Whisper Aero

Simulations of Distributed Electric Propulsion Concepts and Integration with a Novel Airframe

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Acknowledgements
Suzy Tichenor
Bronson Messer
FUND3D Team (especially Eric Nielsen, Aaron Walden)

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LOCATION

Leading the electric jet age in Crossville, TN

We're building the next generation of electric propulsion technology for drones, aircraft, and more that are **dramatically quieter, faster, and cost-effective**

Founded in **2020**
Young & dynamic team that lived and worked together
Supplemented by Industry leading contracting experts

Mark Moore

CEO

36 Years Innovating at NASA & Uber Elevate

Putting things in context

Evolution of the Airplane

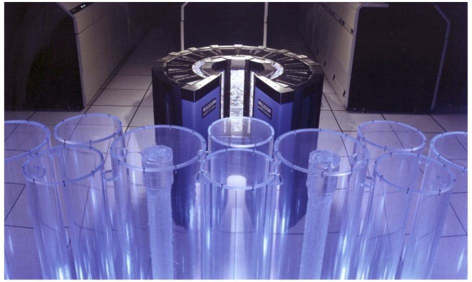
Noisy, Fuel Consumption, CTOL, Turbofan Engines

1980’s

2000’s

Quiet, Battery, Distributed Electric, VTOL

2020’s



Gigaflops

Petaflops

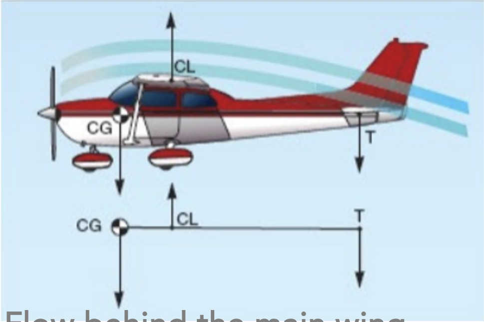
Exaflops

Outboard Horizontal Tail (OHT)

Motivation for a different Airplane Configuration

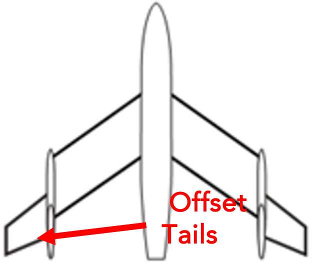
Realities of Airplane Design

Wing Tip Vortices Result in Drag Penalty & Detriment to Fuel Efficiency



Flow behind the main wing results in downwash on the horizontal tail

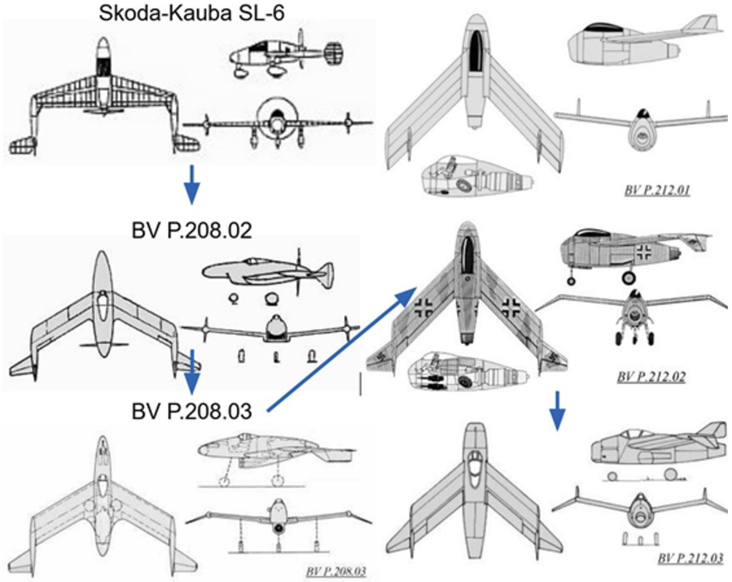
Blohm and Voss



Boom Mounted OHT

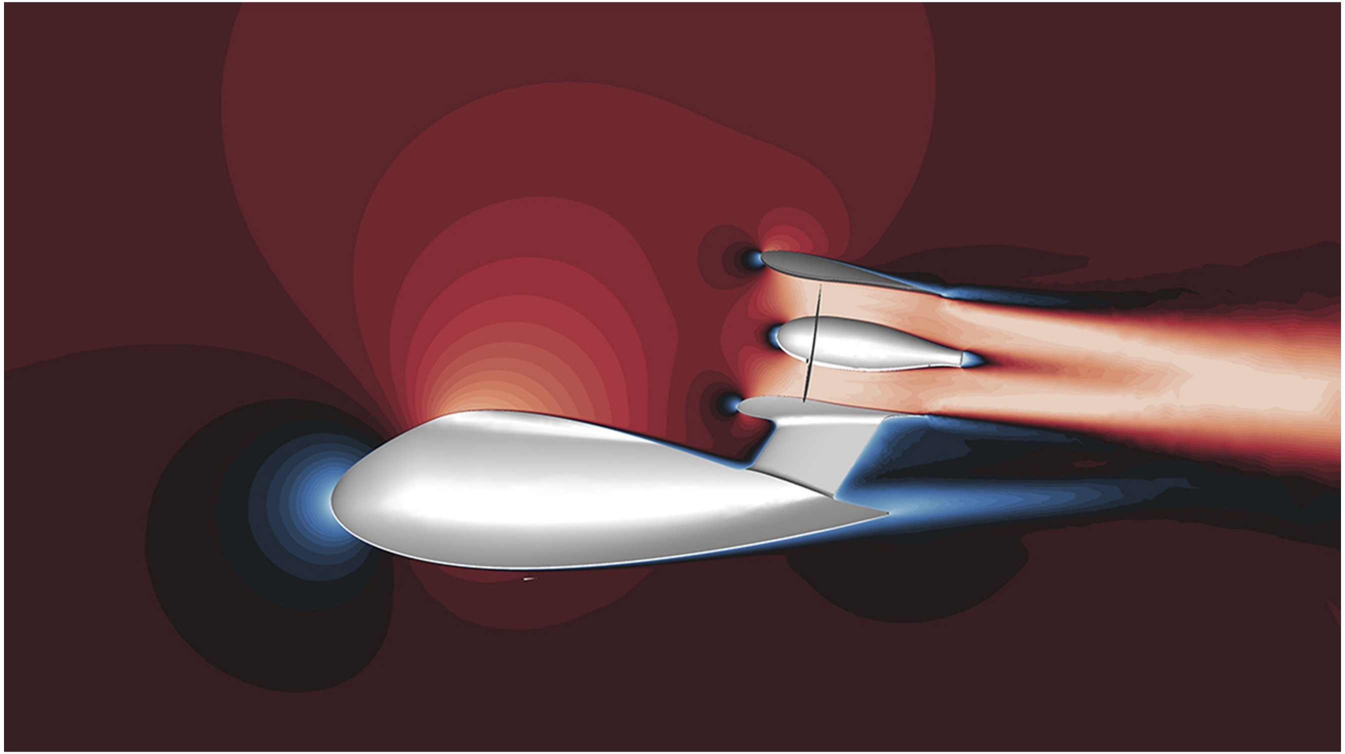
Spaceship One

Evolution of OHT



OHT Configuration CFD Studies

Drone Architecture with a Podded Configuration

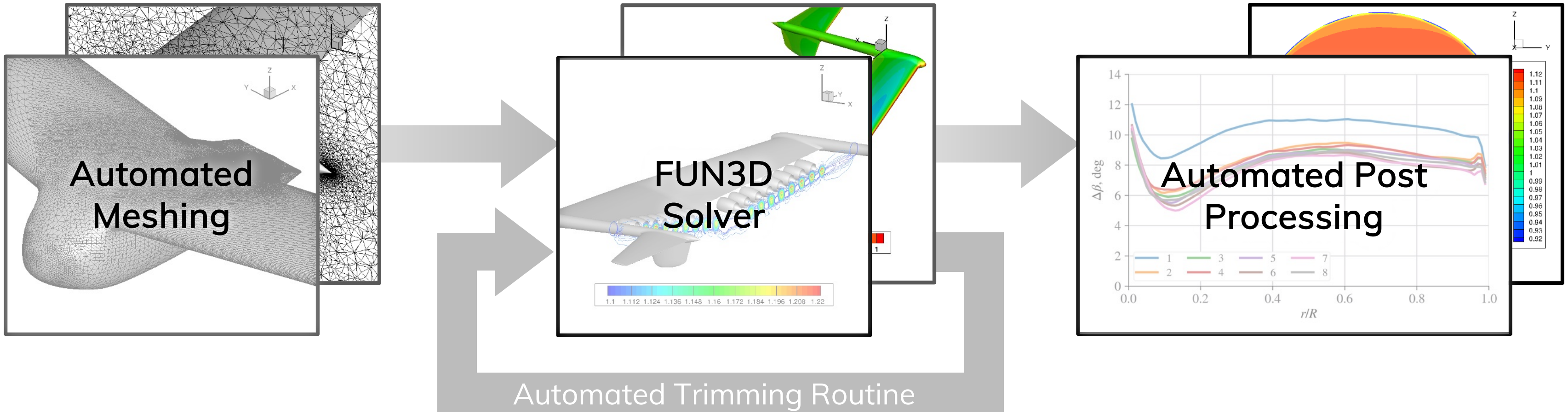


CFD Simulations are required to study the interactions between the propulsor and the airframe

- Net drag is a result of the airframe and external surfaces of the propulsor
- The fan is modeled as an actuator disk
- Flow power is the result of the kinetic energy flux behind the rotor plane
- At each condition, the aircraft is trimmed to get the net forces to be zero in the lift and drag directions
- This requires multiple simulations for a given condition
- The simulations were performed with FUN3D CFD code
- The mesh sizes varied from 11 million grid points to 32 million grid points depending on the architecture

Workflow

Automated Framework for Integration Studies

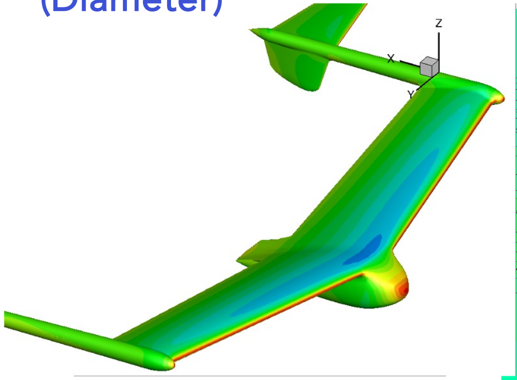


CFD Integration Studies

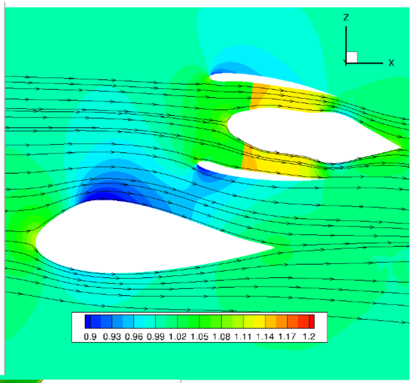
Baseline Comparison	Fan Diameter	Tilt Angle	Vertical Spacing	Propulsor Count	Wake Ingestion

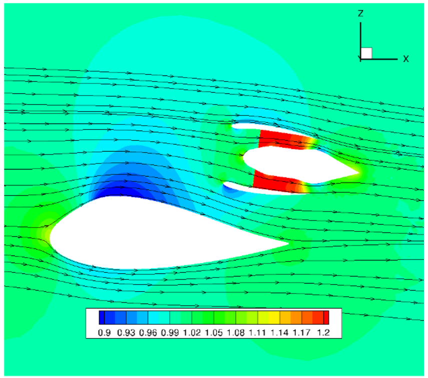
Integrated Propulsor Sizing Studies

Propulsor Sizing Studies (Diameter)

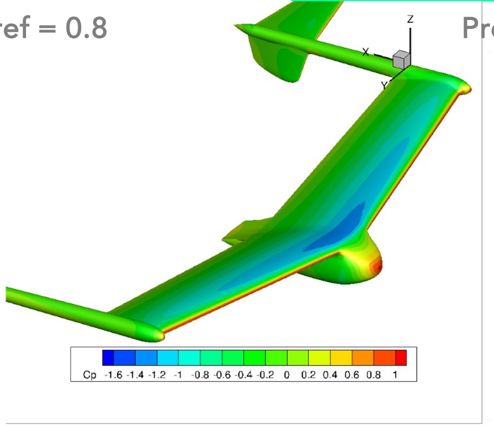


D/Dref = 0.8





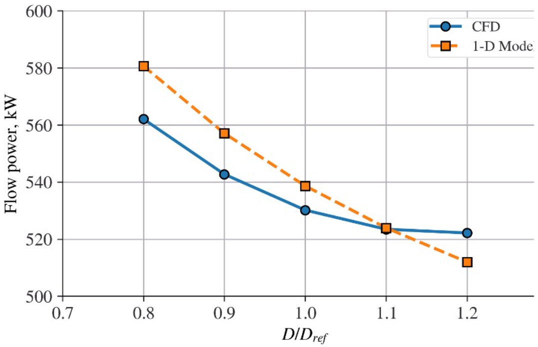
Pressure Distribution at D/Dref=1.2 and D/Dref=0.8



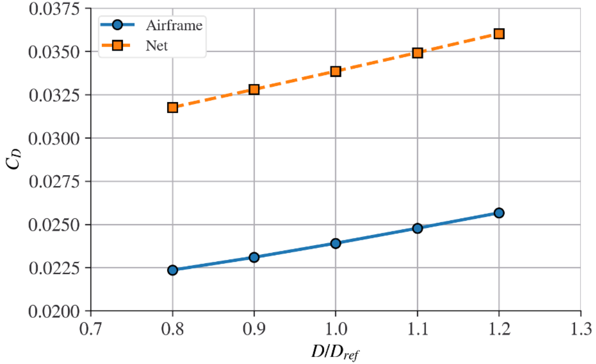
D/Dref = 1.2

Objectives are to study fan performance, as a function of propulsor size

- Trade-off between Fan Pressure Ratio and duct drag
- Mismatch in CFD and Meanline Tool because of fixed airframe drag approx.
- Influence on pressure fields both on the airframe and propulsor



Variation of Flow Power



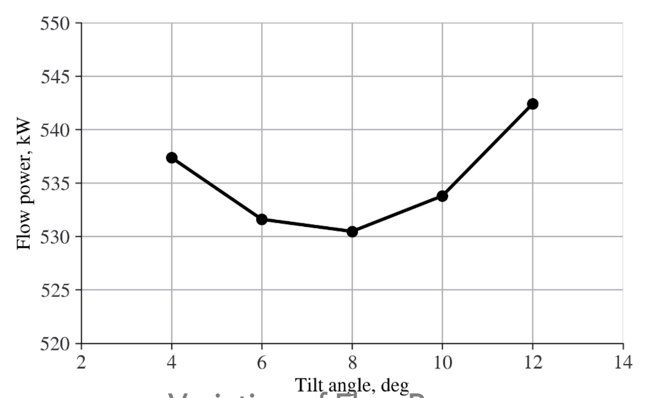
Drag Coefficient

CFD Simulations

Podded Propulsor Airframe Integration - Tilt Angle

Objectives are to study fan performance, pressure distortion into the fan

- Tilt angle of propulsor wrt airframe was varied from 4 - 12 deg
- Delta Beta is the variation of inflow angle in the relative frame of the rotor
- Delta Beta angle is indicative of unsteady loading noise and stall margin



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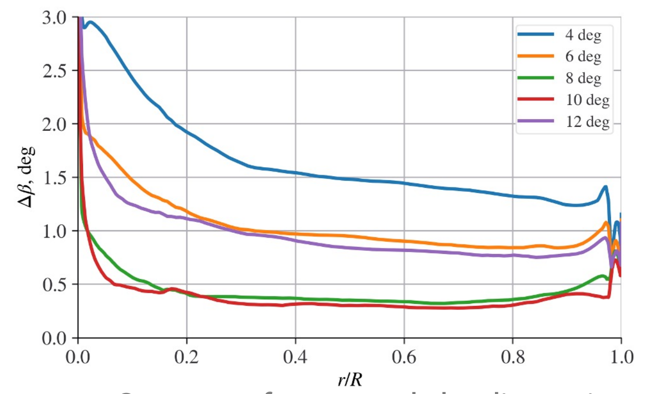
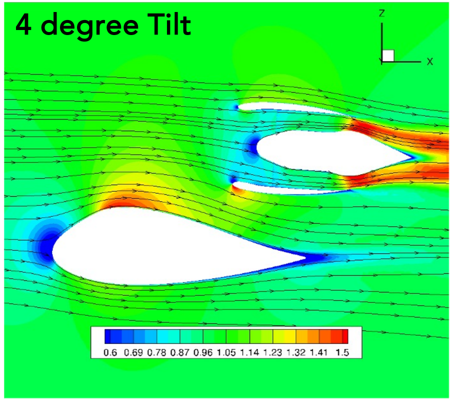
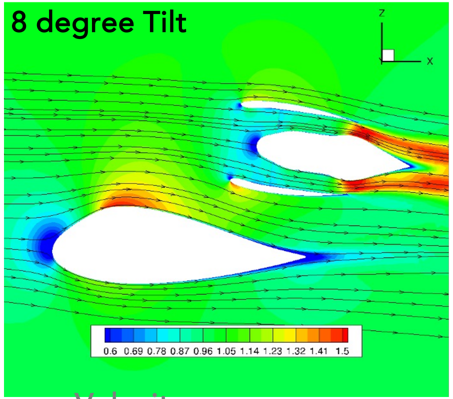
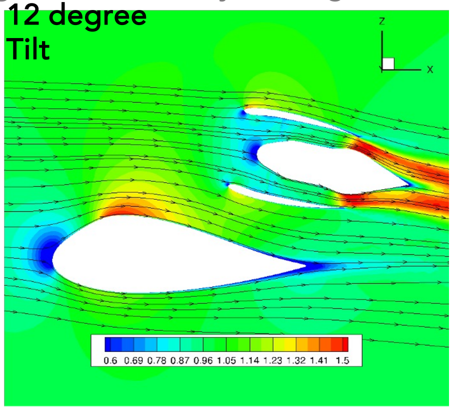


Surrogate for unsteady loading noise



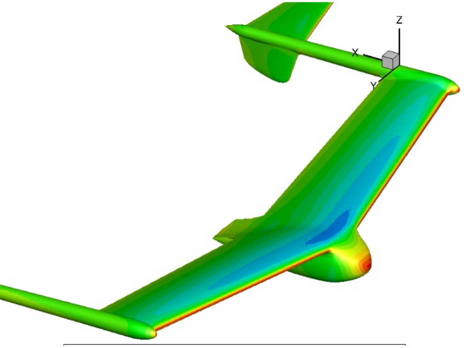




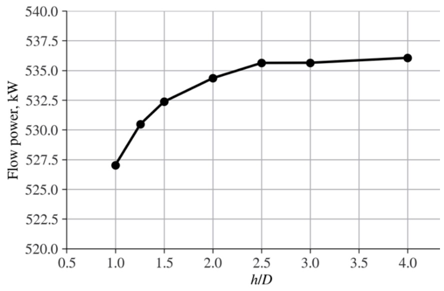
Velocity Distributions

CFD Simulations

Integrated Propulsor Spacing Studies



h/D = 1



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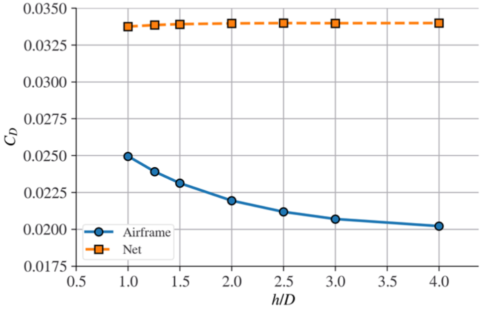
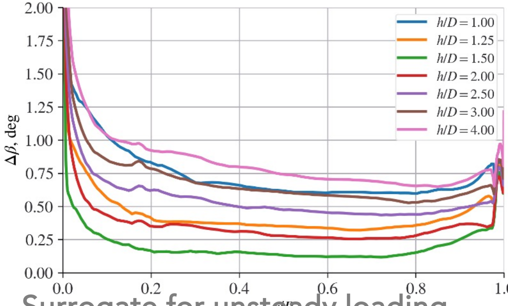


Net & Airframe Drag



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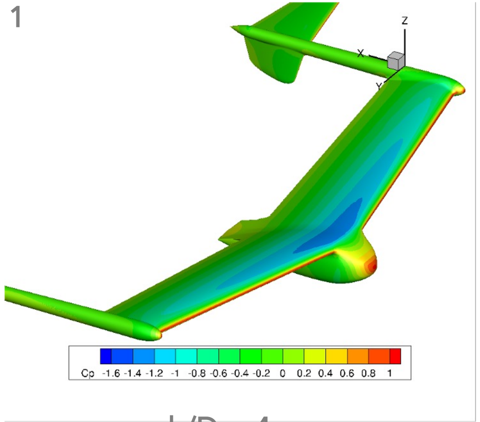
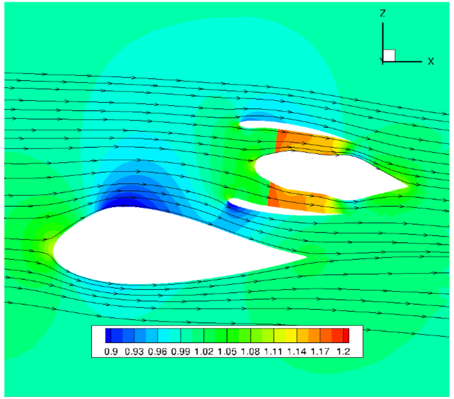
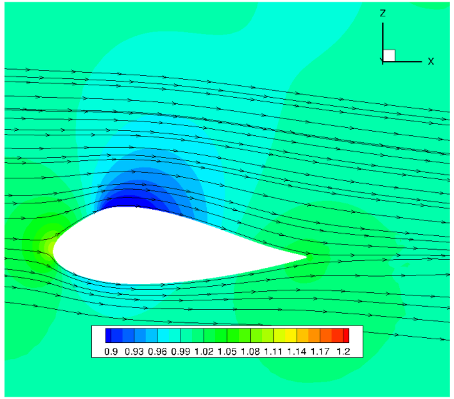


h/D = 4

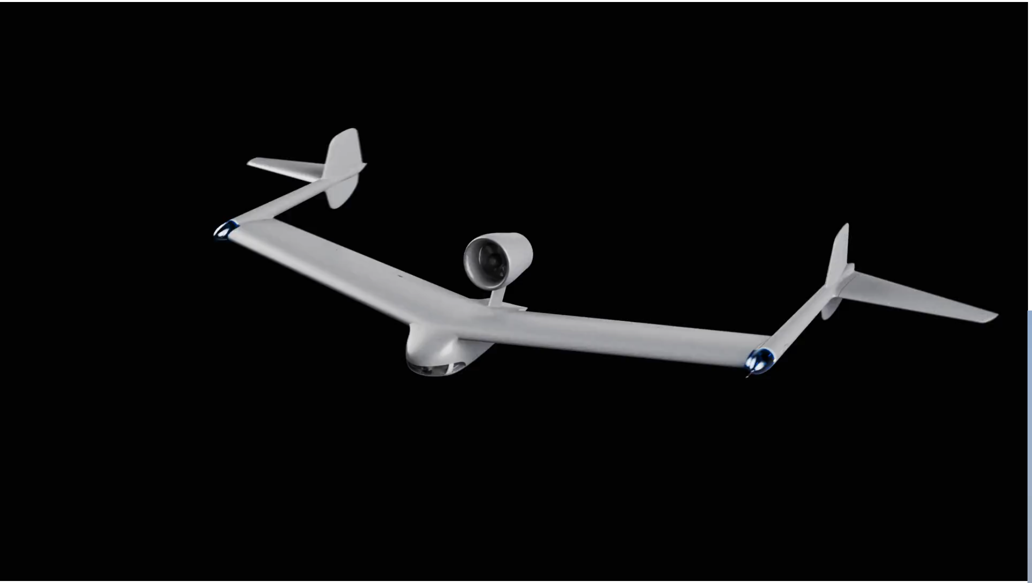




Pressure Distribution at n/D=1 and h/D=4

Whisper Demo Drone

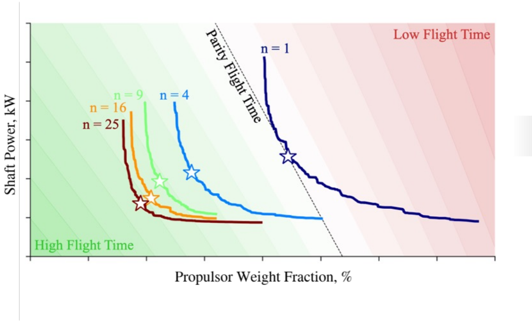
Test Campaign of Drone Flights



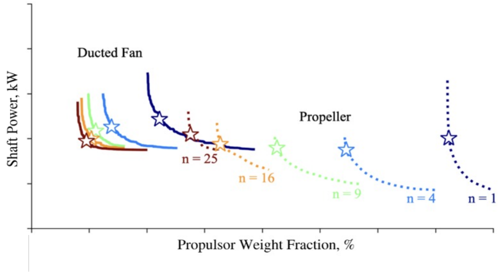
Scaling to larger Airplanes

Propulsion Design and Integration for Regional Air Mobility

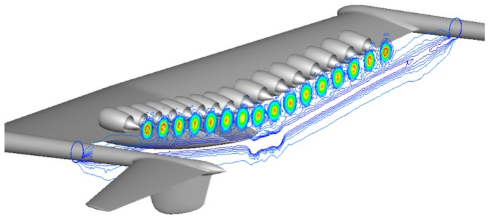
Ducted Fan Optimization



Open Rotor Comparison



RANS Integration Study



Study evaluates propulsion design, optimization, and integration for the Regional Air Mobility (RAM) market.

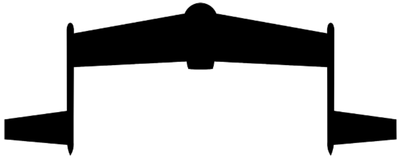
Key Questions are about (i) Scaling the Architecture (ii) Distributed Electric Propulsion Concepts and (iii) Integration

Propulsion system optimization for ducted fans

Vehicle Comparison and Problem Formulation

Whisper Jet - RAM

250 KTAS, 57′ Span



Full Scale - RAM

250 KTAS, 48′ Span

¼ Scale Demo Drone - ISR

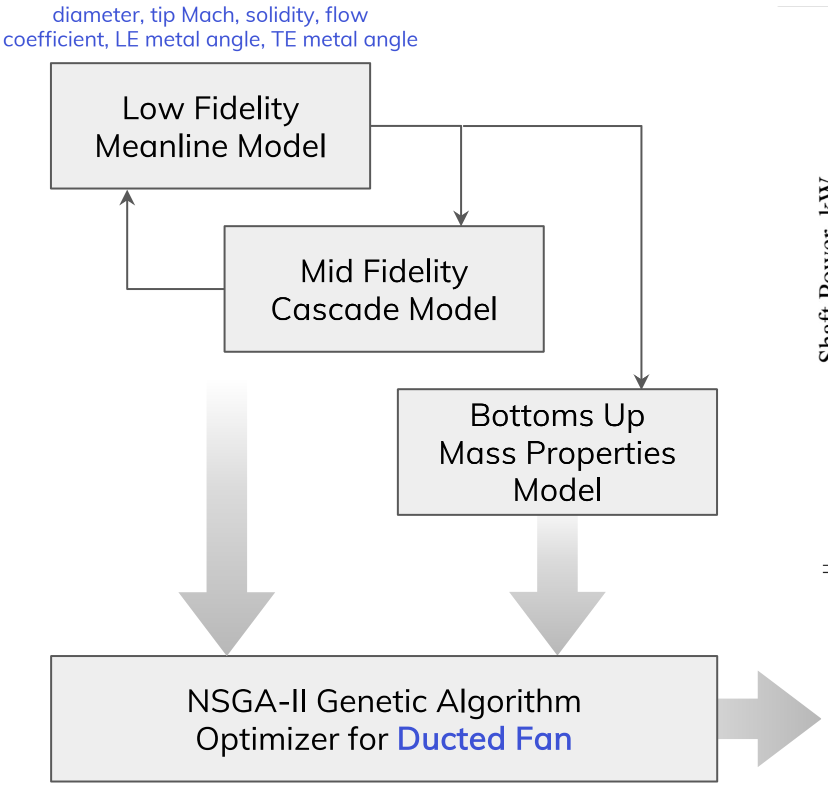
45 KTAS, 12′ Span

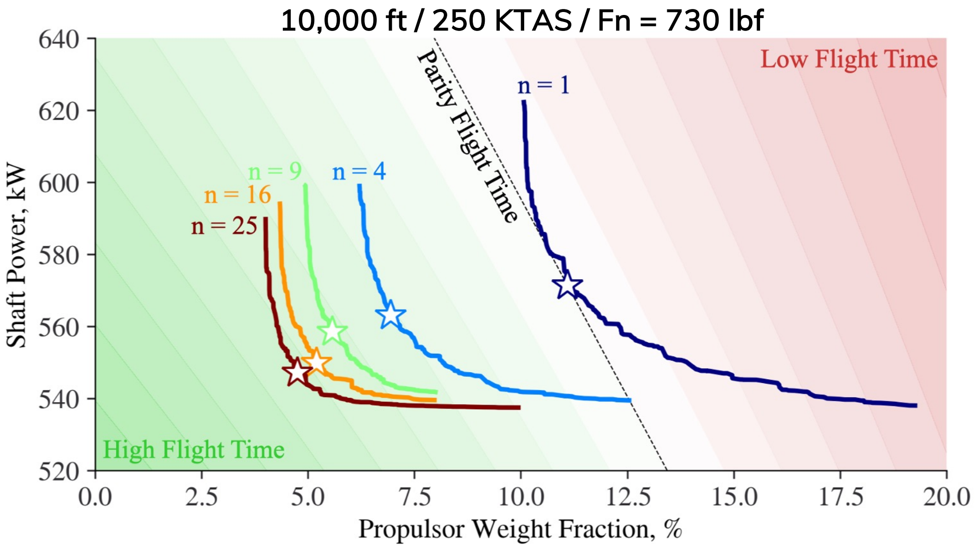
minimize :	P_{cruise}	Net shaft power
	m	Propulsion weight
with respect to :	D	Rotor diameter
	U_{tip}	Tip wheel speed
	σ	Blade solidity
	ϕ	Rotor flow coefficient
	κ_1	Leading edge metal angle
	κ_2	Trailing edge metal angle
subject to :	$n \cdot F_{\text{cruise}} \geq 730\,\text{lbf}$	Cruise net thrust
	$n \cdot F_{\text{SLS}} \geq 3870\,\text{lbf}$	Takeoff net thrust
	$\sigma \leq \sigma_{\text{crit}}$	Stress surrogate model
	Diffusion factor = const	Rotor diffusion factor
	$i_{\text{cruise}} = \text{const}$	Cruise rotor incidence angle
	$M_\infty = 0.39$	Cruise Mach
	Altitude = 10,000 ft	Cruise Altitude
	$D_{\text{hub}}/D = 0.40$	Hub diameter ratio

Problem Formulation - Fixed MTOW

Propulsion Weight ↔ Battery Weight

Pareto Optimal Ducted Fans Achieve Maximum Flight Time





Number of propulsors	1	4	9	16	25
Fan diameter, in	29.6	16.1	11.1	9.5	7.8
Fan pressure ratio	1.140	1.120	1.113	1.089	1.086
Propulsive efficiency, %	74.8%	76.3%	77.0%	78.5%	79.2%
Cumulative Span / Wingspan	5%	11%	17%	26%	34%

Propulsive effy. defined as $\eta = nF_{\text{cruise}}U_\infty / P_{\text{cruise}}$

Distribution Reduces Electric Machine Weight

$$\text{Thrust} \propto \text{Power} \propto \text{Area} \propto 1/n$$

$$\text{Fan Diameter} \propto \sqrt{\text{Area}} \propto 1/\sqrt{n}$$

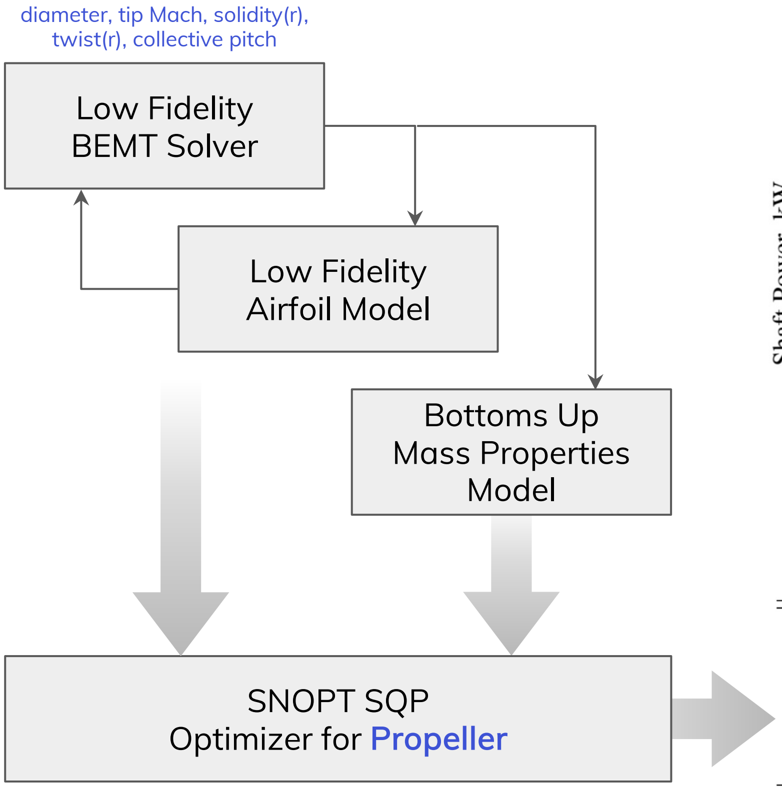
$$\text{RPM} \propto 1\,/\,\text{Fan Diameter} \propto \sqrt{n}$$

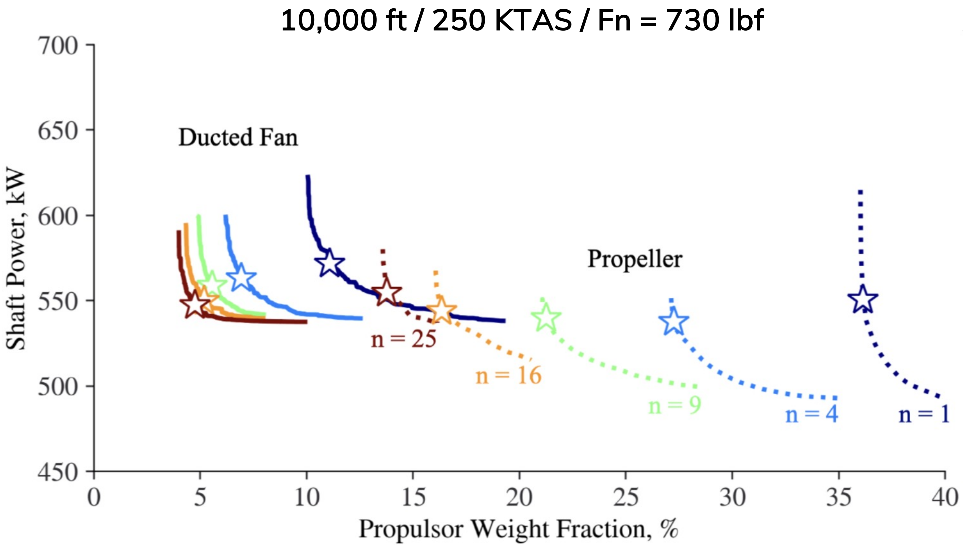
$$\text{Torque} \propto \text{Power}\,/\,\text{RPM} \propto 1/\sqrt{n^3}$$

$$\text{Total Weight} \propto n \cdot \text{Torque} \propto 1/\sqrt{n}$$

Direct drive electric propulsion systems incentivize distribution due to advantageous motor scaling laws

Ducted Fans Outperform Propeller at $M_\infty = 0.39$

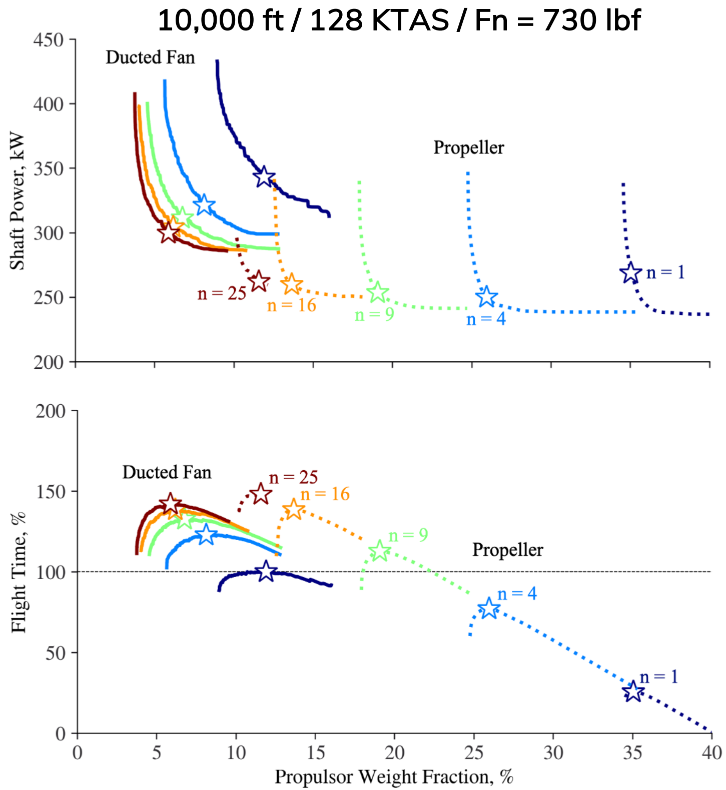




Number of propulsors	1	4	9	16	25
Rotor diameter, in	269.1	97.9	55.7	39.0	30.6
Propulsive efficiency, %	75.7%	77.2%	76.7%	75.2%	74.1%
Cumulative span / wingspan	47%	68%	87%	109%	133%

Propulsive effy.fy. defined as $\eta = nF_{\text{cruise}}U_\infty / P_{\text{cruise}}$

Open Rotor Outperforms Ducted Fan at $M_\infty = 0.20$



Despite conclusions for 250 KTAS cruise, open rotor outperforms ducted solutions in terms of propulsive efficiency for 128 KTAS cruise

However,

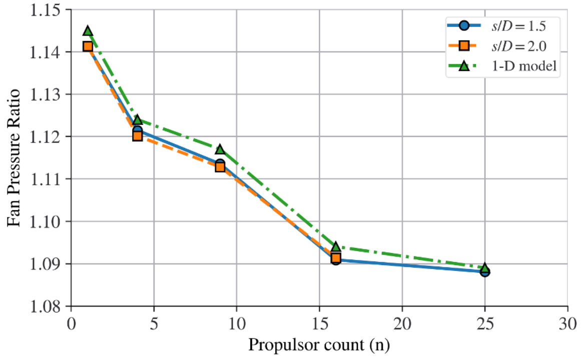
- Open rotor requires variable pitch to achieve feasible design vs fixed pitch ducted fan
- Propeller is still poorly matched to motor, resulting in high motor weight for direct drive solution
- High performing propeller solutions likely represent infeasible physical integrations

Integration Study

Propulsor Count Study Affirms 1D Study Results

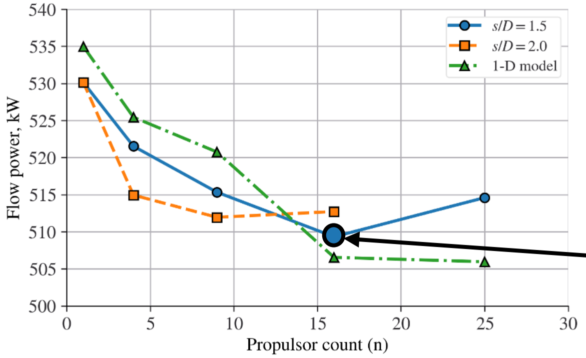
Fan Pressure Ratio

The RANS CFD solver process uses iterative solver to adjust angle of attack and propulsor actuator disk thrust coefficient to fully trim out Cx and Cy. Fan pressure ratio is treated as a follow out and demonstrates alignment between the 1D model and CFD. **This is indicative of a well aligned drag model, duct drag, and propulsor discharge coefficient.**



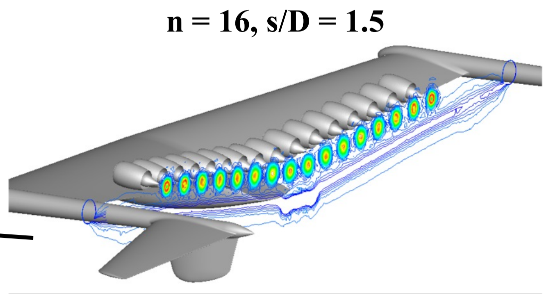
Flow Power

In addition to the aforementioned reduction in weight due to distribution, the 1D model predicted a reduction in flow power due to selection of more efficient designs as distribution was increased. The CFD largely predicts the same trend, **however as propulsors approached the booms, the large washout angles on the main wing caused a reduction in outboard propulsor efficiency.**



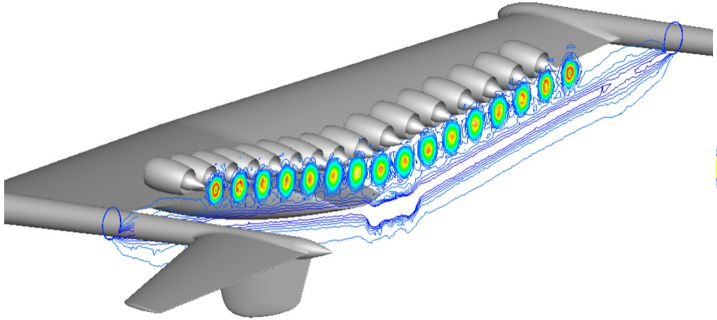
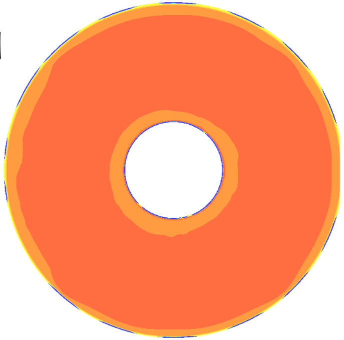
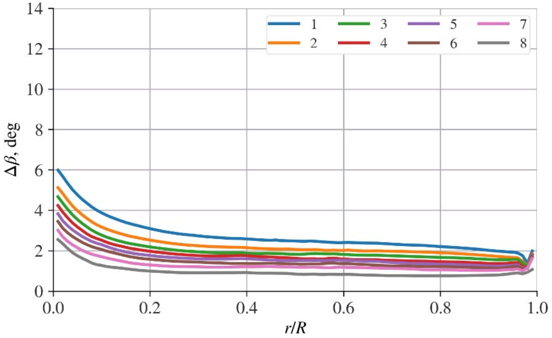
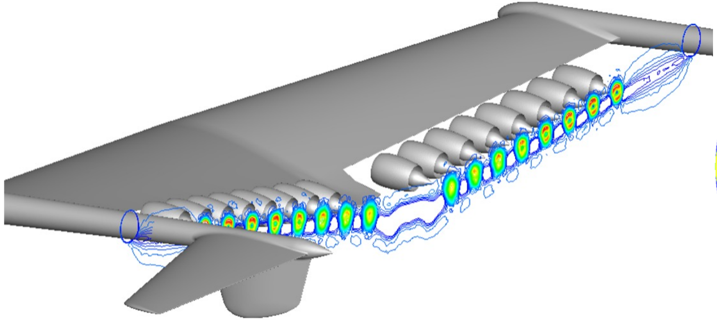
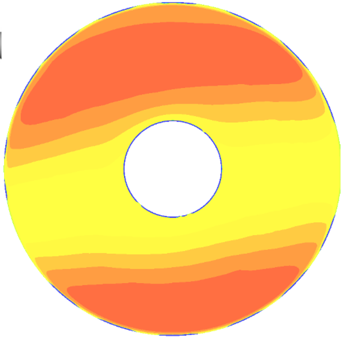
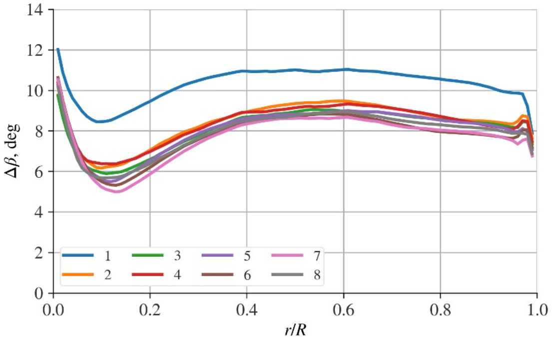
Total Pressure Contours

Propulsors were integrated in a podded configuration above the trailing edge as a means to provide **clean inflow that uses the main wing to provide pre-turning of the flow at off-design conditions. Propulsor-propulsor interaction effects were found to be minimal,** even for the s/D = 1.5 spacing configuration shown below.



Integration Study

Wake Ingestion Incurs 5x Unsteady Rotor Loading

	AIP Total Pressure	AIP Total Pressure	Unsteady Rotor Incidence
Podded			
Wake Ingestion			

Conclusions of Ducted Fan Studies

Propulsion Optimization

A mean-line model is coupled to a mid-fidelity cascade solver and a bottoms up weight model. Both evolutionary and gradient based models are used for multi-objective optimization to support the Regional Air Mobility mission.

High speed performance: Ducted fans provide 75% - 80% propulsive efficiency for high speed missions and provide favorable air gap speeds for rotor-motor coupled design

Open Rotor Comparison: Ducted fans outperformed high activity factor open rotors for a M0.40 kt cruise speed by 25% in flight time. However, for M0.20 cruise speed, open rotor efficiency improved and outperformed ducted fans by 5%.

Complexity: To achieve parity performance, the open rotor solutions required collective pitch control to provide a feasible solution

Distribution Study

A 1D model is used to select pareto optimal propulsion systems for electric ducted fans and open rotors. Results are compared to RANS CFD to evaluate airframe integration effects of a highly distributed (n = 25) podded configuration.

Motor weight scaling: For an electric motor, weight scales with torque and the total system torque scales with $1 / \sqrt{n}$. Therefore high distribution (and high air gap speed) minimizes system weight.

Optimal selection: As thrust is distributed and system weight is reduced, the optimal selection moves towards more efficient designs with reduced FPR, thus improving propulsive efficiency by 4% from $n = 1 \rightarrow 25$

CFD Study: CFD validated the 1D model and show interactional effects are minimal. However, tuning of each propulsor's integration is required to maximize benefit.

Propulsion Integration

A GPU enabled RANS CFD solver is coupled to an automated analysis framework to explore five integration variables. Fully trimmed solutions quantify effect on performance and fan face distortion.

Power balance: A 1D model is compared to RANS CFD and alignment to within 1% is shown for the baseline configuration. A Cx and Cy trimmed solution coupled to a power balance method is used for configuration comparisons.

Static pressure distortion: A surrogate metric is developed for unsteady blade loading and the impact of several integrations is assessed.

Total pressure distortion: A podded vs wake ingestion study revealed an unsteady inflow variation on the order of 9 deg for a wake ingesting geometry vs 2 deg at midspan

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Propulsion Integration

A GPU enabled RANS CFD solver is coupled to an automated analysis framework to explore five integration variables. Fully trimmed solutions quantify effect on performance and fan face distortion.

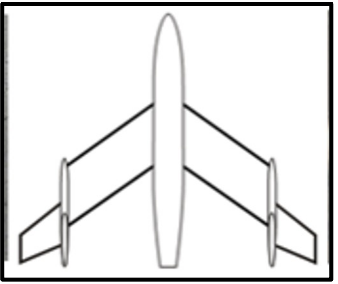
Power balance: A 1D model is compared to RANS CFD and alignment to within 1% is shown for the baseline configuration. A Cx and Cy trimmed solution coupled to a power balance method is used for configuration comparisons.

Static pressure distortion: A surrogate metric is developed for unsteady blade loading and the impact of several integrations is assessed.

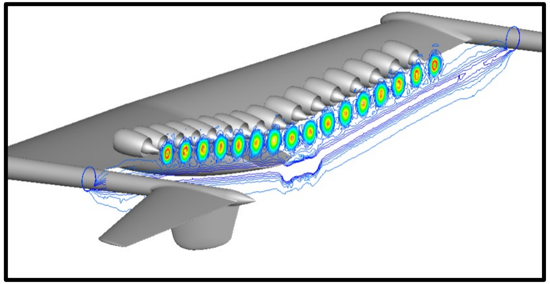
Total pressure distortion: A podded vs wake ingestion study revealed an unsteady inflow variation on the order of 9 deg for a wake ingesting geometry vs 2 deg at midspan

Whisper Jet

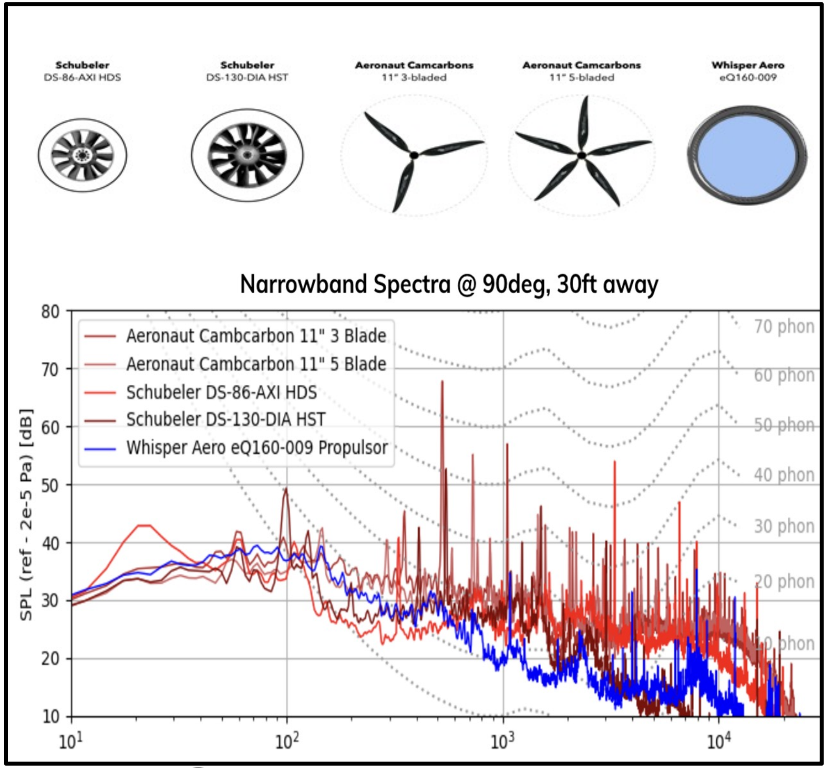
Summing It All UP

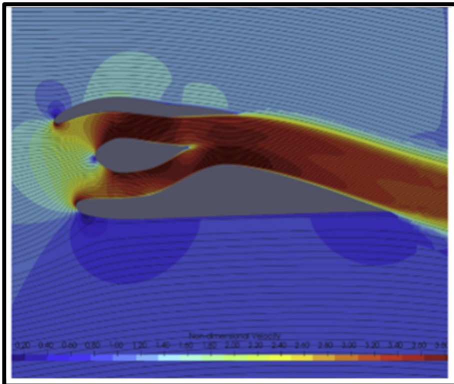


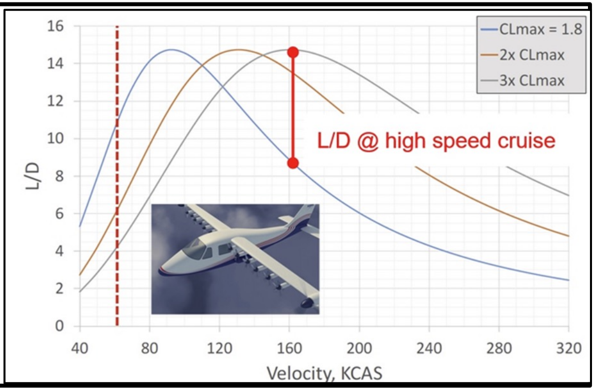
1 OHT Configuration



2 Distributed Ducted Fans



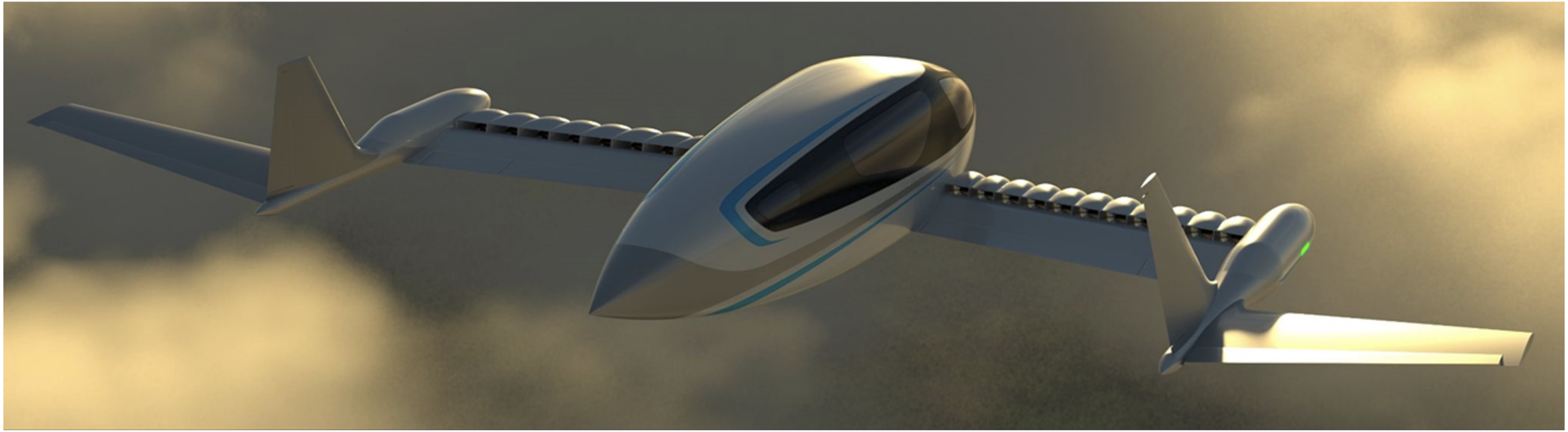




4 Jetfoil Integration gives low stall speed with high wing loading

3 Ultra-Quiet Propulsion

Unveiling the WhisperJet




Whisper Aero