Aerodynamic shape optimization of the STARC-ABL Concept for minimal inlet distortion

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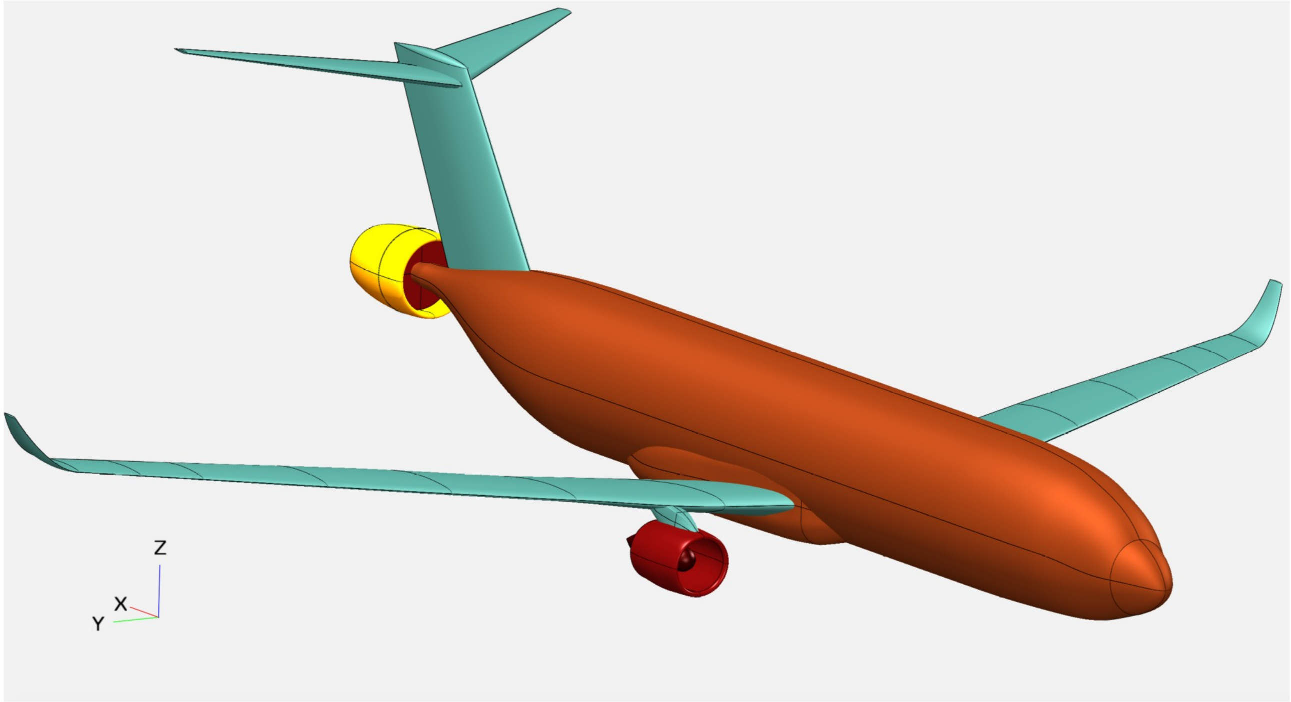
STARC-ABL

STARC-ABL: Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion

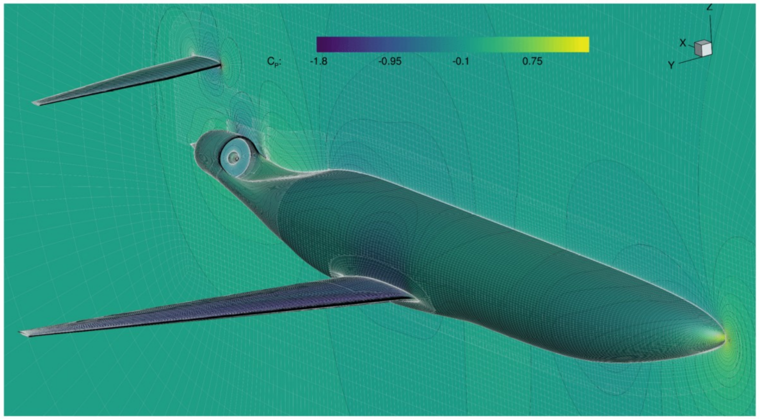
STARC-ABL Geometry

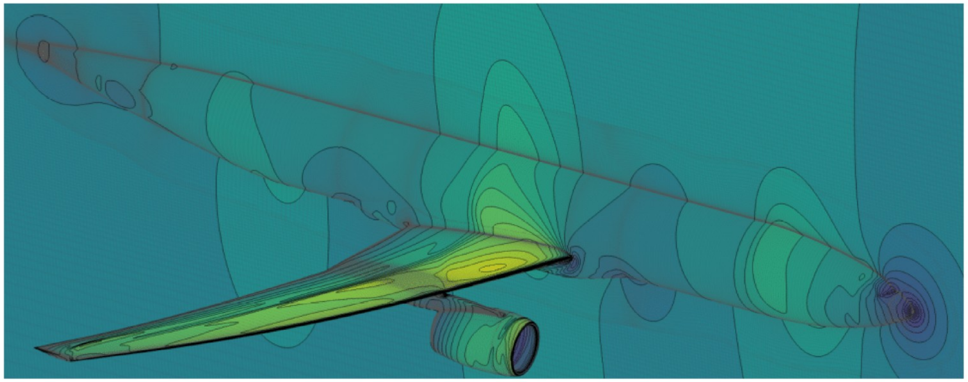
- Defined using Vehicle Sketch Pad (VSP)
- Two simplified geometries considered for optimization:
  - Body-Duct (bd) configuration
  - Wing-Body-Duct (wbd) configuration
- Model closely replicates the dimensions of a Boeing 737-800 sized aircraft



ADFlow

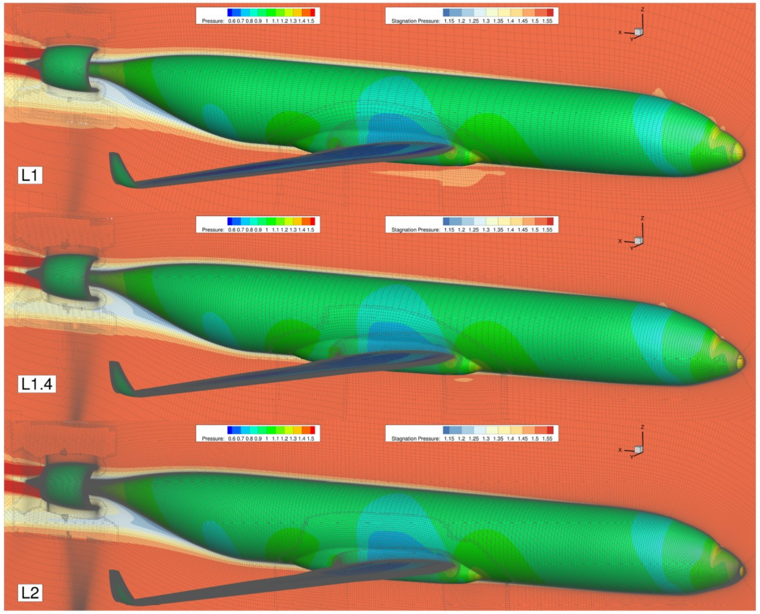
- Automatic-Differentation Flow Solver
- Second order finite volume RANS
- Standard SA turbulence model
- Point-matched multiblock or overset grids
- Multiple solvers: Runge Kutta (RK), DDADI, approximate Newton Krylov (ANK) and Newton Krylov (NK) algorithms
- Extremely fast convergence for small design changes
- Actuator Zone with source terms to model aft propulsor





Overset Meshes

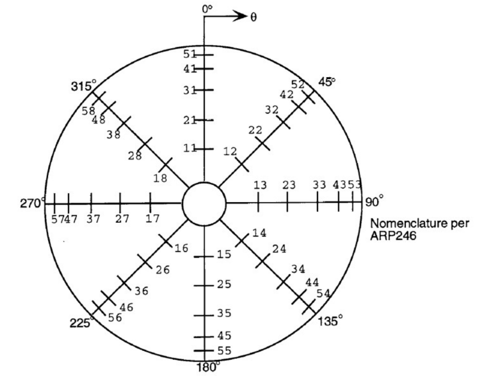
- Surface patches interpolated from plot3d VSP output
- Chimera Grid Tools (CGT) for volumetric extrusion
- Consistent refinement between levels

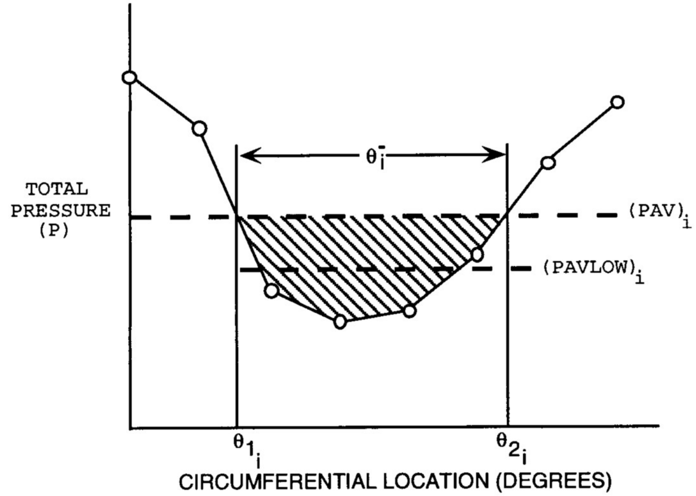


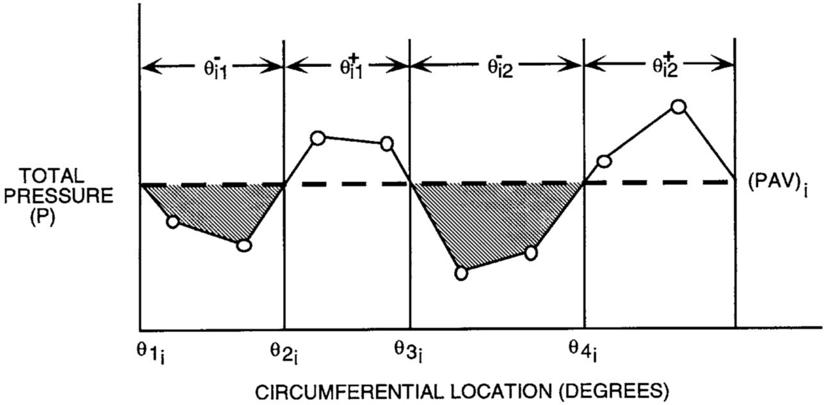
Mesh	Chordwise cells (wing)	Spanwise cells (wing)	Circumferential cells (duct)	$y^+_{\max}$	Total cells	ARP 1420 Distortion	C_D (counts)
wbd L1	92	135	60	~1.47	6 075 628	0.0506	246.86
wbd L1.4	134	188	84	~0.69	15 895 100	0.0505	245.67
wbd L2	192	266	120	~0.40	45 536 903	0.0510	244.38
bd L1	—	—	60	~0.37	2 925 912	0.0189	96.56
bd L1.4	—	—	84	~0.26	19 248 040	0.0194	96.39
bd L2	—	—	120	~0.18	22 127 620	0.0201	96.36

ARP 1420 Distortion Metric

- Describes inlet distortion for gas turbines
- Two categories:
  - Single per rev, MPR=1 (left)
  - Multiple per rev, MPR > 1 (right)
- Smooth KS function across rings





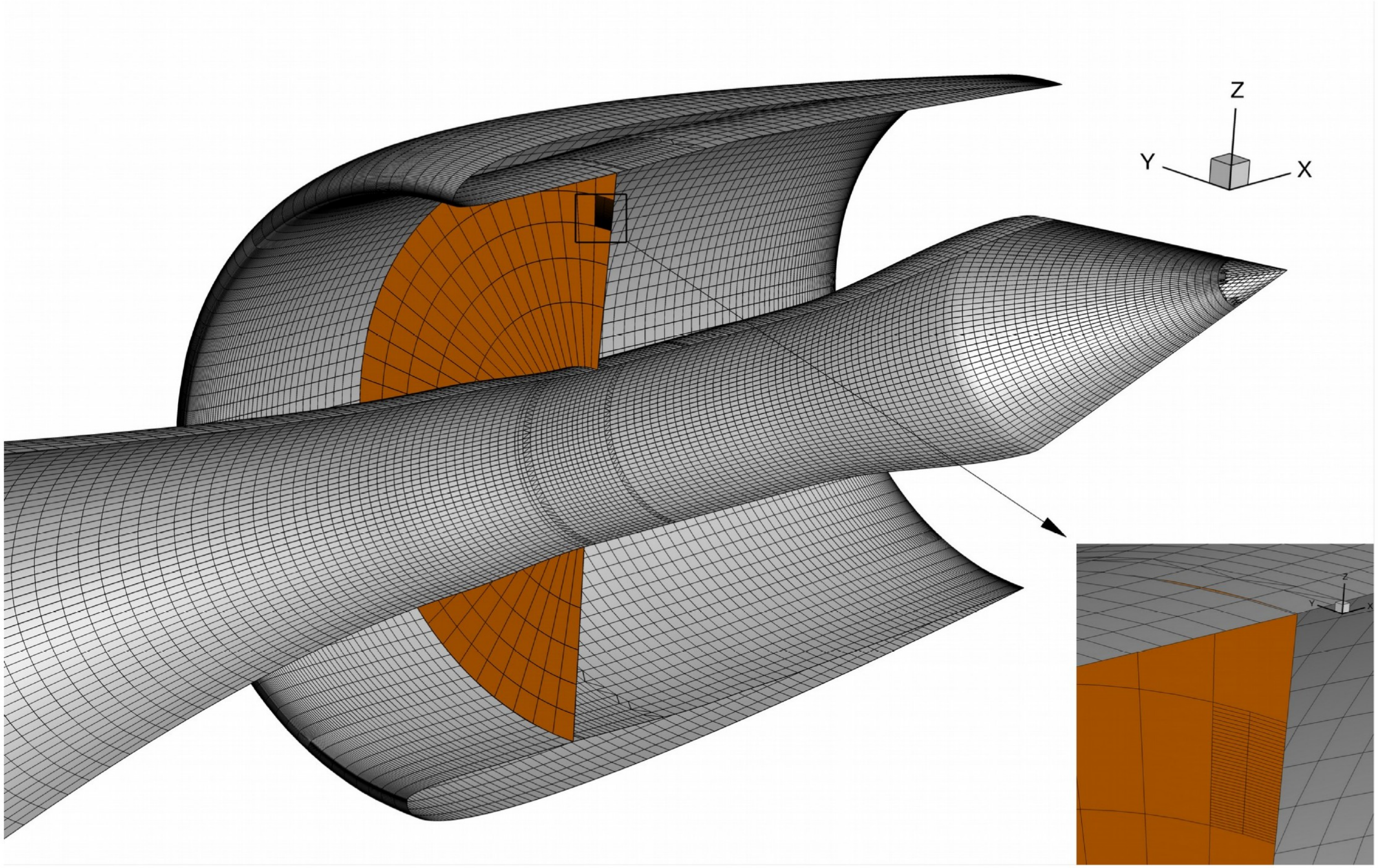


$$I = \left(\frac{P_{avg} - P_{avg_{low}}}{P_{avg}} \right)$$

$$P_{avg_{low}} = \frac{1}{\theta_i^-} \sum_{k=1}^{Q} \int_{\theta_{ik}^-} P(\theta)_i d\theta$$

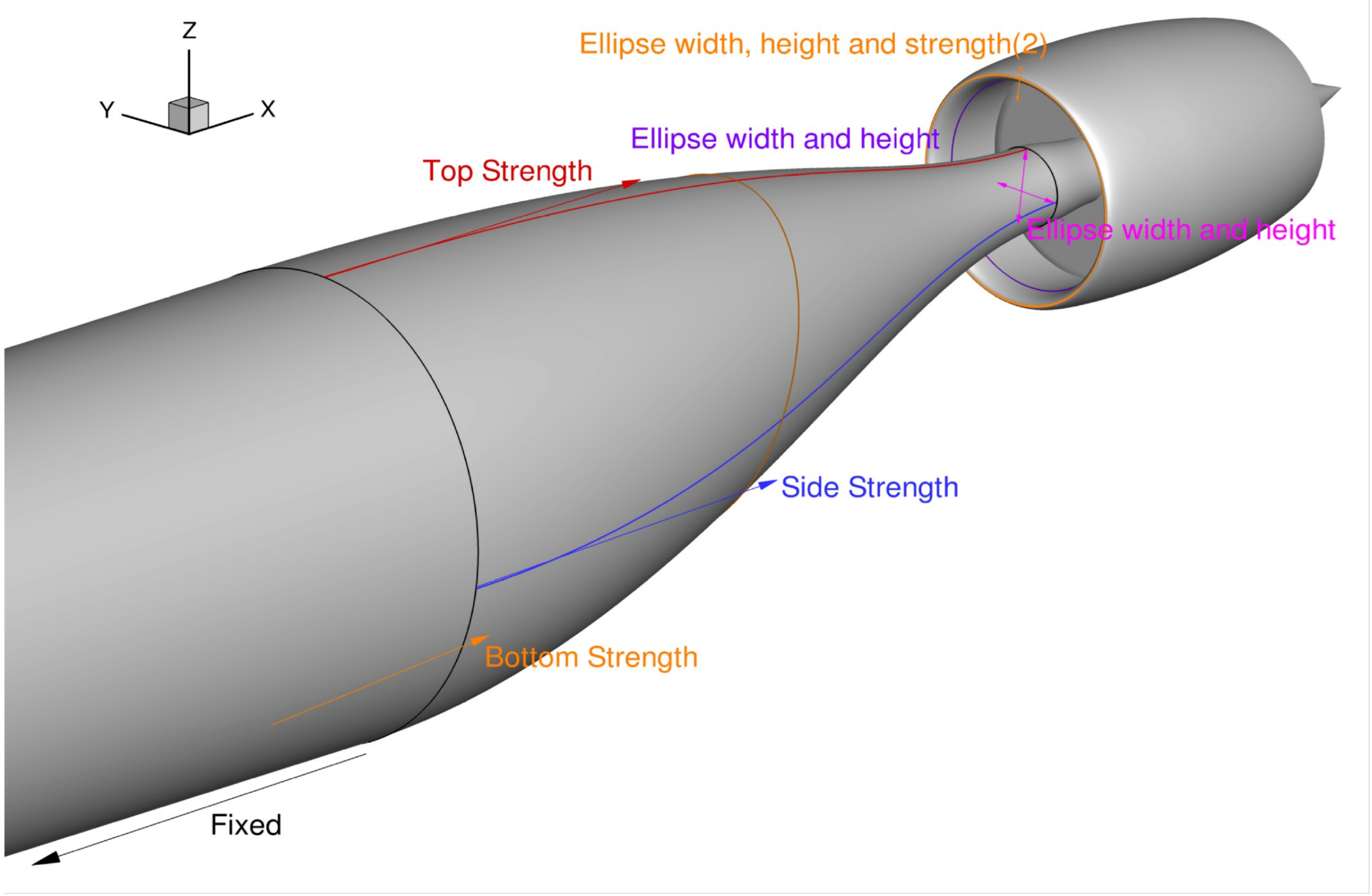
Fan-face Sensor Array

- 5 equal-area rings define a fan face sensor array used to interpolate solution to mass-averaged total pressure
- Sensor values used as input to ARP1420 distortion calculation



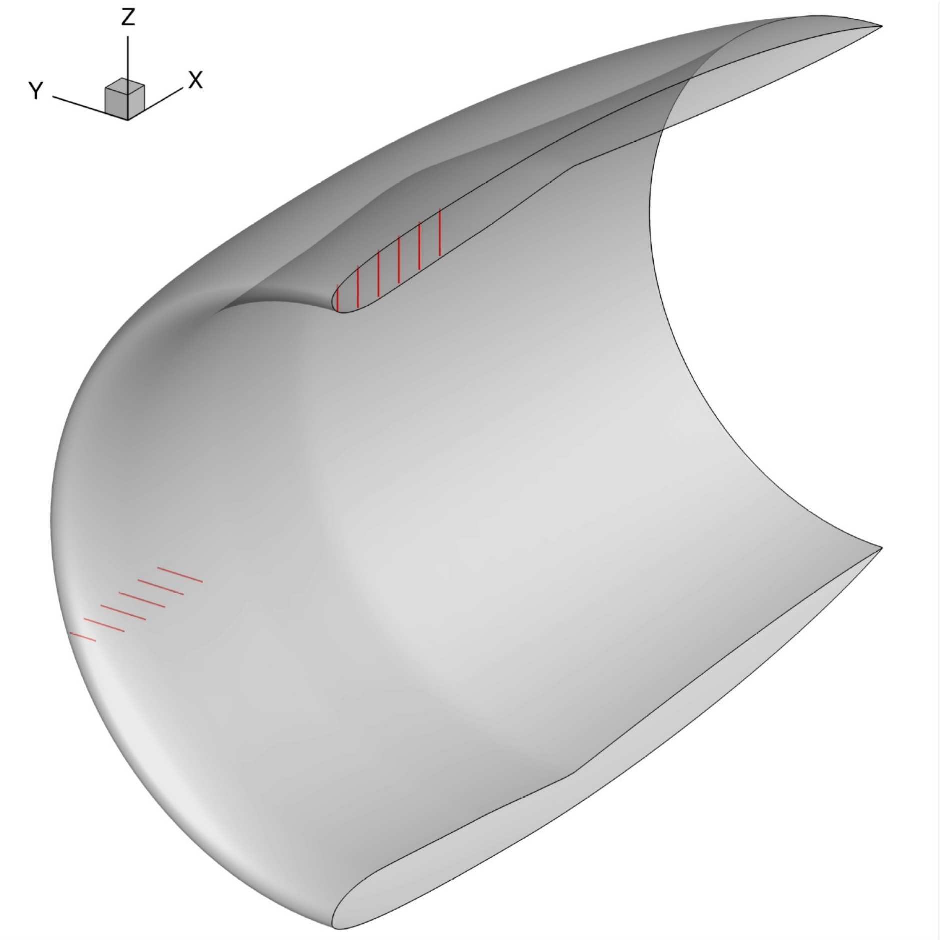
Design Variables

- Python-wrapped Vehicle Sketch Pad (VSP) used directly in optimization
- CFD surface coordinates parameterically attached to discrete representation of VSP surface
- Finite differencing over FD for surface sensitivities
- Design variables are VSP parameters!
- 11 total variables



Geometric Constraints

- Ensures the optimizer does not produce an unrealistically thin leading edge



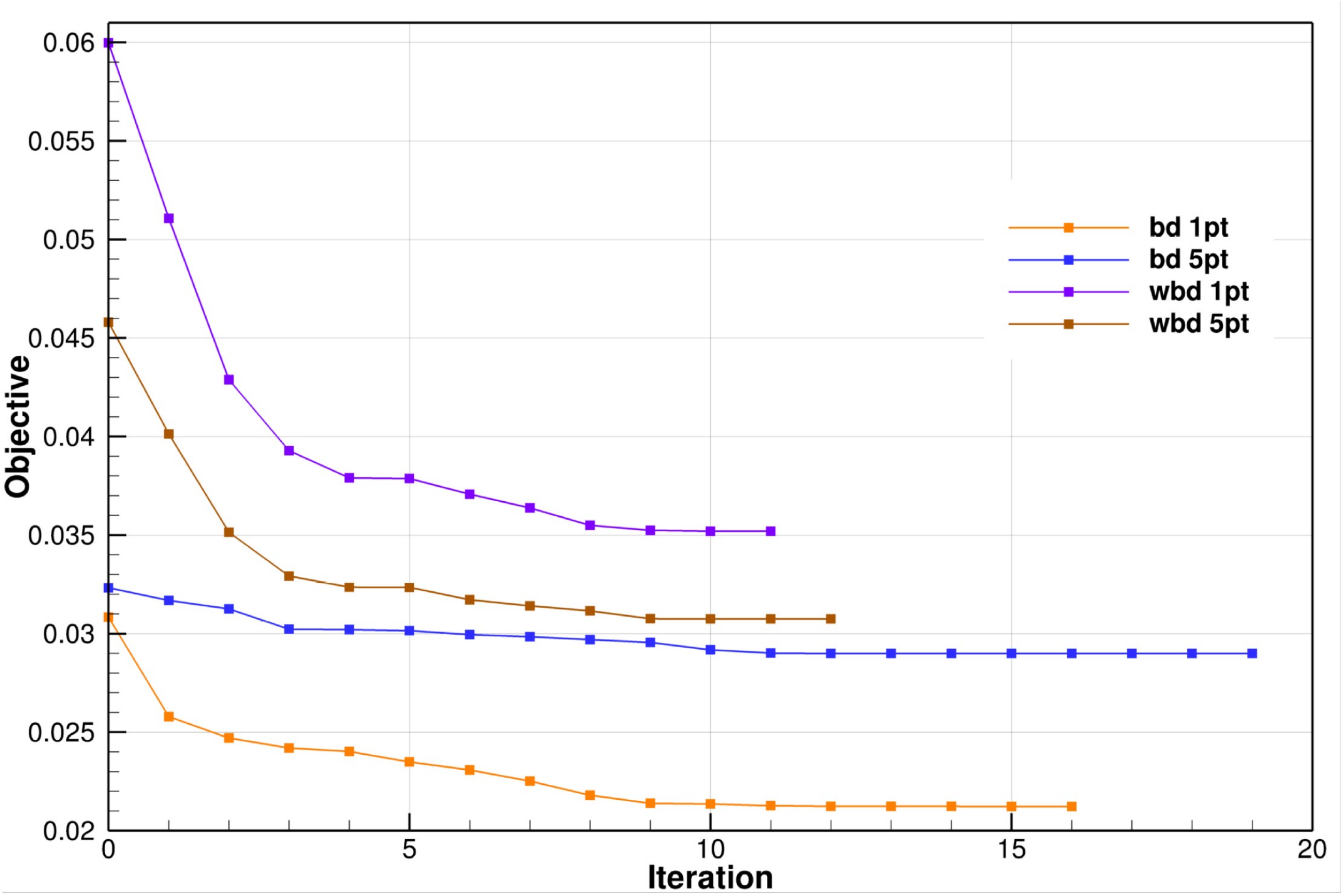
Optimization Formulation

		Quantity
minimize	$\sum_{k=1}^{N} W_k I_k$	Quantity
with respect to	Fuselage shape	5
	Nacelle shape	6
subject to	$C_{D_i} \leq C_{D_{i0}} + .0001$	N
	$t_j \geq 0.95 \times t_{j_{\text{init}}}$	10

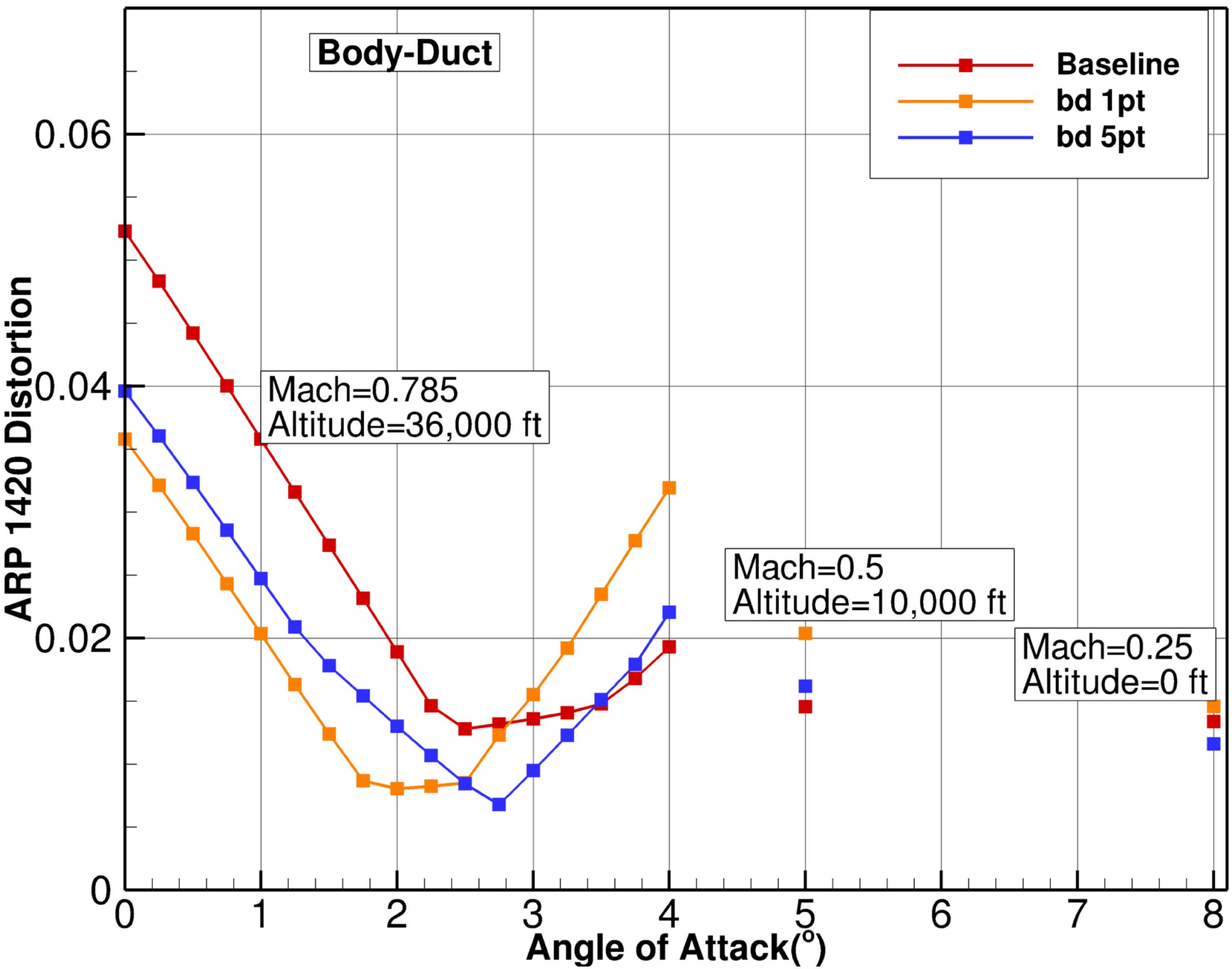
Design Condition	Mach	Angle of attack (°)	Altitude (ft)	Thrust (N)
1	0.785	0.5	36 000	8 500
2	0.785	2.0	36 000	8 500
3	0.785	3.5	36 000	8 500
4	0.50	5.0	10 000	10 800
5	0.25	8.0	0	13 000

Optimization Convergence History

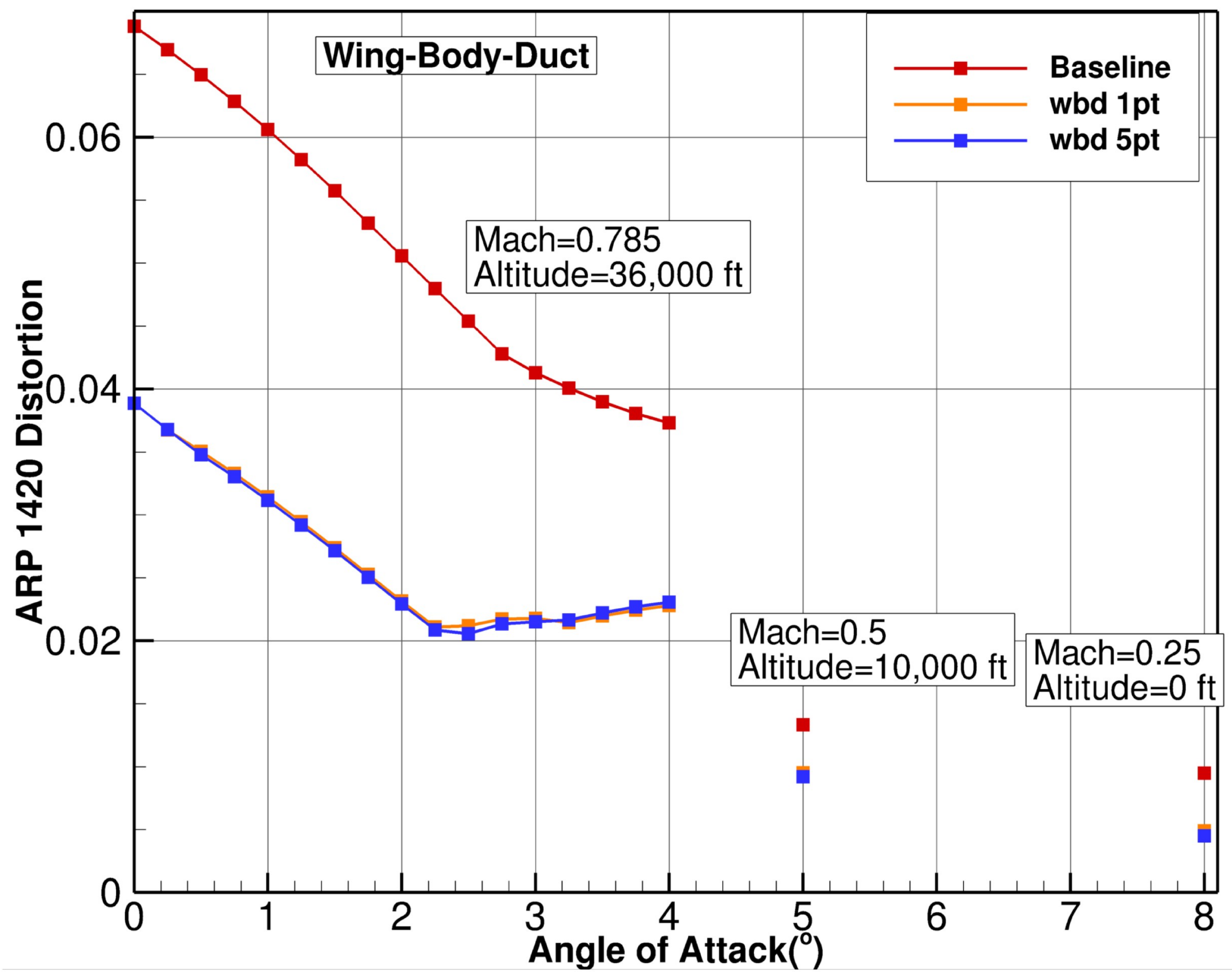
- Smoothed objective
- Between 10 and 20 major iterations required for convergence



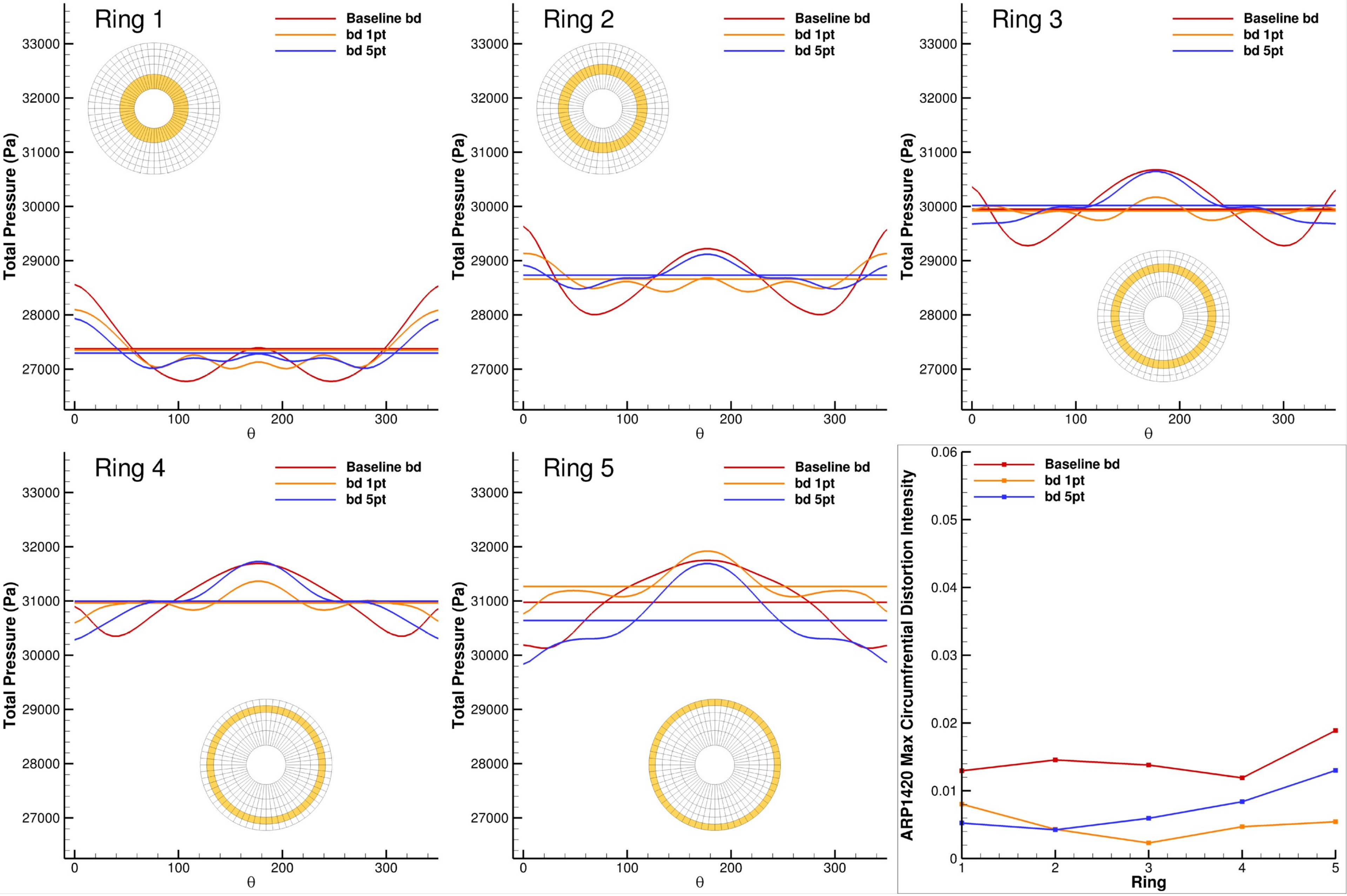
Body-Duct Configuration Polars



Wing-Body-Duct Configuration Polars



Body-Duct Total Pressure Contours



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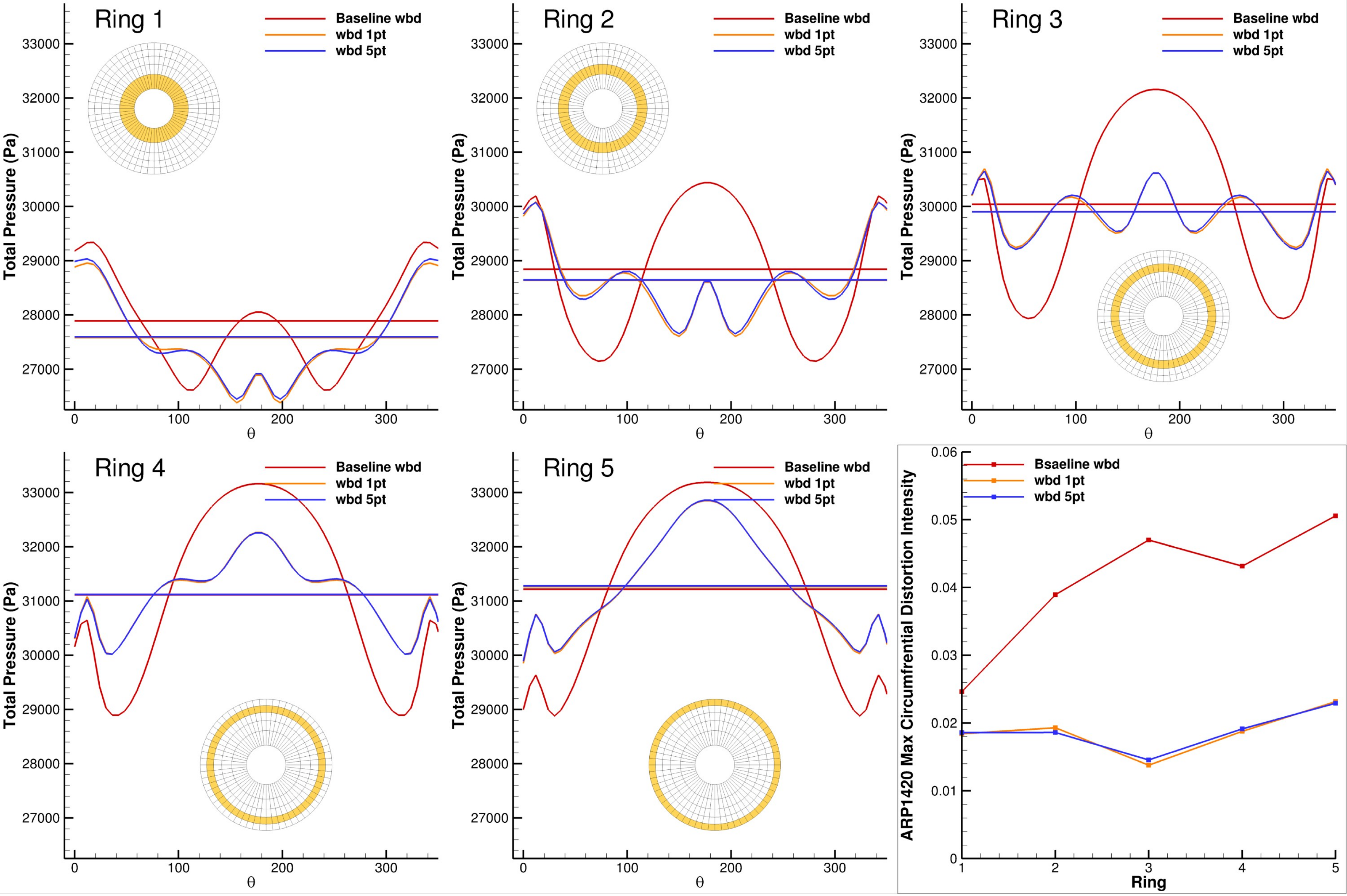

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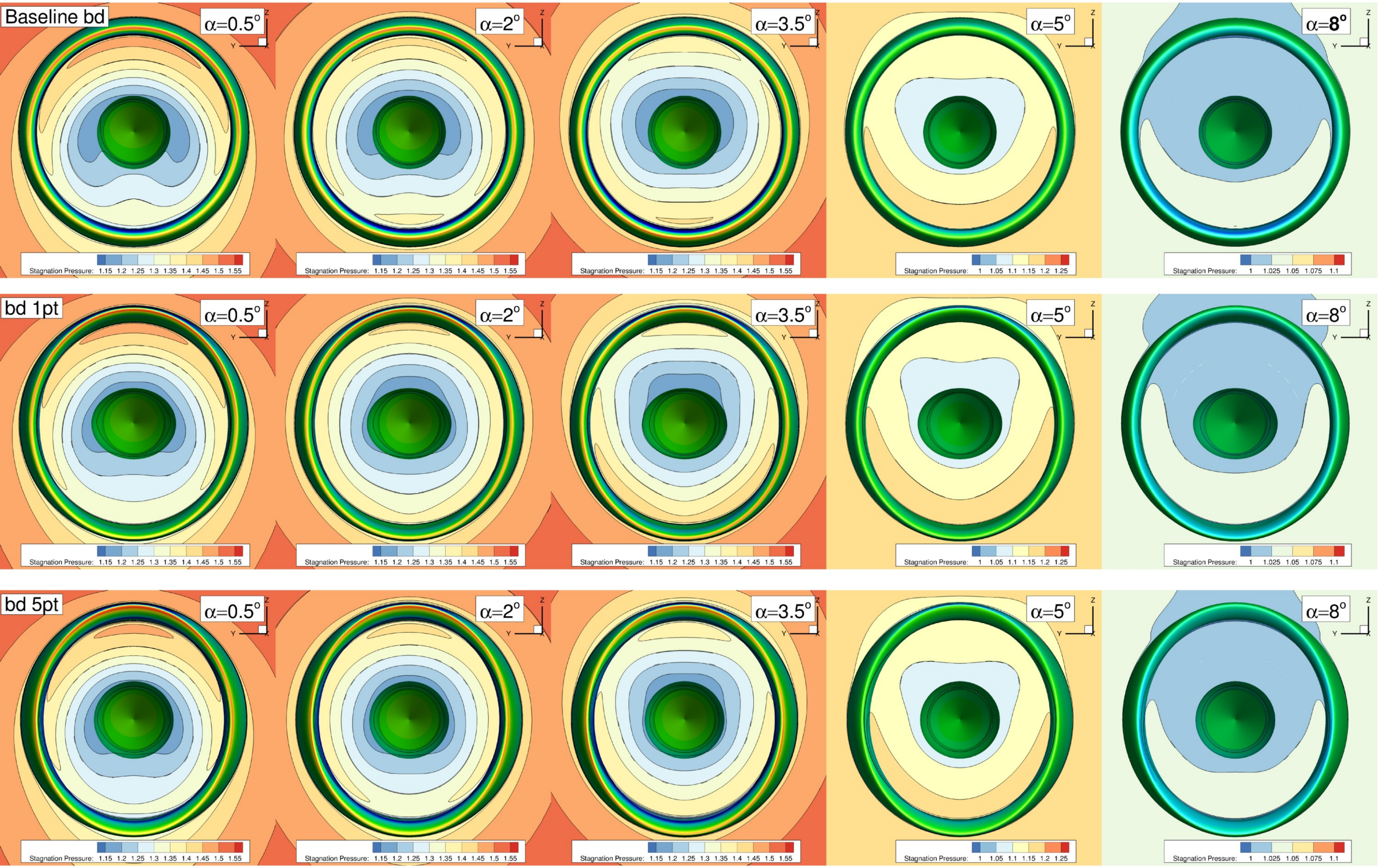

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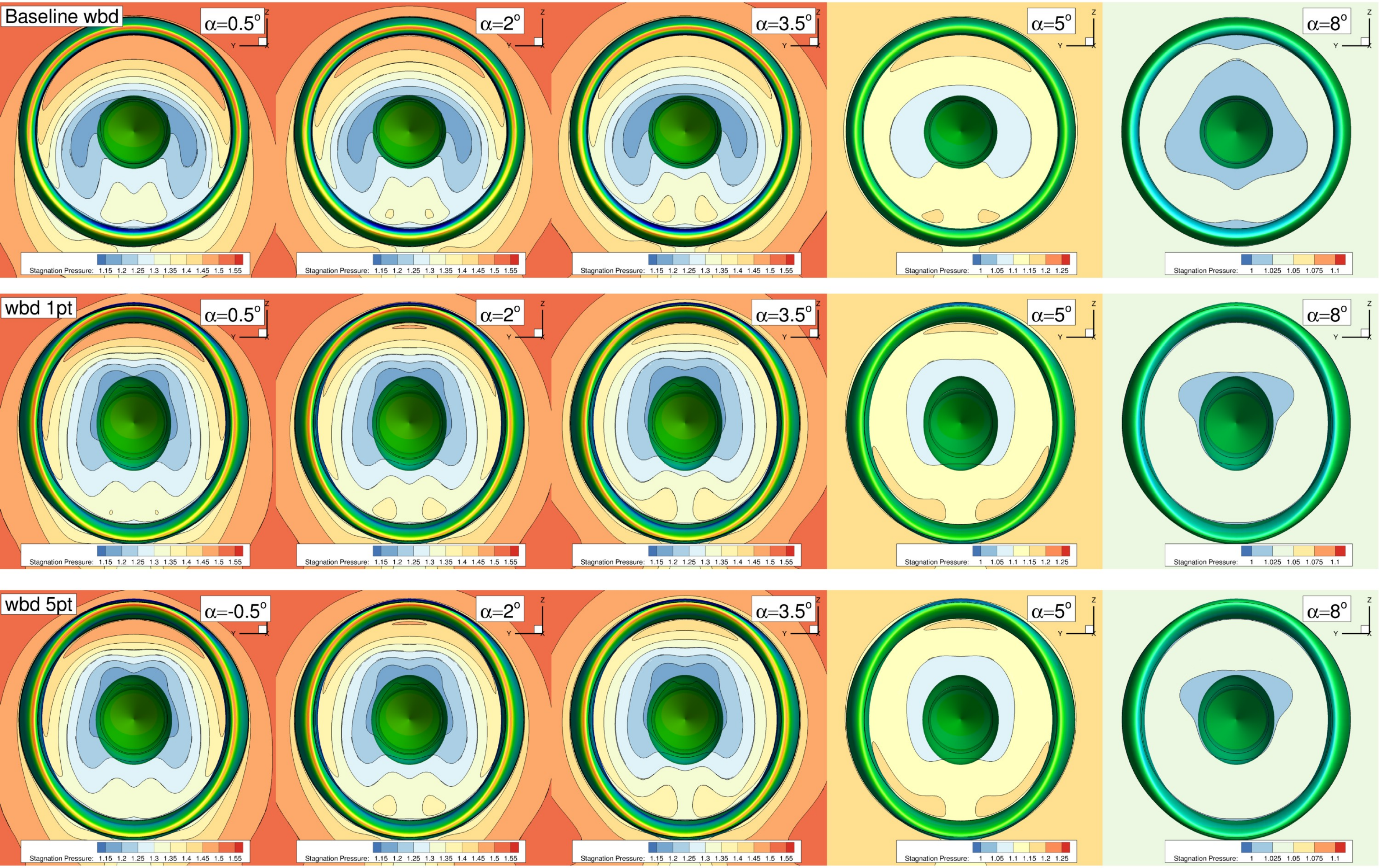
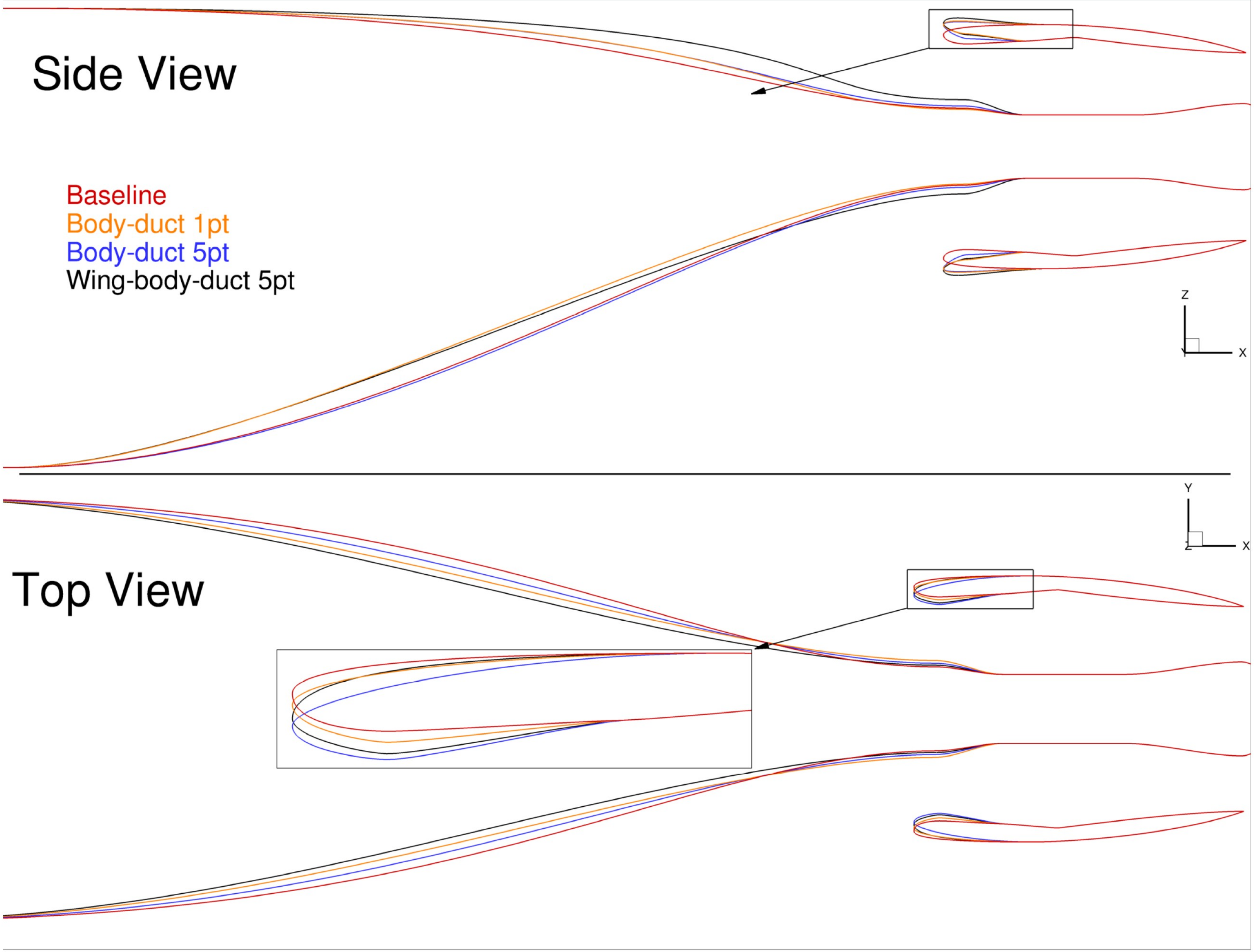


Optimized Cross Sections



Body-Duct Detailed Results

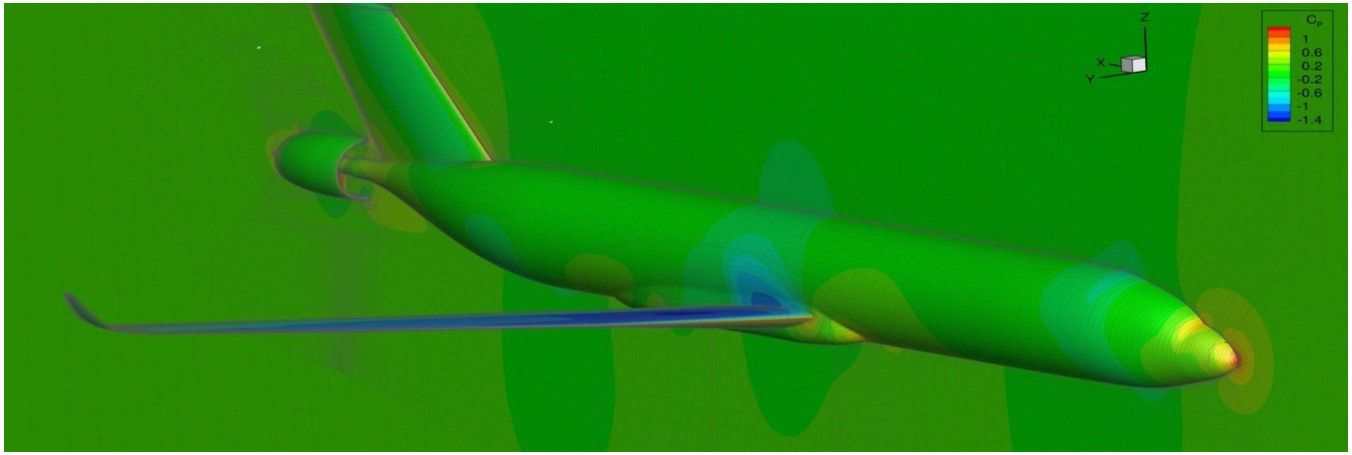
Config	Flight Cond	ARP1420 Distortion	C_D (counts)	$\dot{m}$ (kg/s)	Power (MW)	% Change in Power
Baseline bd	1	0.0442	96.87	76.23	1.1979	–
	2	0.0189	96.57	75.48	1.1910	–
	3	0.0148	96.86	75.42	1.1900	–
	4	0.0146	80.98	170.43	1.1314	–
	5	0.0134	106.48	142.38	1.1611	–
bd 1pt	1	0.0283	96.29	76.40	1.2114	1.13
	2	0.0080	96.12	75.88	1.2062	1.27
	3	0.0235	96.54	76.11	1.2081	1.52
	4	0.0204	80.88	172.61	1.1526	1.87
	5	0.0146	106.79	144.22	1.1813	1.73
bd 5pt	1	0.0323	97.52	76.01	1.2006	0.22
	2	0.0130	97.12	75.37	1.1937	0.22
	3	0.0151	97.94	75.18	1.1930	0.25
	4	0.0162	81.20	170.82	1.1348	0.30
	5	0.0116	107.34	142.51	1.1640	0.25

Wing-Body-Duct Detailed Results

Config	Flight Cond	ARP1420 Distortion	C_D (counts)	$\dot{m}$ (kg/s)	Power (MW)	% Change in Power
Baseline wbd	1	0.0649	194.02	76.81	1.2004	–
	2	0.0506	246.86	75.99	1.1932	–
	3	0.0390	354.32	75.34	1.1871	–
	4	0.0133	272.55	168.40	1.1184	–
	5	0.0050	417.69	149.718	1.2029	–
wbd 1pt	1	0.0350	195.03	76.30	1.2081	0.64
	2	0.0232	247.93	75.72	1.2022	0.75
	3	0.0220	355.43	75.34	1.1984	0.95
	4	0.0095	272.53	169.78	1.1339	1.39
	5	0.0049	416.85	150.46	1.2116	0.73
wbd 5pt	1	0.0348	195.07	76.32	1.2077	0.61
	2	0.0229	247.99	75.73	1.2018	0.72
	3	0.0222	355.51	75.35	1.1982	0.93
	4	0.0092	272.58	169.79	1.1339	1.39
	5	0.0045	416.23	150.58	1.2112	0.69

Conclusions

- ARP1420 Distortion metric may be used as an optimization objective in CFD-based design optimization framework
- Small shape changes to fuselage diffuser and nacelle has significant effect on distortion
- Downwash effect from the wing is a significant distortion driver
- Need to include full nacelle design to ensure consistent thermodynamic solution
- Future work will include the vertical stablizer and the under-wing turbofans



Acknowledgments

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