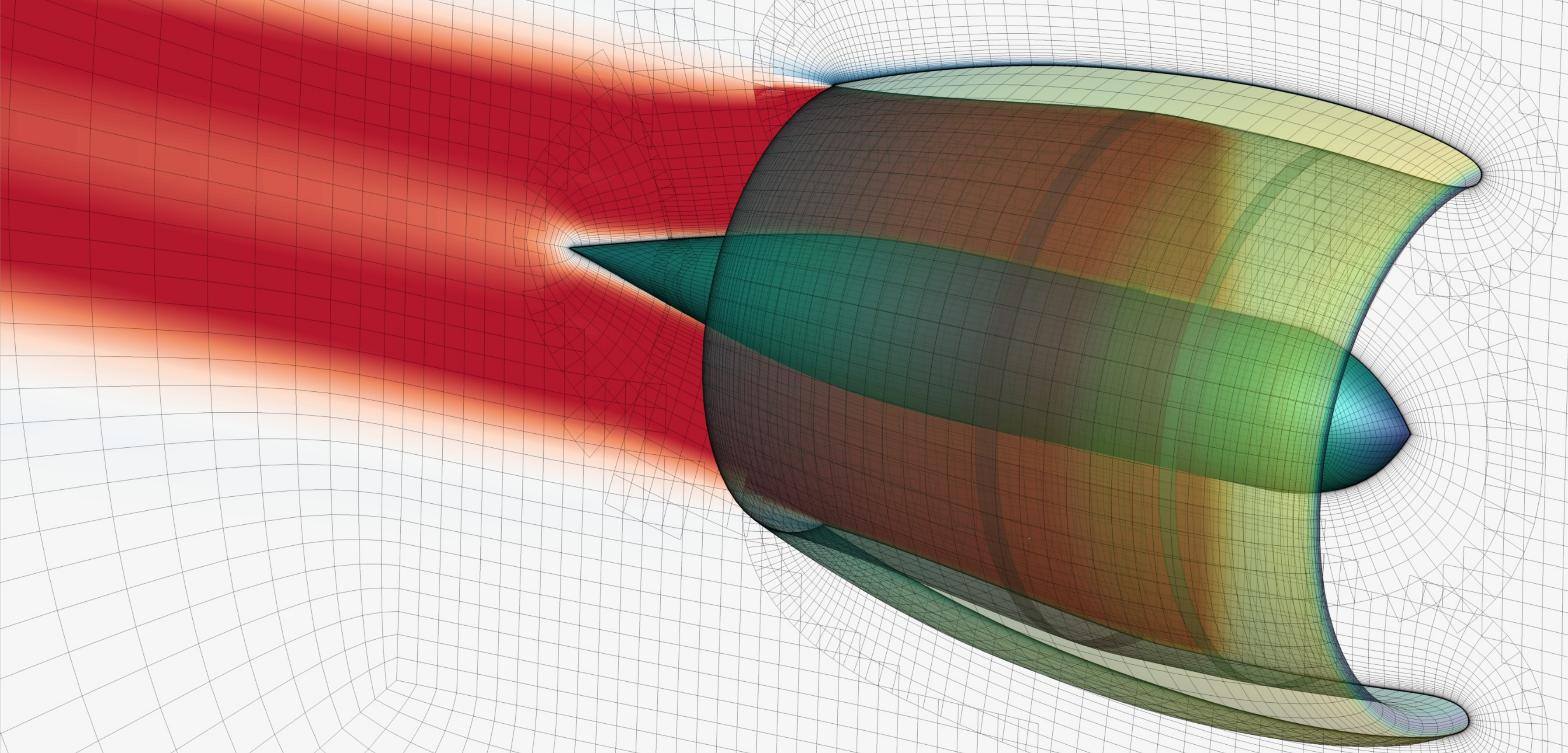
Aeropropulsive Design Optimization and Nonlinear Solver Development in OpenMDAO



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Outline

Introduction

Aeropropulsive Design Optimization

Nonlinear Solver Development

Conclusions

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Aeropropulsive Design Optimization

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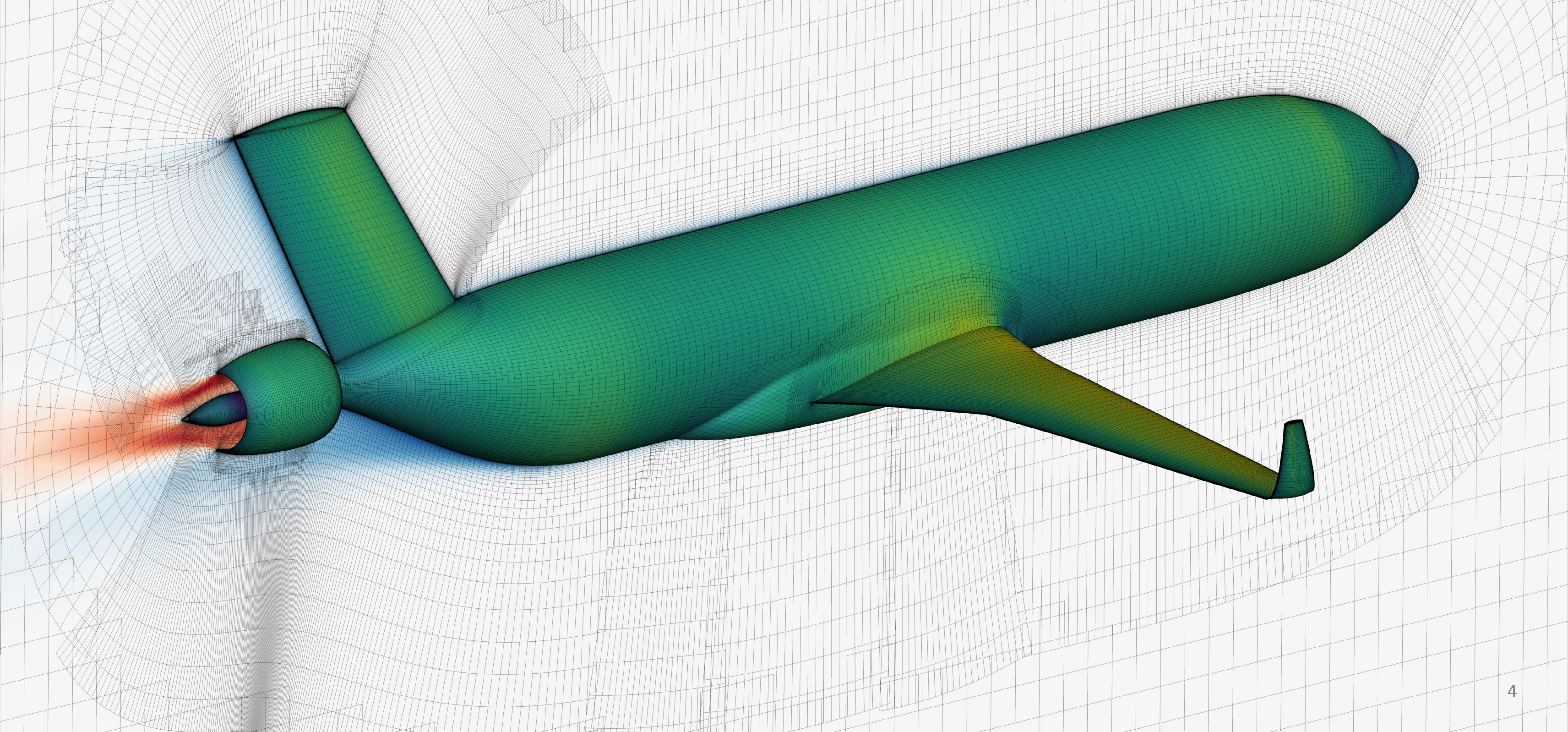
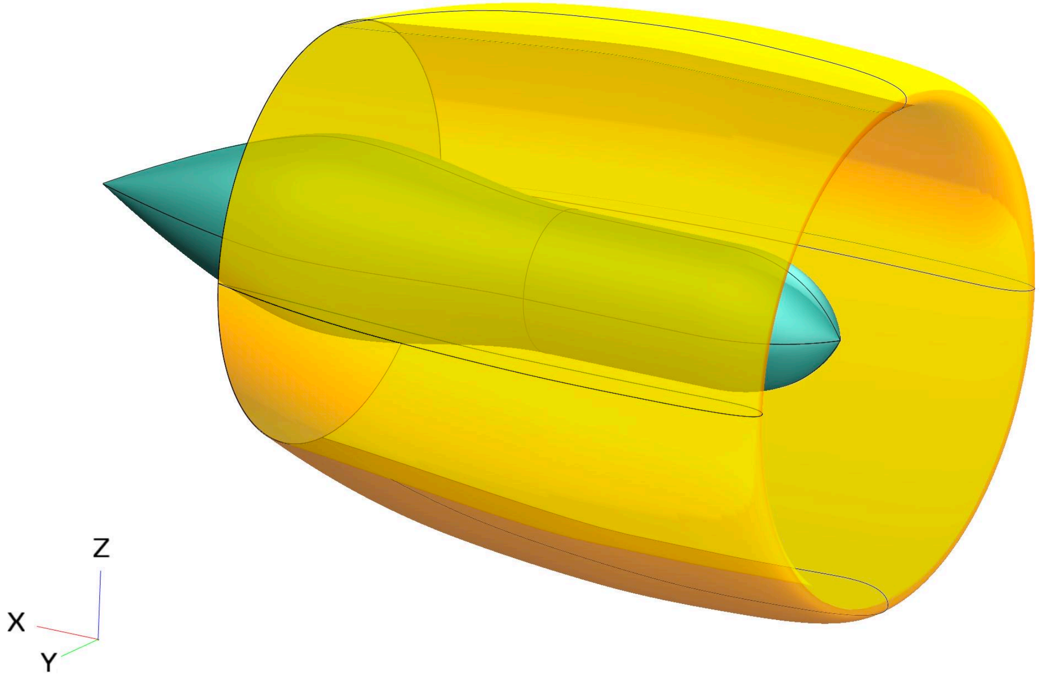
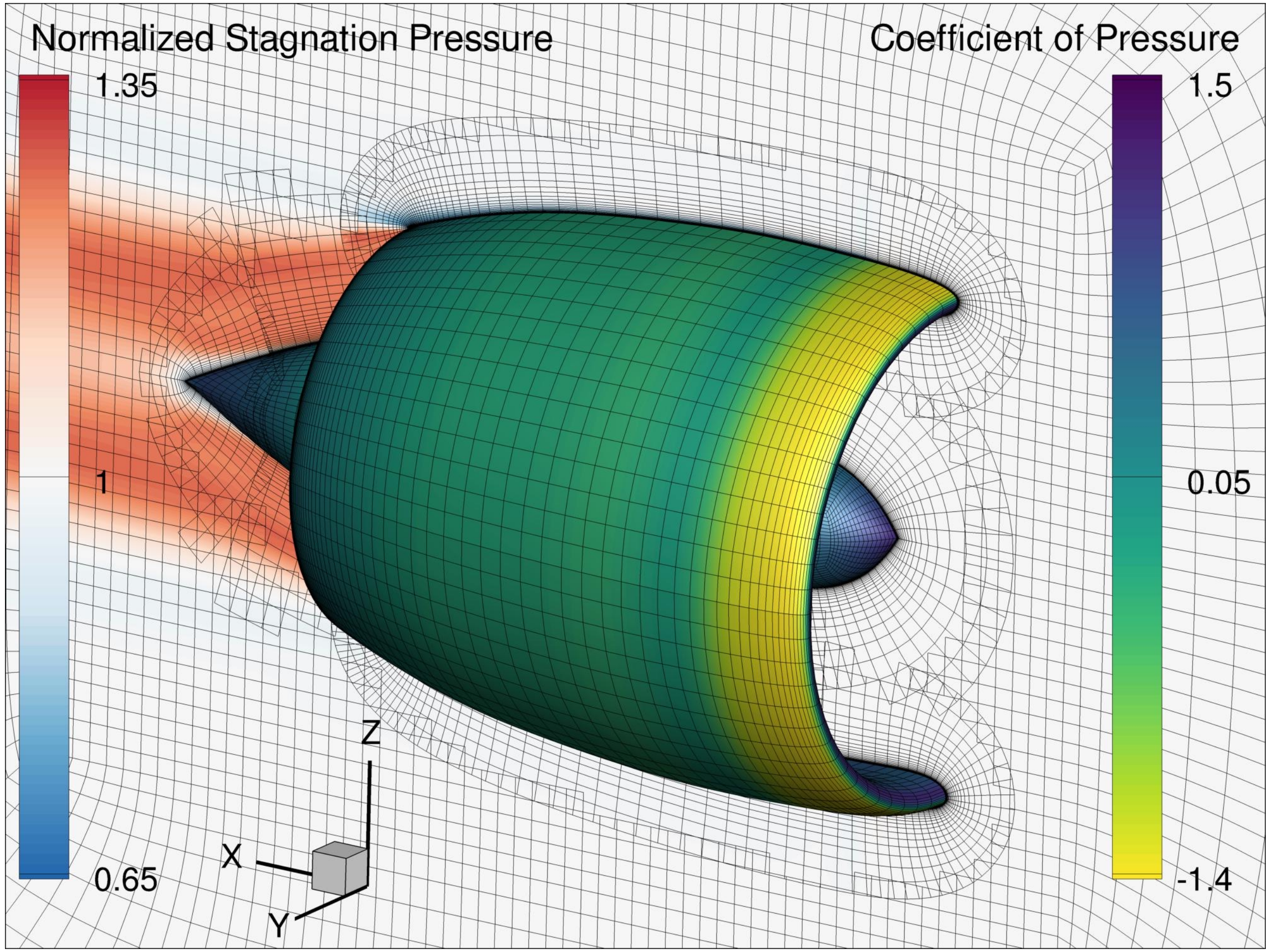
Conclusions

My thesis objective was to advance the state of the art in CFD-based aeropropulsive design optimization



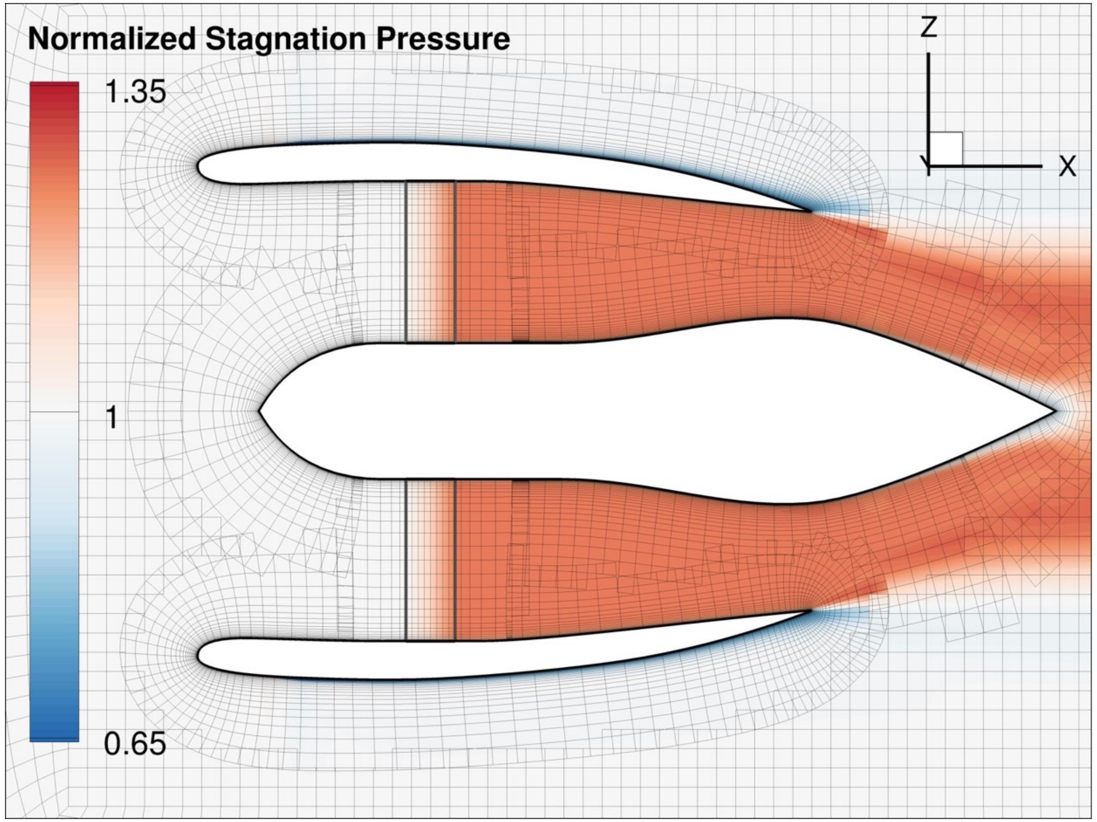
Developed a benchmark podded fan design, which is based on the STARC-ABL's BLI propulsor



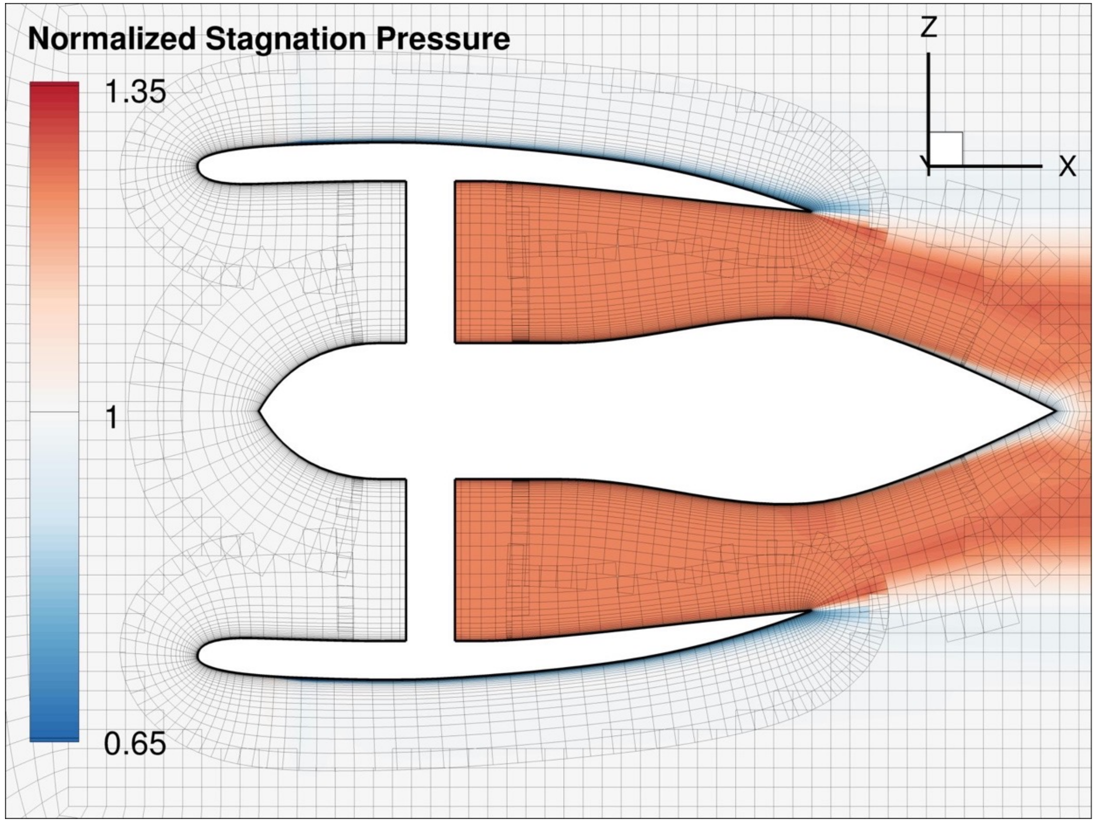


Developed two coupled aeropropulsive models:

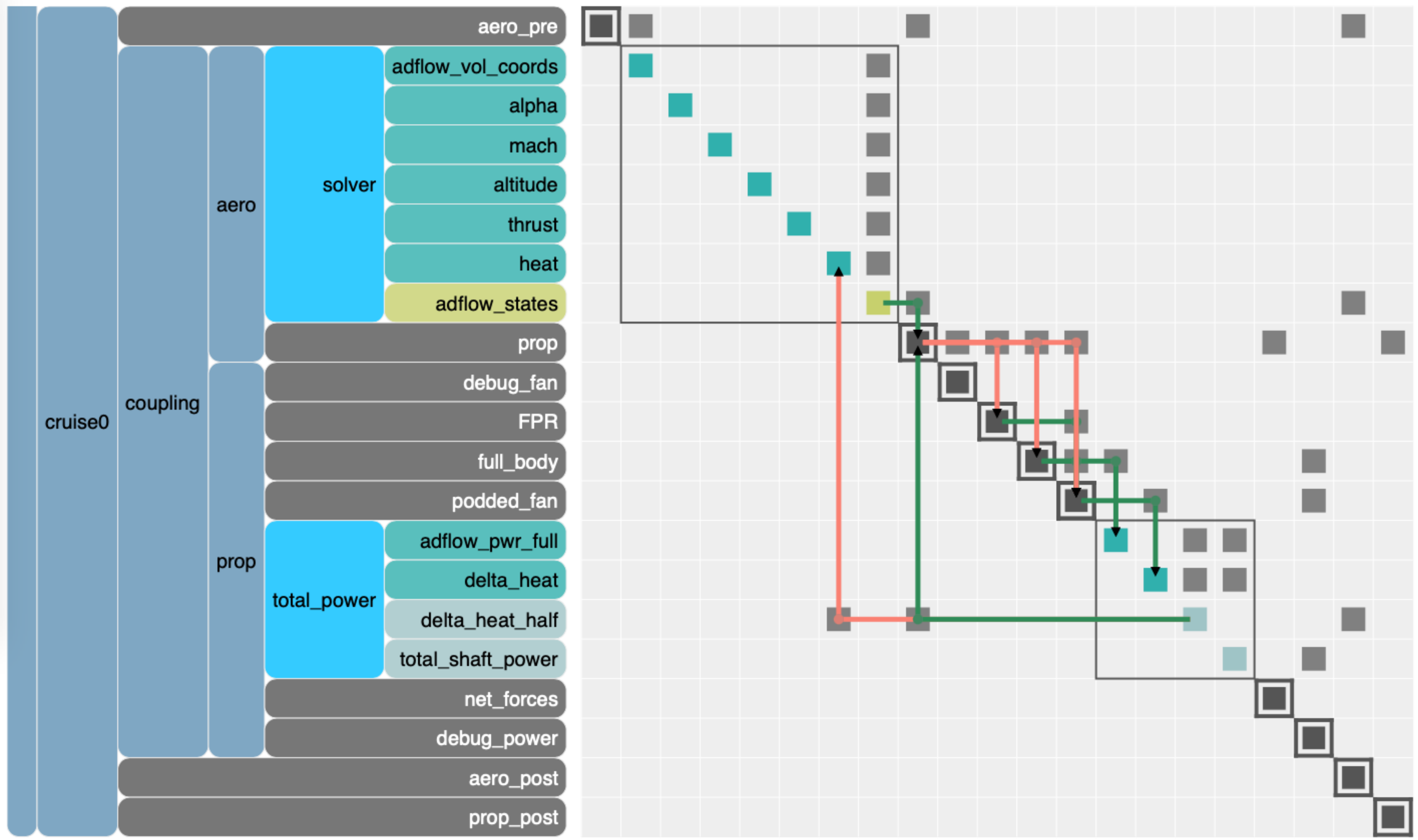
Actuator Zone



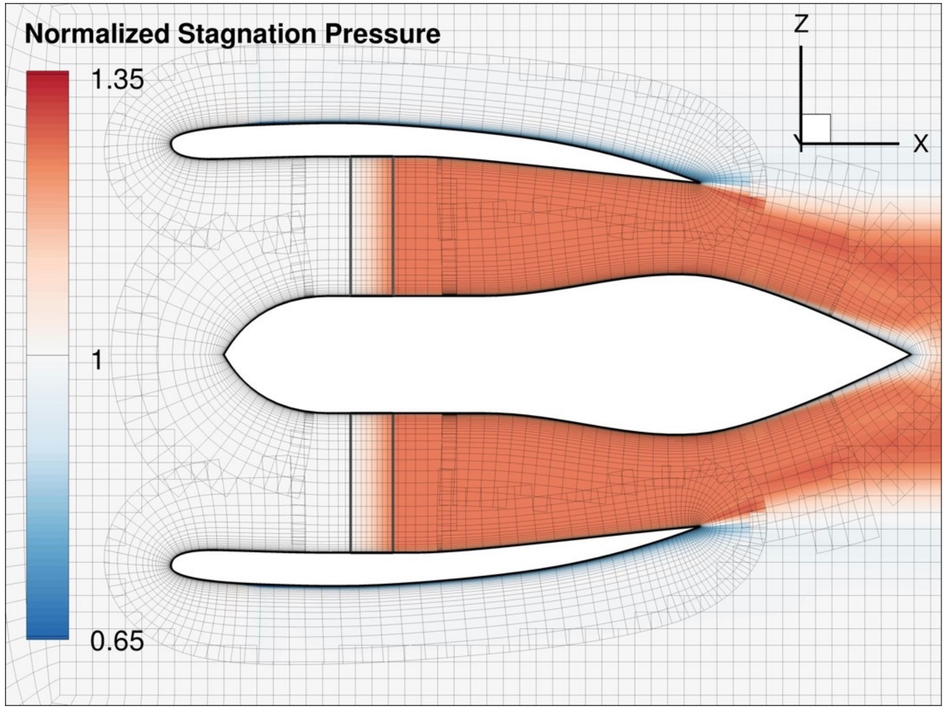
Boundary Condition

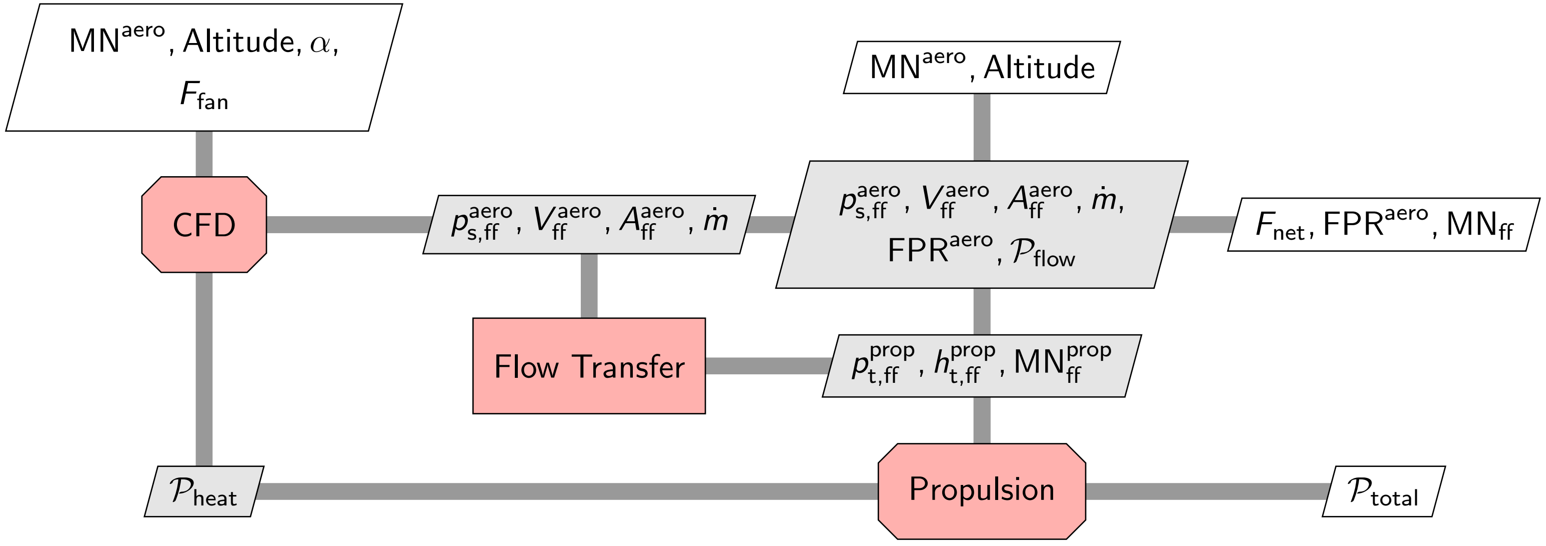


Used NASA's openMDAO framework to implement these coupled models



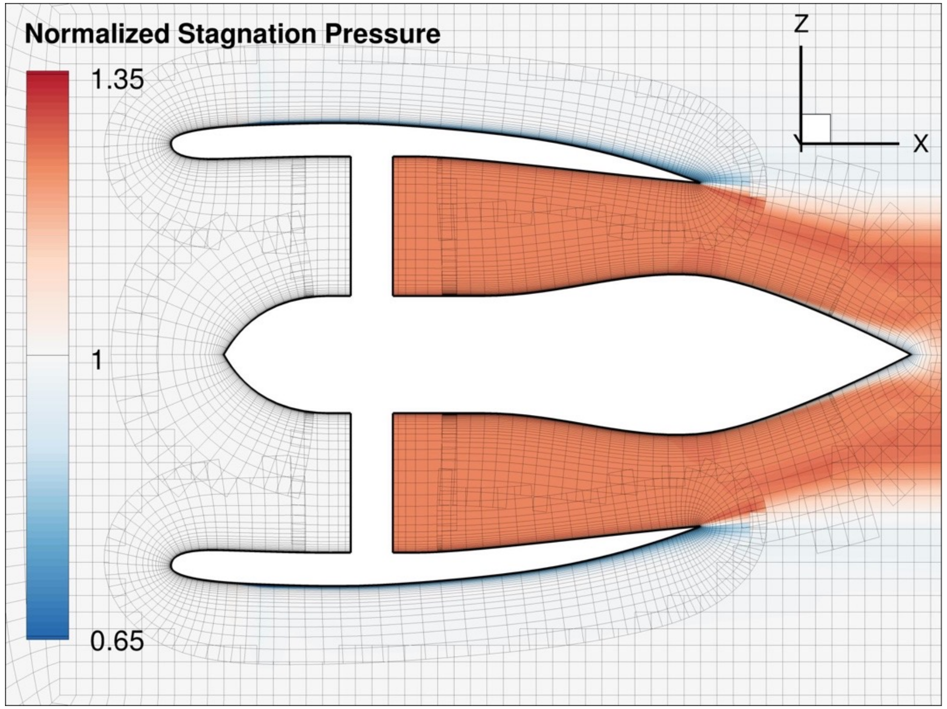
The actuator-zone (AZ) version works with momentum and energy source terms in the CFD model

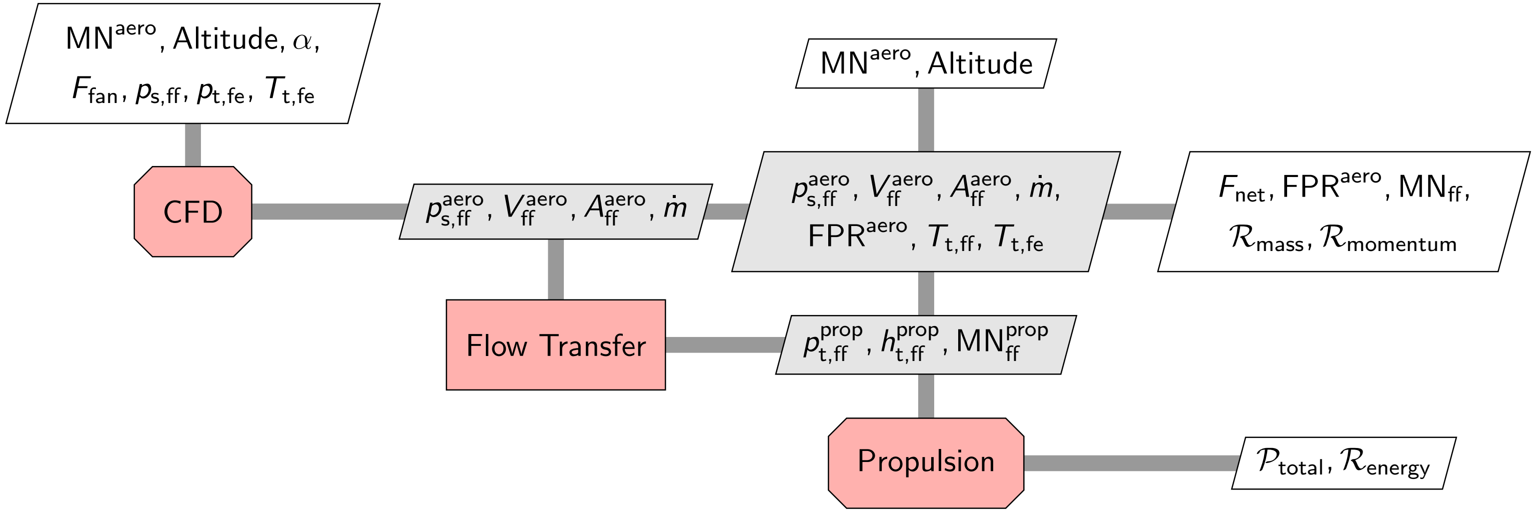




The aerodynamic and propulsion models are fully-coupled using momentum and energy terms

The boundary-condition (BC) version works with subsonic outflow and inflow BCs in the CFD model

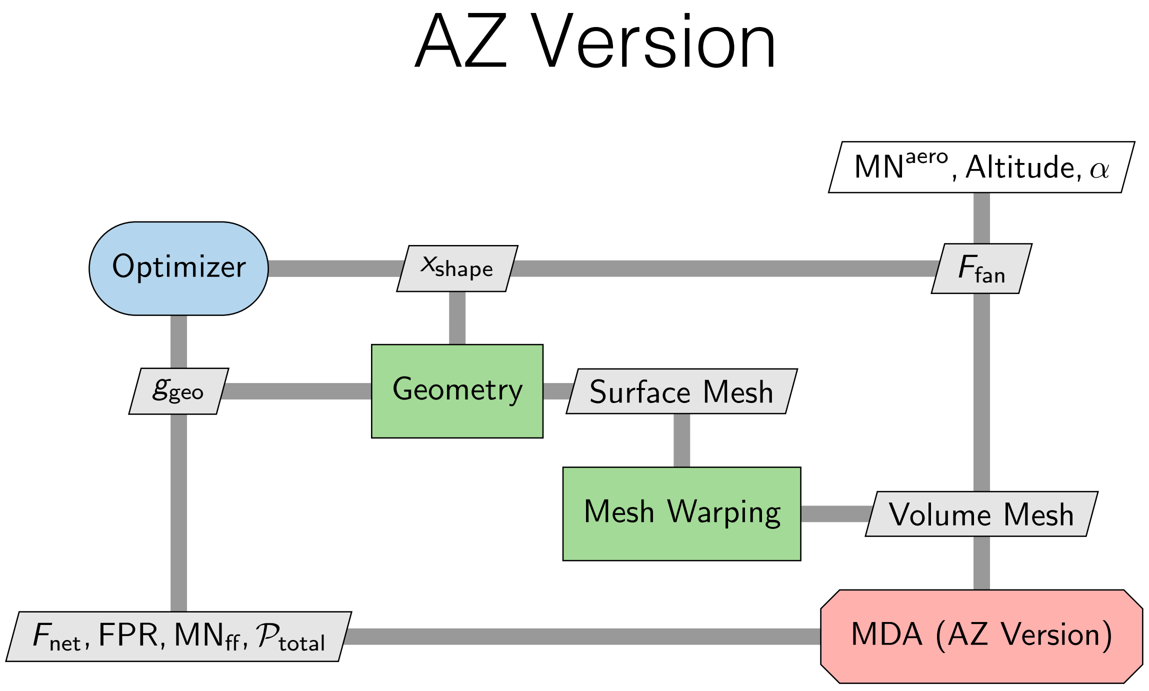


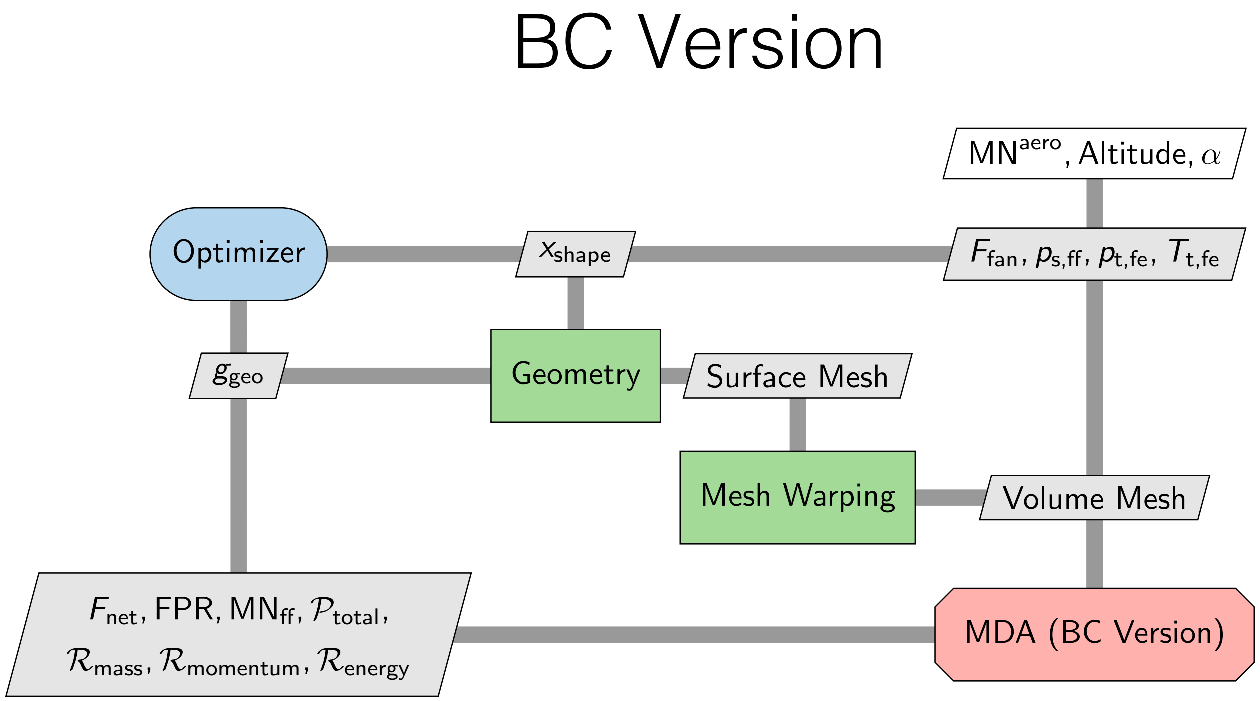


$$\mathcal{R}_{\mathrm{mass}}(p_{\mathrm{s,ff}}, p_{\mathrm{t,fe}}, T_{\mathrm{t,fe}}) = 0$$
$$\mathcal{R}_{\mathrm{momentum}}(p_{\mathrm{s,ff}}, p_{\mathrm{t,fe}}, T_{\mathrm{t,fe}}) = 0$$
$$\mathcal{R}_{\mathrm{energy}}(p_{\mathrm{s,ff}}, p_{\mathrm{t,fe}}, T_{\mathrm{t,fe}}) = 0$$

The fully-coupled model is achieved using constraints that enforce conservation across the fan

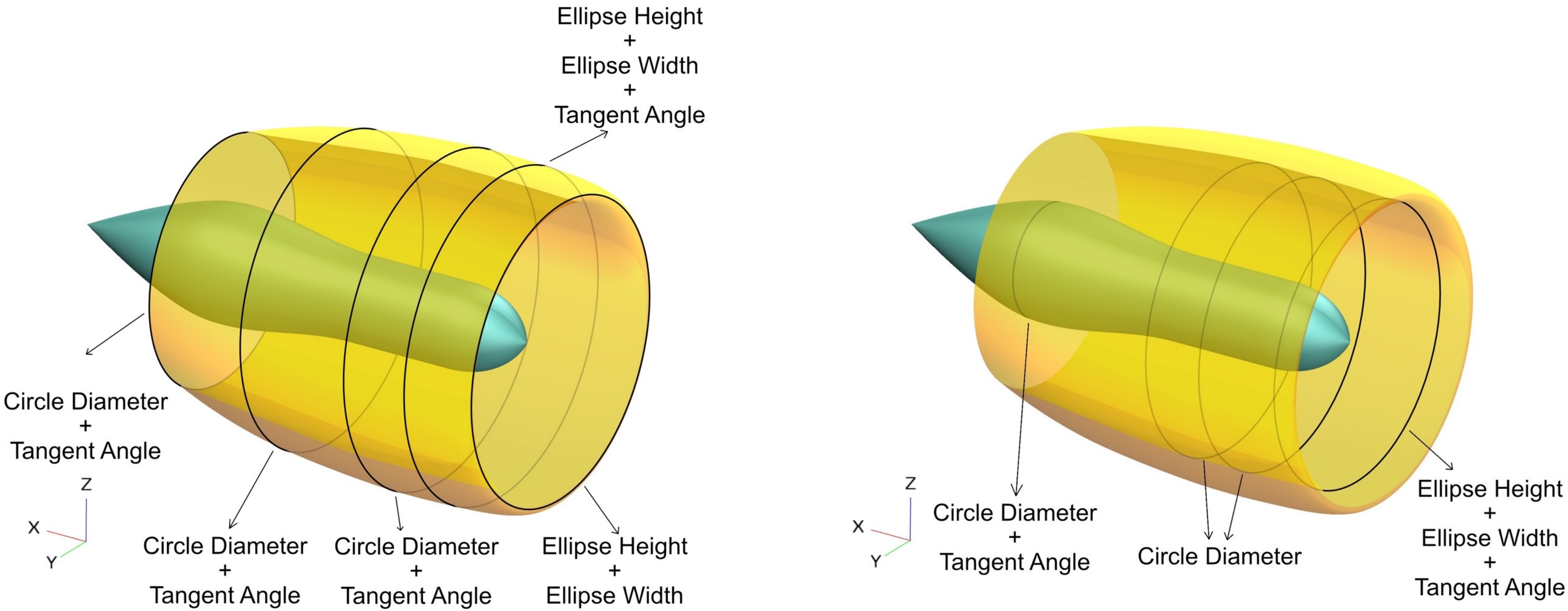
Single-point optimization structure only includes components to modify the design geometry and a single-MDA





Only difference in the BC version compared to the AZ version is the inclusion of BC values and constraints

The geometry is parametrized using OpenVSP



Single-point optimizations minimize power at cruise at a target net thrust and fan pressure ratio (FPR)

AZ Version

	Variable/Function	Description	Quantity
minimize	$\mathcal{P}_{\text{total}}$	Power required for the fan	1
with respect to	F_{fan}	Force applied by the fan	1
	x_{plug}	Plug shape	2
	x_{nacelle}	Nacelle shape	15
		Total	18
subject to	$F_{\text{net}} = F^*_{\text{net}}$	Target net thrust	1
	$\text{FPR} = \text{FPR}^*$	Target FPR	1
	$\text{MN}_{\text{ff}} < 0.6$	Upper limit of fan face Mach number	1
	$0.99 < g_{\text{geo}} < 3.0$	Geometric thickness constraints	14
		Total	17

BC Version

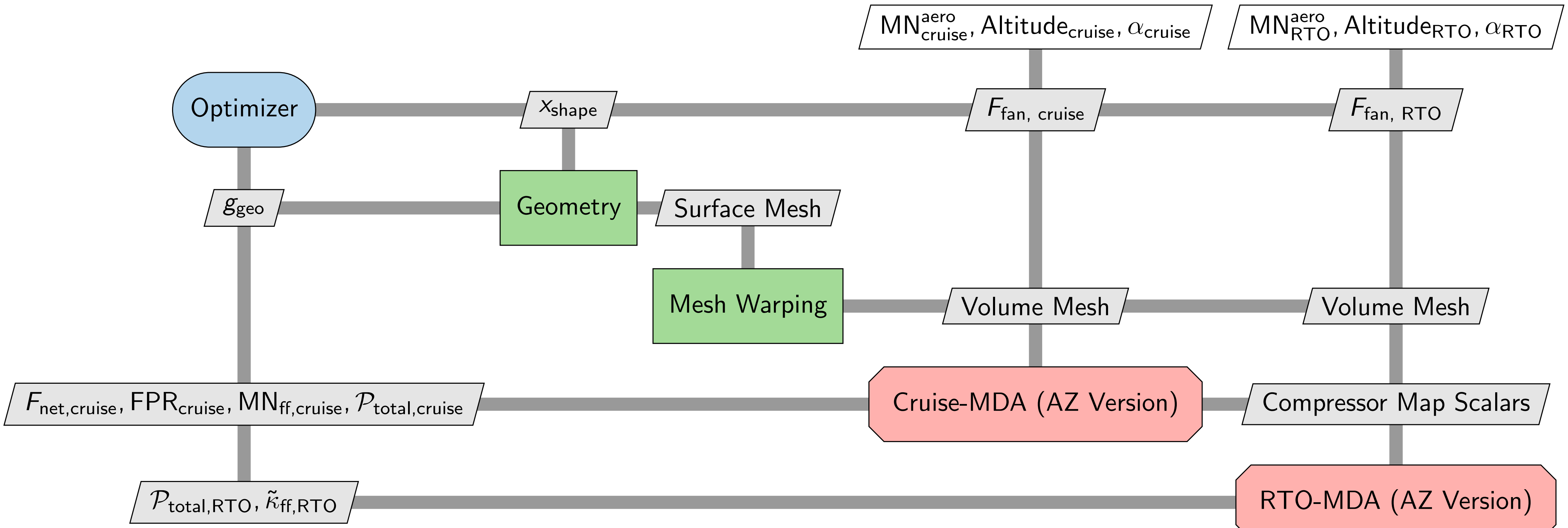
	Variable/Function	Description	Quantity
minimize	$\mathcal{P}_{\text{total}}$	Power required for the fan	1
with respect to	F_{fan}	Force applied by the fan	1
	x_{plug}	Plug shape	2
	x_{nacelle}	Nacelle shape	15
	$P_{\text{s,ff}}$	Static pressure at fan face	1
	$P_{\text{t,fe}}$	Total pressure at fan exit	1
	$T_{\text{t,fe}}$	Total temperature at fan exit	1
		Total	21
subject to	$F_{\text{net}} = F^*_{\text{net}}$	Target net thrust	1
	$\text{FPR} = \text{FPR}^*$	Target FPR	1
	$\text{MN}_{\text{ff}} < 0.6$	Upper limit of fan face Mach number	1
	$0.99 < g_{\text{geo}} < 3.0$	Geometric thickness constraints	14
	$\mathcal{R}_{\text{mass}} = 0$	Conservation of mass across the fan	1
	$\mathcal{R}_{\text{momentum}} = 0$	Conservation of momentum across the fan	1
	$\mathcal{R}_{\text{energy}} = 0$	Conservation of energy across the fan	1
		Total	20

We performed a parameter sweep of 5 net thrust and 5 FPR values for a total of 25 optimizations with each model

AZ Version

BC Version

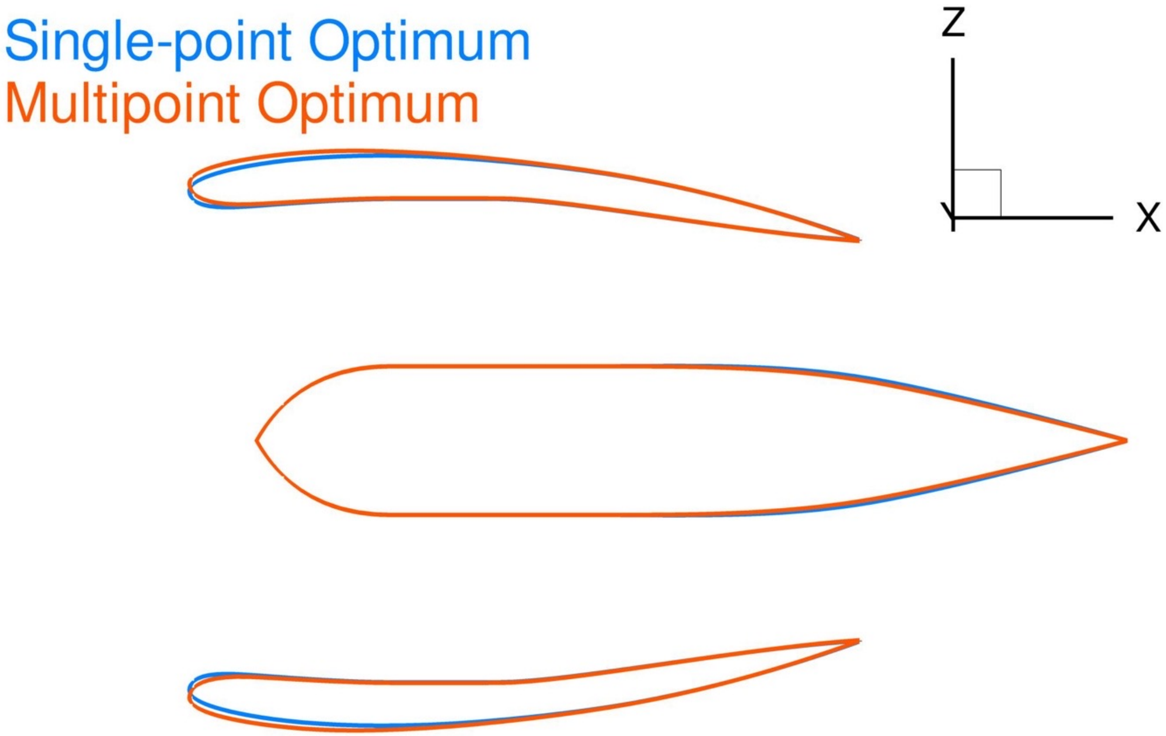
Multipoint optimizations simulate the same design at multiple flight conditions

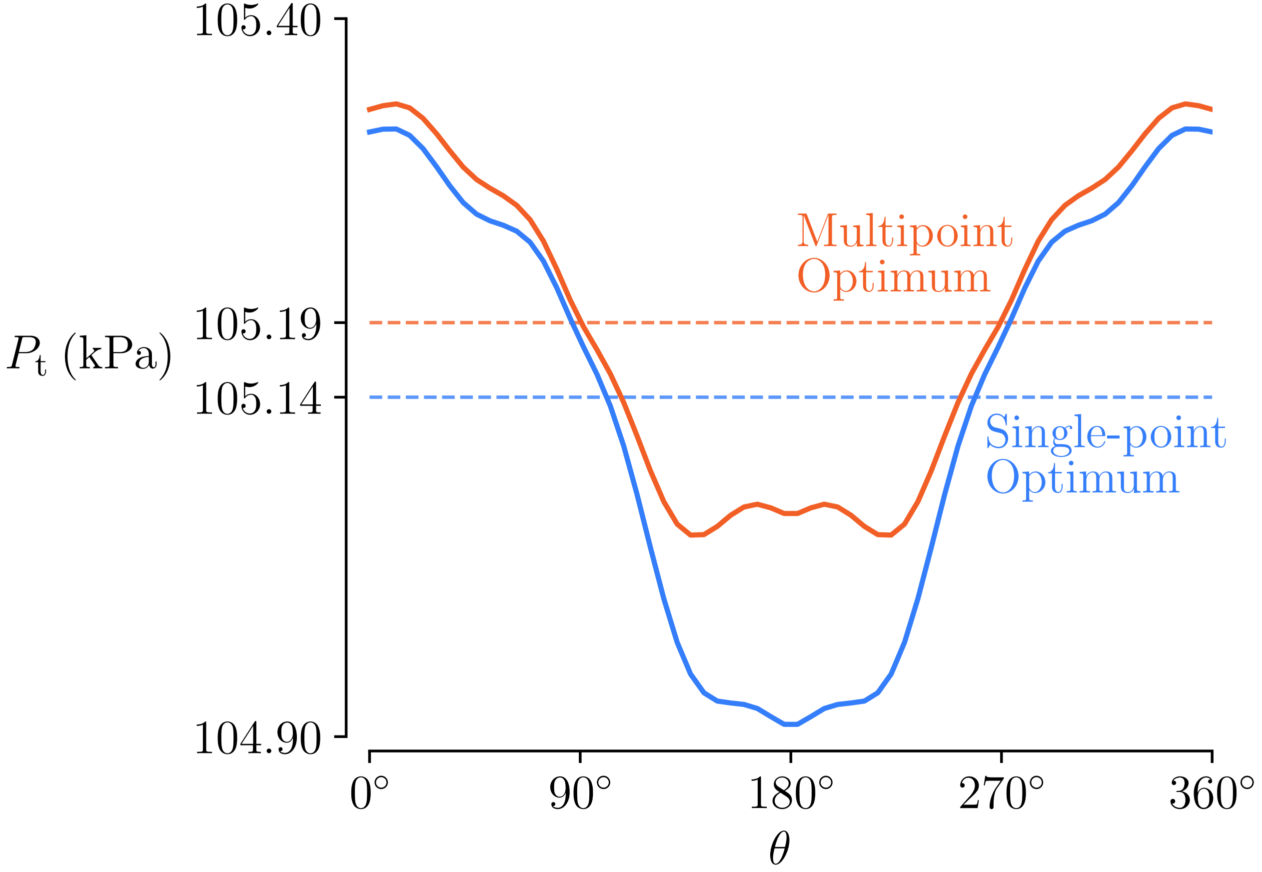


Multipoint optimizations also include a fan-face distortion constraint at rolling take off (RTO)

	Variable/Function	Description	Quantity
minimize	$\mathcal{P}_{\text{total, cruise}}$	Power required for the fan at cruise	1
with respect to	$F_{\text{fan, cruise}}$	Force applied by the fan at cruise	1
	$F_{\text{fan, RTO}}$	Force applied by the fan at RTO	1
	x_{plug}	Plug shape	2
	x_{nacelle}	Nacelle shape	15
		Total	19
subject to	$F_{\text{net, cruise}} = F^*_{\text{net, cruise}}$	Target net thrust at cruise	1
	$\text{FPR}_{\text{cruise}} = \text{FPR}^*_{\text{cruise}}$	Target FPR at cruise	1
	$\text{MN}_{\text{ff, cruise}} < 0.6$	Upper limit of fan face Mach number at cruise	1
	$\mathcal{P}_{\text{total, RTO}} = \mathcal{P}_{\text{total, cruise}}$	RTO total power constraint	1
	$\tilde{\kappa}_{\text{ff, RTO}} < 0.001$	Upper limit of KS-aggregated fan face distortion at RTO	1
	$0.99 < g_{\text{geo}} < 3.0$	Geometric thickness constraints	14
		Total	19

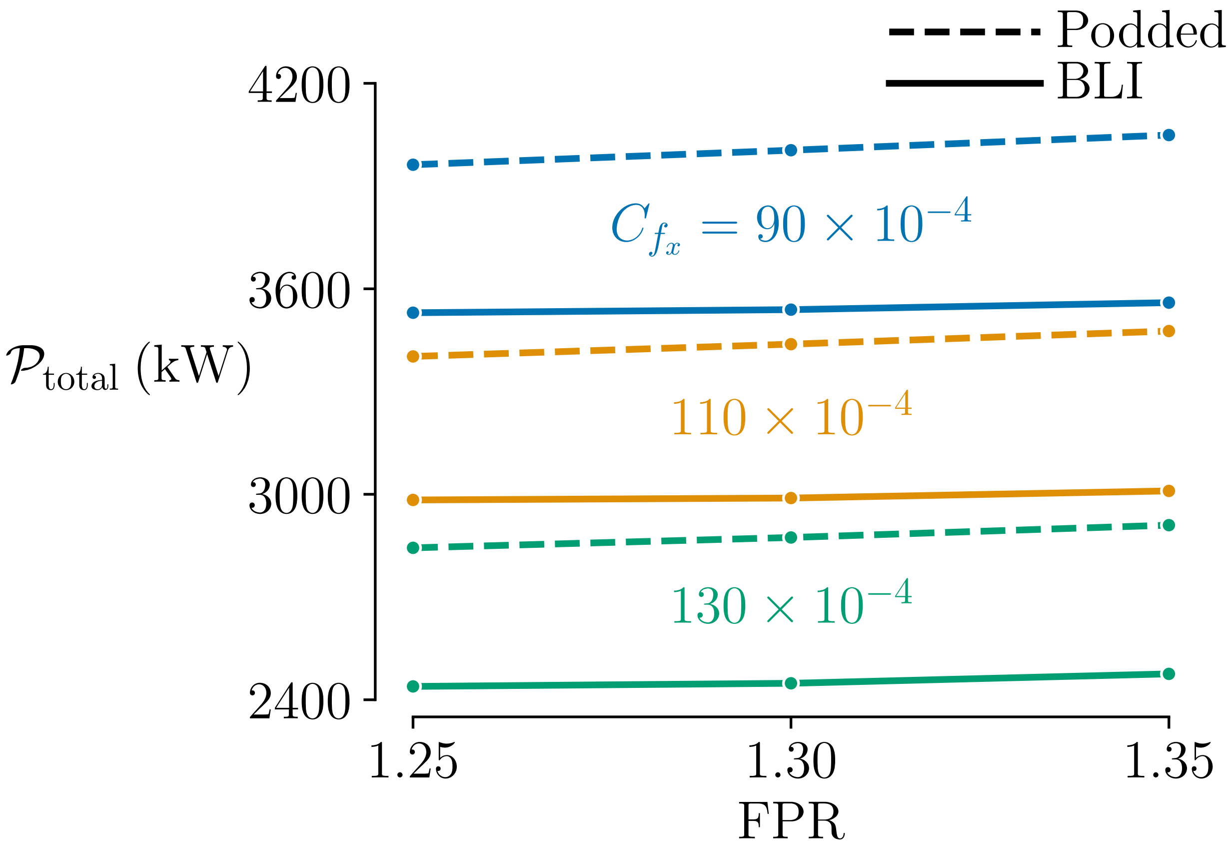
Multipoint optimization reduced the fan face distortion at RTO by 35%, at the cost of 0.12% higher power at cruise

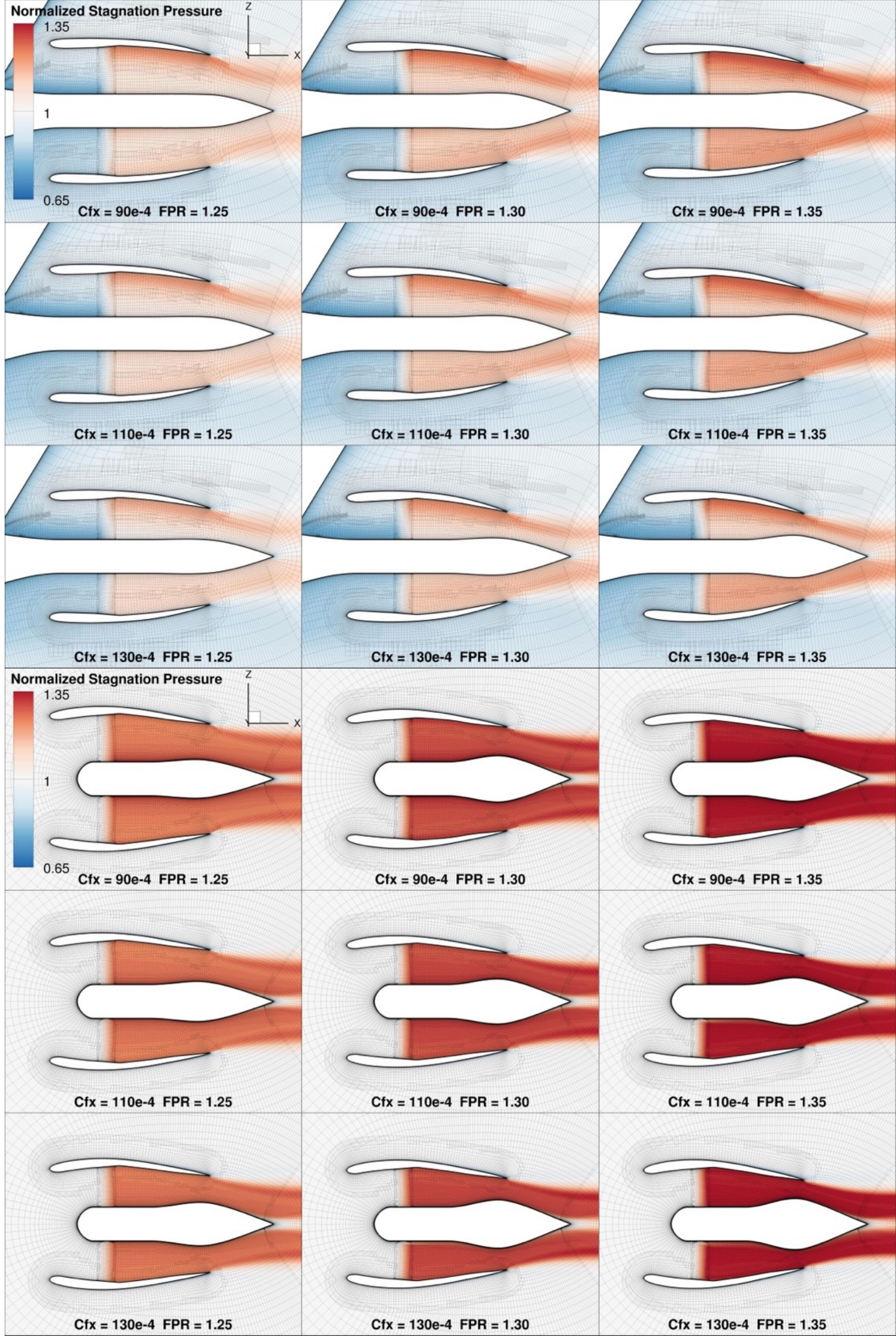




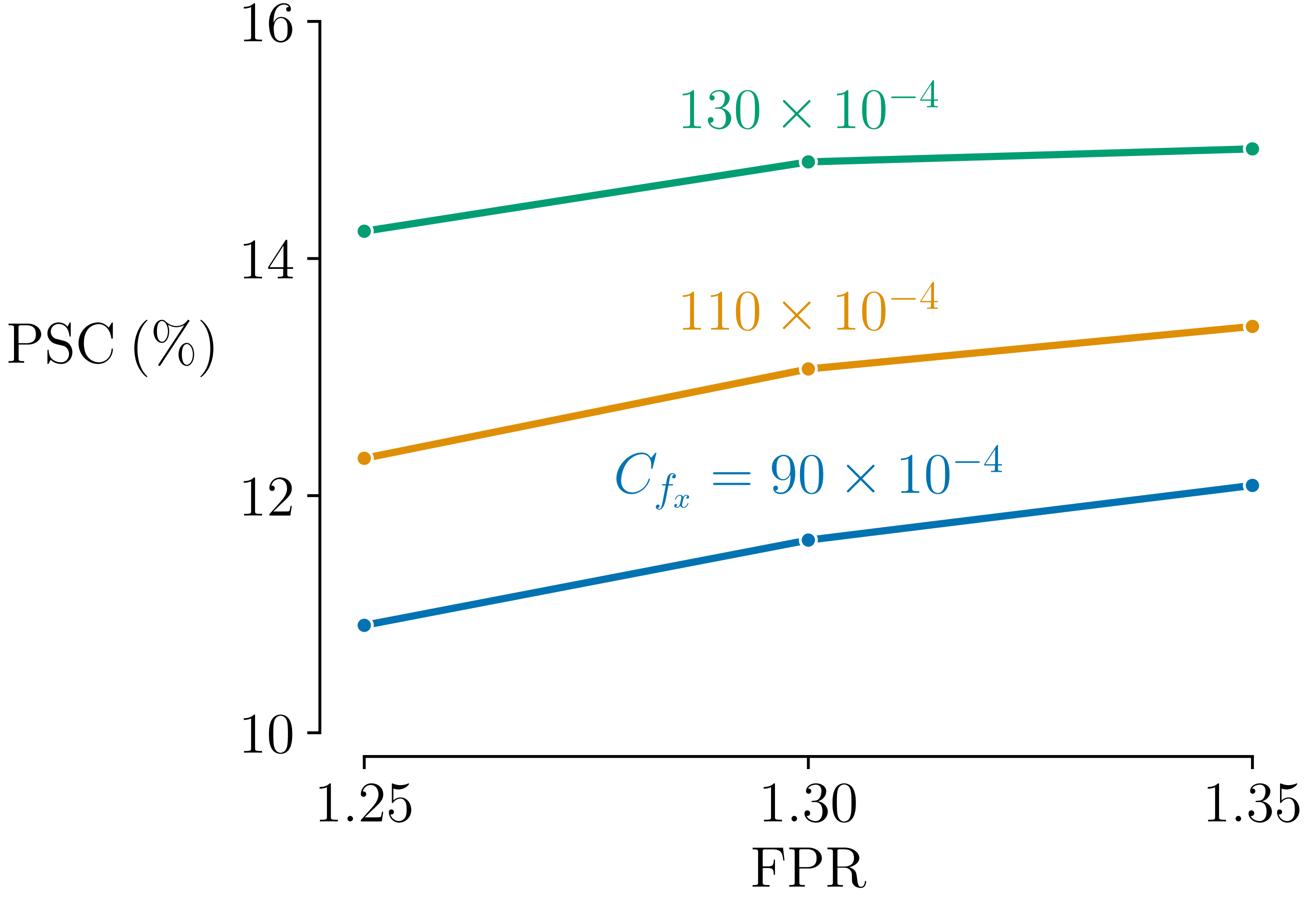
Multipoint design optimization can significantly improve off-design performance at the cost of a small performance penalty at the design point

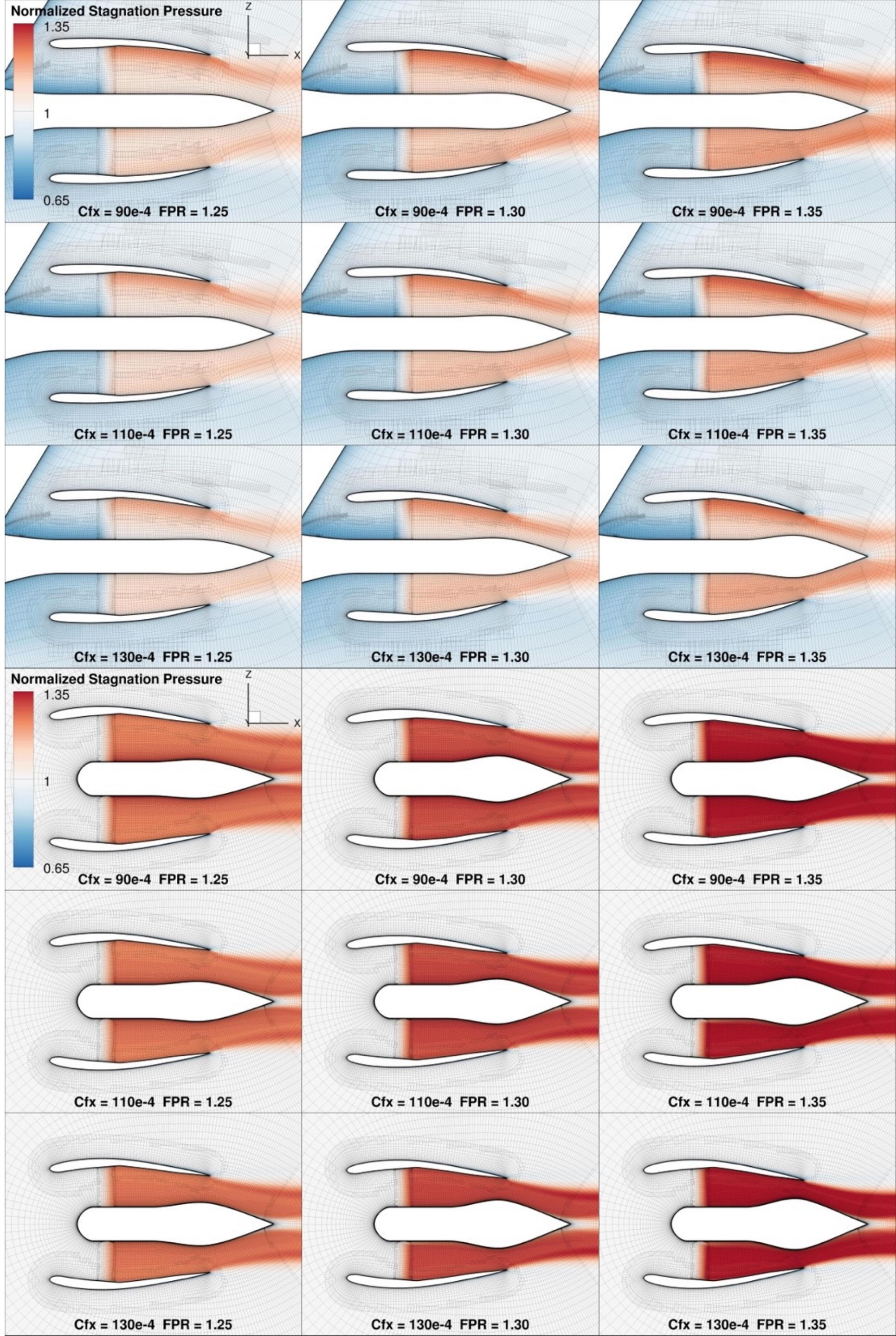
We performed 18 CFD-based aeropropulsive design optimizations



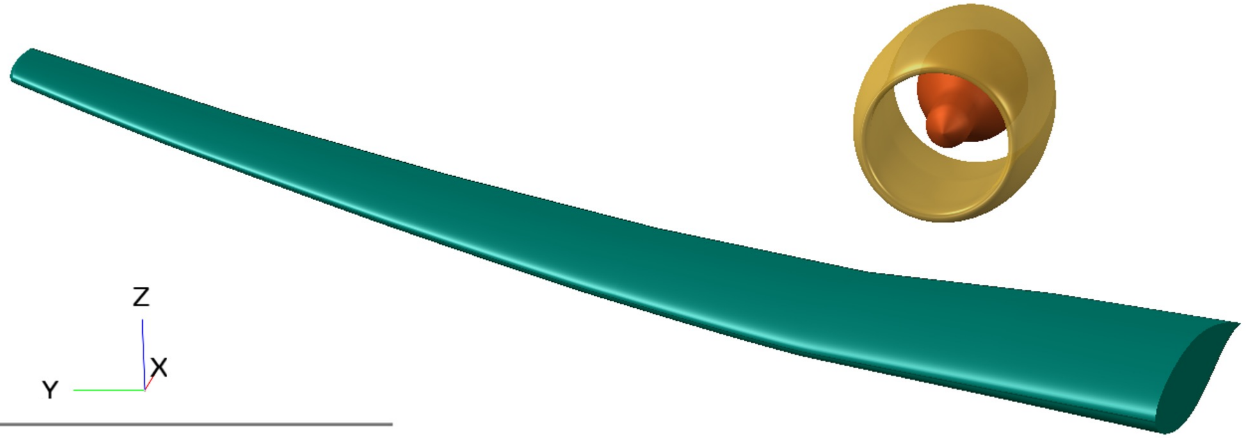


We computed the PSC values at 9 design points



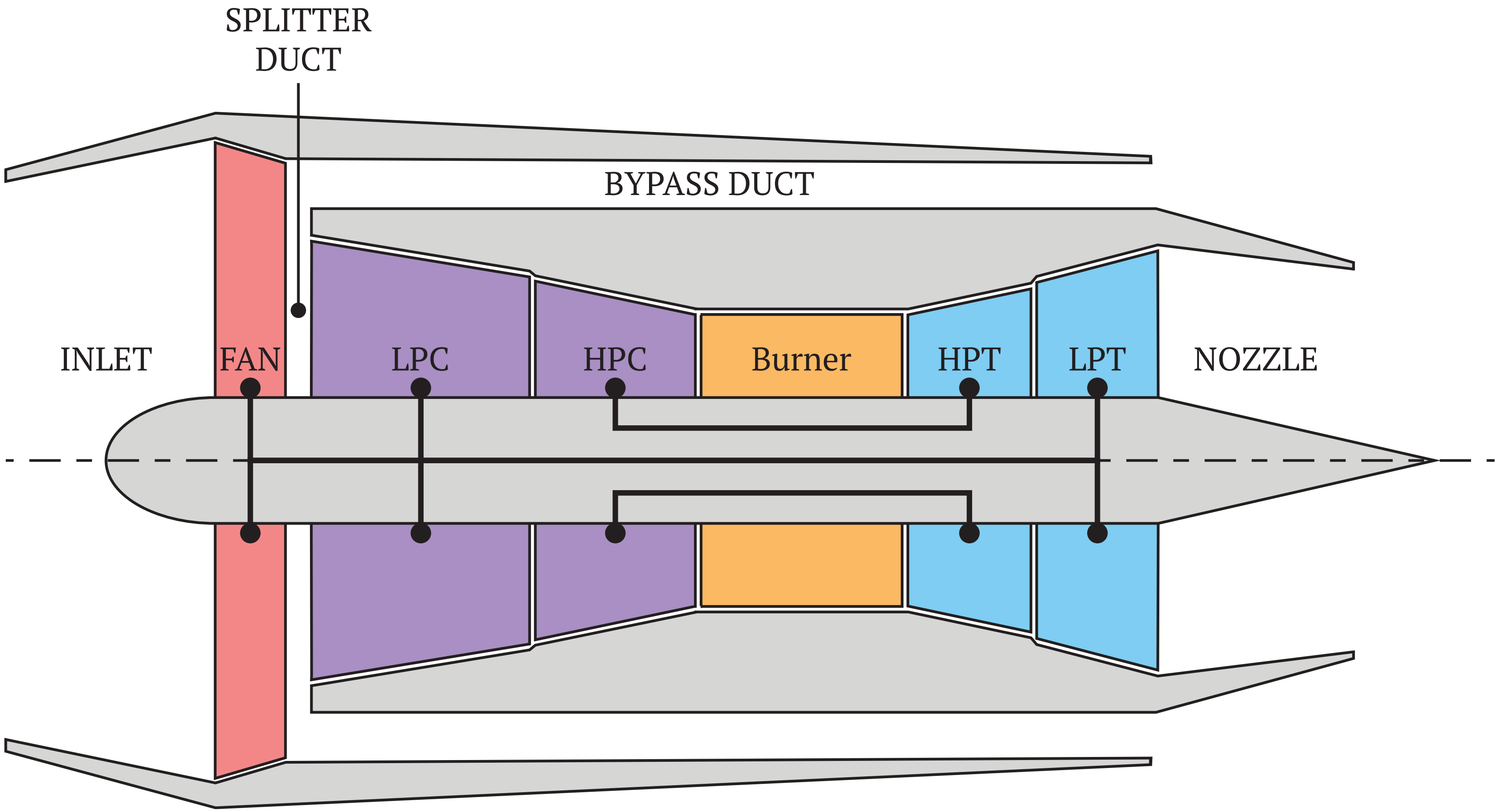


Saja Kaiyoom is using the methodology on other coupled aircraft design problems

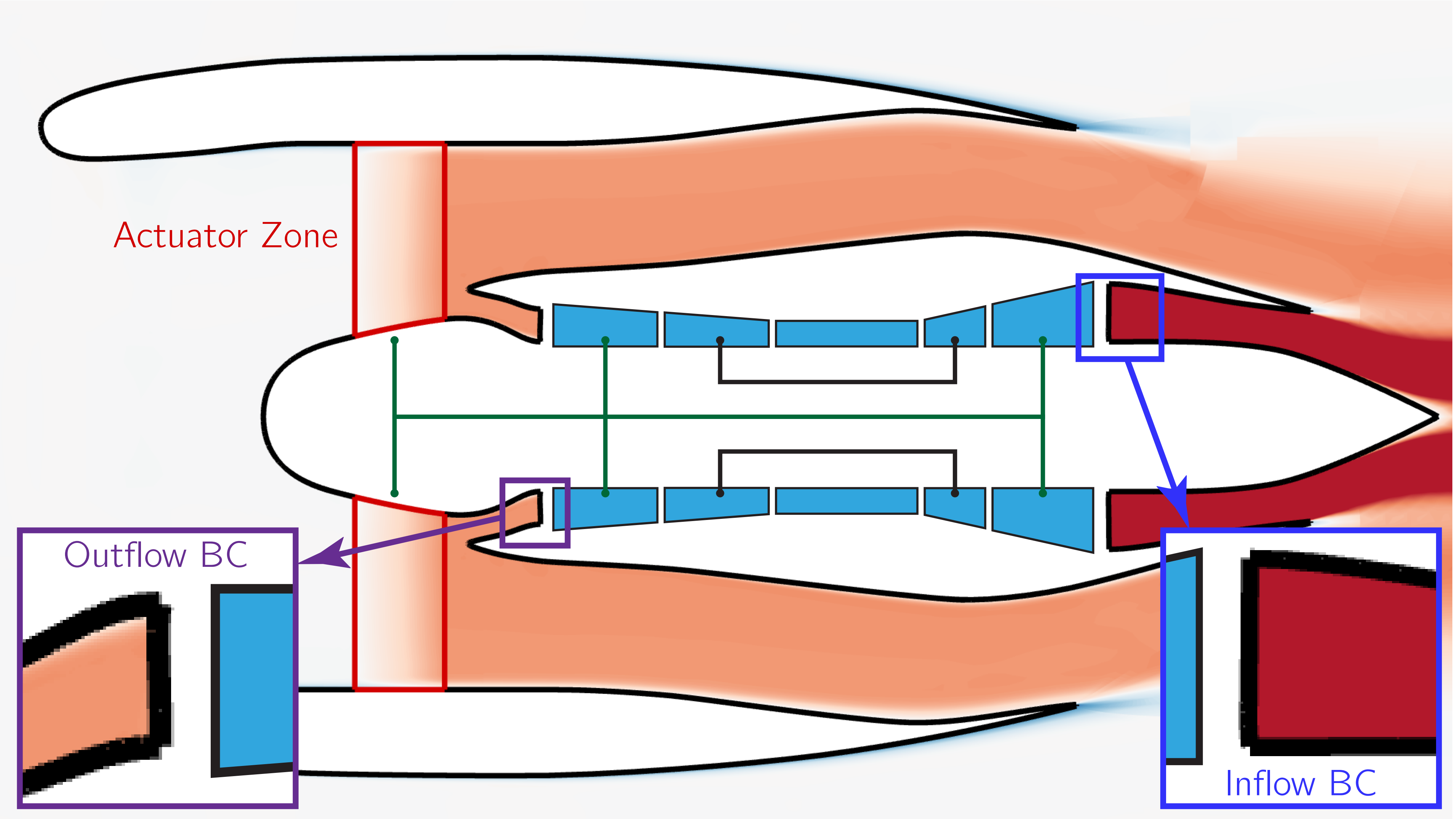


	Function/Variable	Description
Minimize shaft power of the fan		
With respect to	X_{Geo}	Geometry design variables
	T_{Fan}	Fan thrust
	α	Angle of attack
Subject to	$T_{total} = T^*_{total}$	Total net thrust
	$FPR = FPR^*$	Fan pressure ratio
	$C_L = C^*_L$	Lift coefficient
	$M_{fan} \leq M_{fan_{\max}}$	Fan face mach number constraint
	$t_{\min} \leq t_{Wing} \leq t_{\max}$	Thickness constraint for wing
	$t_{\min} \leq t_{Nacelle} \leq t_{\max}$	Thickness constraint for nacelle
	$V \geq V_{\min}$	Volume constraint for wing

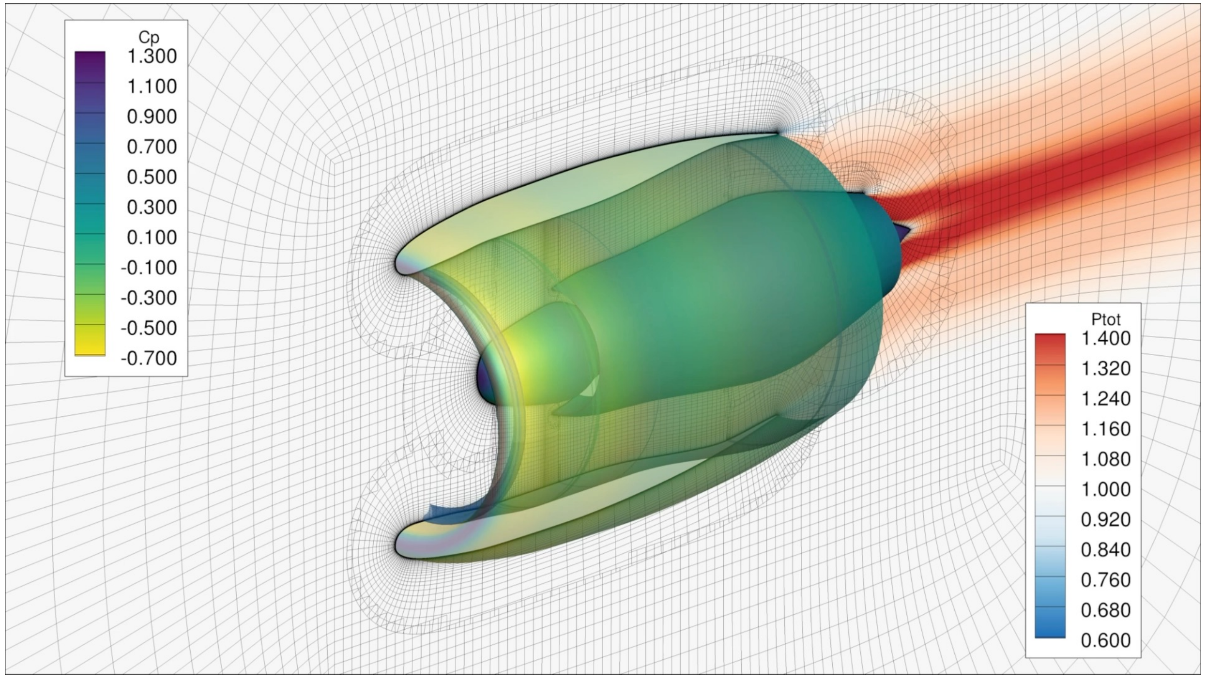
Andrew Lamkin is developing the capability further to optimize complete turbofan engines

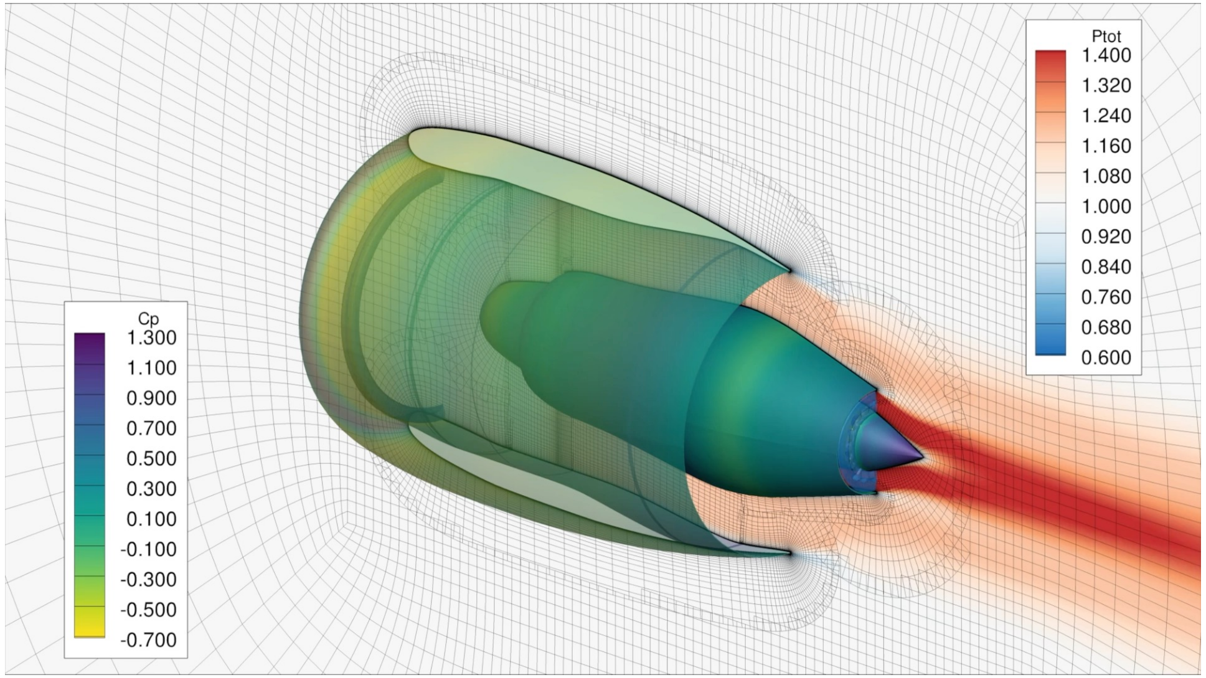


The turbofan model uses both AZ and BC coupling approaches



We are making steady progress in complete engine optimization!





The optimizer finds a shock free design at the optimum
and minimizes variations in pressure coefficient along the nacelle.

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Eleventh International Conference on Computational Fluid Dynamics (ICCFD11), Maui, HI, USA, July 11-15, 2022

ICCFD11-2022-0702

A Nonlinear Schur Complement Solver for CFD-Based Multidisciplinary Models

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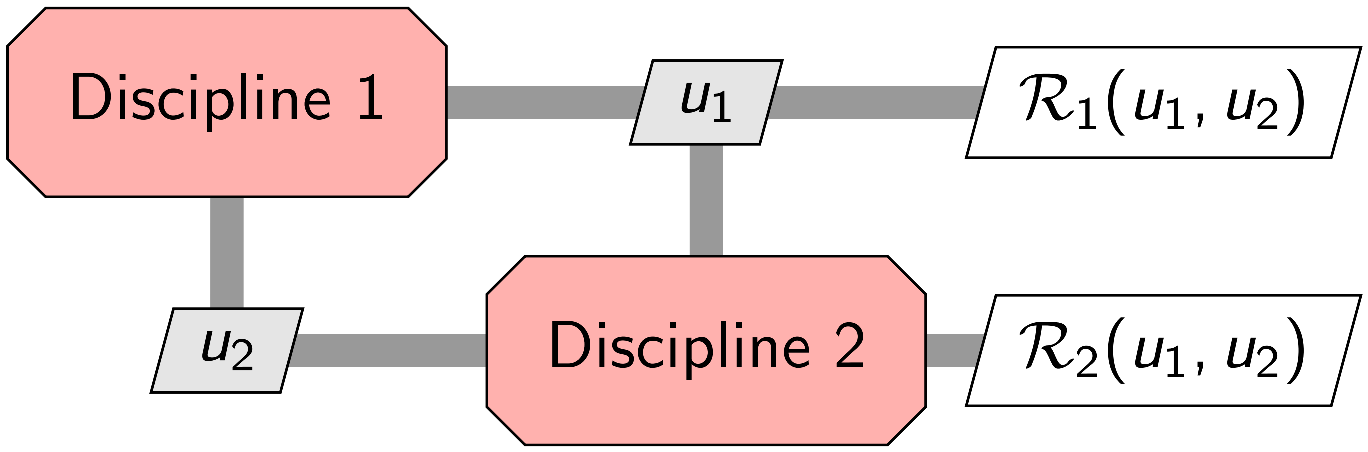
Equality constraints commonly show up in engineering design optimization

Minimize	C_D
with respect to	X_{Shape}
	α
subject to	$C_L = {C_L}^*$

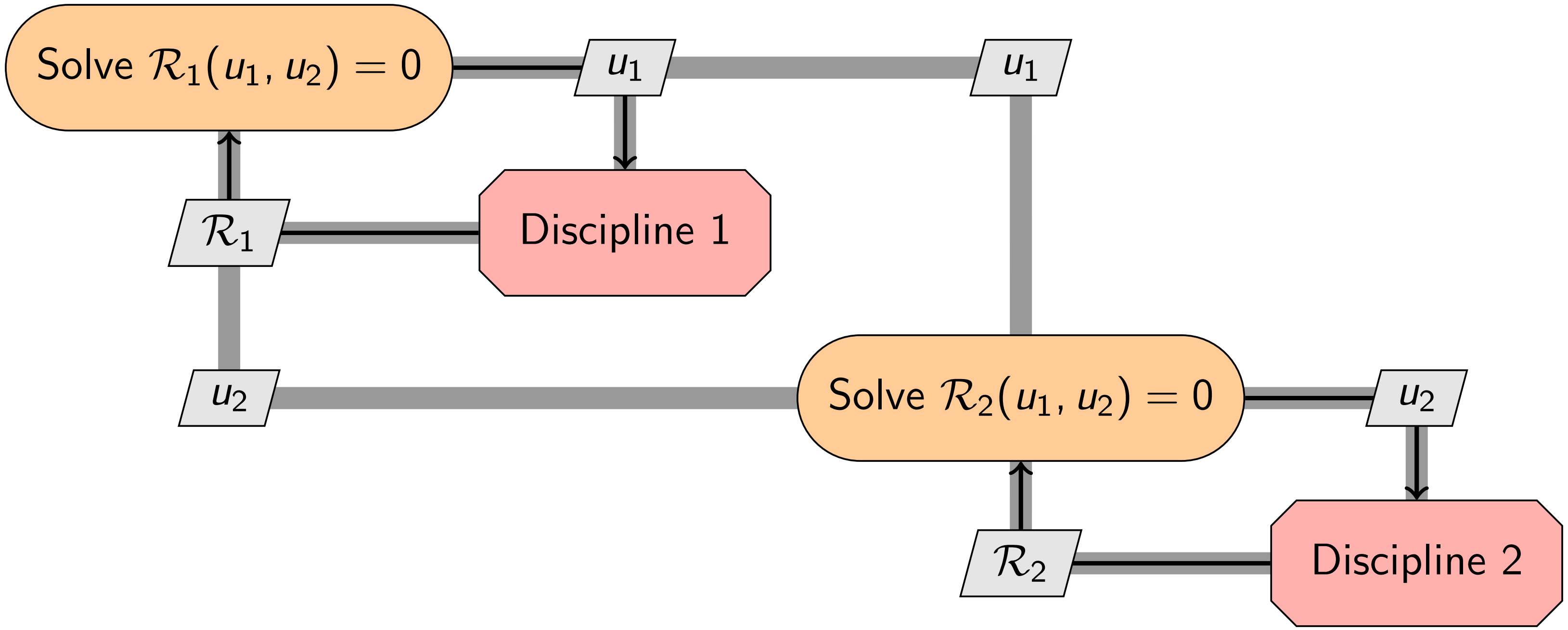
The lift constraint can be satisfied by solving an additional "balance" equation

Minimize	C_D	
with respect to	X_{Shape}	$R_{CFD}(u_{CFD}, \alpha) = 0$
	α	$R_{C_L}(u_{CFD}, \alpha) = C_L - {C_L}^* = 0$
subject to	$C_L = {C_L}^*$	

Models with balance components can be divided into two "disciplines"

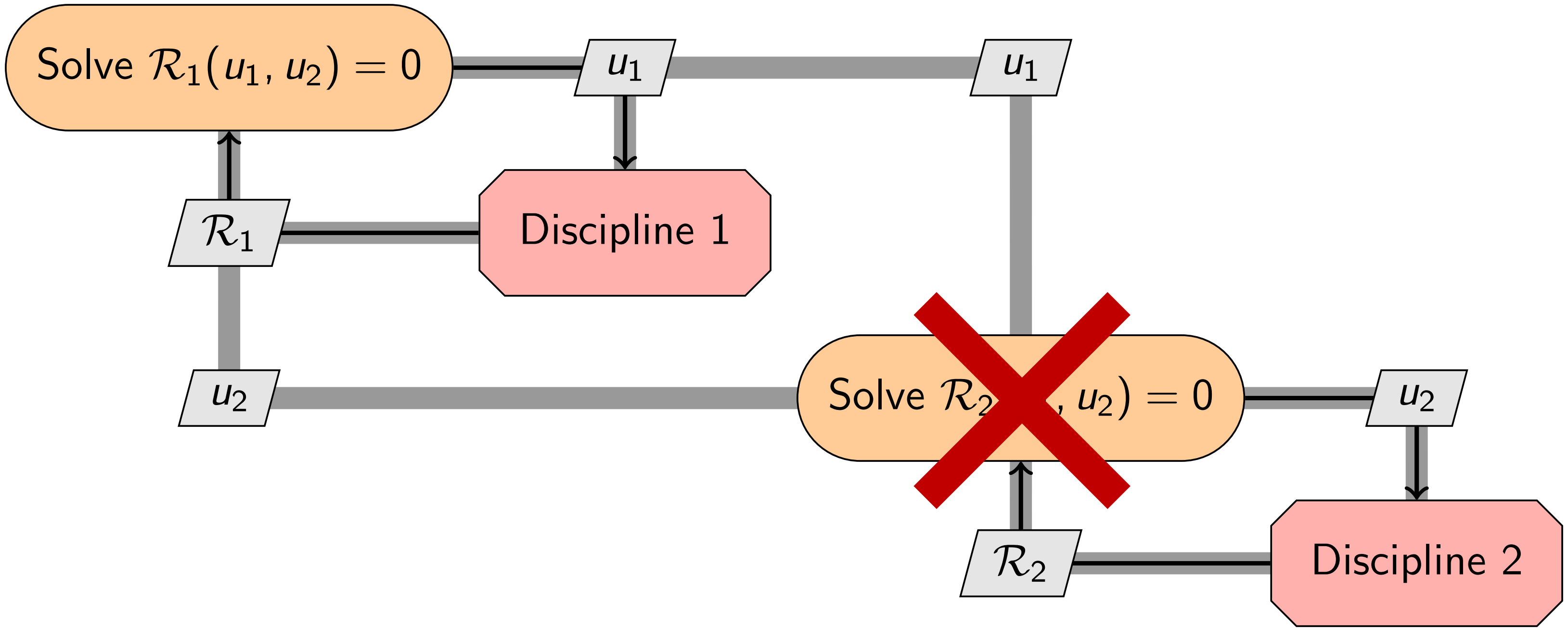


The nonlinear block Gauss–Seidel method is the most common approach for solving these models



Each disciplinary model is solved individually, and the process is iterated until the coupled system converges

Gauss–Seidel-based methods cannot be used with saddle point problems

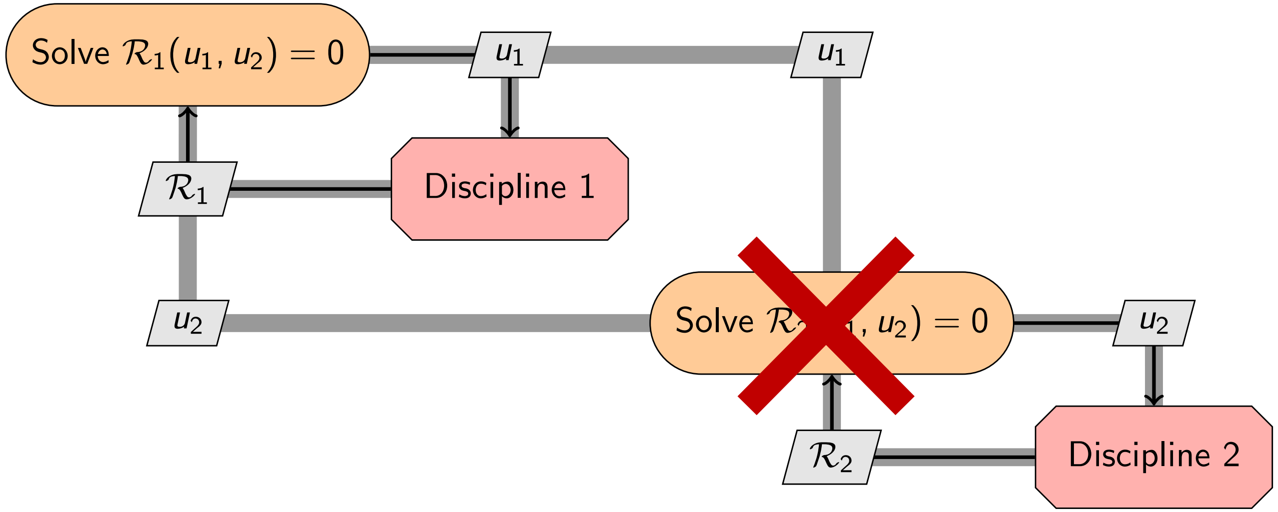


Saddle point problems appear when a given discipline cannot be solved by just varying its own states

The diagonal sub-block of the Jacobian matrix is non-invertible with saddle point problems

$$R_{CFD}(u_{CFD}, \alpha) = 0$$

$$R_{C_L}(u_{CFD}, \alpha) = C_L - {C_L}^* = 0$$



$$\frac{\partial \mathcal{R}}{\partial u} = \begin{bmatrix} \frac{\partial \mathcal{R}_1}{\partial u_1} & \frac{\partial \mathcal{R}_1}{\partial u_2} \\ \frac{\partial \mathcal{R}_2}{\partial u_1} & 0 \end{bmatrix}$$

The residuals of the second discipline do not depend on its own states directly

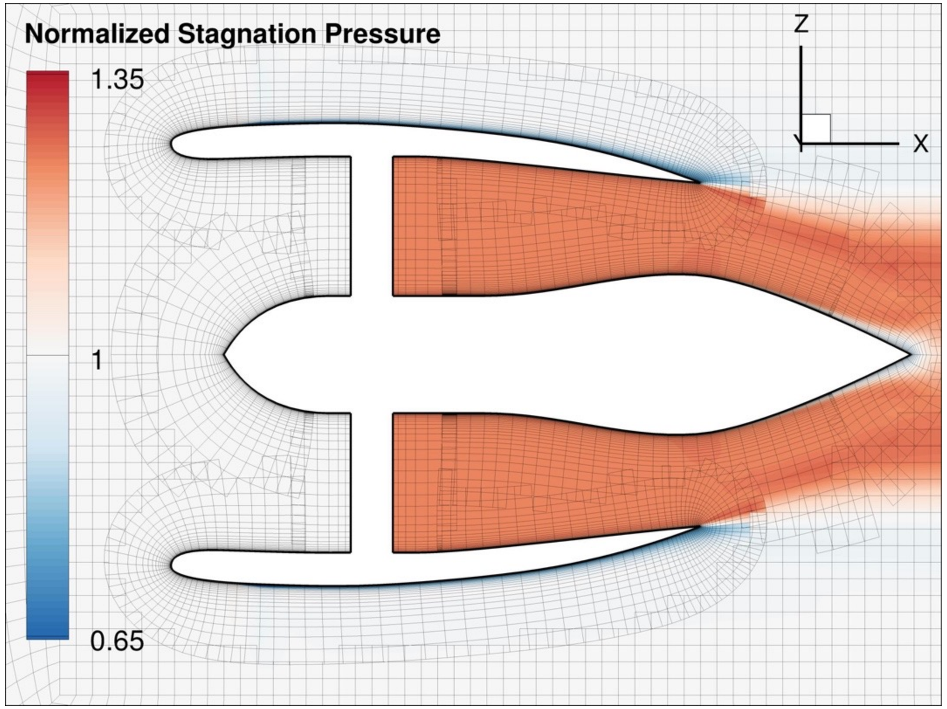
The NSC solver iterates between the two disciplines until convergence

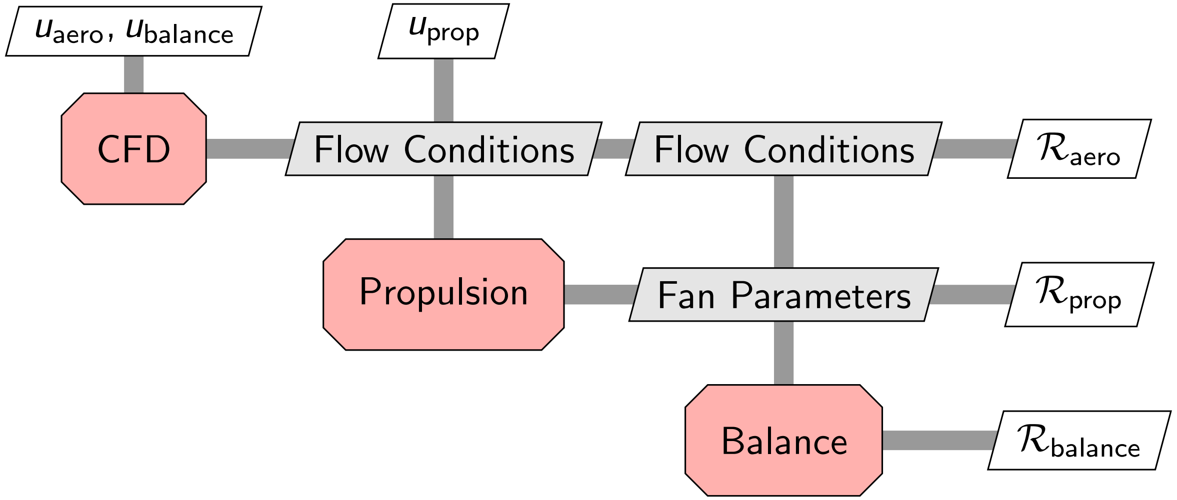
1. Solve $\mathcal{R}_1(u_1, u_2) = 0$ by varying u_1
2. Update u_2 using the Schur complement:

$$\left(\frac{\partial \mathcal{R}_2}{\partial u_2} - \frac{\partial \mathcal{R}_2}{\partial u_1} \left(\frac{\partial \mathcal{R}_1}{\partial u_1} \right)^{-1} \frac{\partial \mathcal{R}_1}{\partial u_2} \right) \Delta u_2 = -\mathcal{R}_2(u_1, u_2)$$

3. Repeat until convergence

The benchmark aeropropulsive model uses subsonic outflow and inflow BCs in the CFD model

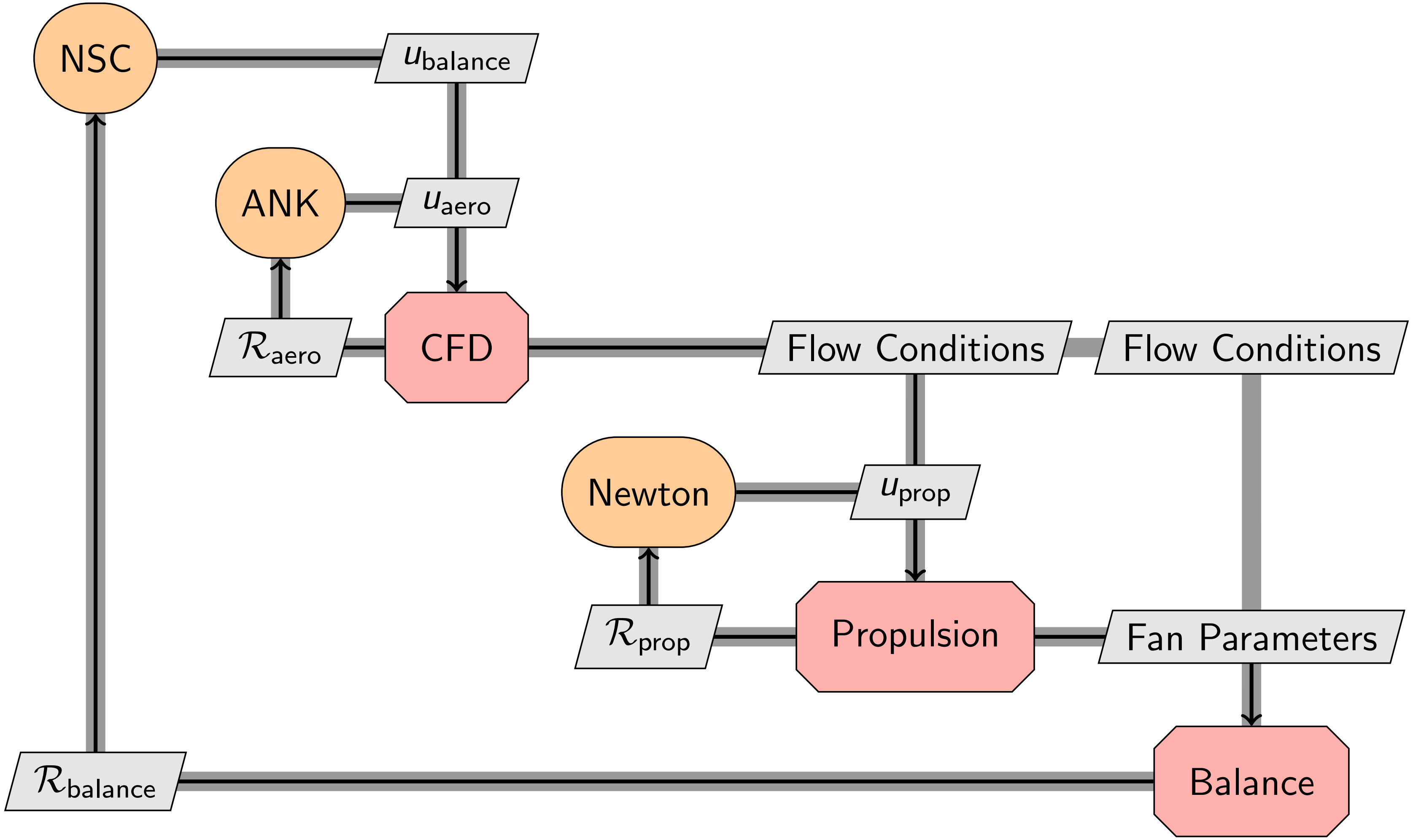




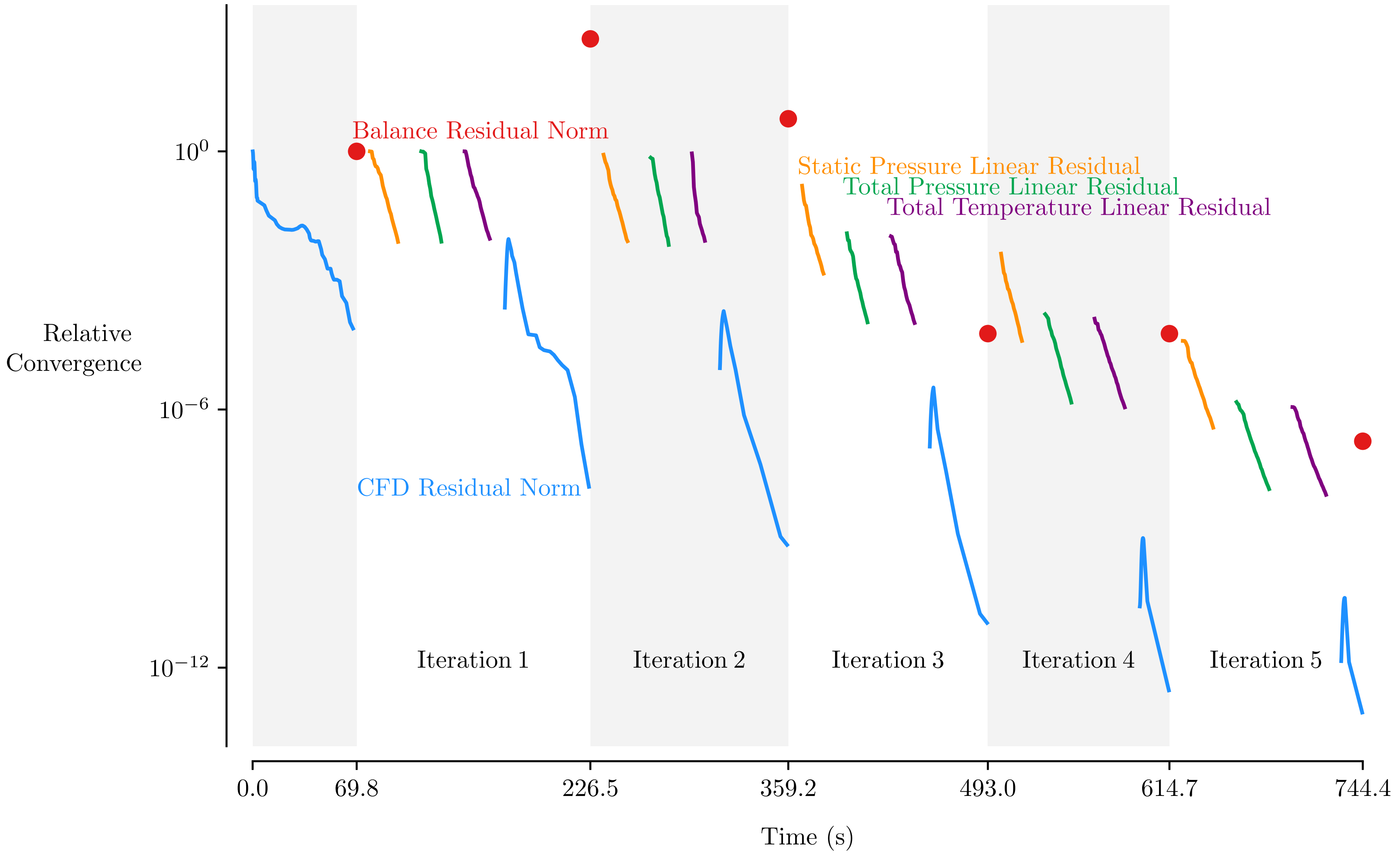
$$\mathcal{R}_{\text{mass}}(p_{\text{s,ff}}, p_{\text{t,fe}}, T_{\text{t,fe}}) = 0$$
$$\mathcal{R}_{\text{momentum}}(p_{\text{s,ff}}, p_{\text{t,fe}}, T_{\text{t,fe}}) = 0$$
$$\mathcal{R}_{\text{energy}}(p_{\text{s,ff}}, p_{\text{t,fe}}, T_{\text{t,fe}}) = 0$$

The fully-coupled model contains balance equations that enforce conservation across the fan

We use the NSC solver together with the specialized disciplinary solvers



The solver partially converges all systems until the coupled system reaches convergence



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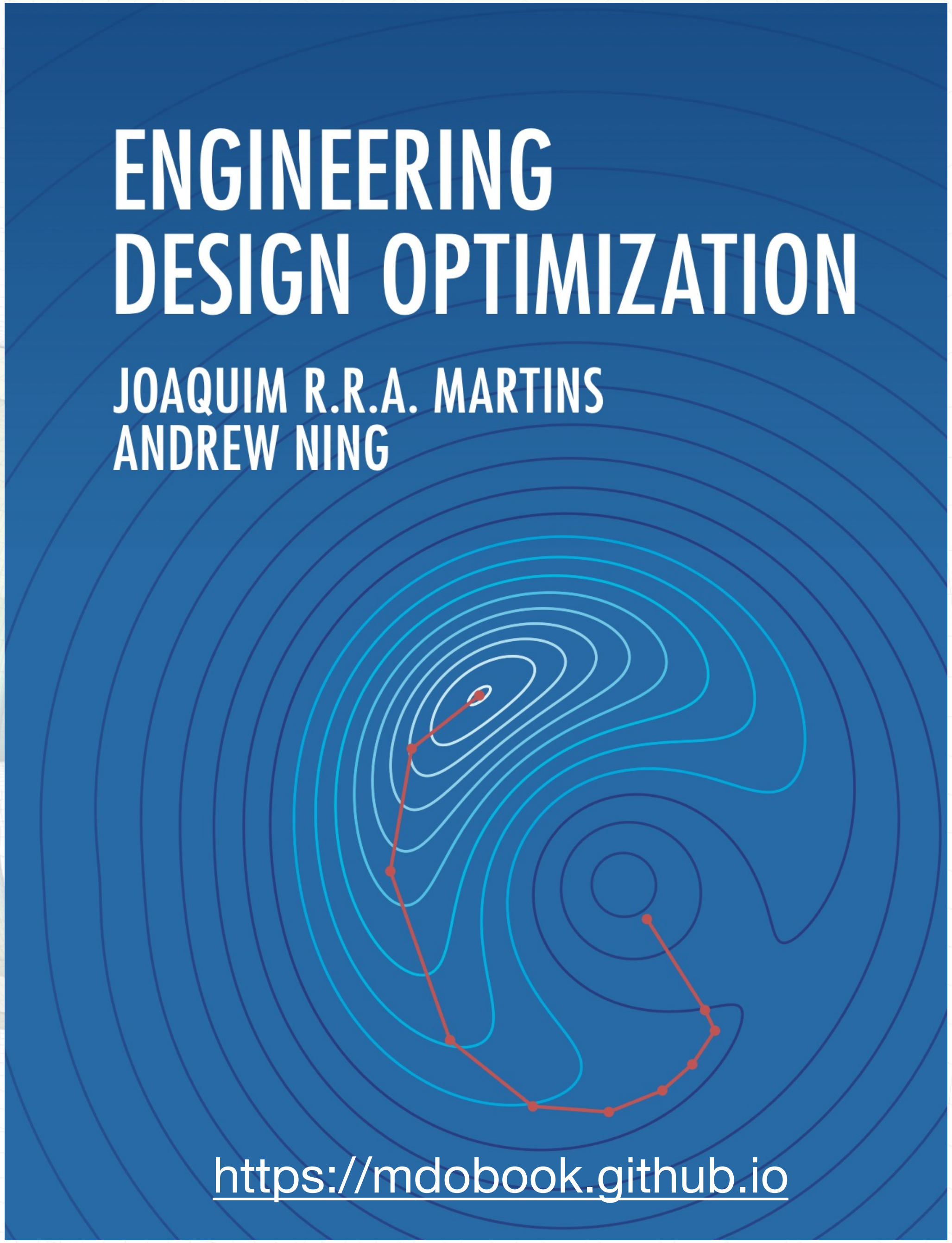

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