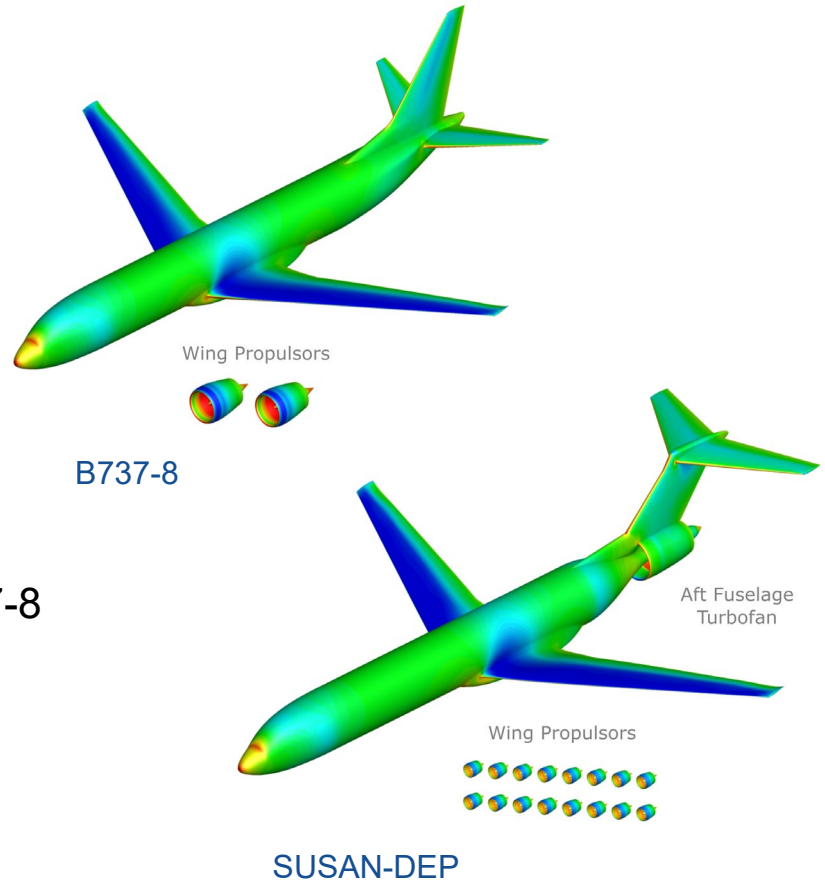
SUSAN-DEP

SUSAN Electrofan's DEP systems contribute to a much lower total drag cost per unit thrust compared to the B737-8. However, the BLI aft fuselage turbofan is less efficient in $T/D_{t\text{-}i}$ than the Turbofan-147s.

*Thrust is defined as gross thrust

Conclusions

- SUSAN-DEP experiences **7% more drag** than the B737-8
  - Higher lift-induced drag from increased weight
  - Higher viscous drag from larger aircraft components and integrated tail system
  - Much lower thrust-induced drag due to DEP (based on comparisons with SUSAN-Pod)
- SUSAN-DEP requires **6% more shaft power** than the B737-8
  - Higher adiabatic fan efficiency due to lower fan pressure ratios
  - Accounts for 10% power loss from electrical transmission for DEP propulsors
- SUSAN-DEP has a **19% higher aeropropulsive range efficiency** than the B737-8
  - Much lower TSFC based on conceptual propulsion models



The design problem of the SUSAN Electrofan is to offset higher airframe drag and power losses from electrical transmission with aeropropulsive benefits of DEP, while achieving a net aircraft level benefit from improvements to thermal efficiency (and hence TSFC). These trades becomes more favorable as EAP systems reduce in weight and improve in efficiency.

Acknowledgments

- Funding for this work was provided by the **NASA Convergent Aeronautics Solutions (CAS) project**

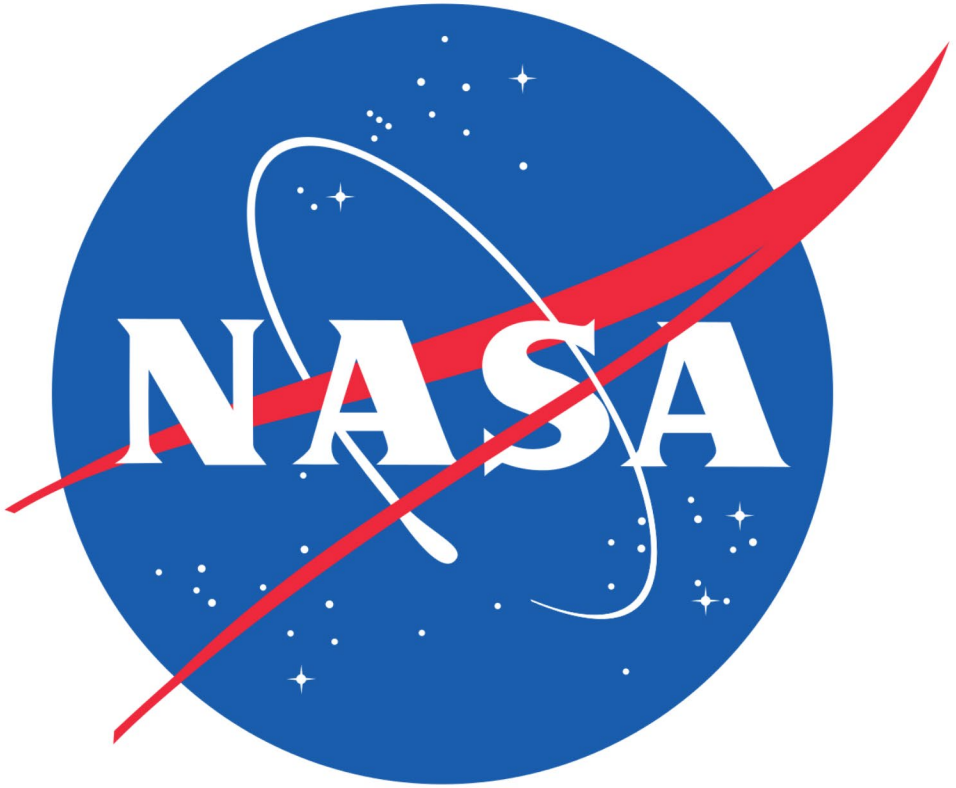




- Computational resources provided by the NASA High-End Computing Capability (HECC) program through the **NASA Advanced Supercomputing (NAS) Division** at Ames Research Center

- Authors gratefully acknowledge technical support and guidance from **SUSAN Electrofan team**; special mentions include:
  - Matthew J. Ha (Glenn) for propulsion system models
  - Timothy P. Dever (Glenn) for power systems support
  - Erik J. Stalcup and Jonah Sachs-Wetstone (Glenn) for thermal systems support
  - Ralph H. Jansen (Glenn) for leadership and guidance

- Appreciation extended to Chase Ashby and Scott Neuhoff for internal review



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