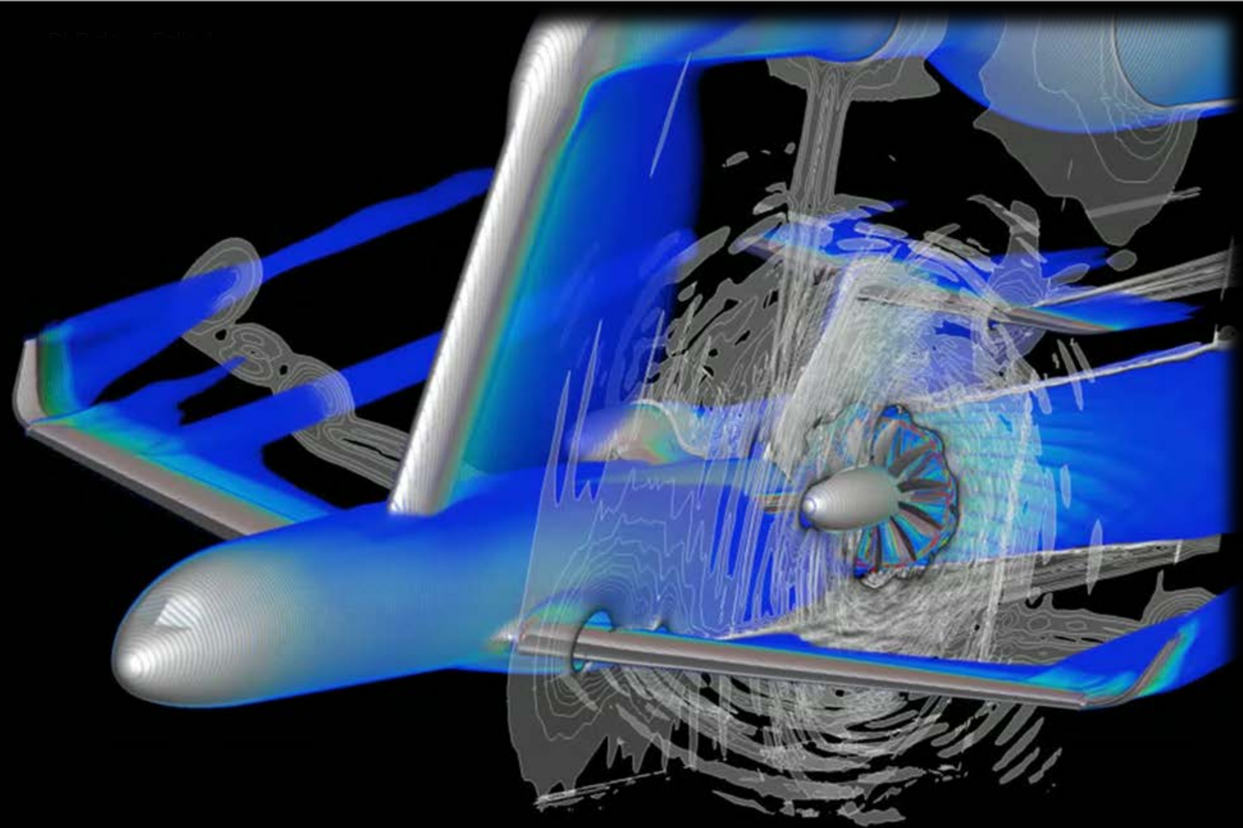

Engine-Airframe Integration for Environmentally Friendly and Economically Viable Future Transport Aircraft

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Institute of Aerodynamics & Flow Technology
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6th UTIAS International Workshop on Aviation and Climate Change
May 16-18, 2018
University of Toronto
Institute for Aerospace Studies
Toronto, Ontario, Canada

DLR

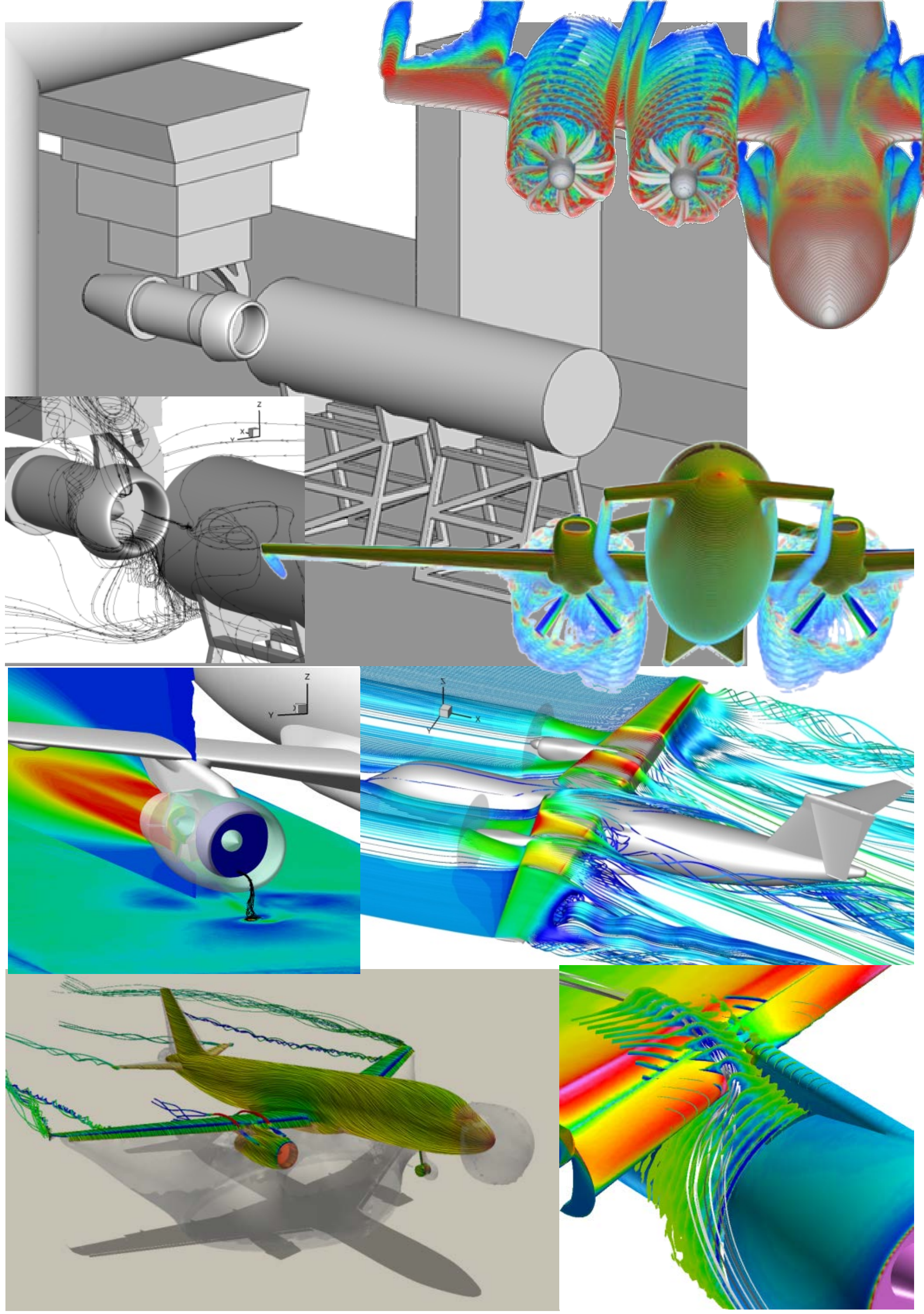
DLR Institute of Aerodynamics & Flow Technology
Engine Integration Activities - History

Turbofans:

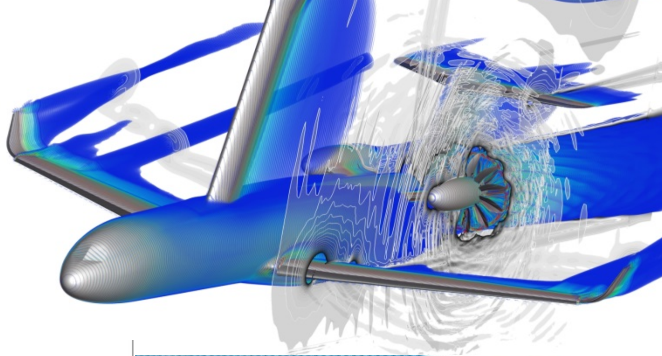
- Integration activities since 1990s
- Analysis and design of installed through flow nacelles & turbo powered simulators
- Experimental & numerical work (internal, DLR-ONERA, EU, Lufo, DLR-RRD, …)
- Analysis and optimization of under wing & rear mounted installations

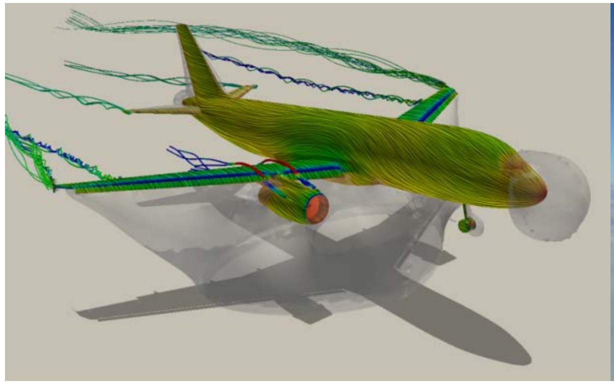
Propeller & CROR:

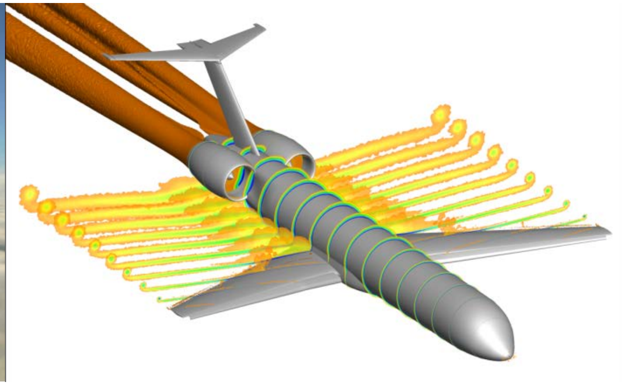
- CFD-based open rotor analysis experience built up during the past 15 years
- Propeller: cooperation with Airbus
- CROR activities since 2007: internal, Rolls-Royce, Airbus, EU-JTI Clean Sky

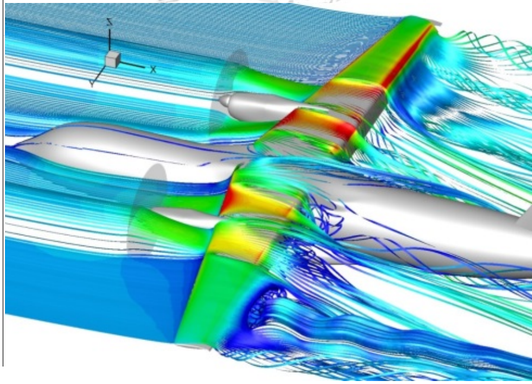


Engine-Airframe Integration: New Challenges
Key Driver for Future Efficient Transport Aircraft









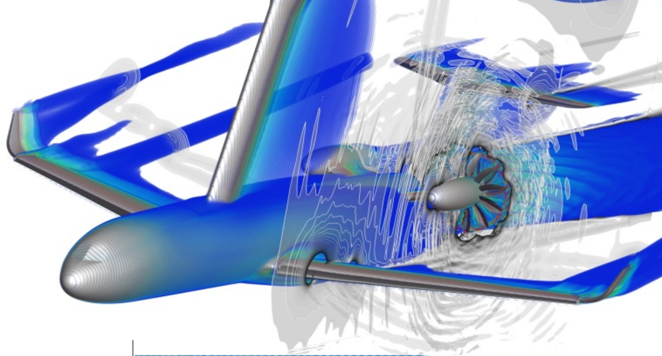
Turbofans:

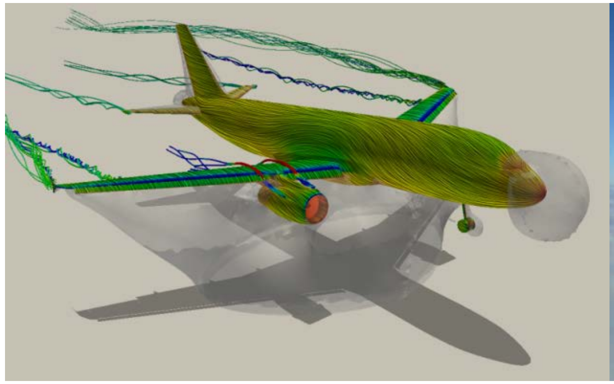
- Novel engine-airframe integration concepts - out of necessity:
  - Under-wing close-coupled UHBR installations
- Novel engine-airframe integration concepts - potentially enabling further system efficiency benefits:
  - Over-wing (close-coupled) UHBR installations
  - Aft-fuselage (or over-wing) BLI UHBR installations

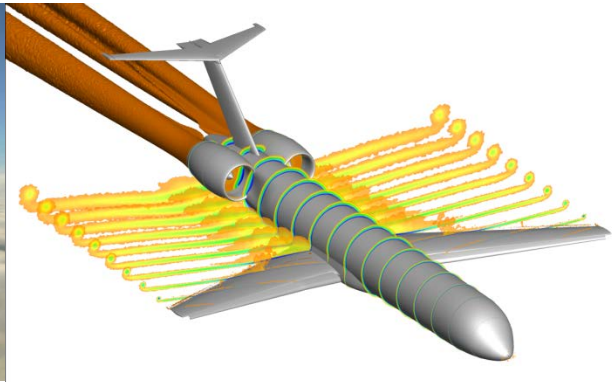
Propeller & CROR:

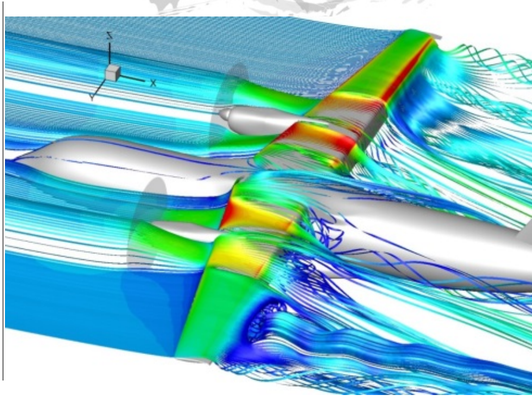
- Novel propeller concepts and installations for low-noise regional aircraft
- Novel CROR/Open Rotor concepts and installations for regional & short-medium haul transport aircraft

Engine-Airframe Integration: New Challenges
Key Driver for Future Efficient Transport Aircraft









Turbofans:

- UHBR in general:
  - Improved modeling/prediction capabilities for UHBR engine-airframe installations
- BLI:
  - UHBR capabilities PLUS refined analysis and evaluation capabilities

Propeller & CROR:

- Good aerodynamic/aeroacoustic toolsets established allowing for support of configuration analysis
- Extension of multi-physics analysis capabilities through improved integration of structural & aeroelastic tools

Engine-Airframe Integration for Environmentally Friendly and Economically Viable Future Transport Aircraft

- Introduction & Motivation

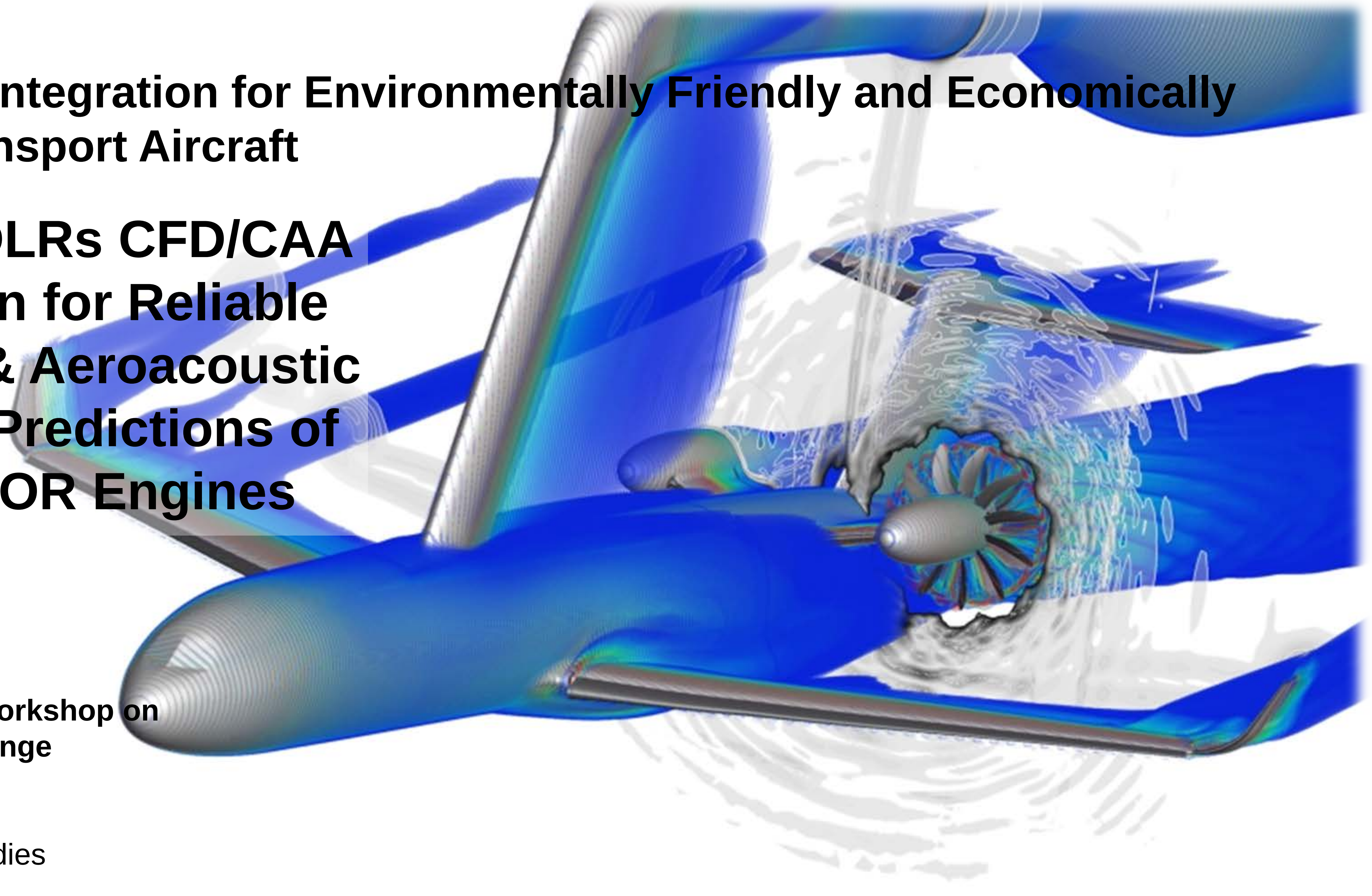
- CROR: Validation of DLRs CFD/CAA Process Chain for Reliable Aerodynamic & Aeroacoustic Performance Predictions of Installed CROR Engines
  - The EU 7th FP Clean Sky JTI-SFWA Project
  - Test Case Description
  - Numerical Approach Description
  - Aerodynamic & Aeroacoustic Analysis & Validation

- UHBR Turbofans: Simulation Capabilities for UHBR Turbofans Featuring a Rotating Fan
  - The CS2 ASPIRE Project
  - Numerical Approach Description
  - Test Case Description
  - Aerodynamic Anlaysis & Validation

- Conclusions and Outlook

DLR

Engine-Airframe Integration for Environmentally Friendly and Economically Viable Future Transport Aircraft



Validation of DLRs CFD/CAA Process Chain for Reliable Aerodynamic & Aeroacoustic Performance Predictions of Installed CROR Engines

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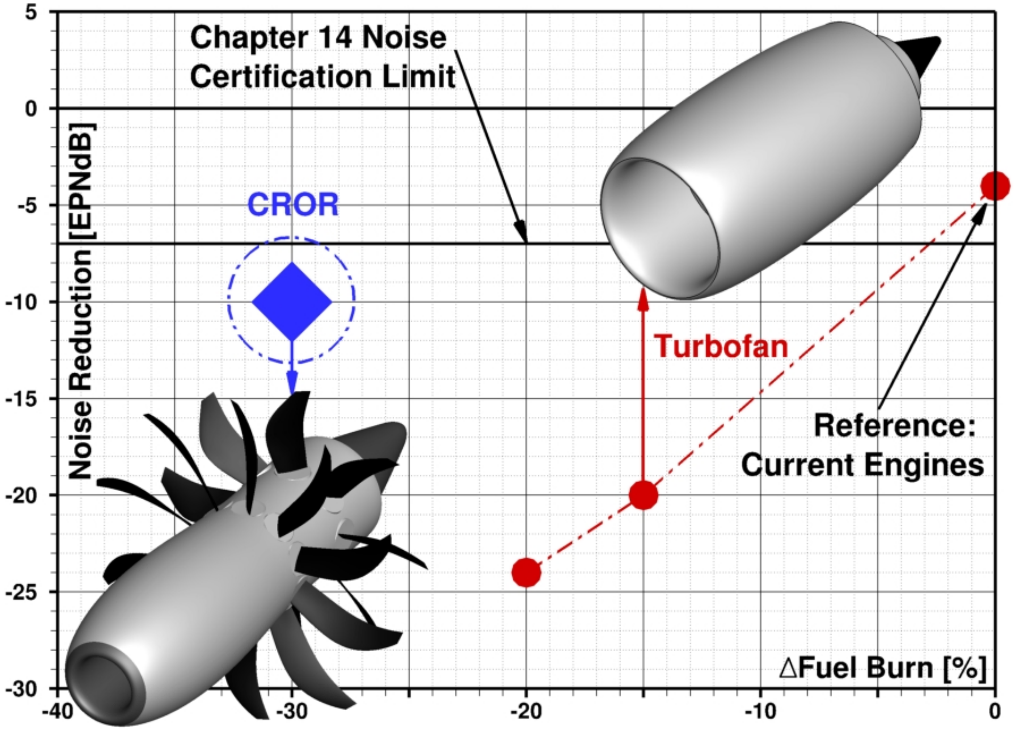
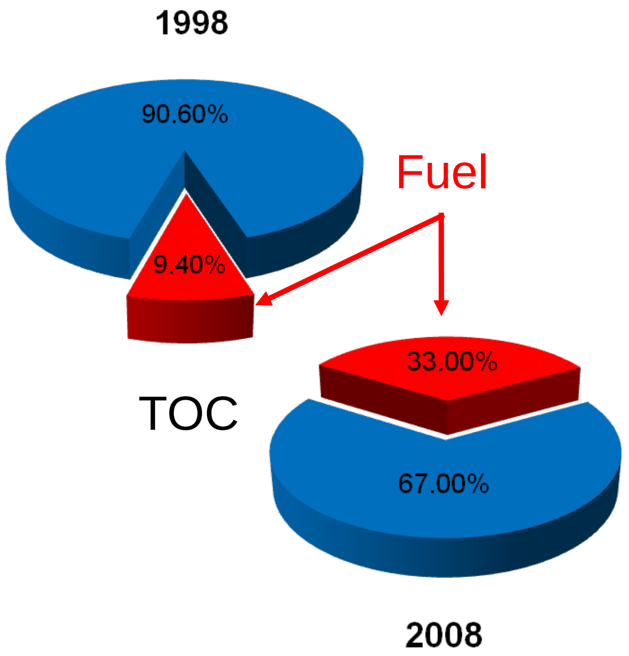
Introduction & Motivation:
CROR Propulsion Efficiency Advantage





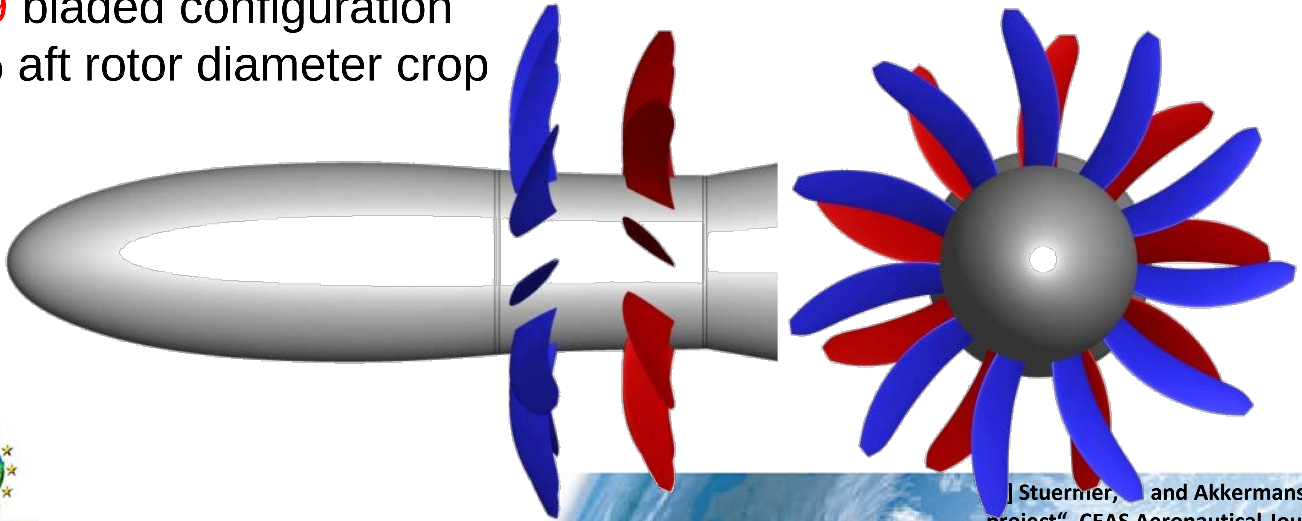
$$F = m(v_9 - v_0)$$

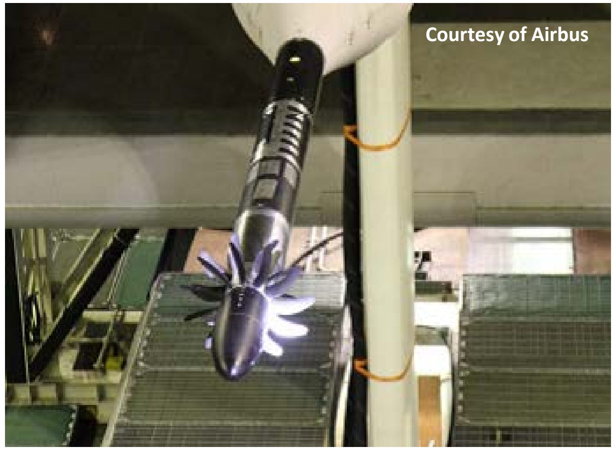
$$\eta = 2/(1 + v_9/v_0)$$

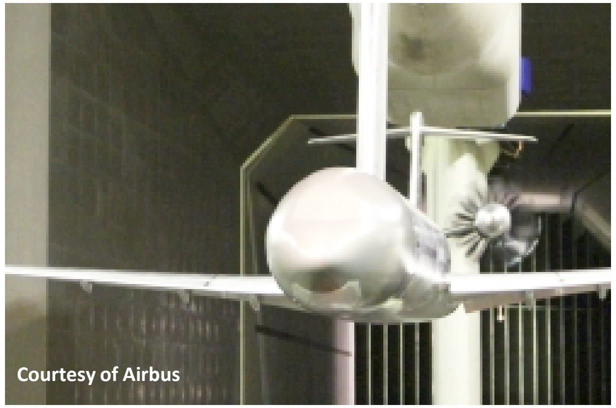
- Environmental & fuel cost concerns drive need for propulsion system advances
- CROR propulsive efficiency better than TF by a comfortable margin but technical challenges on installation, noise and safety/certification remain
- Rotor-rotor interaction are primary noise source mechanisms

The EU Clean Sky JTI SFWA Project

- Broad scope of CROR research being addressed in the EU Clean Sky Joint Technology Initiative Smart Fixed Wing Aircraft Project (JTI SFWA) since 2008 [1]
- Focus of Airbus-led CROR-WP 2.2:
  - De-risk CROR as engine for single-aisle aircraft
  - Studies of novel noise reduction technologies
  - Comprehensive aerodynamic & aeroacoustic WTT of 1/7th-scale Z08- and 1/5th-scale Z49-model at low- and high-speed flight conditions
  - Numerical studies in support of test preparation and for tools validation
- Generic Airbus-designed AI-PX7 CROR is the focus engine configuration [2]
  - 11x9 bladed configuration
  - 10% aft rotor diameter crop

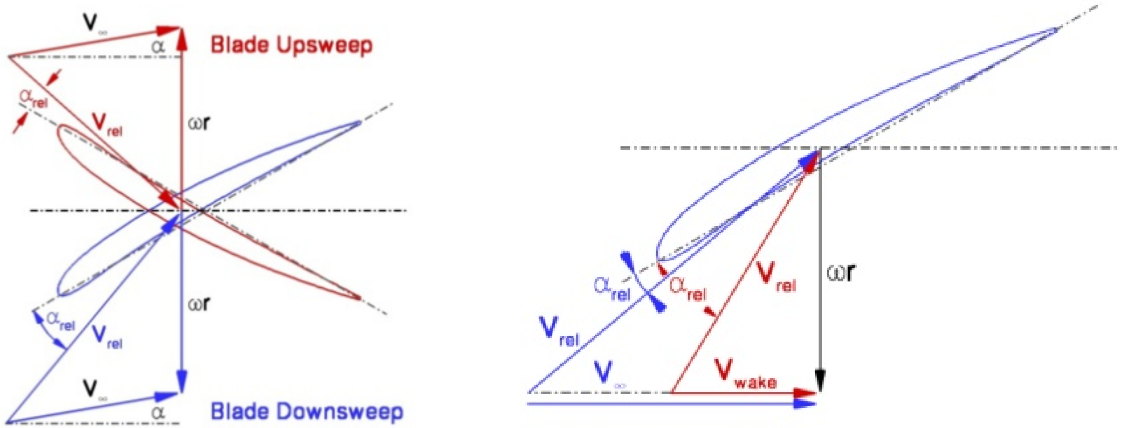






] Stuermer, and Akkermans, R.: “Multidisciplinary analysis of CROR propulsion systems: DLR activities in the JTI SFWA project“, CEAS Aeronautical Journal, 2014.
[2] Negulescu, C.: “Airbus AI-PX7 CROR Design Features and Aerodynamics“, SAE Int. J. Aerosp, Vol. 6, 2013.

JTI-SFWA Task 2.2.4.5: Installation Effects Analysis
Z08 CROR Test Cases

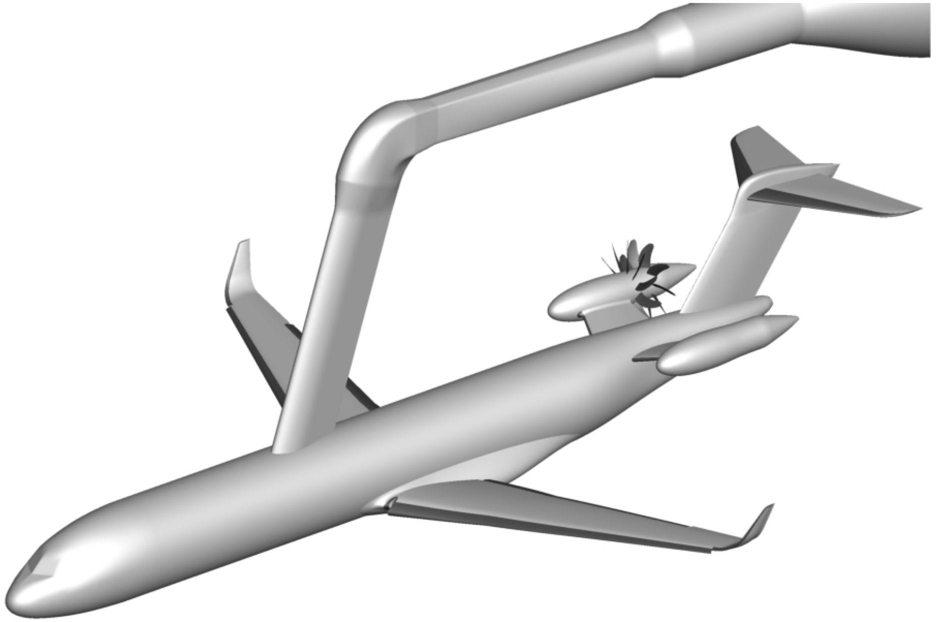


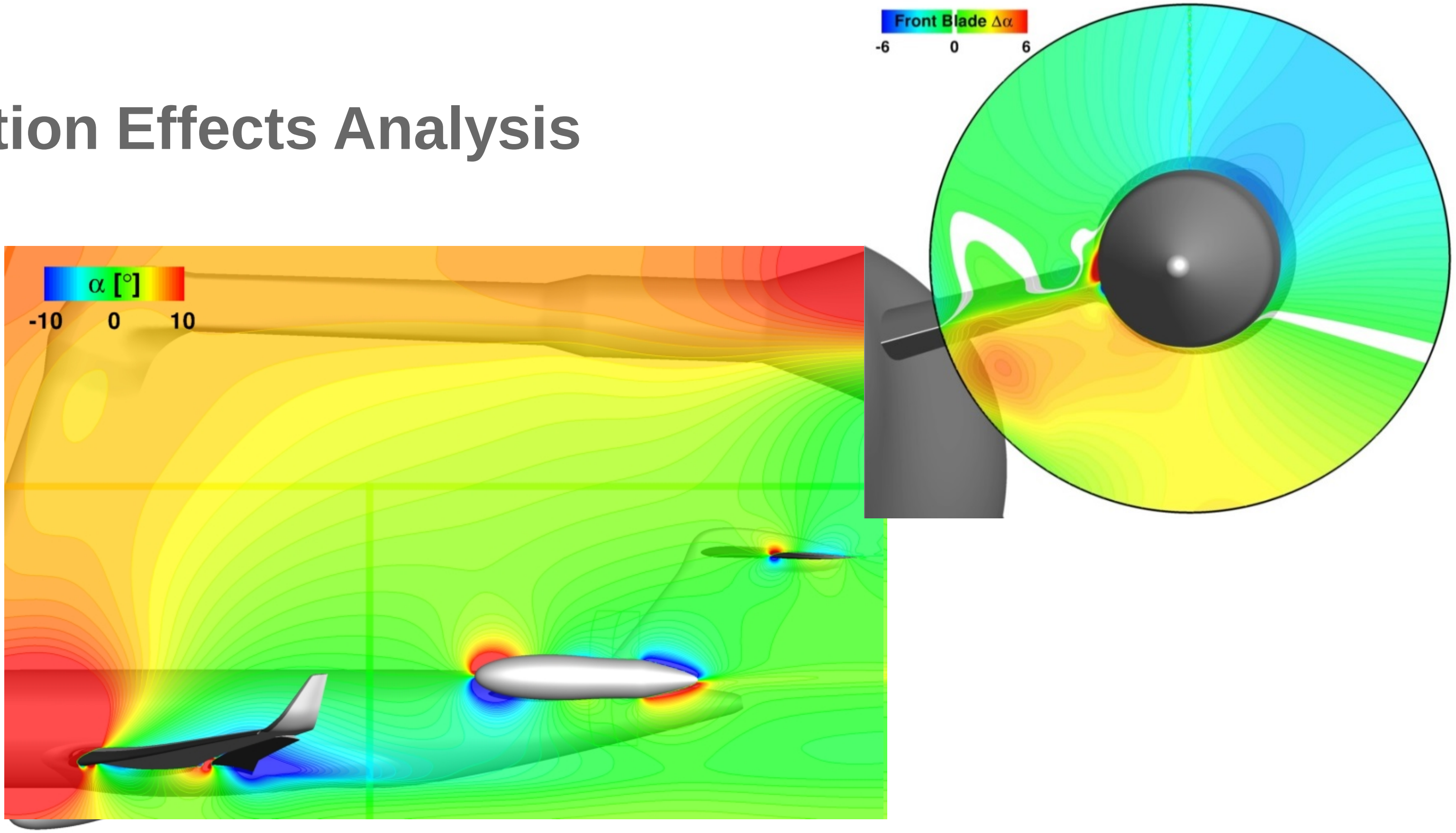
	Mach	α [º]	n [rpm]	$\beta_{75,F}$	$\beta_{75,A}$
Isolated: R34P87D472	0.2	0	$n_F=n_A$	Identical	Identical
Isolated: R34P87D473	0.2	3	$n_F=n_A$		
Pylon: R21P28D206	0.2	3	$n_F=n_A$		
Aircraft: R69P274D1760	0.2	8	$n_F=n_A$		

- Family of 1:7-scale Z08-CROR models tested @ low-speed flow conditions in DNW-LLF
- Previous publications [3,4]: Baseline validation and study of installation effects using isolated & semi-installed Z08-CROR test
  - Angle of attack
  - Pylon wake
- Present work: Demonstration of applicability of methods and approaches to a complete aircraft

[3] Stürmer, Arne und Akkermans, R.A.D.: "Validation of Aerodynamic and Aeroacoustic Simulations of Contra-Rotating Open Rotors at Low-Speed Flight Conditions", AIAA2014-3133, AIAA Aviation 2014, 16-20 Jun 2014, Atlanta, GA, USA.
[4] Stürmer, Arne: "Validation of Installation Effect Predictions Through Simulations of Contra-Rotating Open Rotors at Low-

JTI-SFWA Task 2.2.4.5: Installation Effects Analysis
Z08 CROR Test Cases





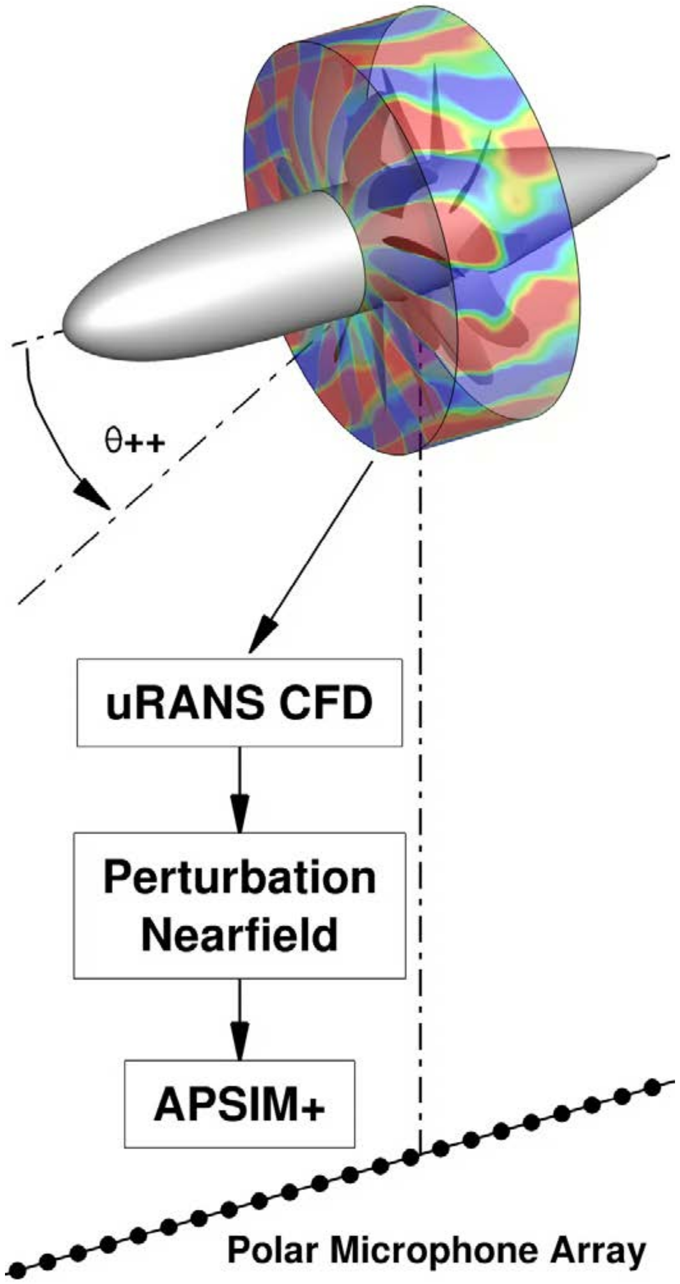
- Aircraft is modeled in take-off high-lift configuration with defelected sealed slat and flap
- Study of necessity of including sting in validation CFD/CAA activities:
  - Notable impact on empennage flowfield, e.g. in angle of attack distributions
  - Strong impact on CROR performance expected due to differences in perturbed front rotor inflow
- Sting required and included in simulations
- Single (right hand) CROR case selected to reduce uncertainty in (aeroacoustic) evaluation

DLR-AS CROR Studies:
Typical Numerical Approach

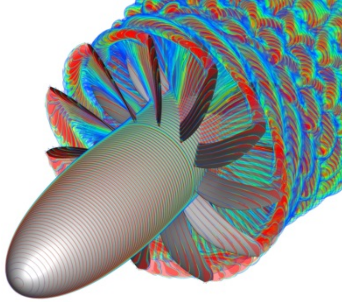
- Typically **multi-disciplinary simulations** done, coupling **aerodynamics (DLR TAU-Code)** and **aeroacoustics (DLR APSIM+Code)**

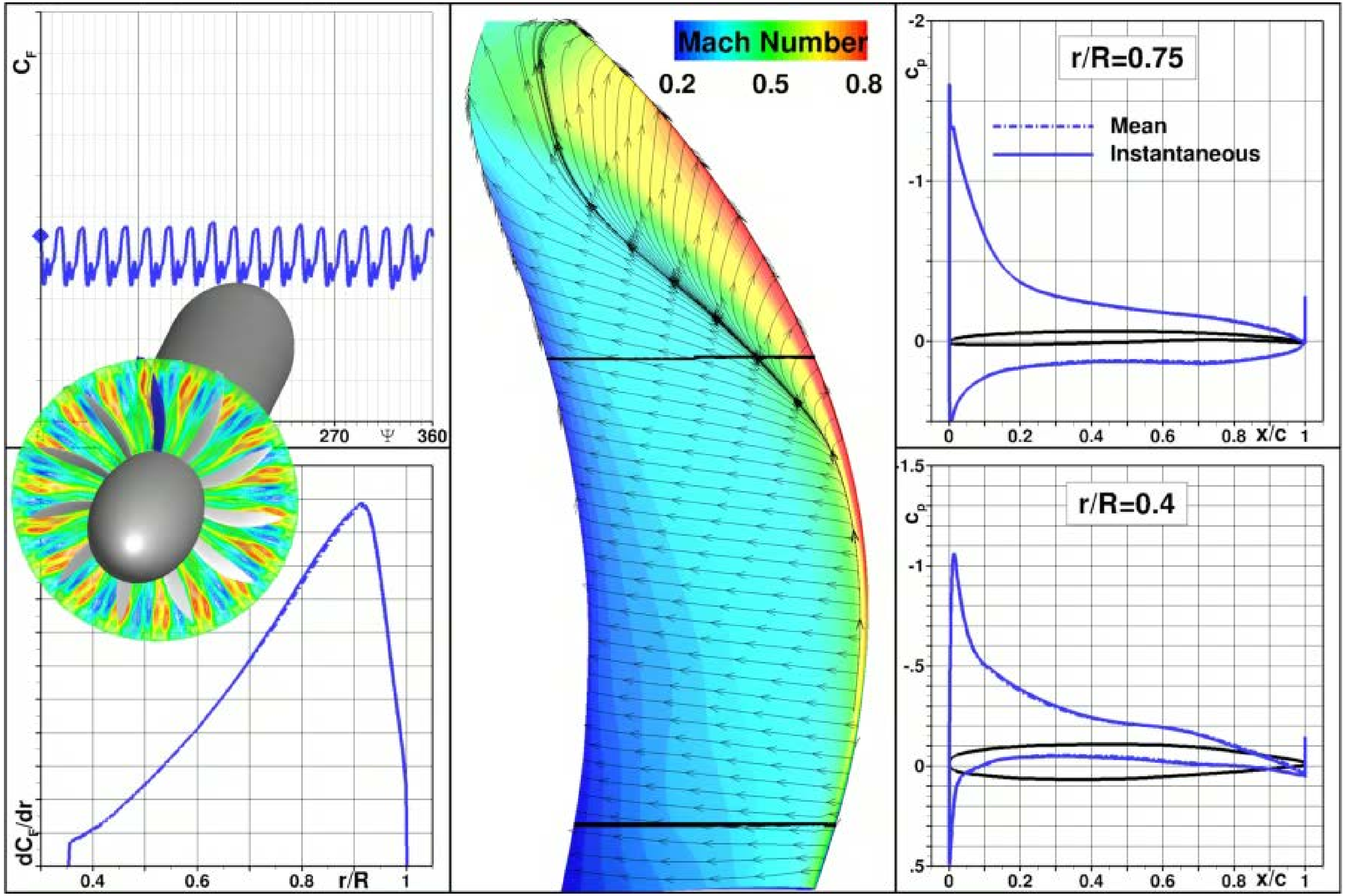
- TAU uRANS simulations for aerodynamic data & input for the CAA-analysis
  - 2nd order dual time method for unsteady flows
  - 2nd order central scheme for spatial discretization
  - LUSGS time integration
  - SA turbulence model with vortical correction
  - Chimera & motion libraries for moving bodies
  - Simulations run using 720 cores of DLR C2A2S2E cluster in Braunschweig
  - 8-block Chimera mesh with 205.0x10^6 nodes

- DLR FW-H Code APSIM+ for farfield noise predictions
  - Permeable surface approach used based on nacelle Chimera data



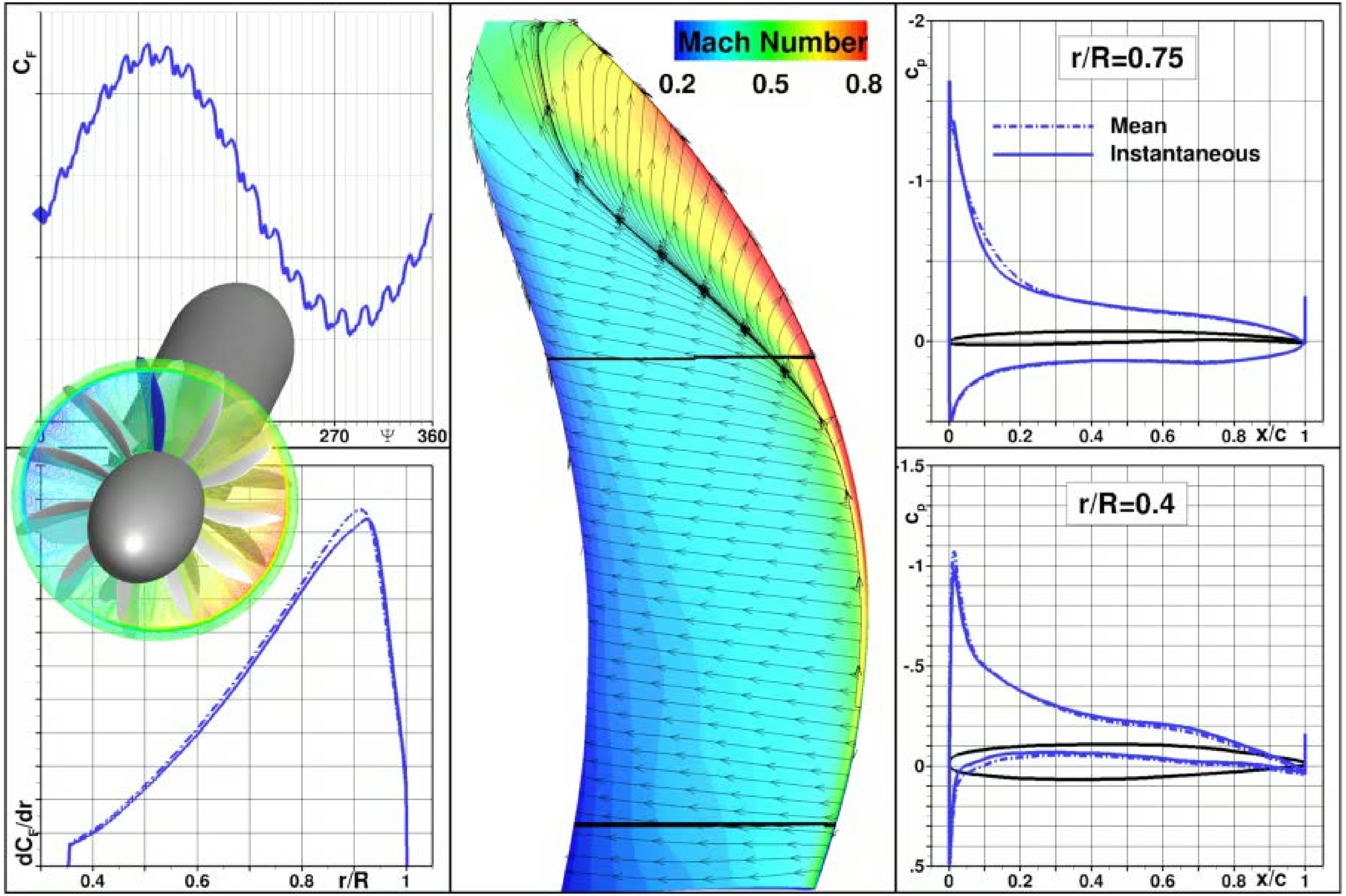
Aerodynamic Analysis: Isolated CROR – Front Blade





Optimized Mesh
2772p

Aerodynamic Analysis: AoA-Effect – Front Blade



Optimized Mesh
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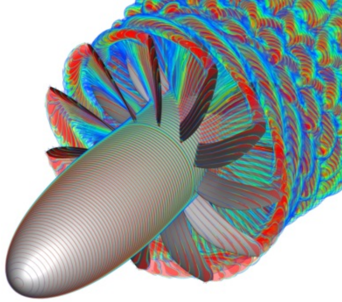
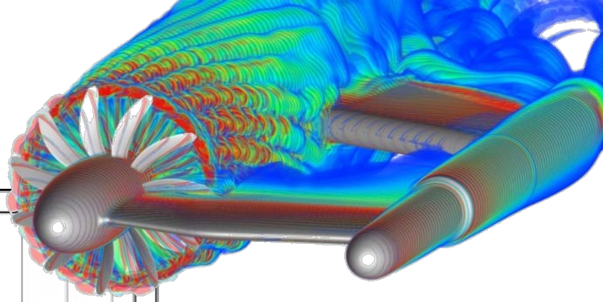
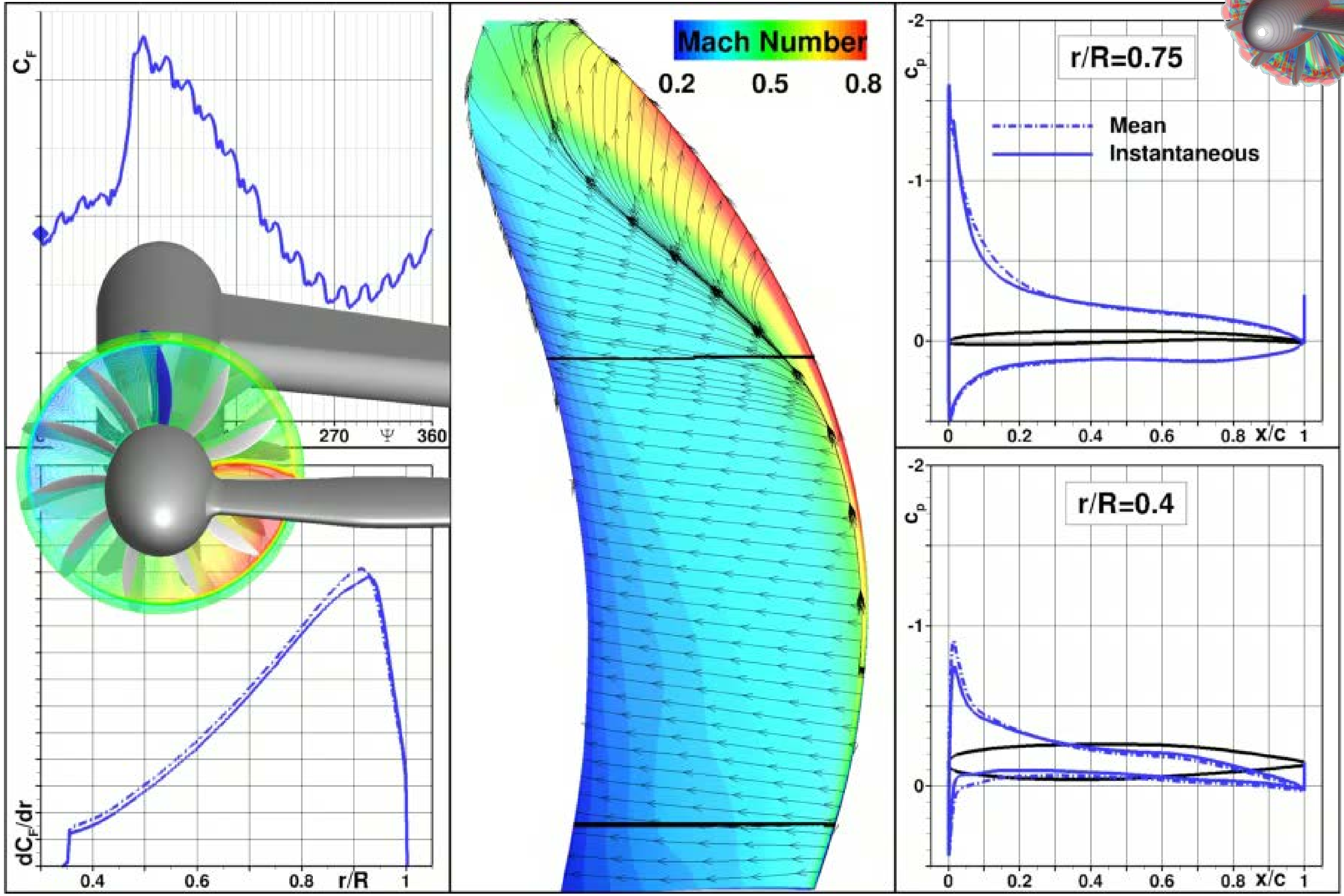


Aerodynamic Analysis: Pylon-Effect – Front Blade





Optimized Mesh
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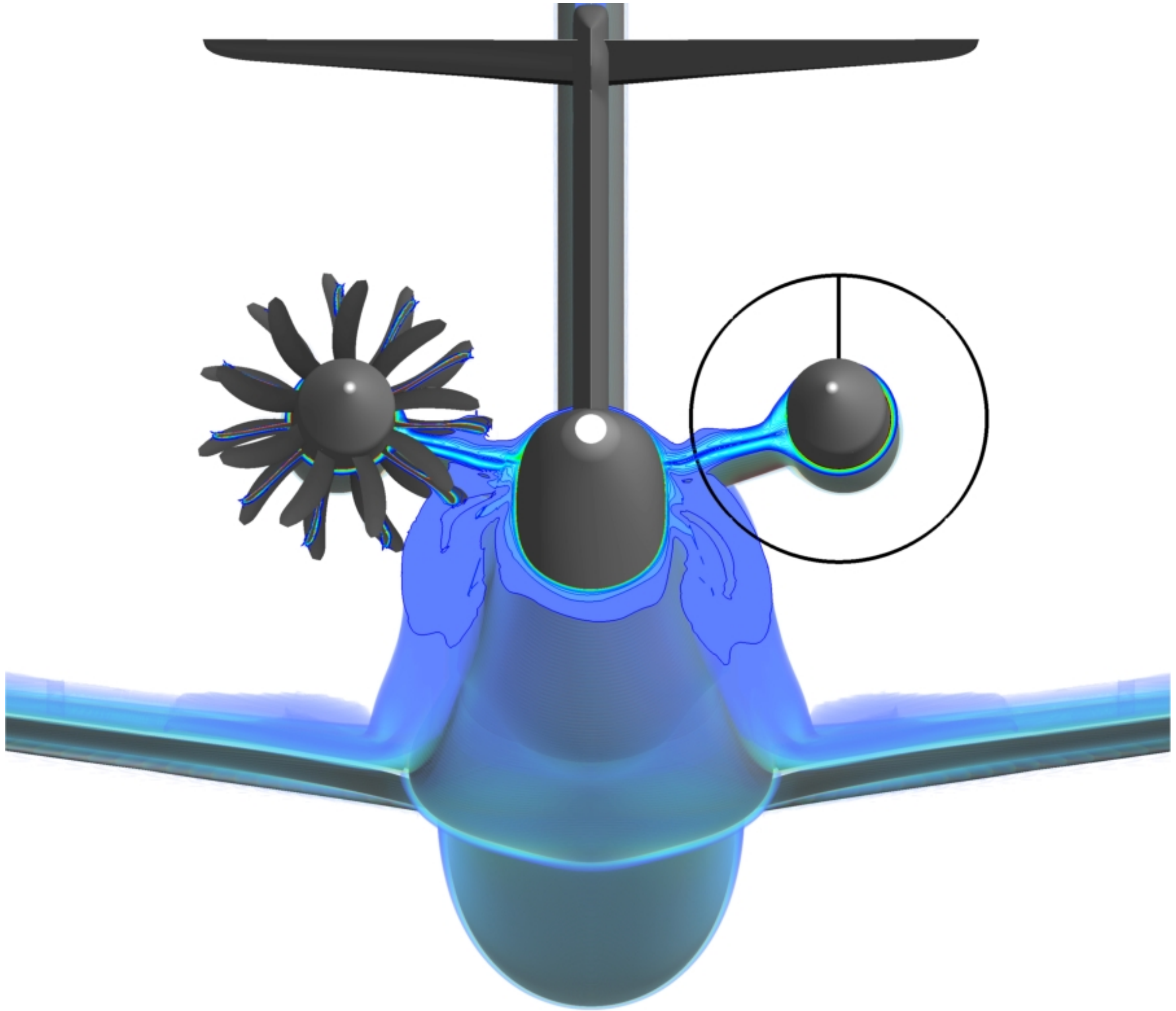
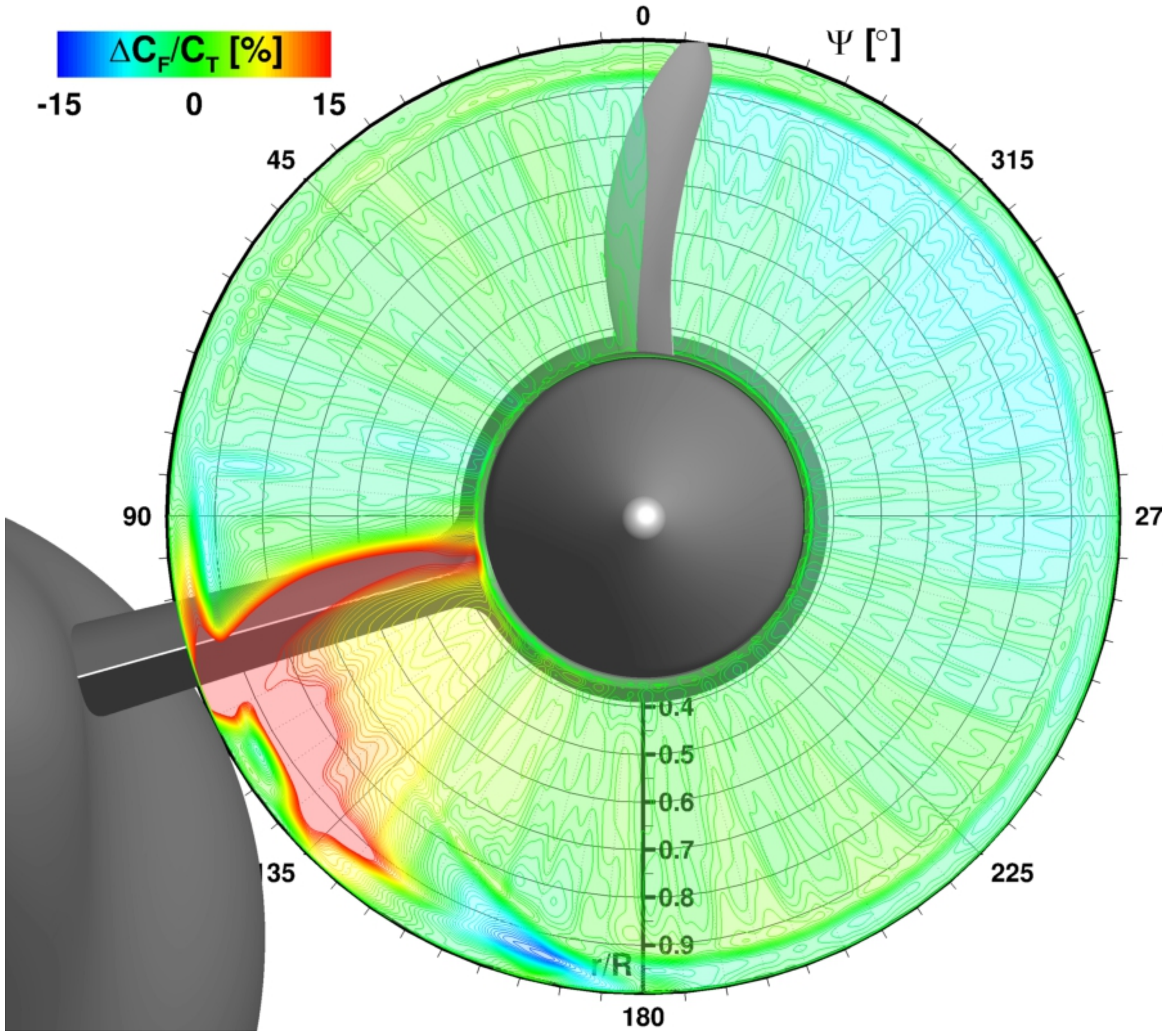
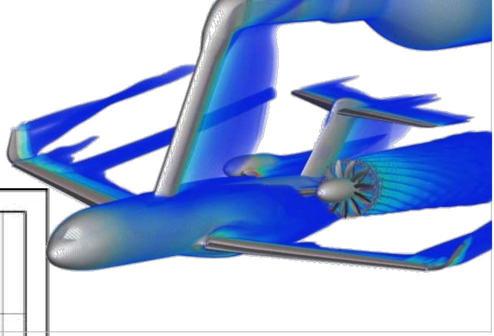
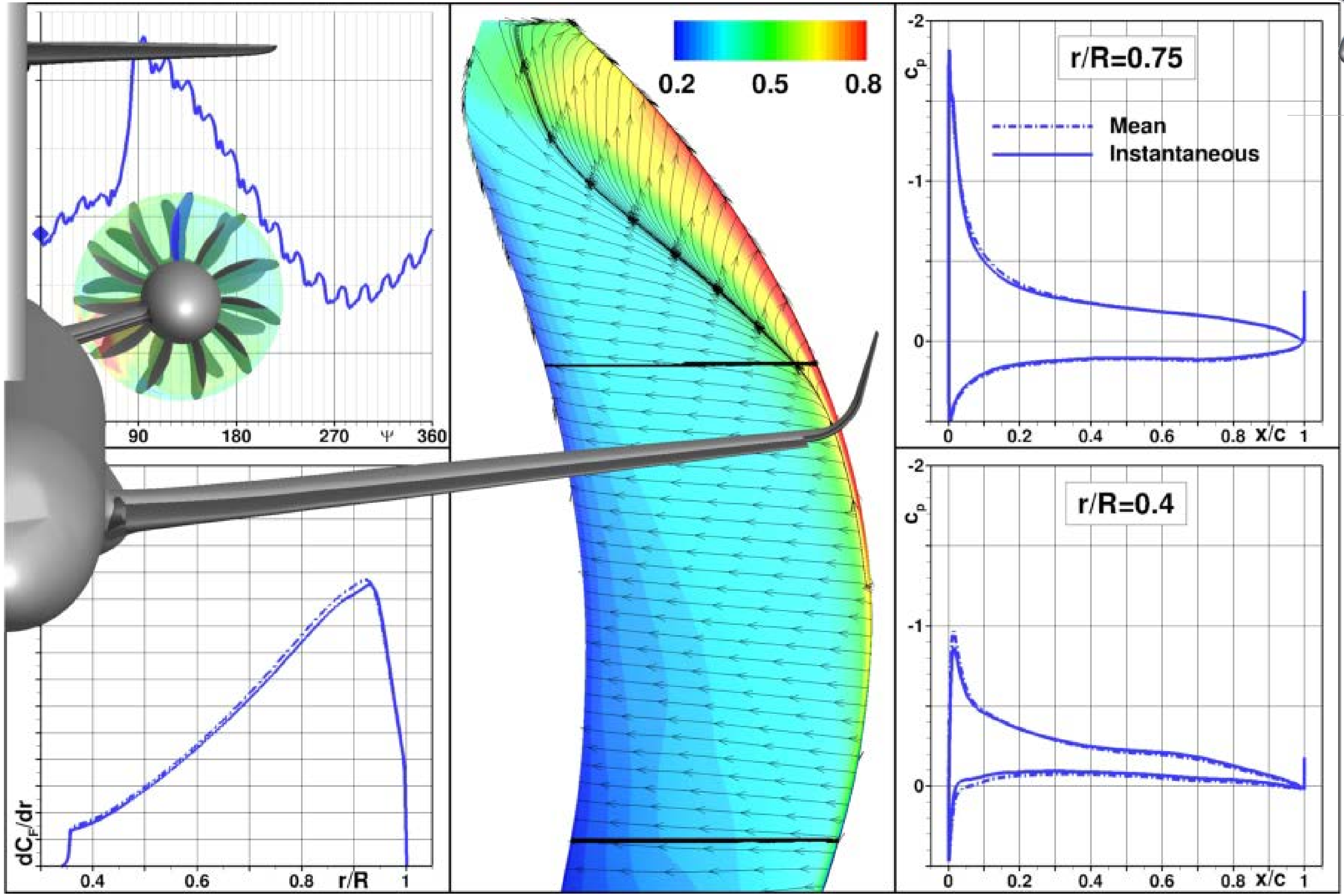
Aerodynamic Analysis: Aircraft-Effect – Front Rotor





Aerodynamic Analysis: Aircraft-Effect – Front Blade

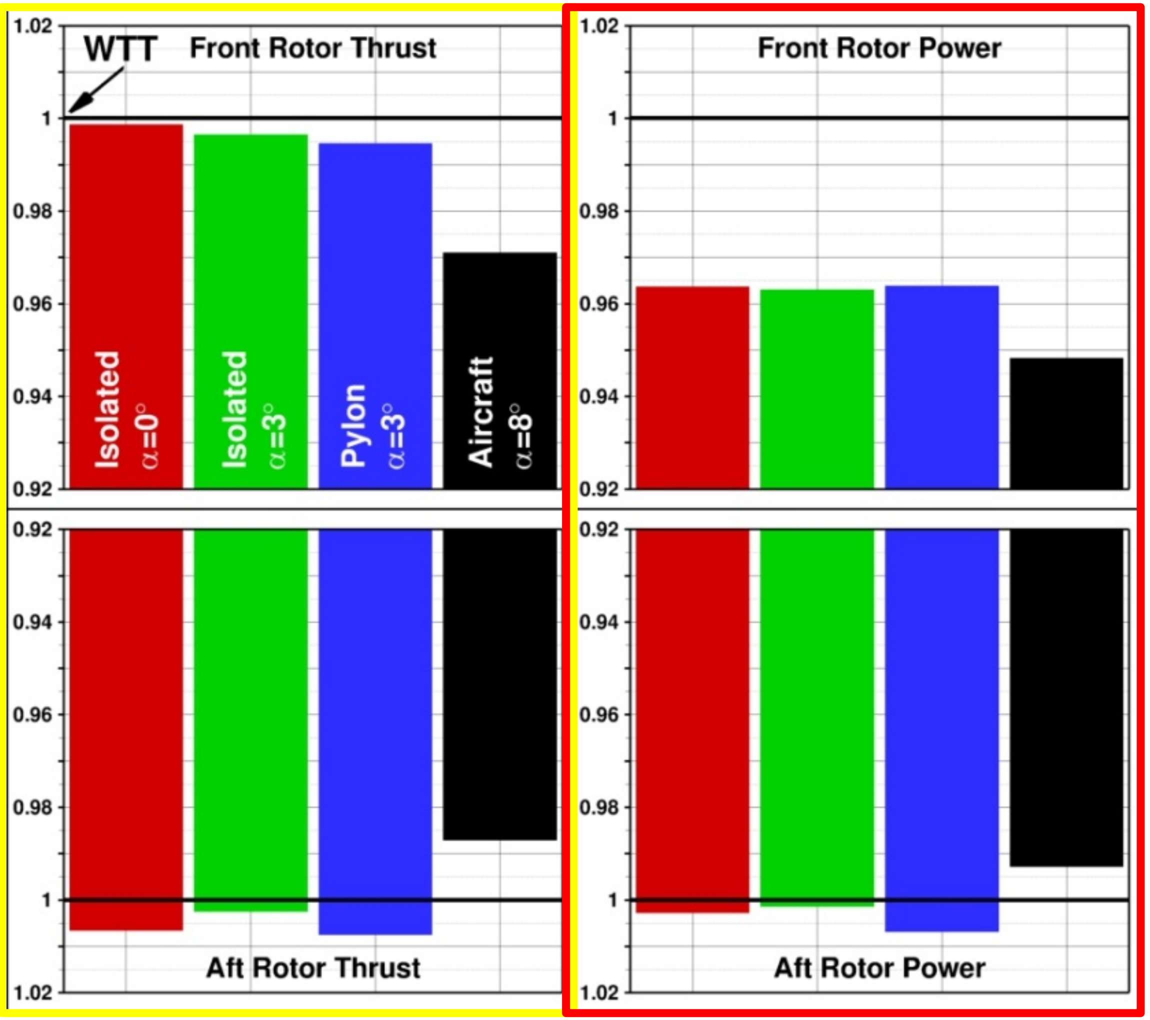




Optimized Mesh
2772p

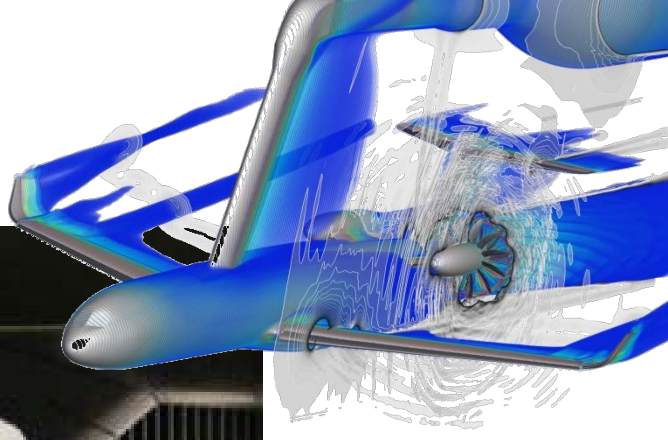
Aerodynamic Analysis: Mean Performance - Validation

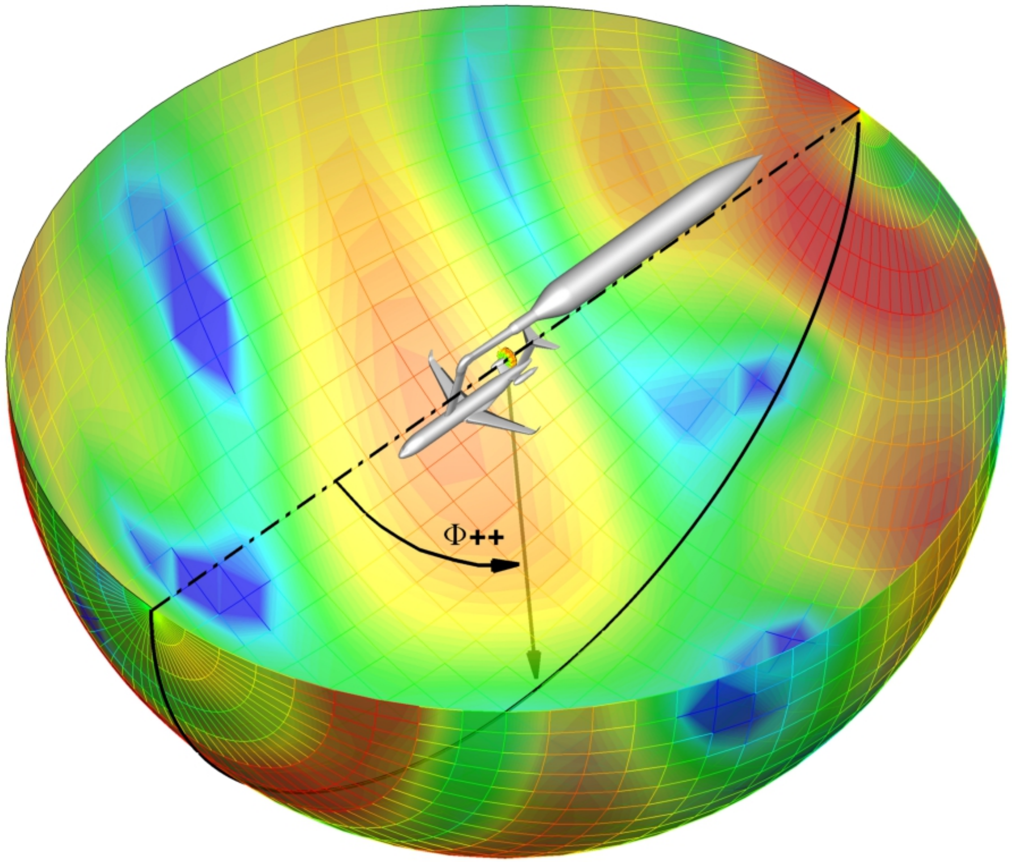
		Isolated @ α=0º	Isolated @ α=3º	Pylon @ α=3º	Aircraft @ α=8º
Front Rotor	T/T_{WTT}	0.9986	0.9967	0.9947	0.9710
	P/P_{WTT}	0.9637	0.9629	0.9639	0.9483
	η/η_{WTT}	1.0406	1.0384	1.0342	1.0276
Aft Rotor	T/T_{WTT}	1.0066	1.0026	1.0073	0.9929
	P/P_{WTT}	1.0029	1.0015	1.0071	0.9977
	η/η_{WTT}	1.0079	1.0046	1.0024	1.0024

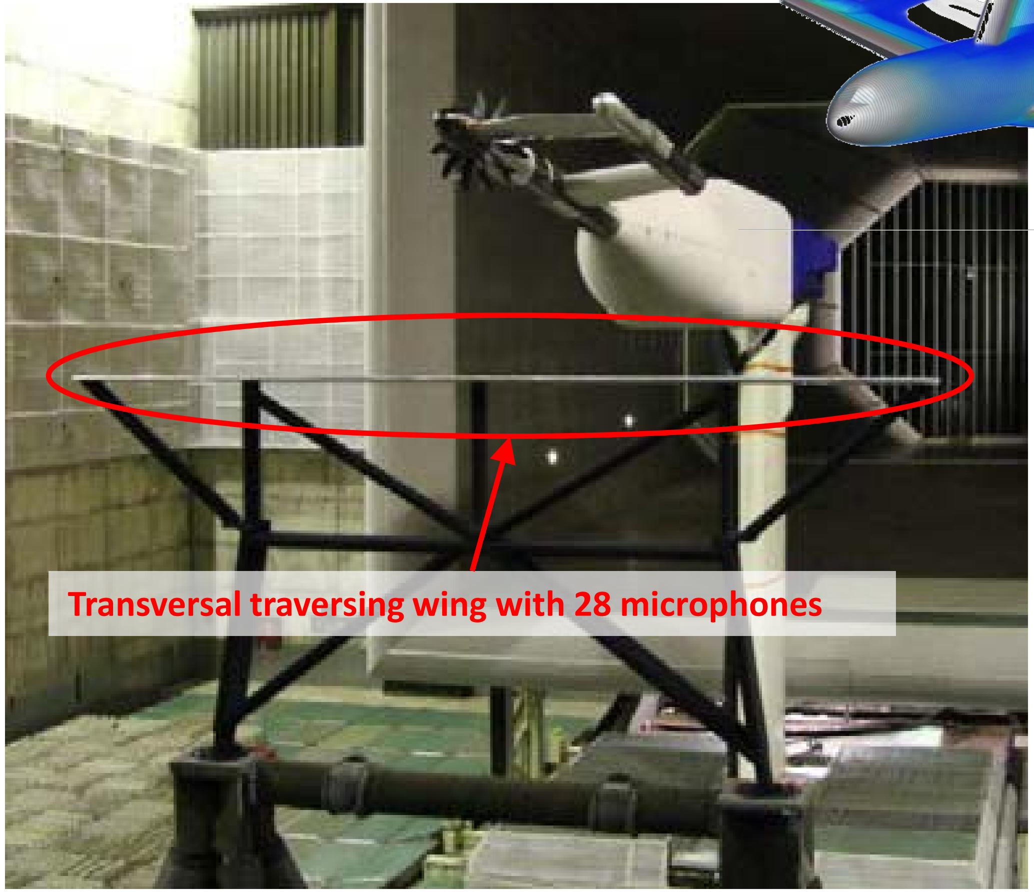


- Very good match with WTT seen in previous studies
- Predictions of
    - Thrust to within <1% accuracy - **consistently**
    - Power at <1%/<4% accuracy - **consistently**
- Slightly larger discrepencies for aircraft case
    - Sting geometry for α=9° was used for simulation at α=8°

Aeroacoustic Analysis: Validation Data and Specifications

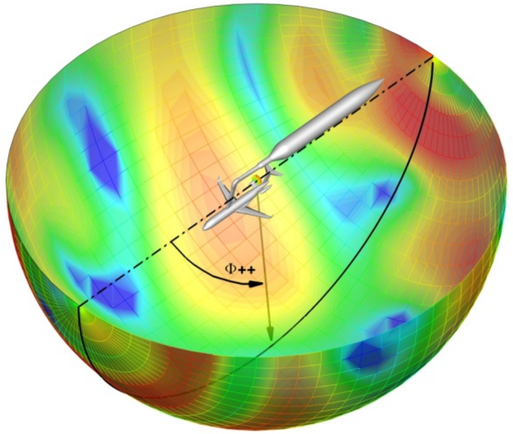


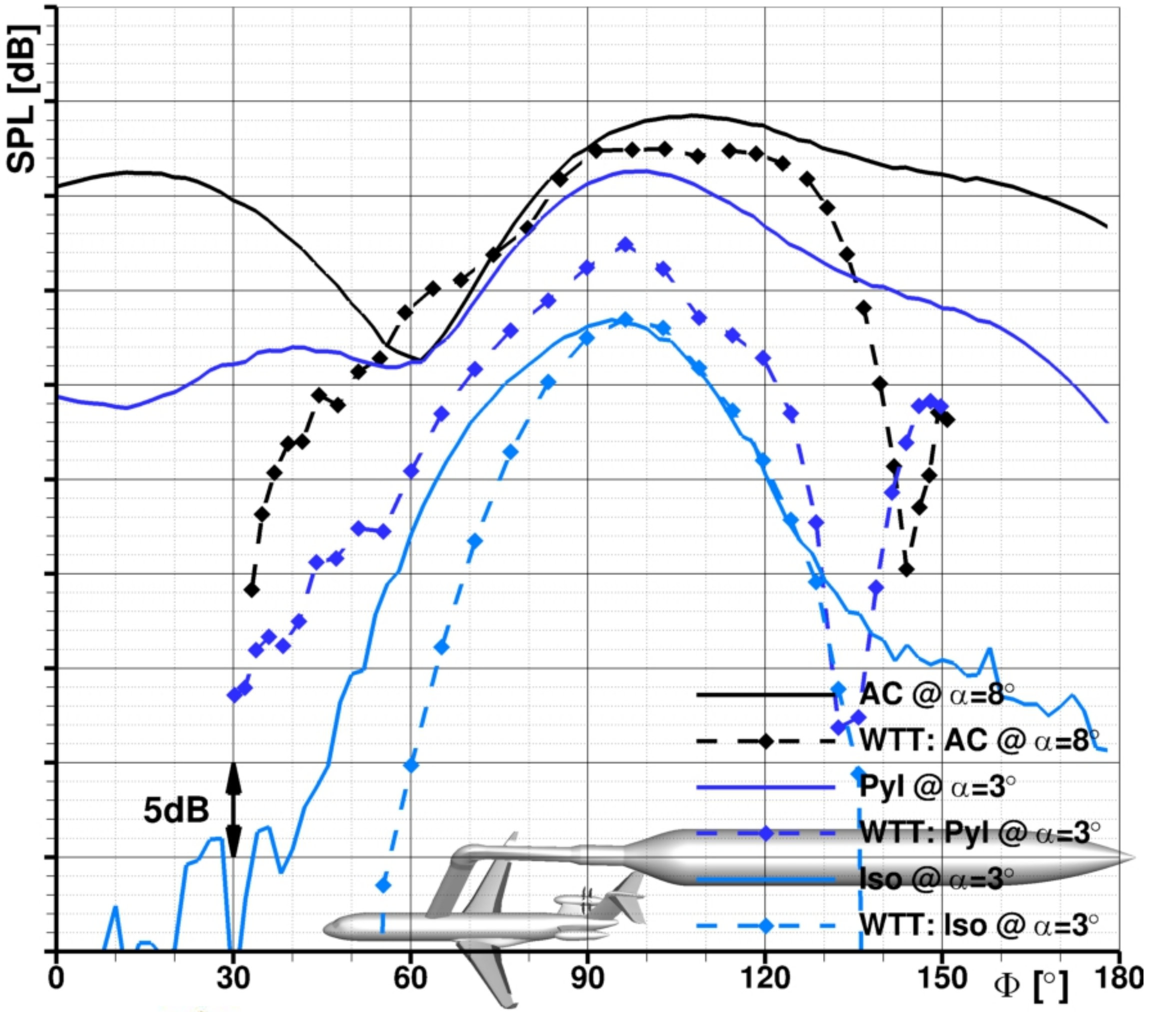




- Validation of numerical results with acoustic data from DNW-LLF WTT
- In-flow traversing microphone array gives azimuthal directivity information
- WTT data post-processed and corrected to represent tonal noise on a 16.6m sphere

Aeroacoustic Analysis: Front Rotor Tone Installation Effect

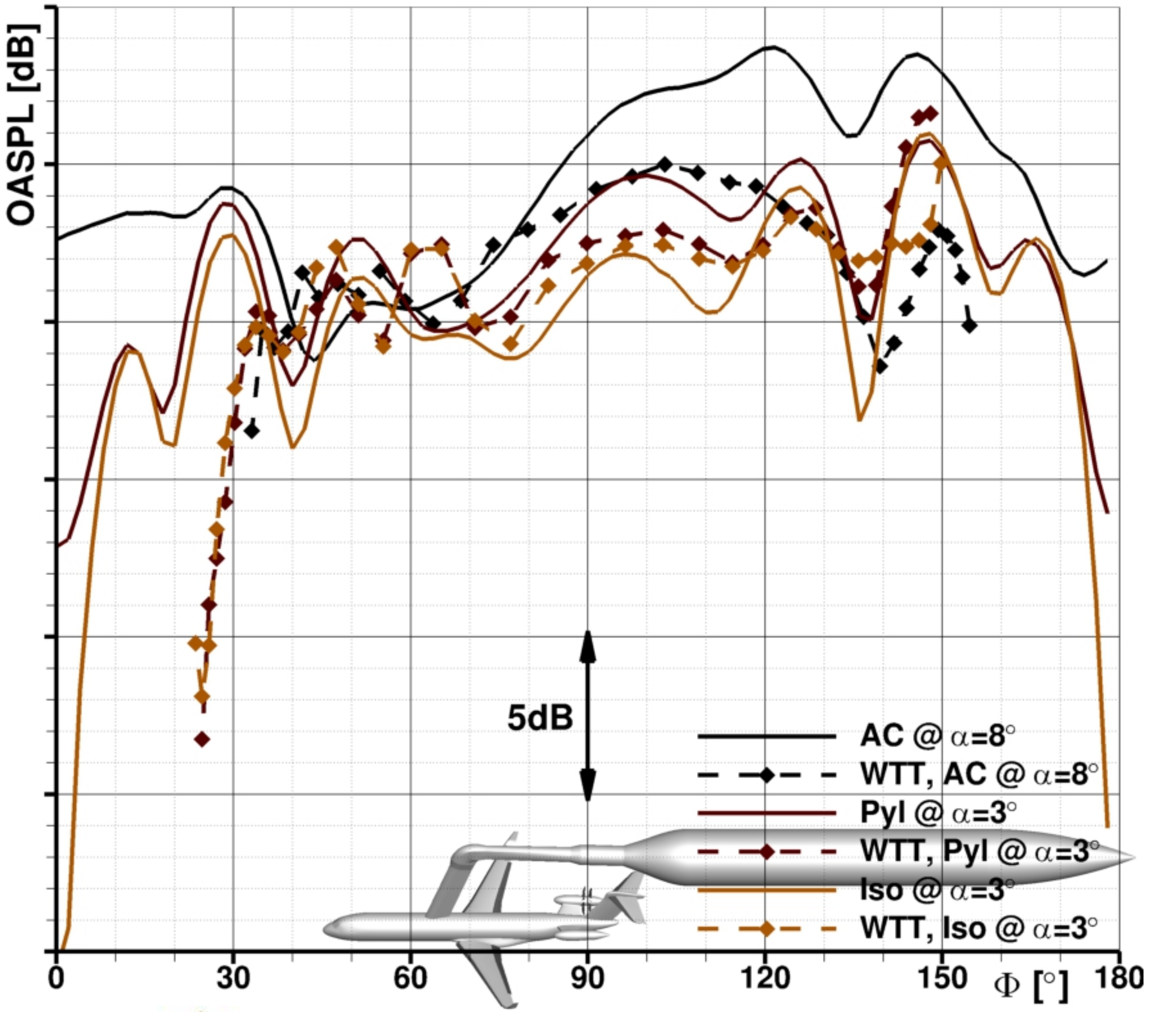


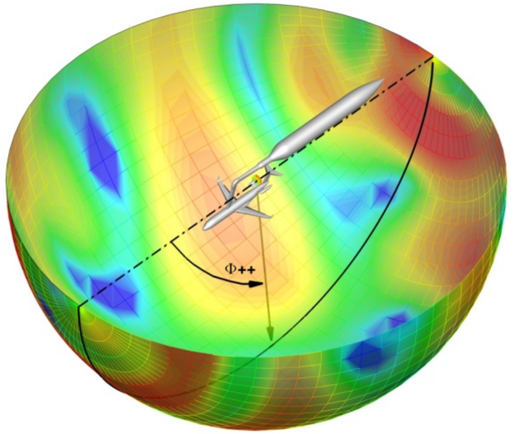


- APSIM+-runs for **all cases** using uRANS input at **highest temporal resolution (2772p)**

- Good prediction of front rotor tone directivity and magnitude for aircraft case between 60<ϕ<130
- Generally well predicted difference of front rotor tone directivity between aircraft and pylon case
- Very good agreement with WTT data for isolated CROR at incidence case
- Trend of pylon effect well predicted, good agreement with WTT in terms of magnitude for most angles

Aeroacoustic Analysis: OASPL Installation Effect





- APSIM+-runs for **all cases** using uRANS input at **highest temporal resolution (2772p)**

- Good prediction of OASPL directivity and magnitude for aircraft case between 30<ϕ<90
- Downstream offset most likely due to neglect of acoustic reflection on tailplanes & stinf
- Very good agreement with WTT data for pylon case
- Good match for isolated CROR at incidence case directivity

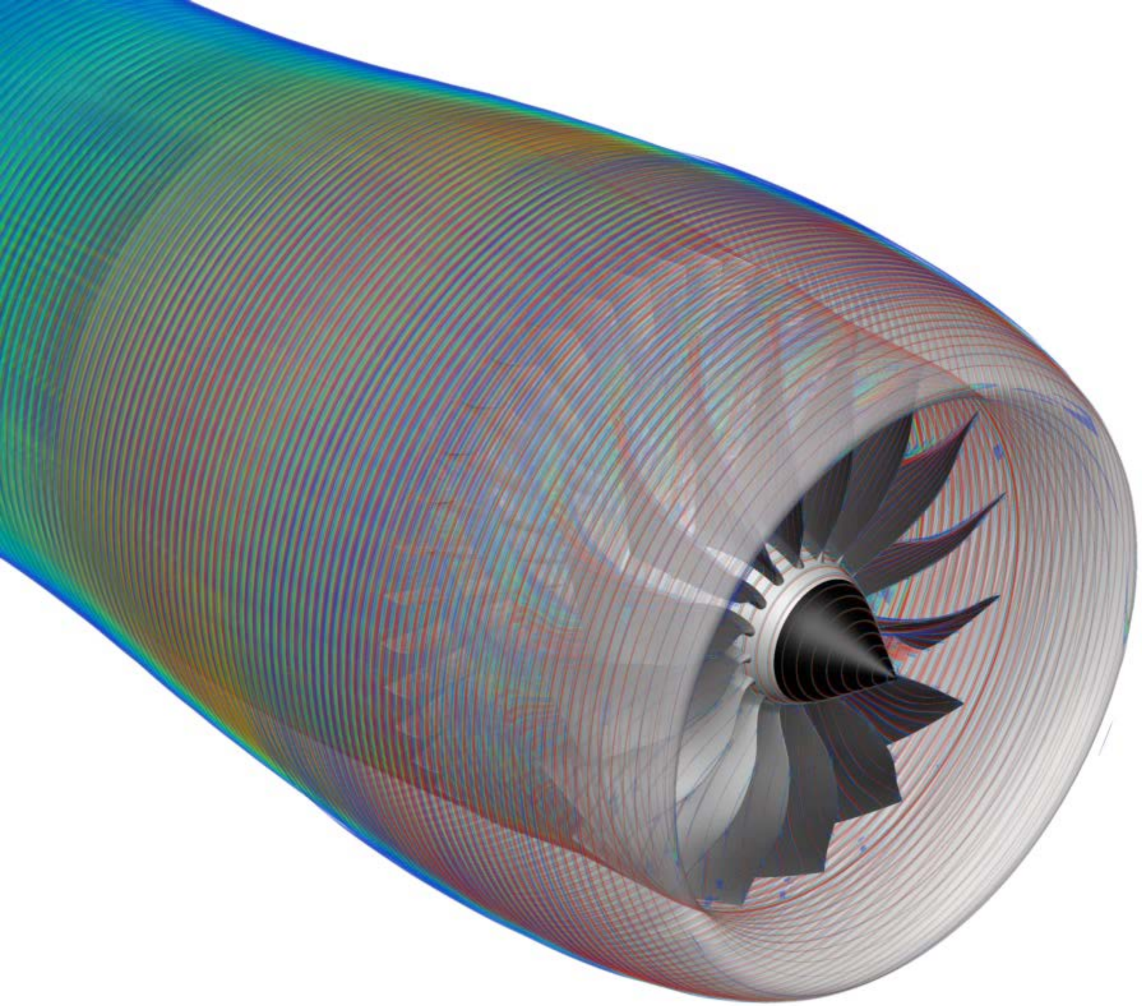
Numerical Approach Validation: Summary & Conclusions

- High-quality experimental data from DNW-LLF tests of the Airbus Z08 CROR configuration in EU JTI SFWA project has enabled a robust validation of DLRs CFD and CAA tools for coupled simulations of CRORs

- uRANS spatial and temporal resolution impact was investigated in detail
  - **Mean aerodynamic performance** – including 1P loads - can be **predicted with high accuracy** practically irrespective of mesh density and time-step size
  - To resolve unsteady aerodynamic rotor-rotor interactions (and thus noise emissions) spatial resolution has an impact – certainly for higher frequency tonal noise predictions
  - **Temporal resolution** requirements must be met to enable **adequate resolution of unsteady flow phenomena** – and thus noise emissions

- **Good prediction of aerodynamic & aeroacoustic installation effects**, in line with WTT
- **Good maturity of CFD/CAA-approach** for the analysis of CROR configuration performance and noise

- **Outlook:** Continued work in progress in CS2 project to investigate and refine additional OR-powered aircraft configurations to **improve economic viability** case for this propulsion system for single aisle aircraft class



Engine-Airframe Integration for Environmentally Friendly & Economically Viable Future Transport Aircraft

Simulation Capabilities for UHBR Turbofans Featuring a Rotating Fan

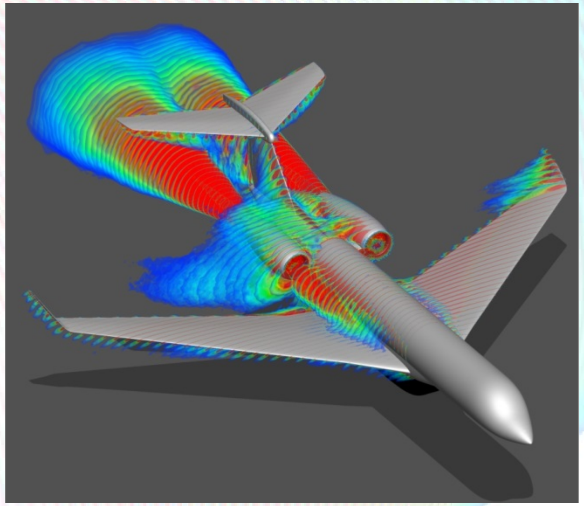
DLR

ASPIRE

Introduction & Overview

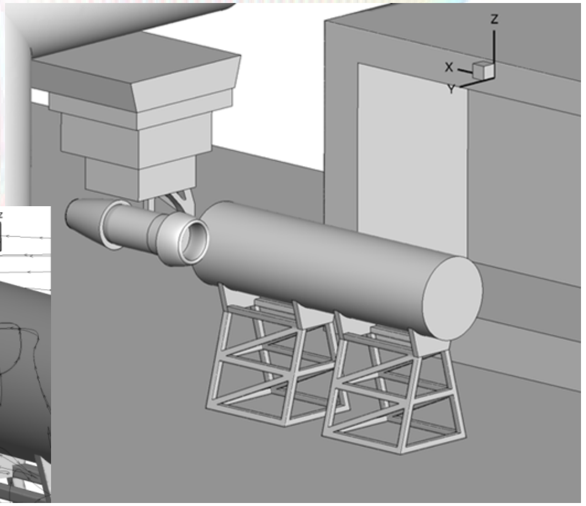
Introduction & Motivation:

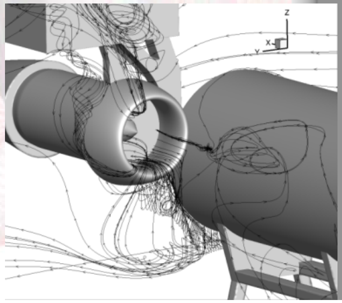
- Future improvements in overall aircraft efficiency require an increasingly closer coupling of airframe and engine – both physically as well as in terms of treatment in the design process.
- More pronounced mutual interactions
- Need to account for relevant (unsteady) engine impacts on the airframe and vice versa
- Today, some critical operating conditions show critical engine-airframe interactions (X-wind)
- ASPIRE: DLR TAU rotating fan unsteady simulations demonstration & validation



The ASPIRE project: *A*erodynamic and acou*S*tic for high-by-*P*ass rat*I*o tu*R*bofan int*E*gration

- 1st call for partners in AIRFRAME-ITD, closely linked to LPA-IADP
- Aerodynamic & acoustic capabilities for close coupled, UHBR turbofan-aircraft integration
- Project partners: Airbus, DLR, NLR, ONERA and TsAGI
- Q1/2016 – Q3/2018



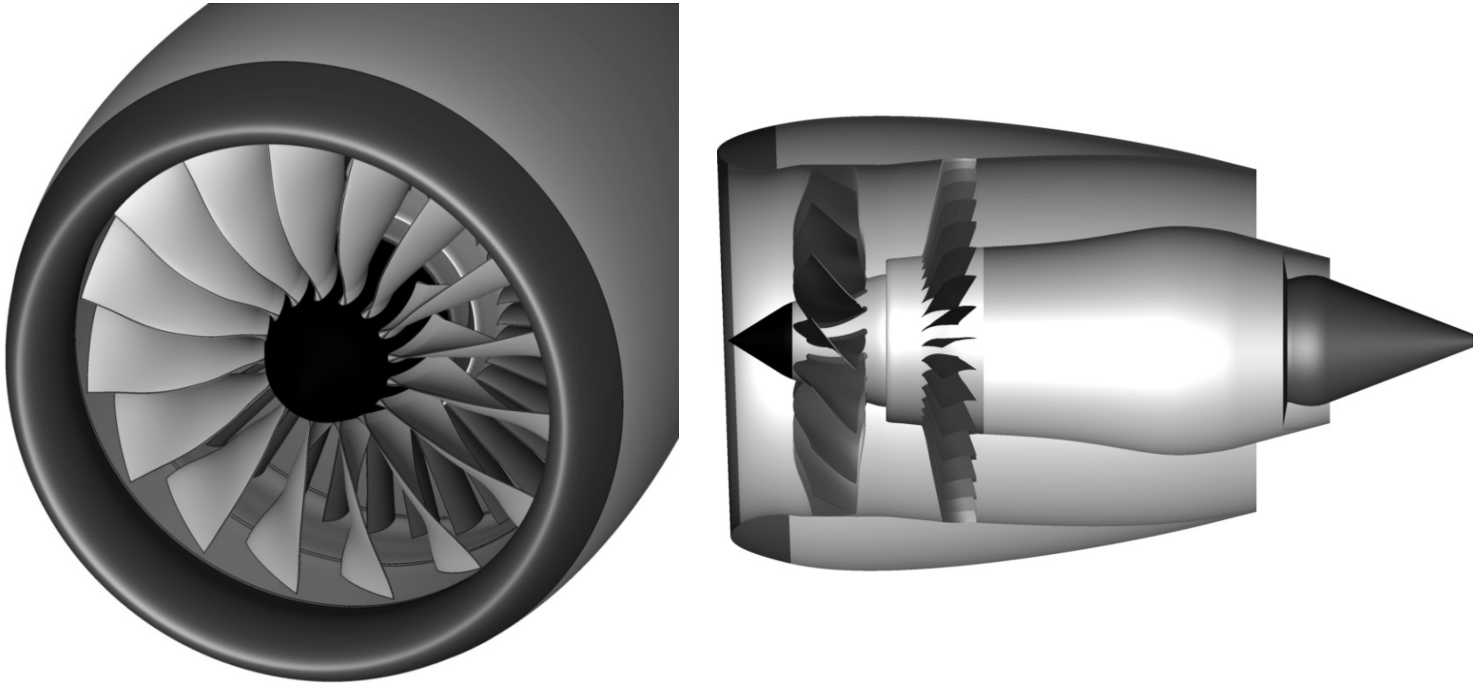


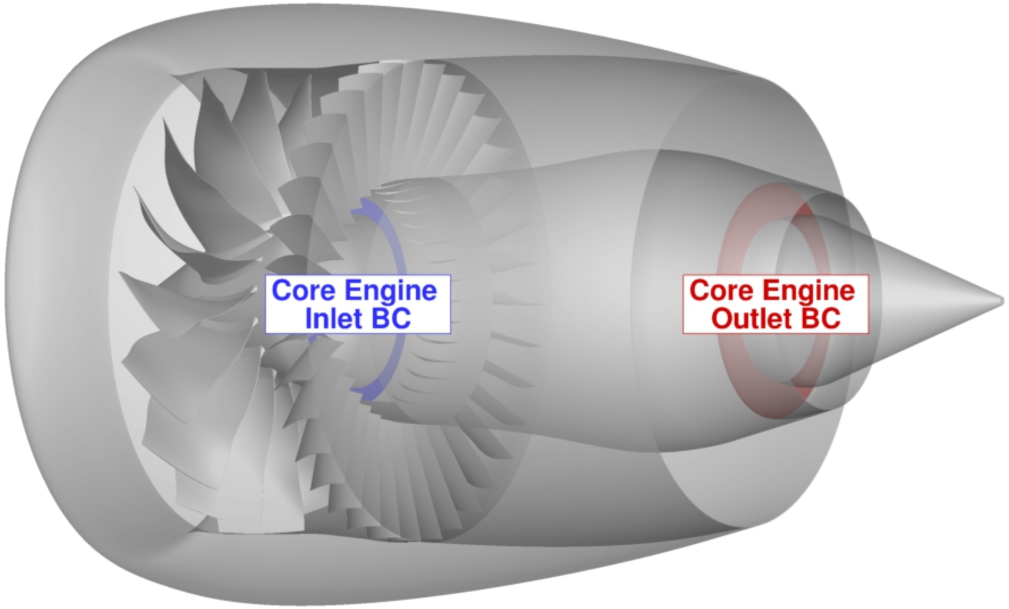
Numerical Approach:

Results Analysis & Discussion

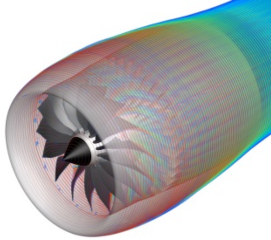
Summary & Outlook

The CS2 ASPIRE Project
Configuration Overview

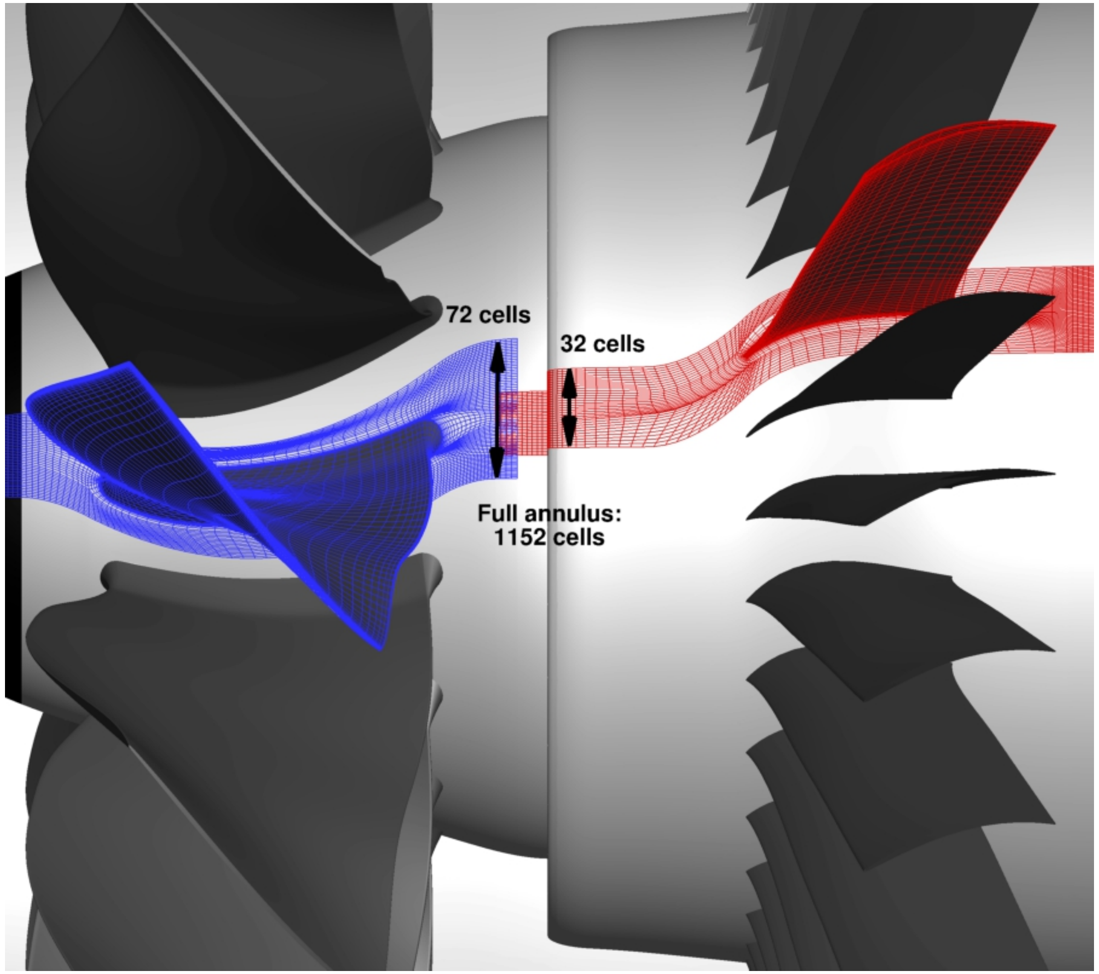




- Generic isolated UHBR engine for single aisle aircraft
  - Generic Fan/OGV-Geometry designed by DLR-AT: 16 fan blades, 36 OGVs
  - Generic (very) short cowl nacelle designed by Airbus
  - Initial simplified isolated engine test case: No pylon, no bifurcations
- Broad range of operating points covering cruise, take-off and approach conditions defined & specified

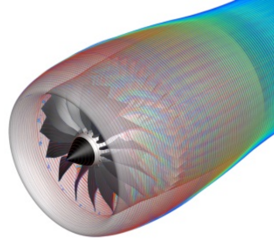


Numerical Approach:
Mesh Philosophy & Generation

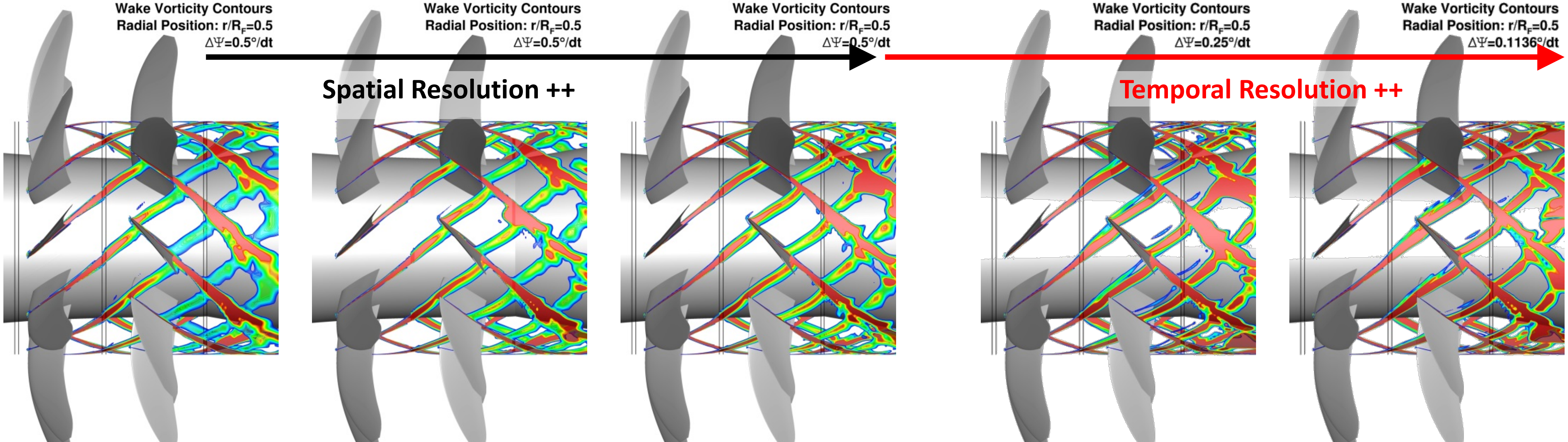


- Analogous to studies performed in task 2.2.4.5 in JTI SFWA:
- Mesh family for a robust validation & parametric study
- 4 block-structured ICEM-Hexa/CentaurSoft CentaurSof mesh blocks (Centaur: Farfield; ICEM: Nacelle, Rotor, OGV)
  - Fine nearfield mesh to resolve acoustic installation & non-linear propagation effects in uRANS
  - Particular focus on rotor-rotor-interface-mesh for optimal wake transfer

	Coarse	Medium	Base
Farfield	2.881.147	6.505.456	8.385.163
Nacelle	10.902.398	35.476.072	83.206.386
Fan	6.632.704	21.438.720	49.700.352
OGV	8.014.500	25.594.344	58.953.708
Total	28.430.749	89.014.592	200.245.609



Numerical Approach: Robust CFD/CAA Validation Study of Spatial & Temporal Discretization



	Coarse	Medium	Base
Δt/rev	90p	90p	90p
	180p	180p	180p
	360p	360p	360p
	720p	720p	720p
	1152p	1440p	1440p
		1728p	2304p

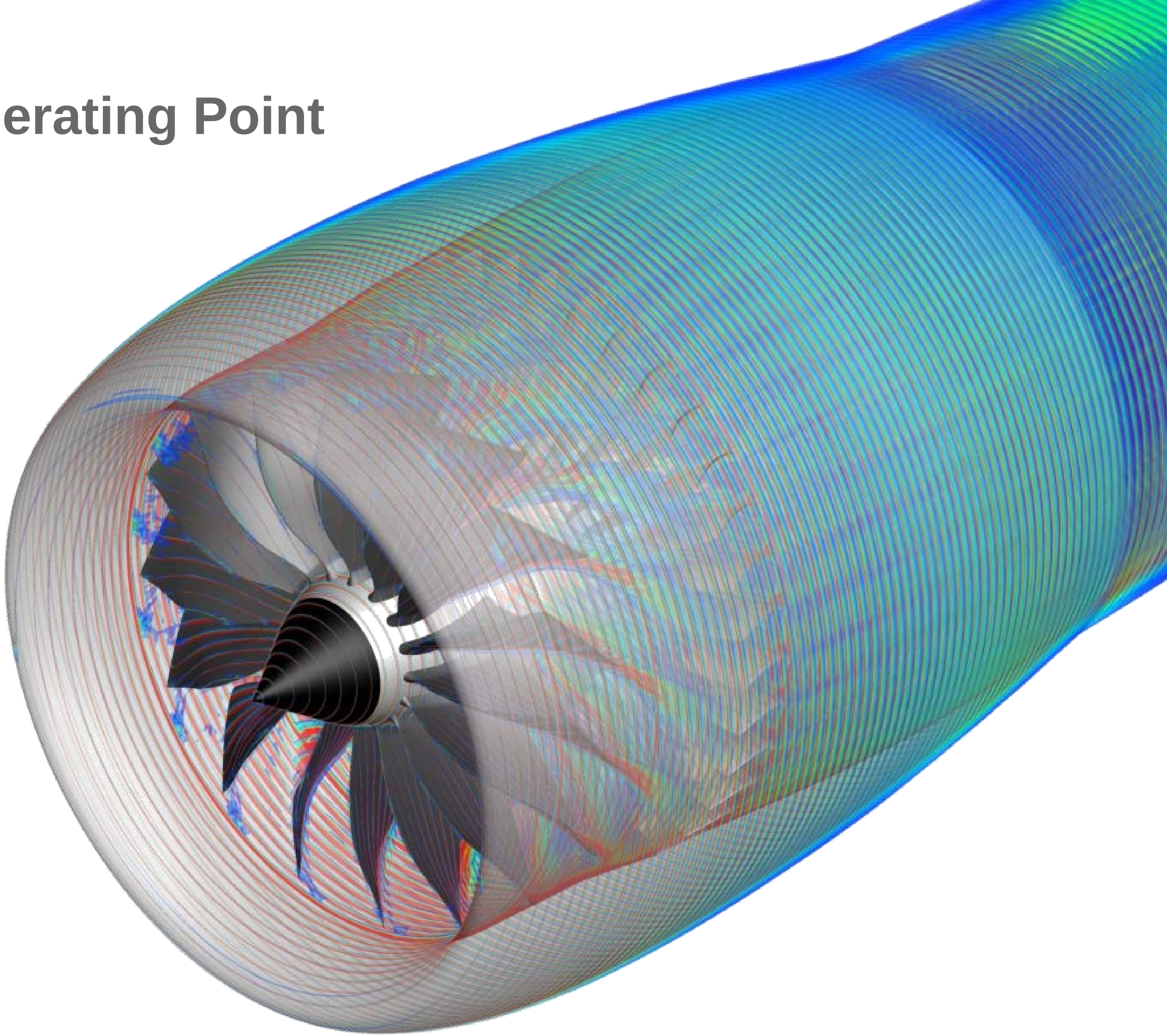
Dependance of the solution quality on spatial resolution [1]
Dependance of the solution quality on temporal resolution
Simulation matrix to study impact of both parameters

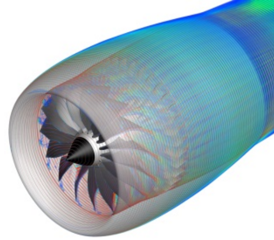
[1] Stuermer, A. and Akkermans, R.: "Validation of Aerodynamic and Aeroacoustic Simulations of Contra-Rotating Open Rotors at Low-Speed Flight Conditions", AIAA 2014-3133, Atlanta, GA, USA, 2014.

Aerodynamic Analysis: Sideline Operating Point
Isolated UHBR Engine @ Sideline

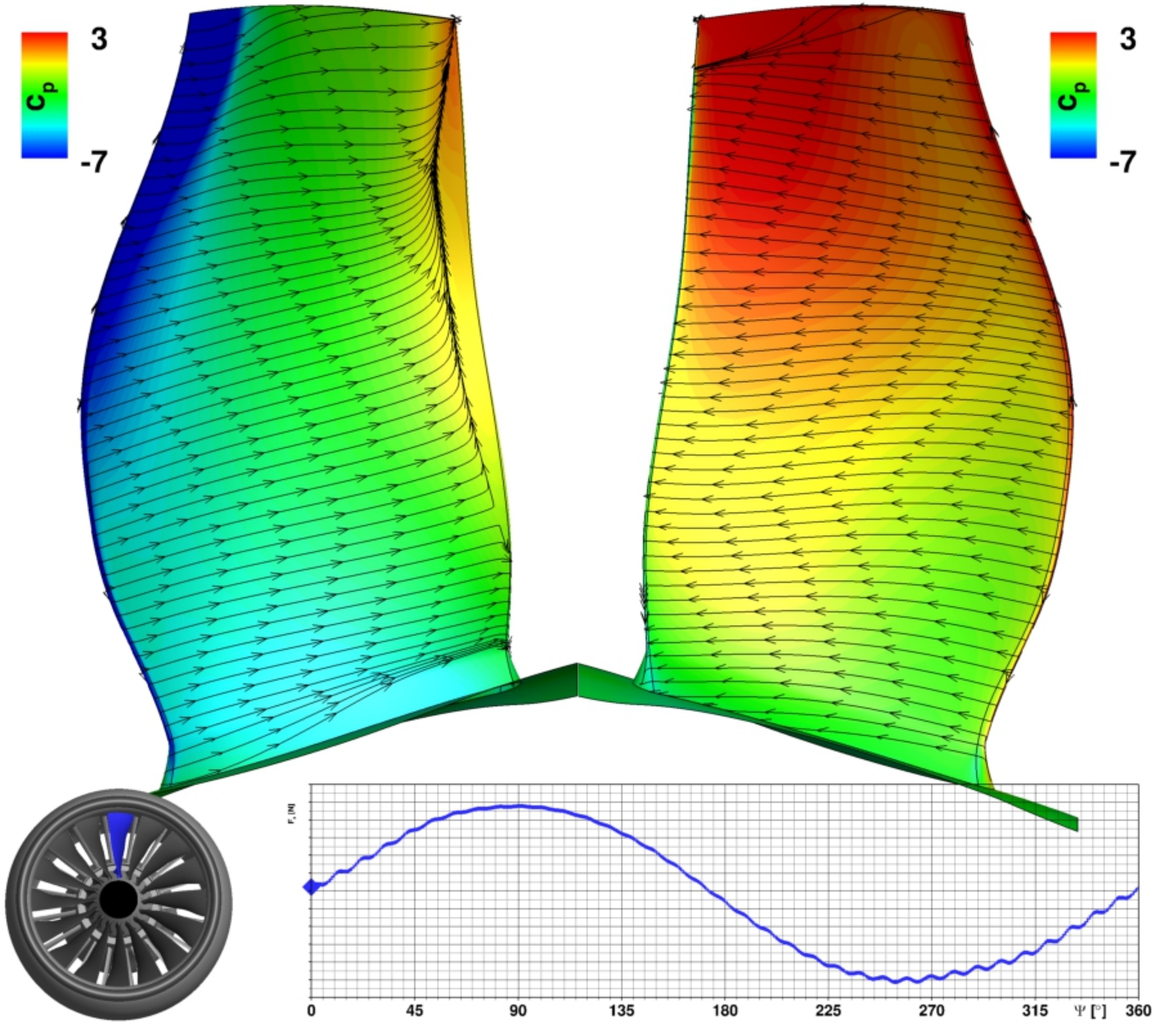
SID Operating Point Specifications	
h [ft]	700
Mn	0.27
α [°]	15

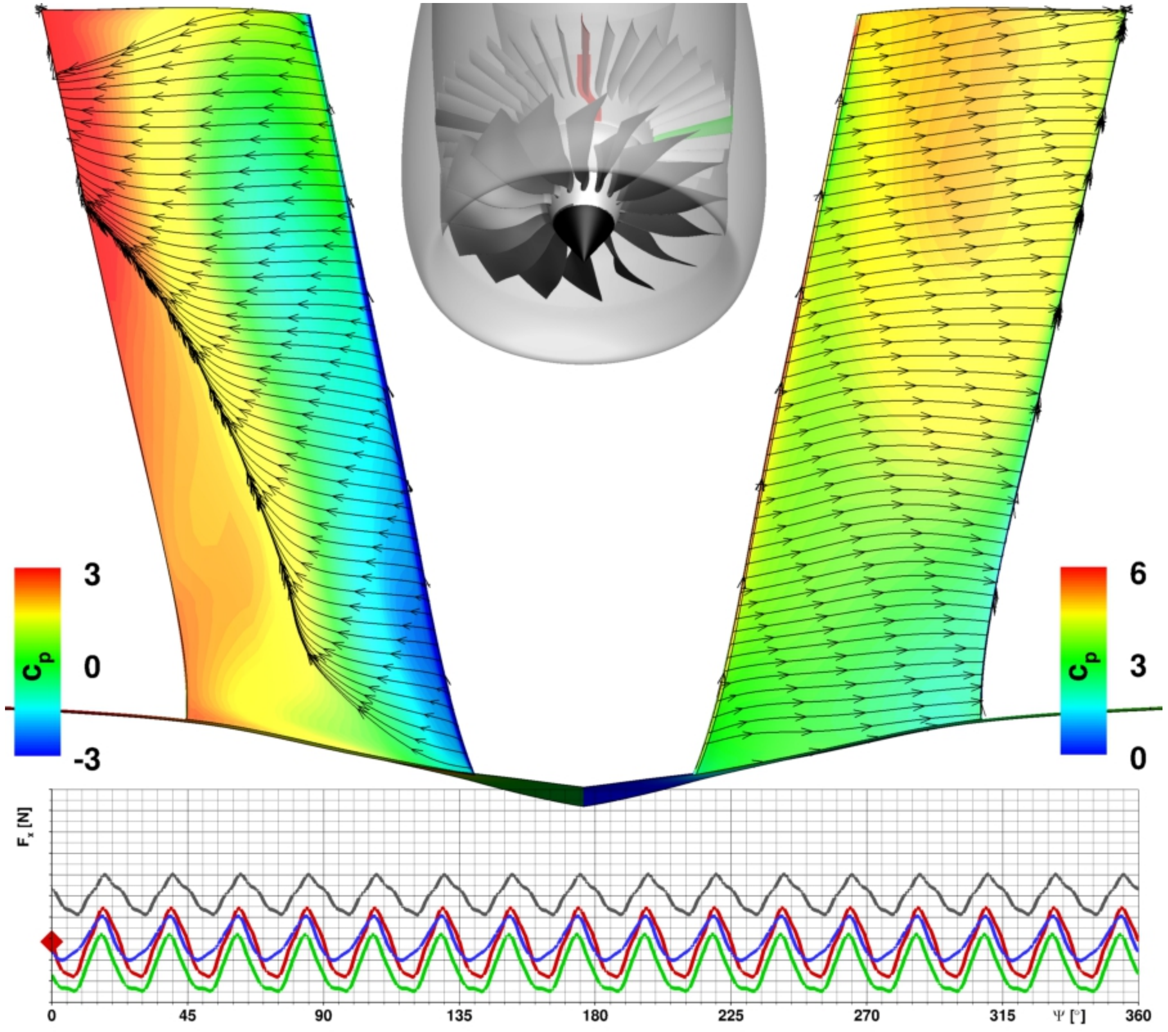
- Simulations run for several enngine operating points
- Here: Focus on sideline case





Aerodynamic Analysis: Isolated UHBR Engine @ Sideline Surface Flow Topology

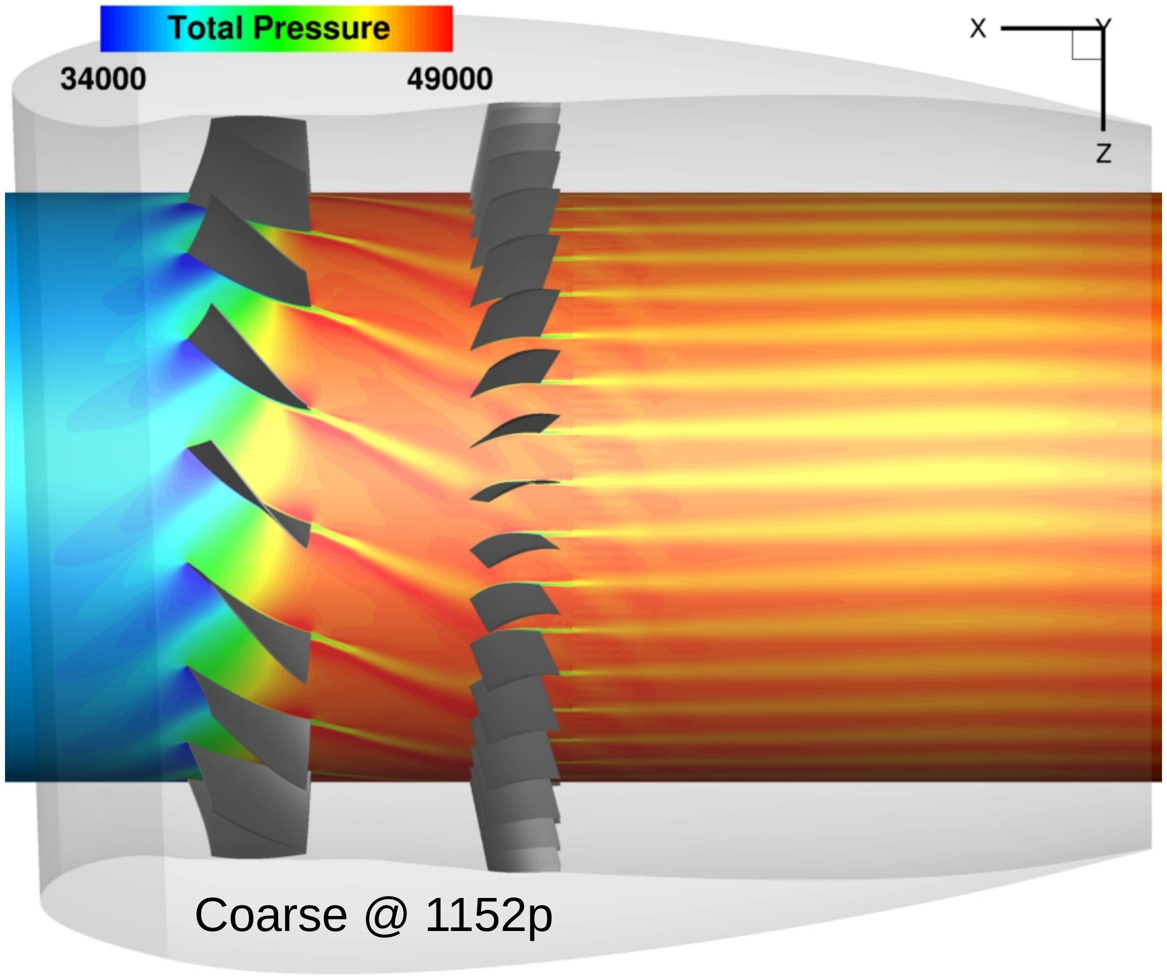


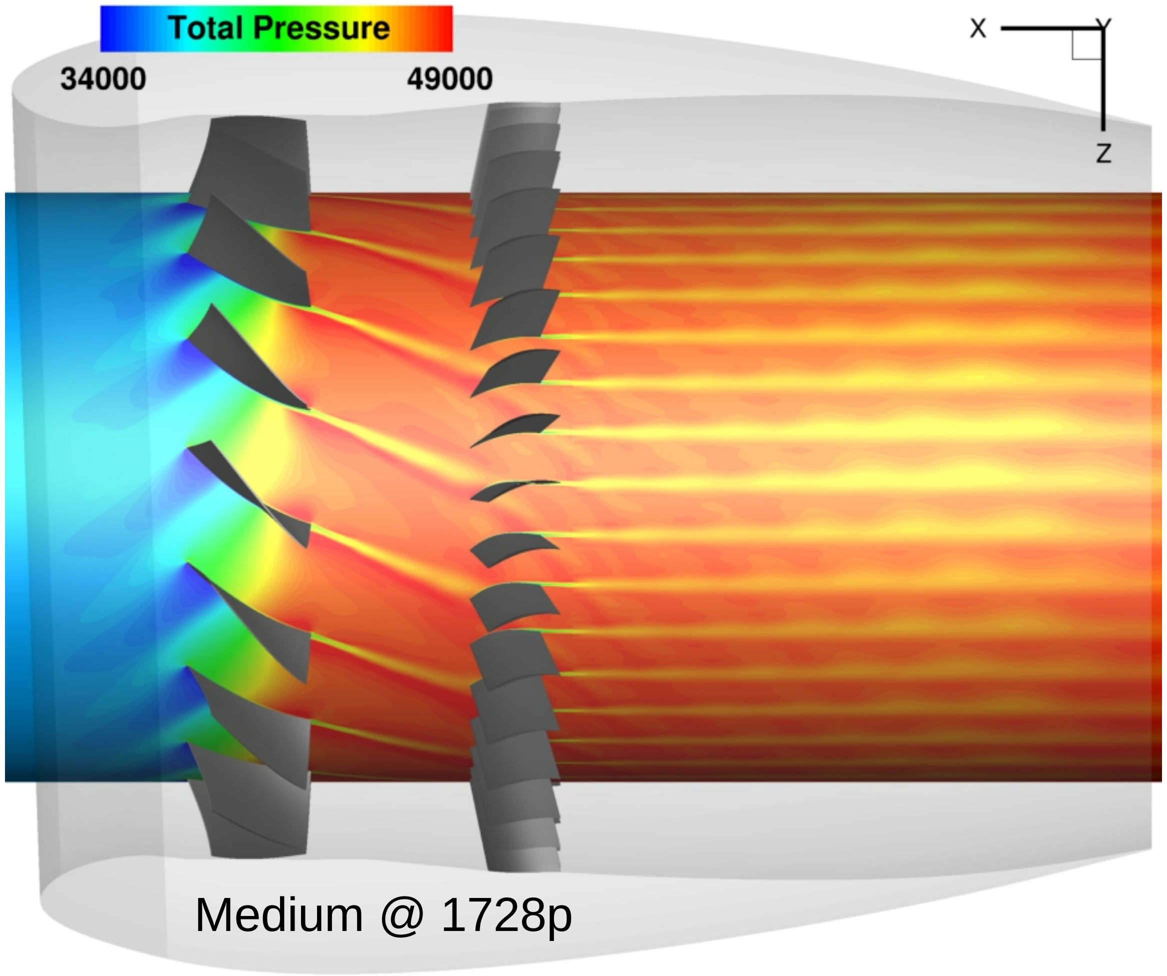


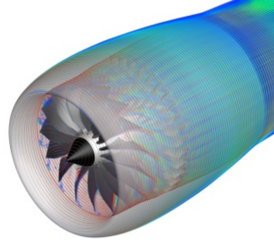
DLR ASPIRE

Medium Mesh

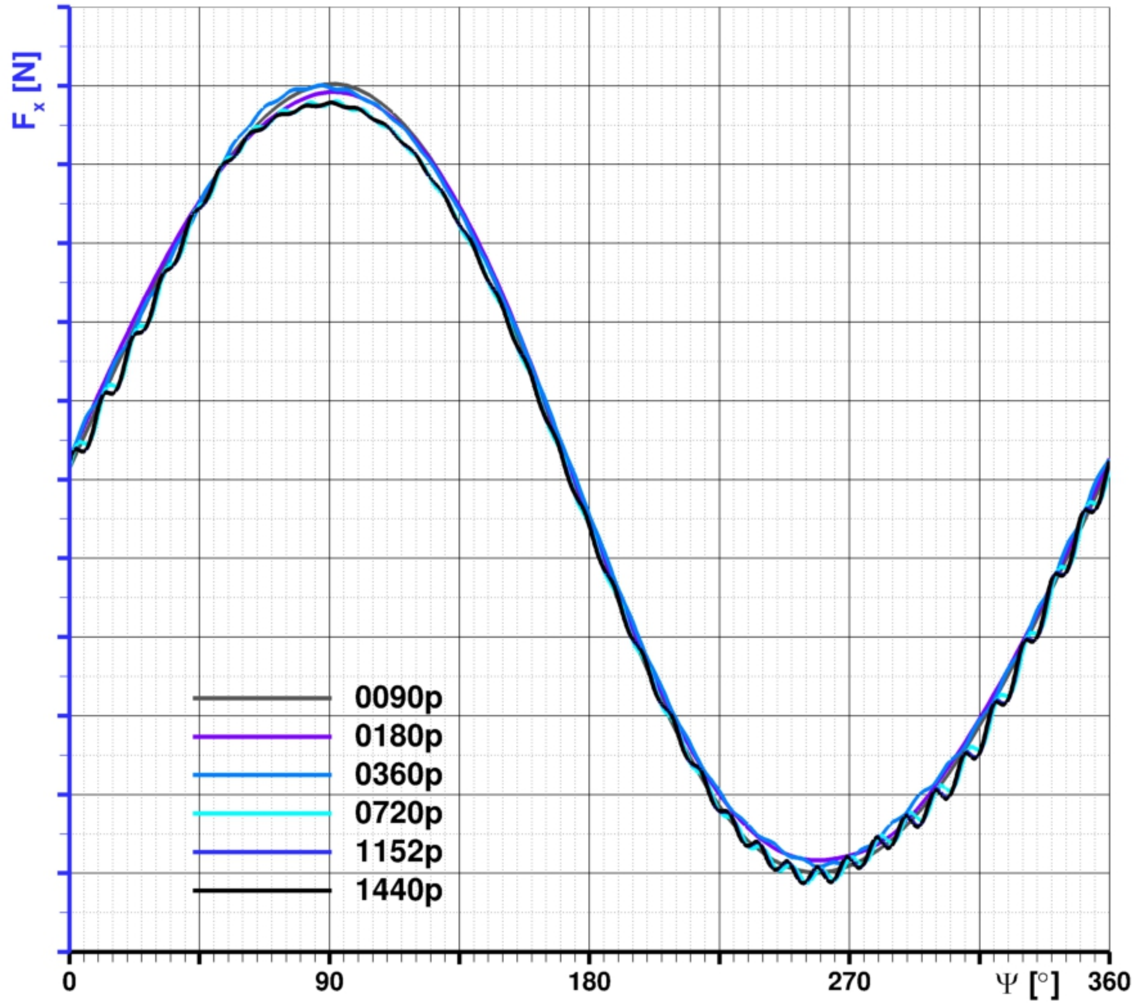
Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
Rotor-Stator Flow Interactions

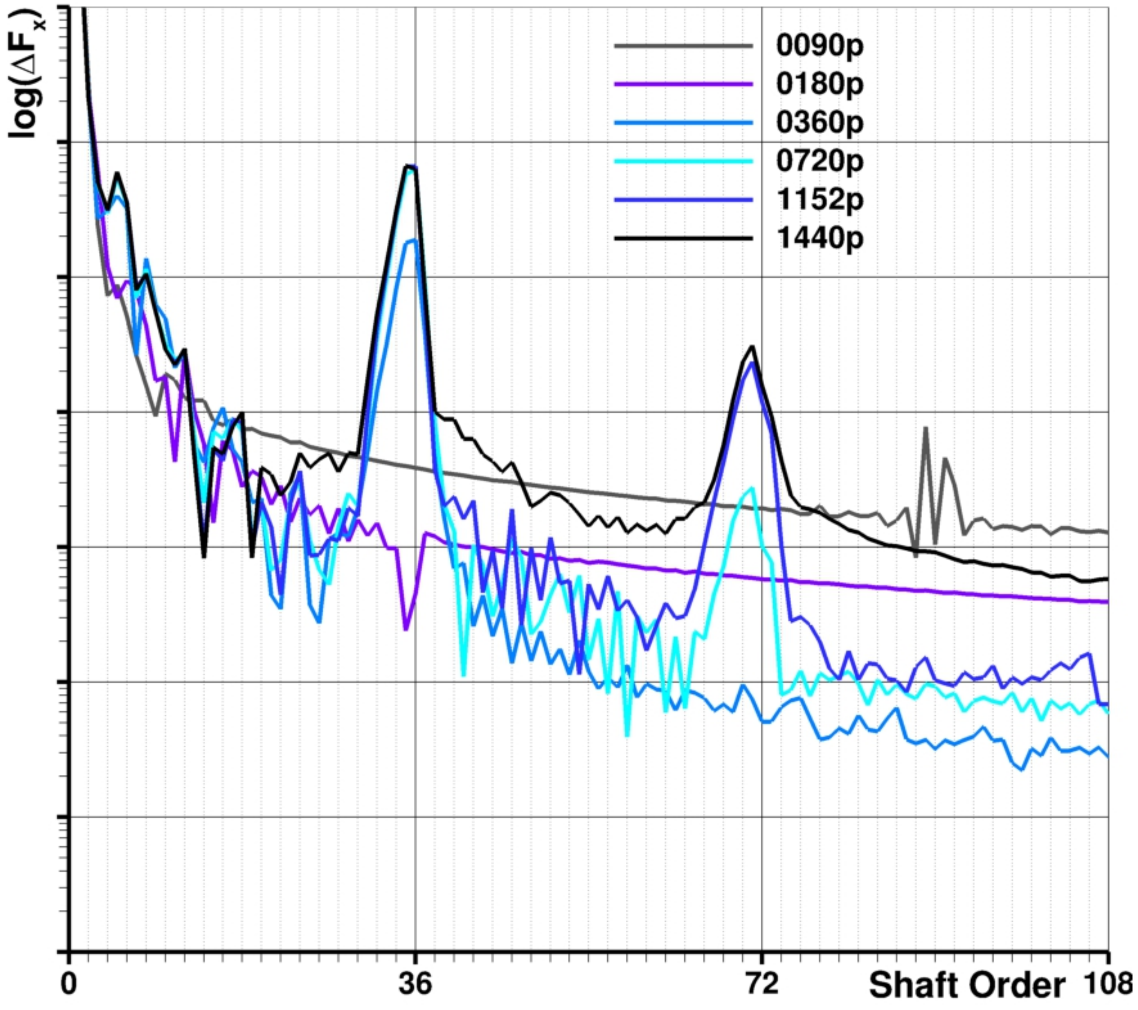




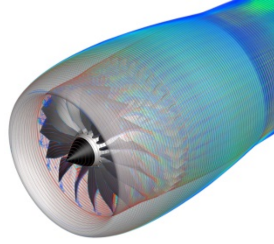


Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
Fan Unsteady Loading

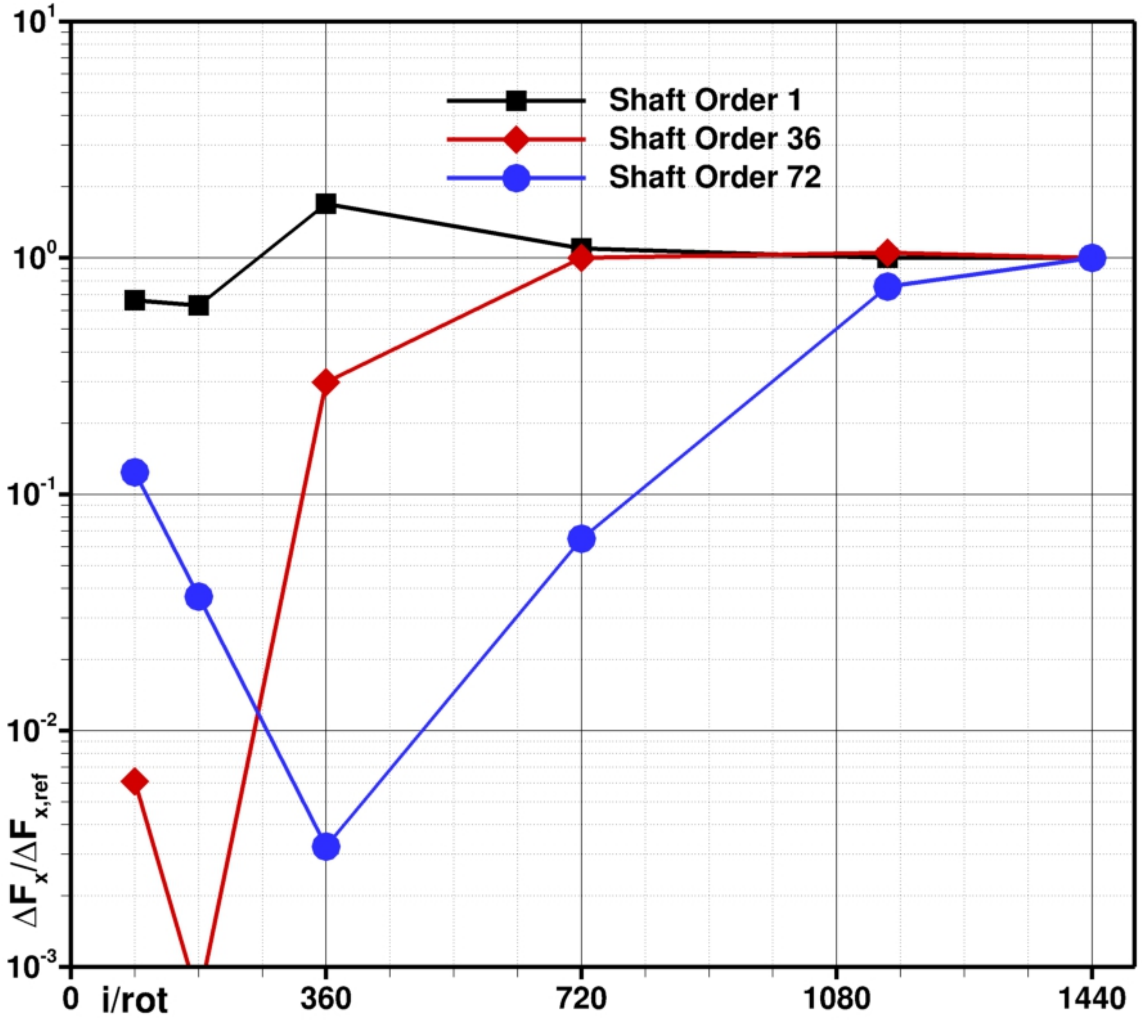


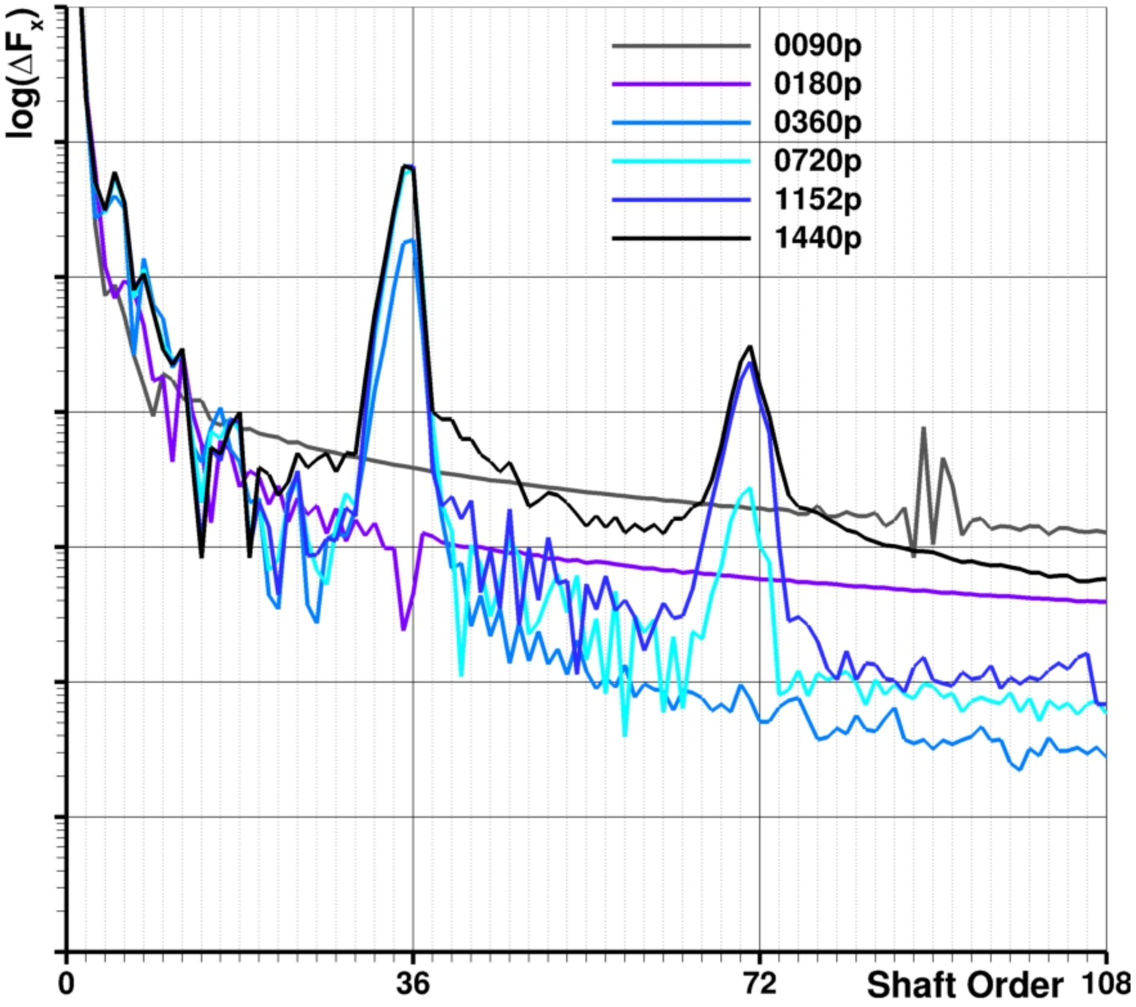


Coarse Mesh



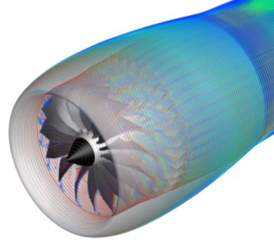
Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
Fan Unsteady Loading

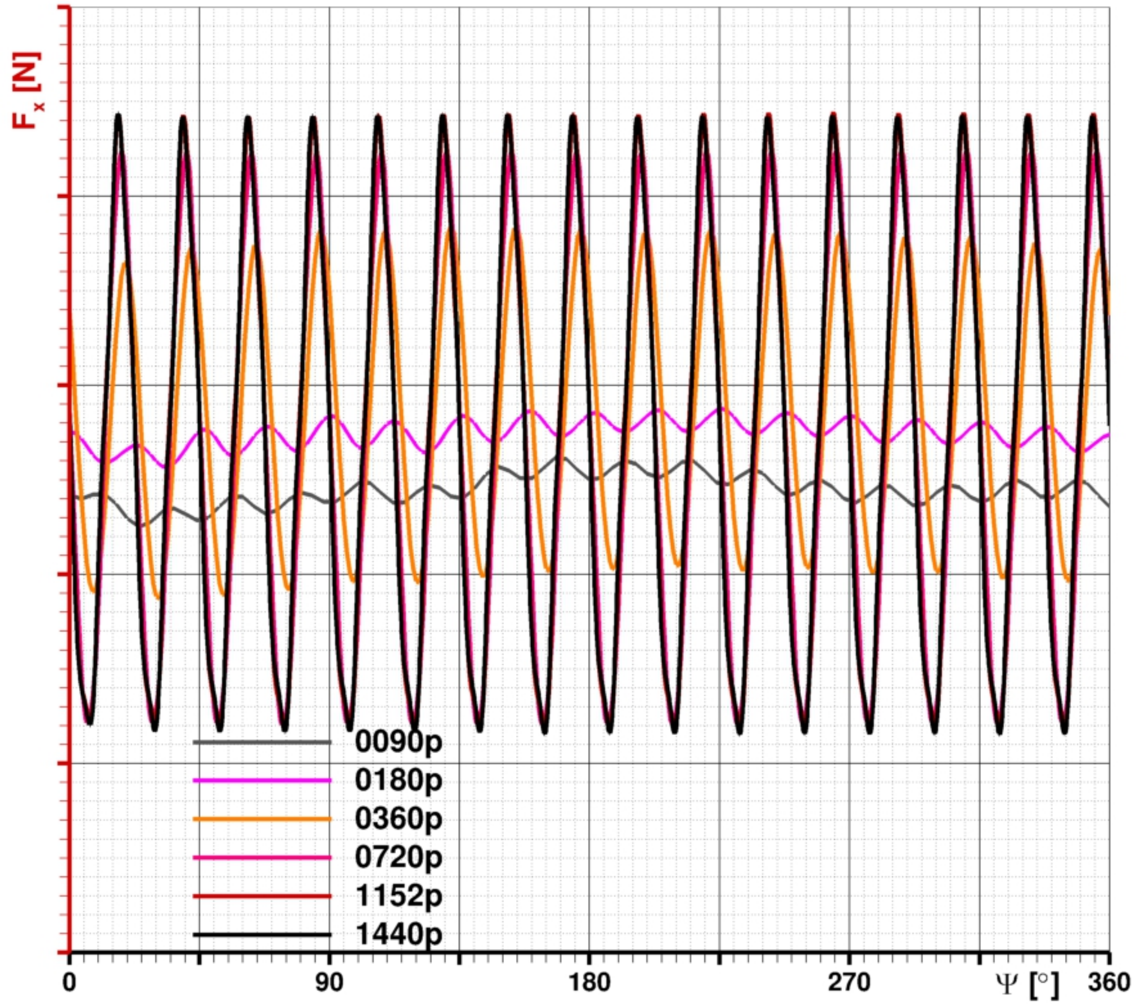


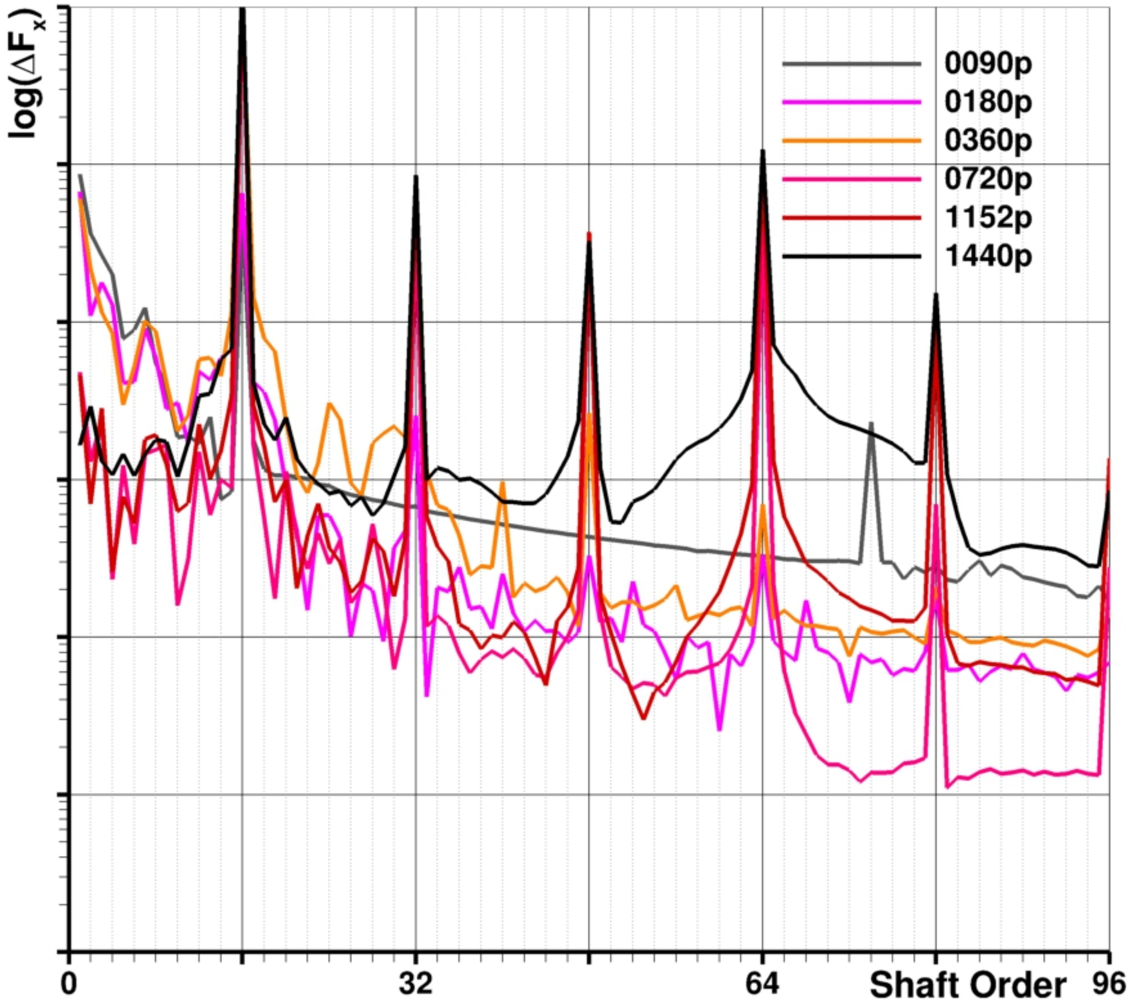


Coarse Mesh

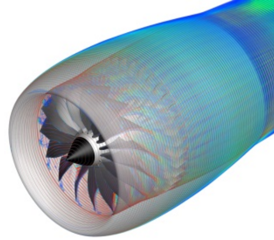
Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
OGV Unsteady Loading



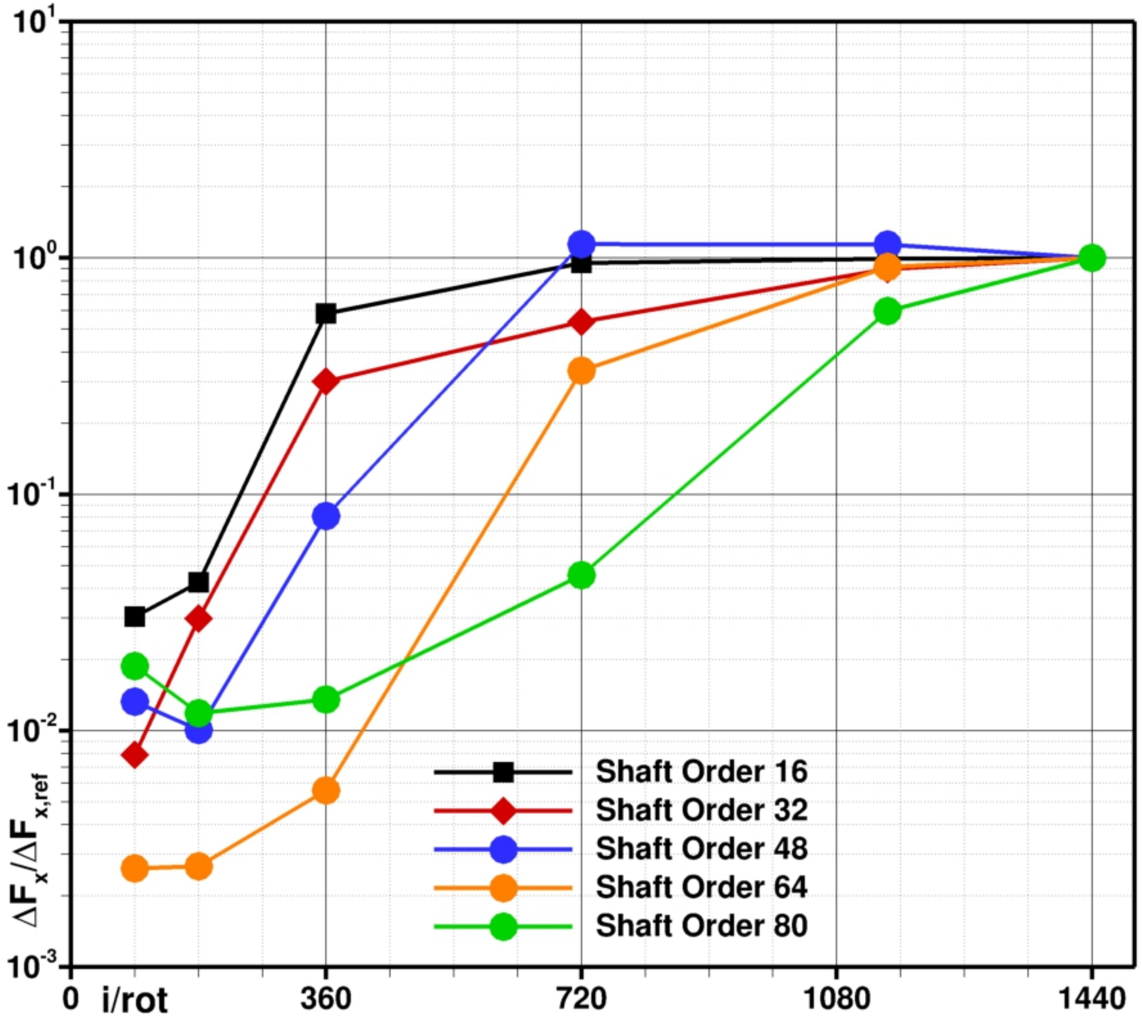


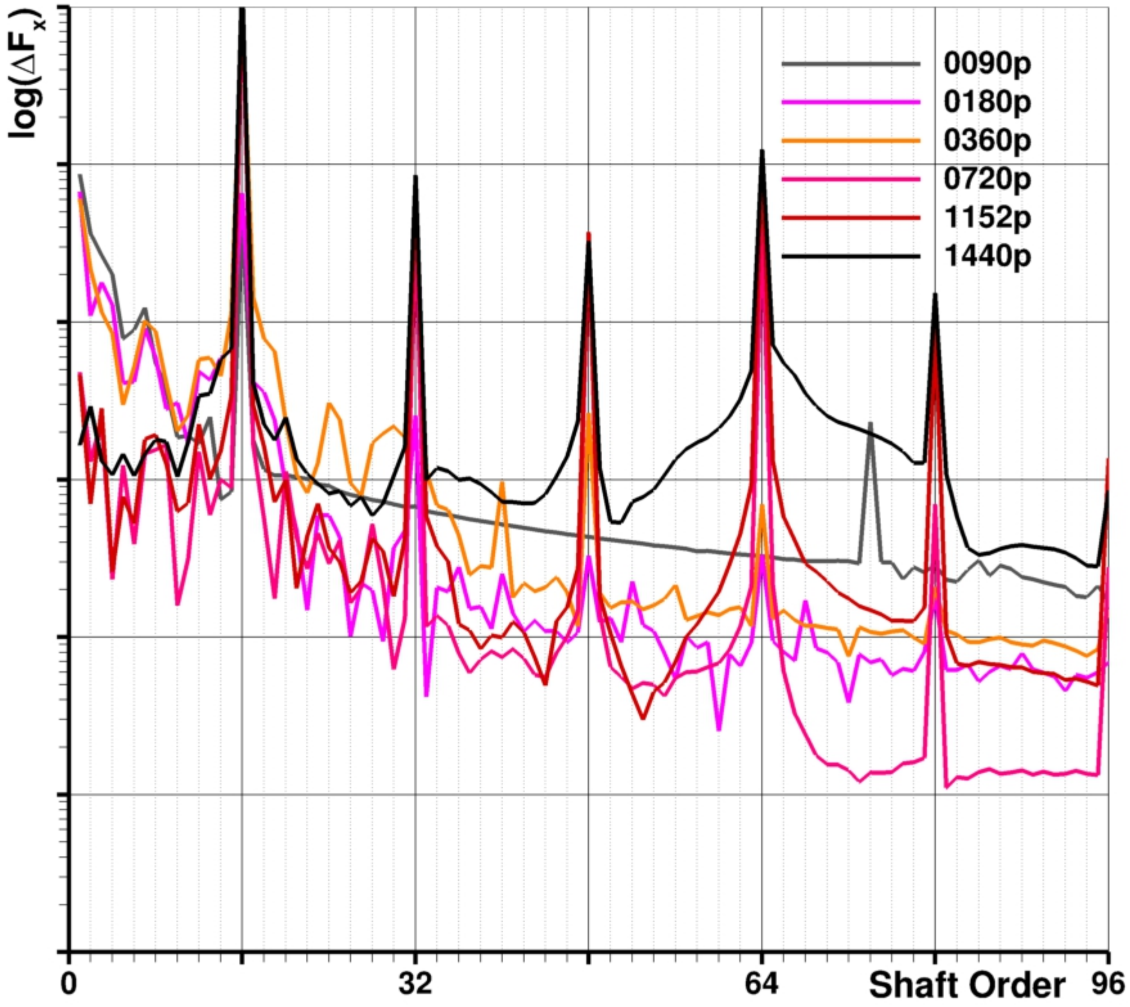


Coarse Mesh

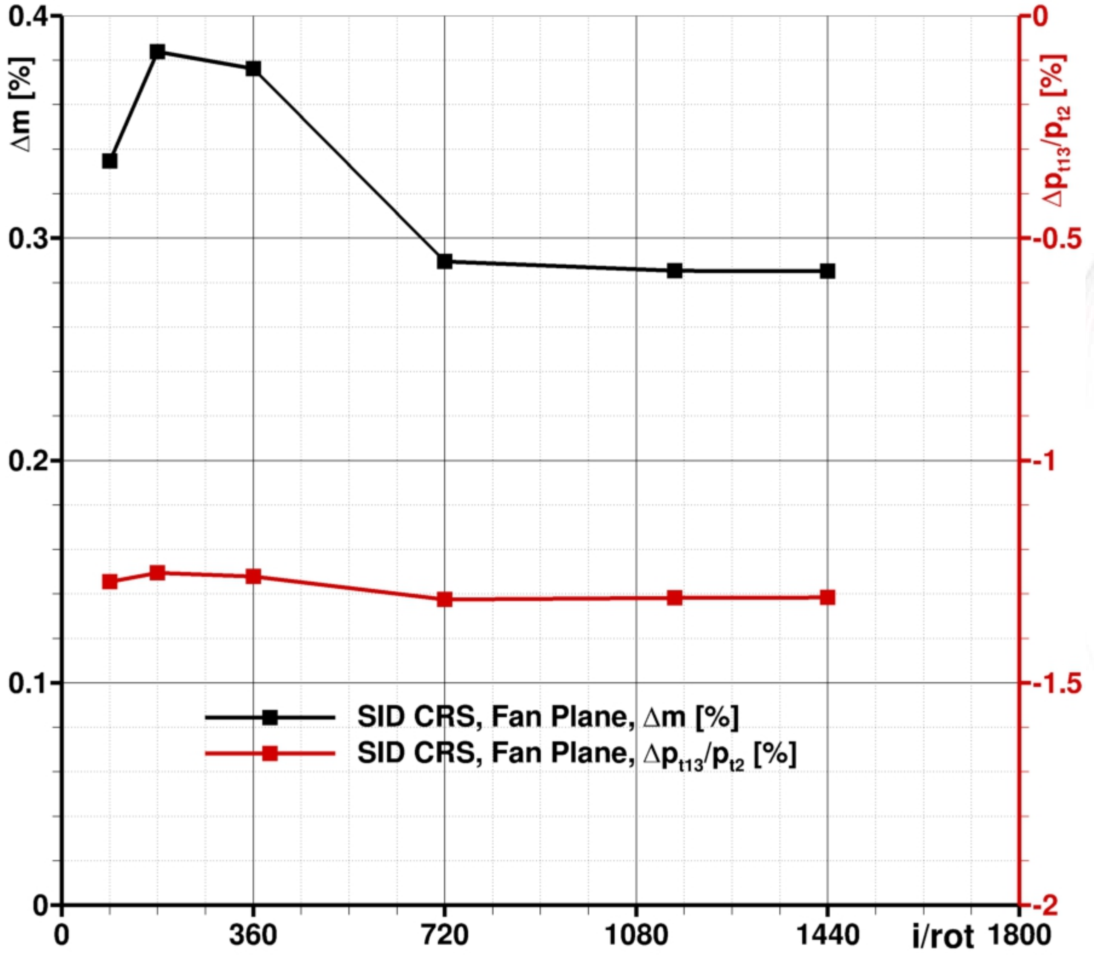


Aerodynamic Analysis: Isolated UHBR Engine @ Sideline OGV Unsteady Loading

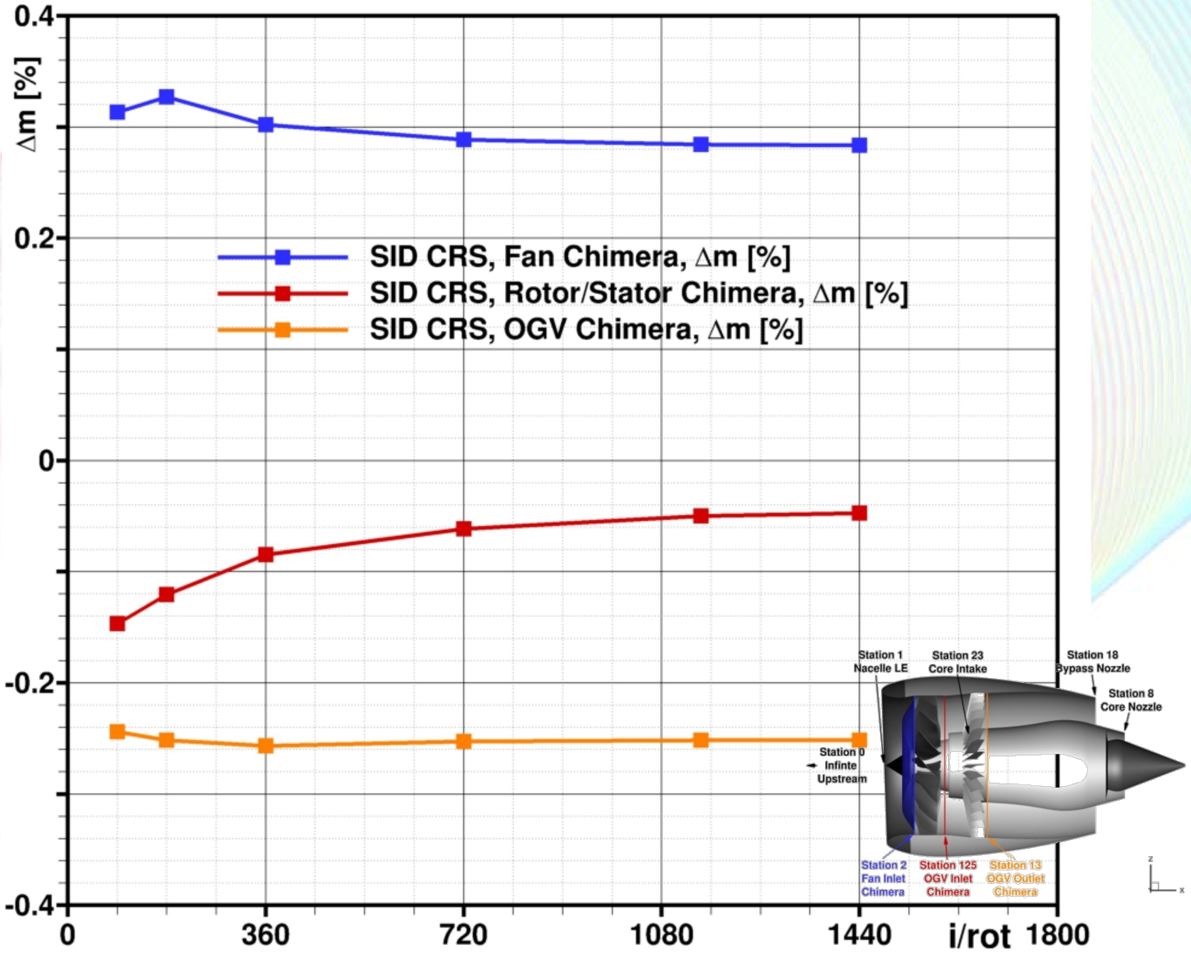




Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
Fan Stage & Chimera Interface Performance Analysis

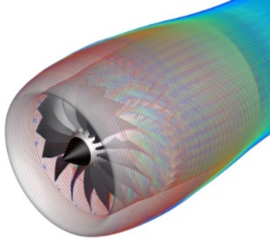


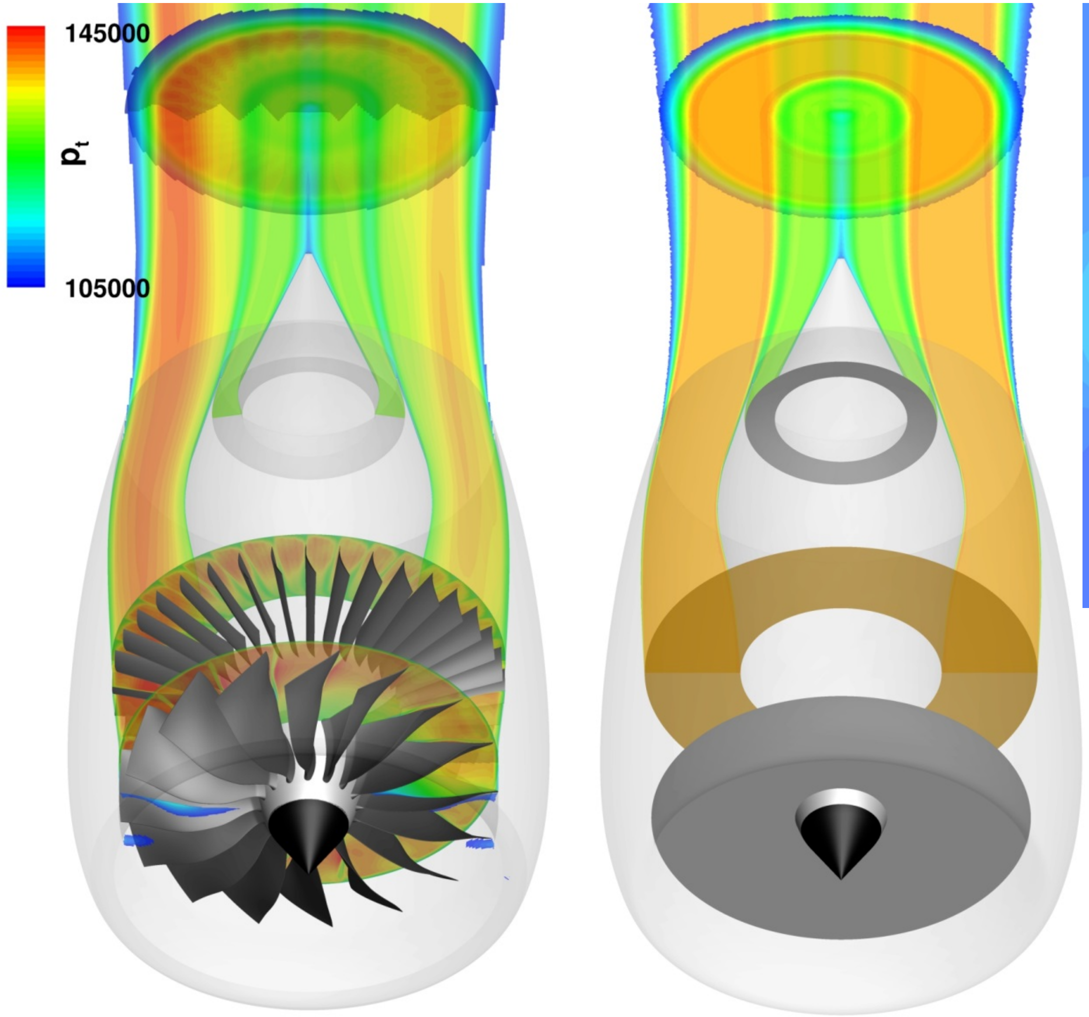
Fan stage performance: Relative error versus specs

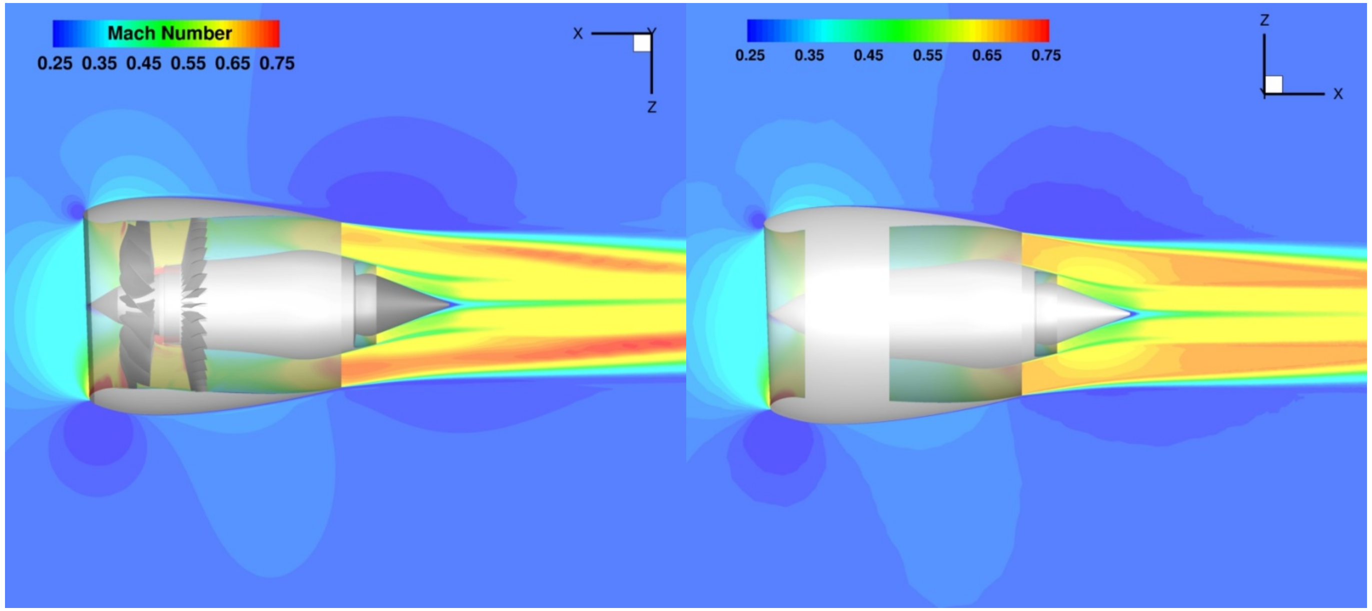


Massflow conservation across Chimera interfaces

Aerodynamic Analysis: Isolated UHBR Engine @ Sideline
Comparison: uRANS with TAU Engine BC







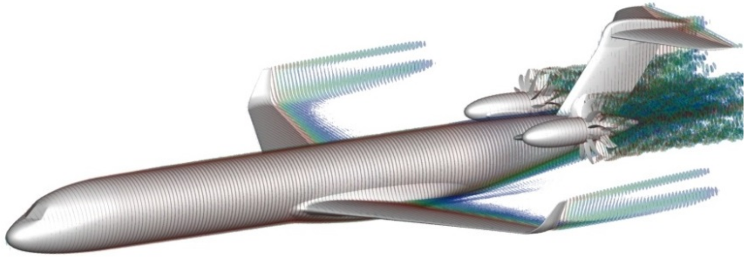
- Classical run of ASPIRE engine at SID with TAU BC

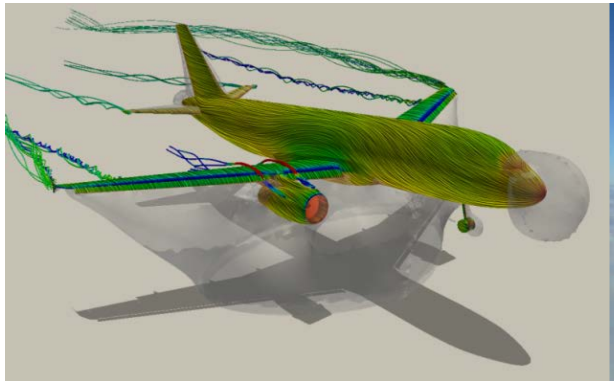
	uRANS	Δ [%]	TAU BC	Δ [%]
m_2 [kg/s]	+0.43		+0.94	
m_8[kg/s]	-0.57		-0.01	

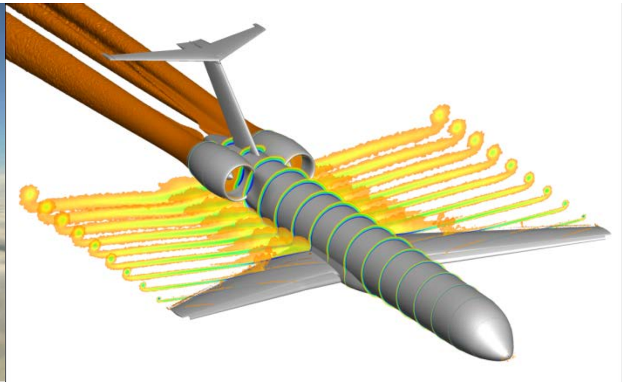
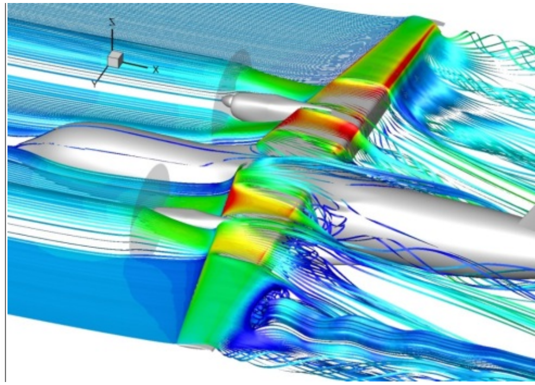
- Azimuthally uniform jet development in BC simulations
    - Non-uniform fan stage loading impact on jet development could be of relevance for some (future) cases

DLR ASPIRE

Engine-Airframe Integration:
Key Driver for Future Efficient Transport Aircraft





Turbofans:

- UHBR-specific tools development and analysis in collaboration with DLR AT, NLR, ONERA, Airbus, RRD, TU BS & others
  - CS2 ASPIRE, CS2 LPA, EU AVACON, LuFo PRESTIGE, SFB880
- BLI-specific tools development and analysis in collaboration with DLR AT, Airbus
  - DLR AGATA, CS2 LPA, Industry contracts

Propeller & CROR:

- Open rotor tools development and analysis in collaboration with NLR, ONERA, Airbus, RRD & others
  - CS2 LPA, LuFo LONOPAIV, SFB880

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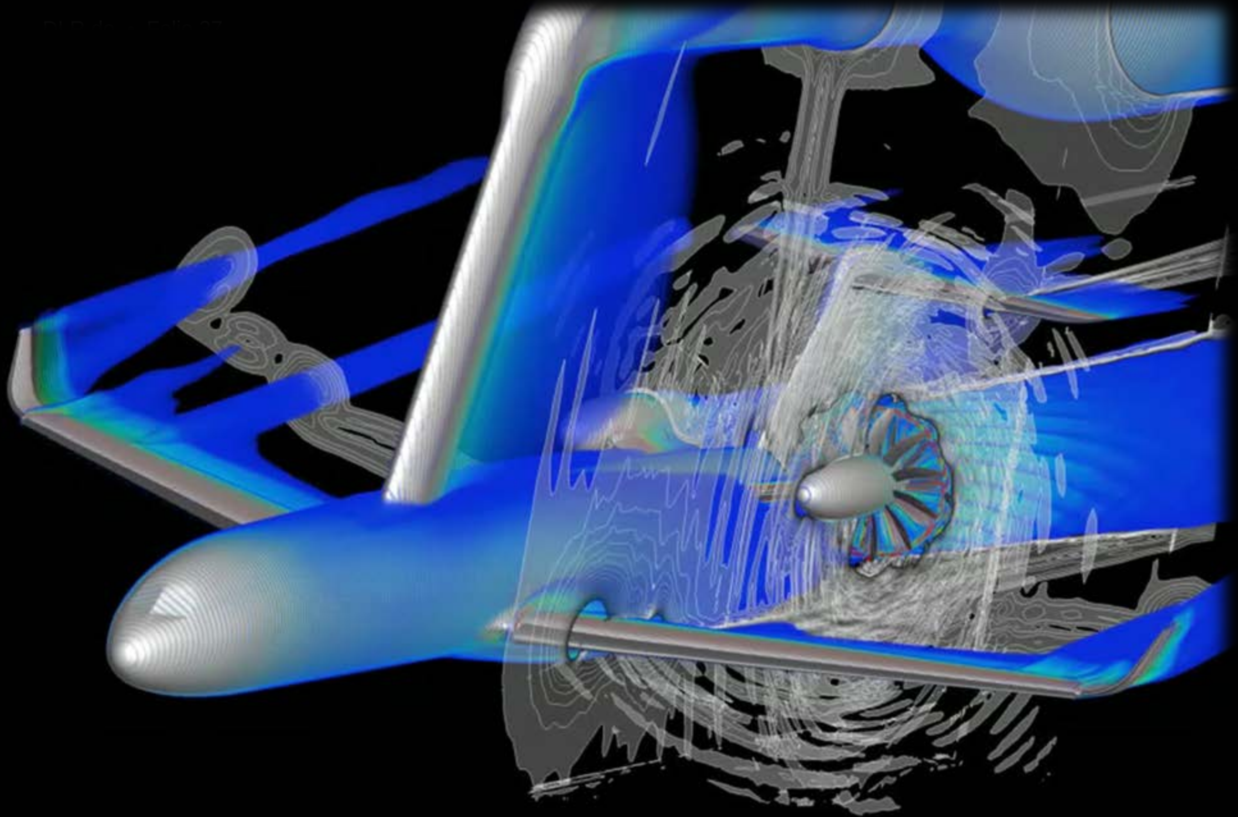

Engine-Airframe Integration for Environmentally Friendly and Economically Viable Future Transport Aircraft

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Questions?

6th UTIAS International Workshop on Aviation and Climate Change
May 16-18, 2018
University of Toronto
Institute for Aerospace Studies
Toronto, Ontario, Canada

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