DLR Contributions to the Development of Engine-Airframe Integration Concepts for Environmentally Acceptable and Economically Viable Transport Aircraft

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5th UTIAS International Workshop on Aviation and Climate Change
May 18-20, 2016
University of Toronto
Institute for Aerospace Studies
Toronto, Ontario, Canada

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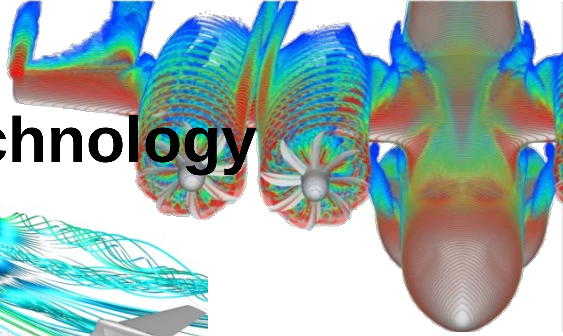
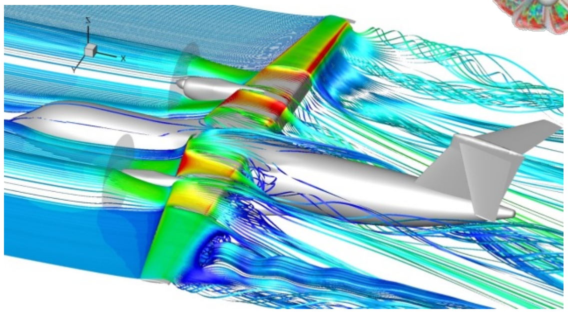
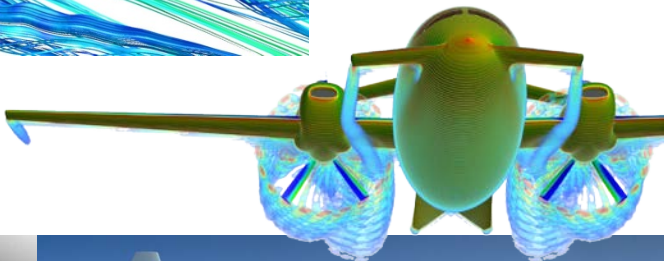
Engine Integration Activities

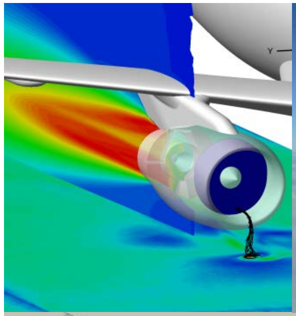


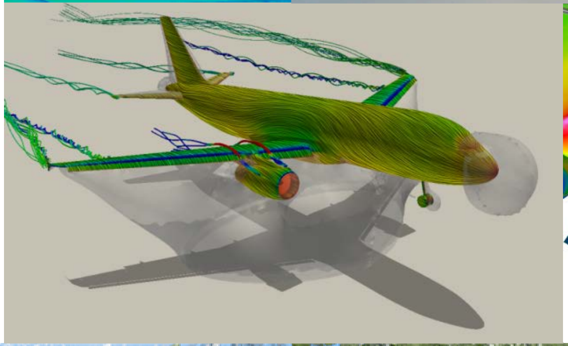


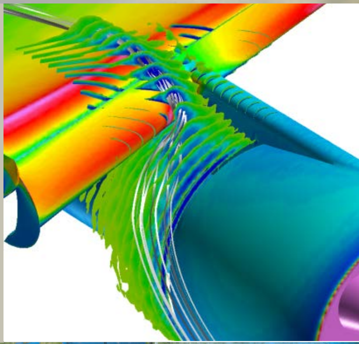


Turbofans:
- Integration activities since 1990s
- Analysis and design of installed through flow nacelles & turbo powered simulators
- Experimental & numerical work (internal, DLR-ONERA, EU, Lufo, DLR-RRD, US)
- Processes analysis and optimization of under wing & rear mounted installations

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







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Maturation of DLRs CFD/CAA Process Chain for High Quality Aerodynamic & Aeroacoustic Performance Predictions of Installed CROR Engines

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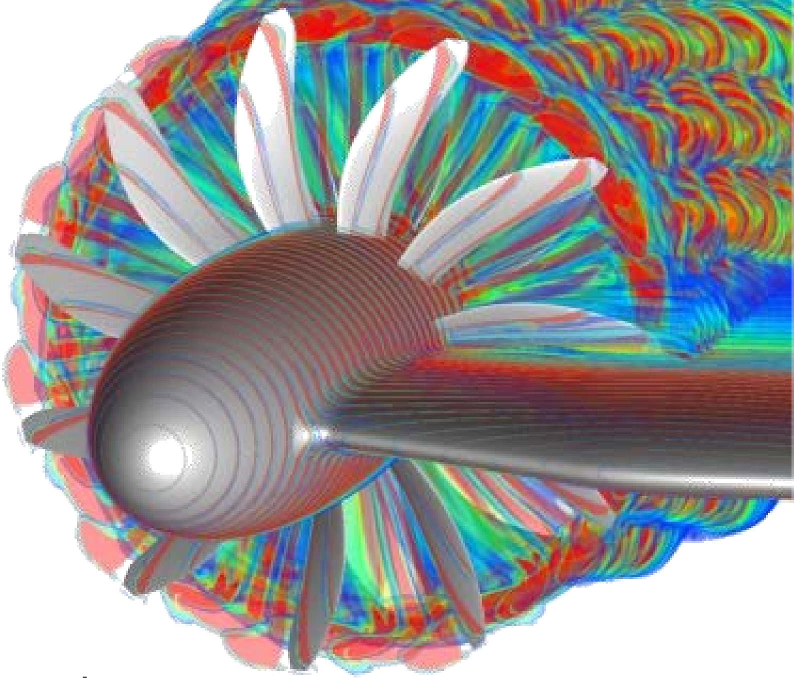

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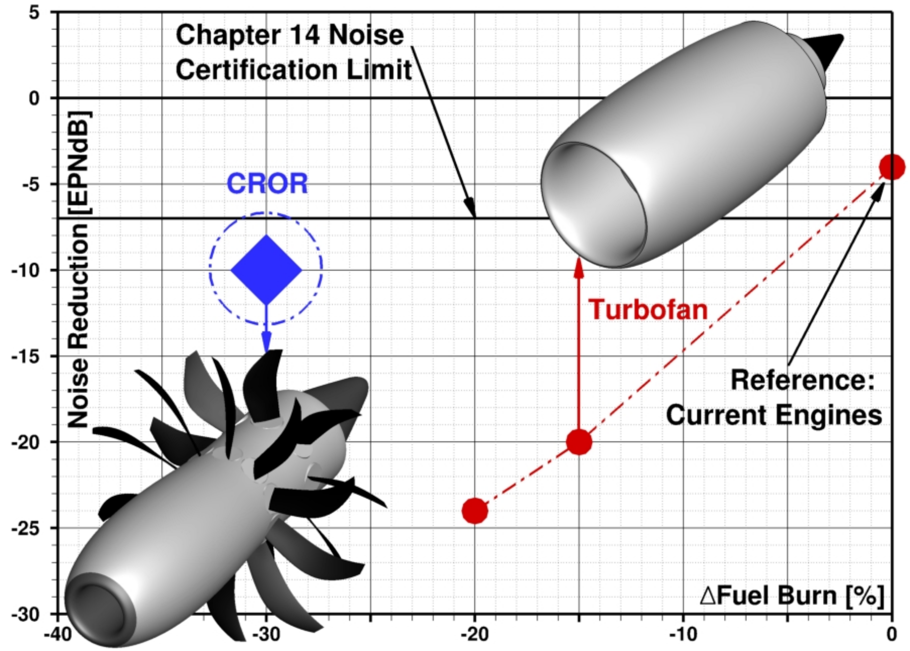
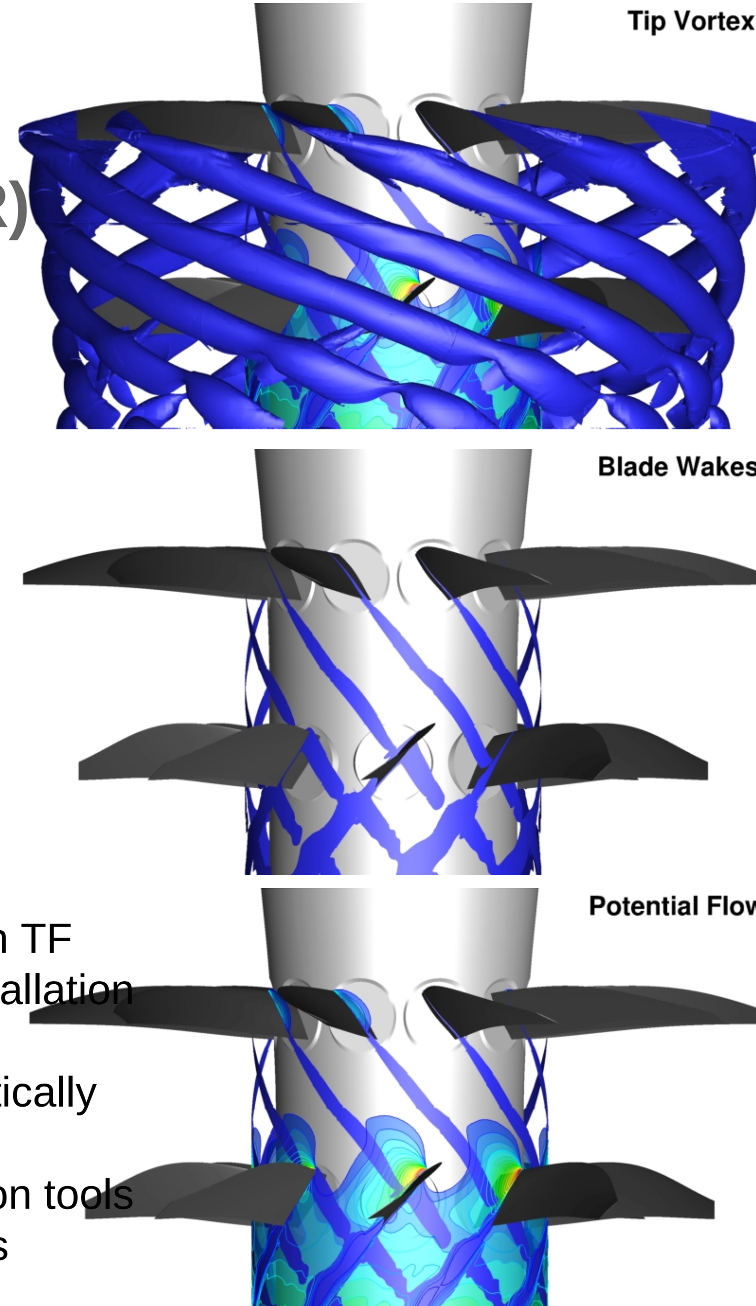
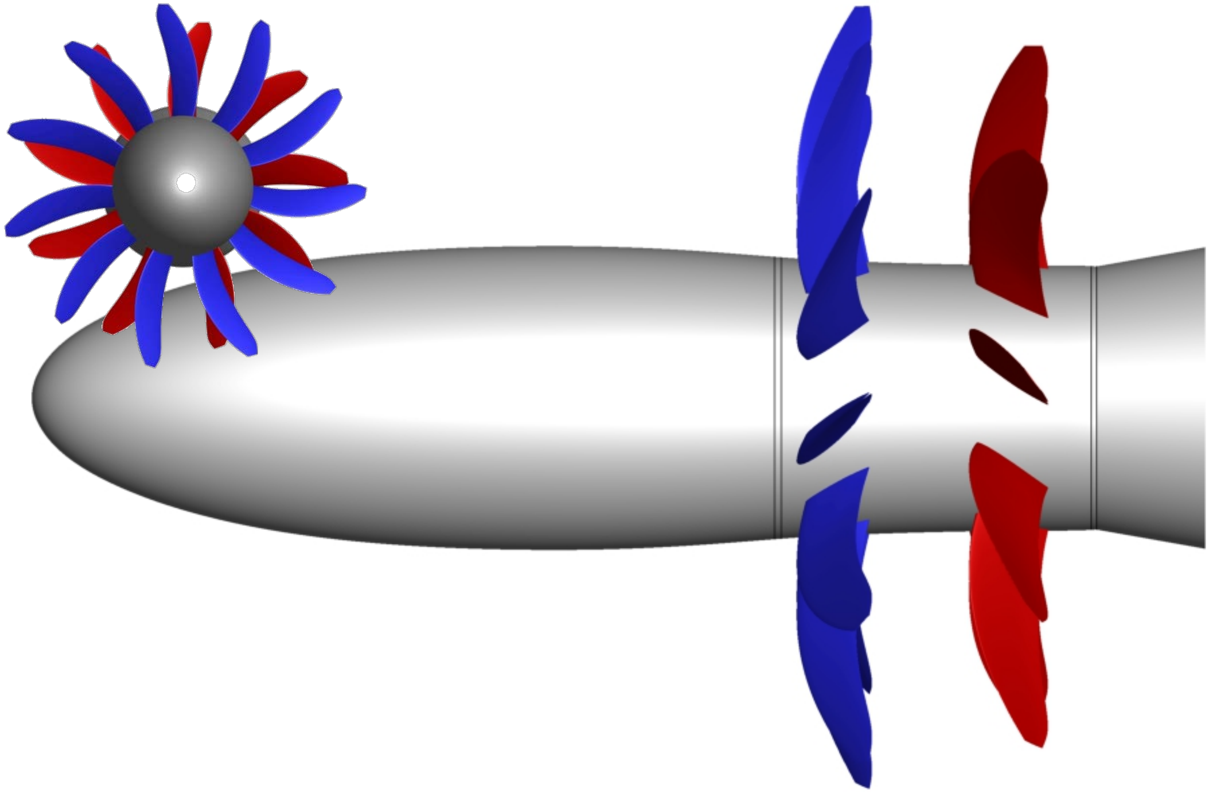
Introduction & Motivation: Contra-Rotating Open Rotor (CROR)

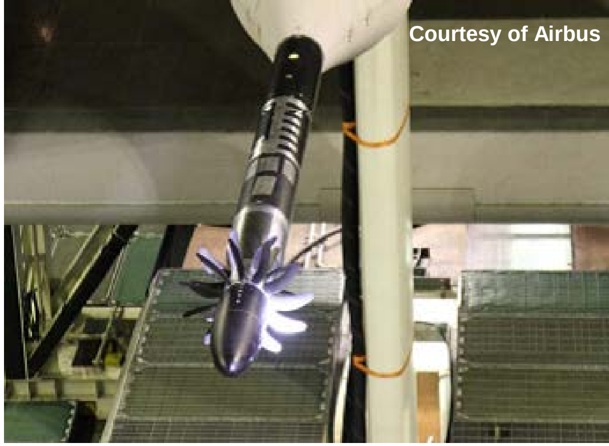


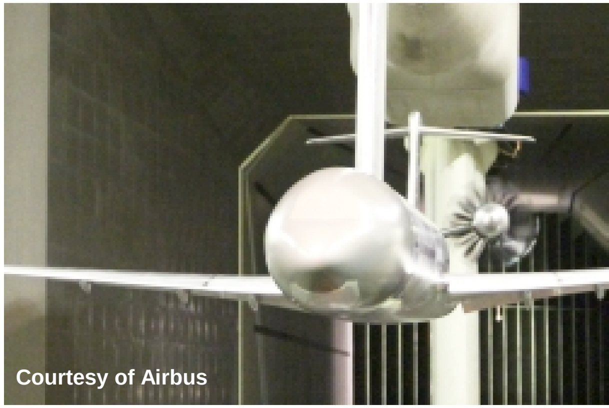


- Notable fuel burn benefit for CROR vs comparable tech TF
- Current research activities primarily address noise, installation effects, certification & overall aircraft economic viability
- ICAO Chapter 14 rules & research progress have practically eliminated noise as CROR show-stopper
- But noise still a design driver, mandating good prediction tools
- Rotor-rotor-interactions are the dominant noise sources

The EU Clean Sky JTI SFWA Project



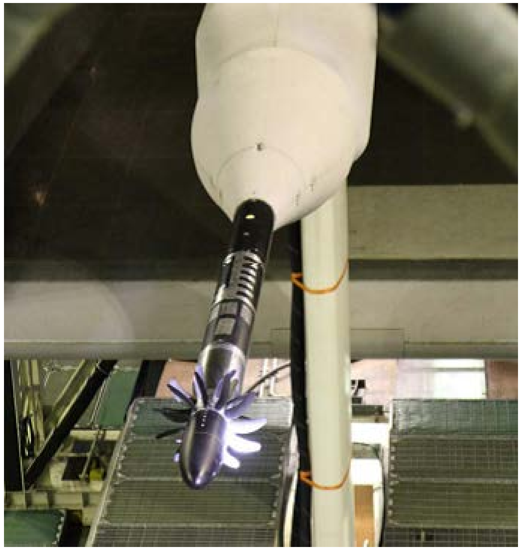


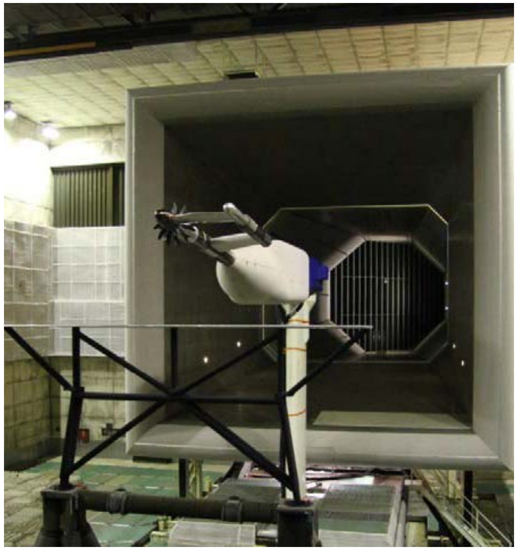


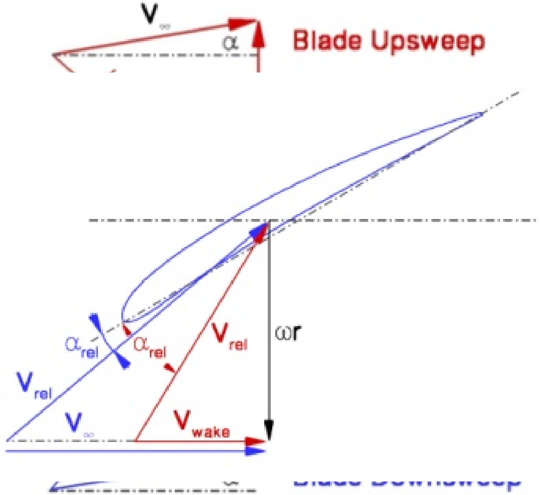
- Generic Airbus-designed AI-PX7 CROR is the focus engine configuration in JTI-SFWA [2]
  - 11x9 bladed configuration
  - 10% aft rotor diameter crop

[1] Stuermer, A. 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





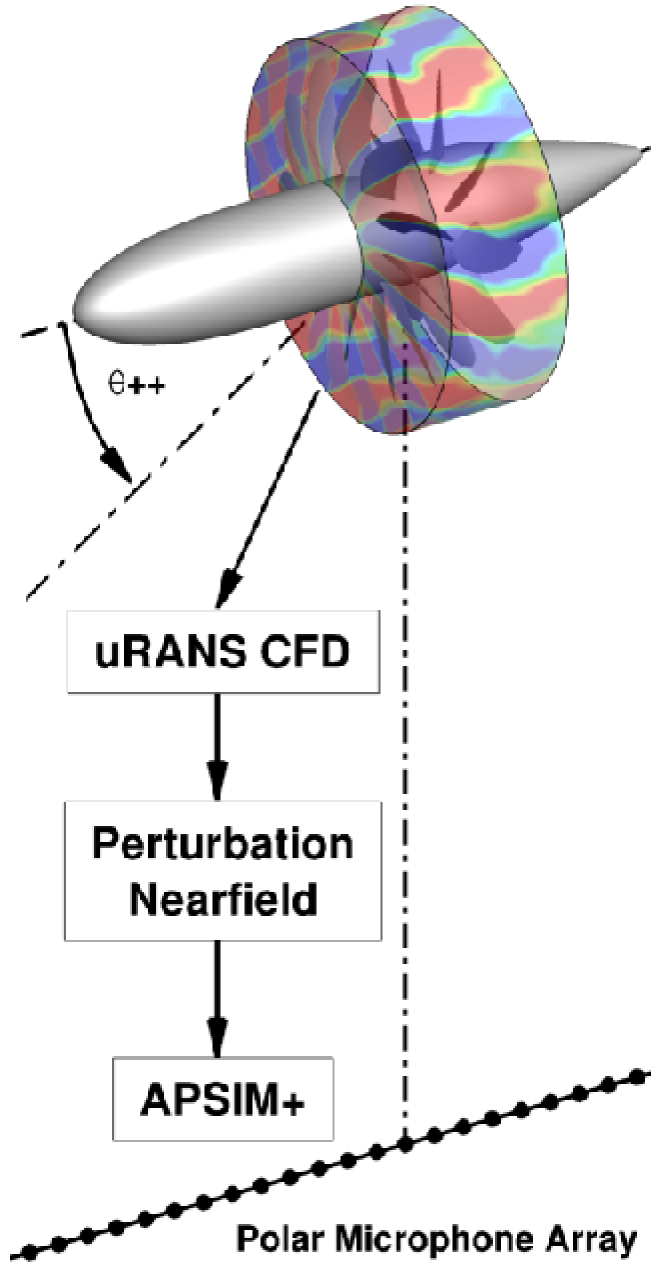


- 1:7-scale Z08-CROR tested @ low-speed flow conditions in DNW-LLF
- Study of installation effects using isolated & semi-installed Z08-CROR test
  - Angle of attack
  - Pylon wake

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

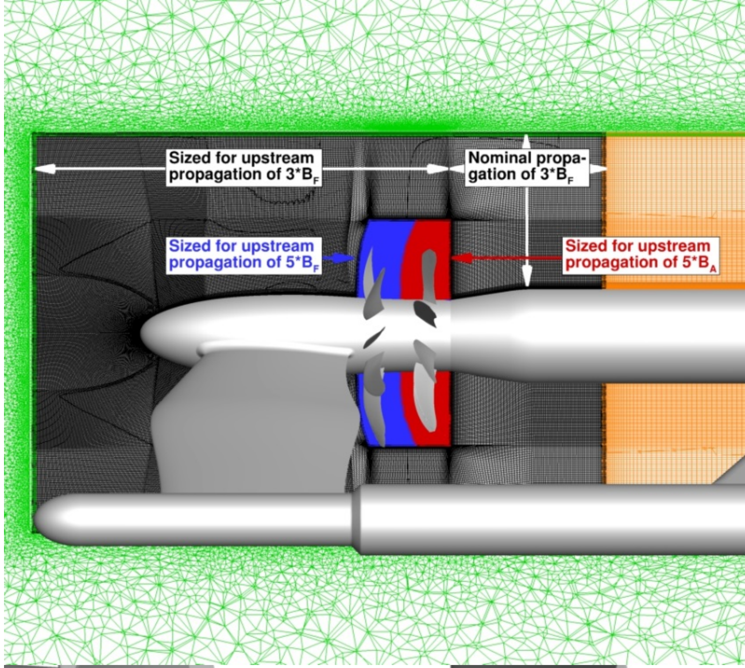
DLR-AS CFD/CAA Analysis: TAU-APSIM+ Process Chain

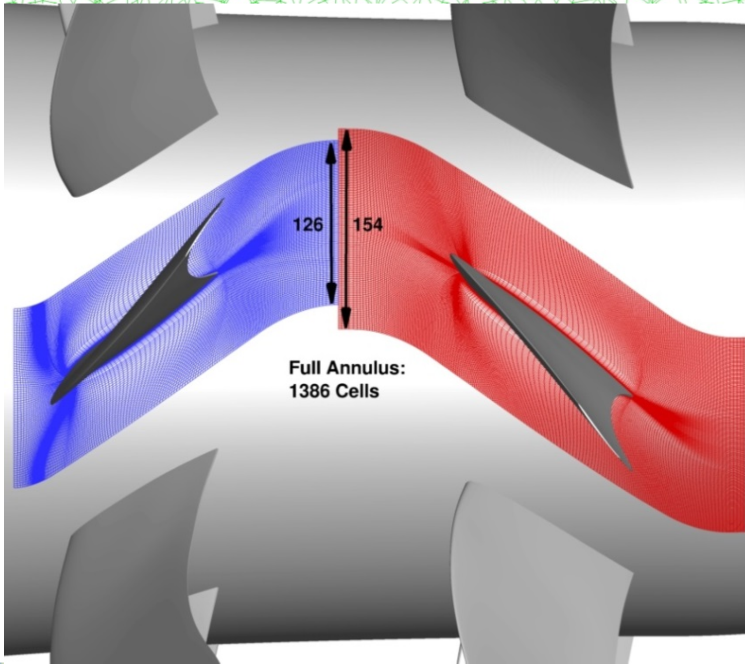
- Multidisciplinary simulations coupling aerodynamics (TAU-Code) & aeroacoustics (APSIM+-Code)
- TAU uRANS-simulations for aerodynamic- & performance analysis and input data for CAA
  - 2nd order dual time method for unsteady flows
  - 2nd order central scheme for spatial discretization
  - LUSGS time integration
  - SA turbulence model with vortical correction
  - Chimera & motion libraries for moving bodies
  - Simulations run using 360-720 CPUs
- DLR FW-H Code APSIM+ for the prediction of farfield noise emissions:
  - Use of the “permeable surface”-approach with uRANS-data on nacelle Chimera boundary



Numerical Approach: Mesh Philosophy & Generation

- Mesh family for a robust validation & parametric study [3]
- 5 block-structured ICEM-Hexa Chimera mesh blocks (Farfield, Front Sting, Aft Sting, Front Rotor, Aft Rotor)
  - Fine nearfield mesh to resolve acoustic installation & non-linear propagation effects in uRANS and enable variations in APSIM+ permeable surface placement
  - Particular focus on rotor-rotor-interface-mesh for optimal wake and tip vortex transfer
- "Optimized" mesh as base for additional test cases
  - Optimized boundary layer resolution & hybrid-unstructured Farfield-Mesh

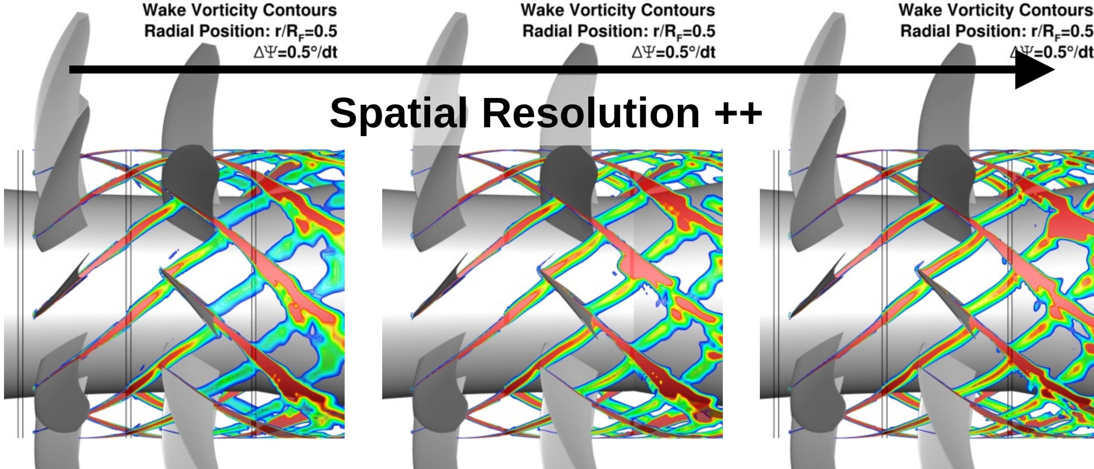


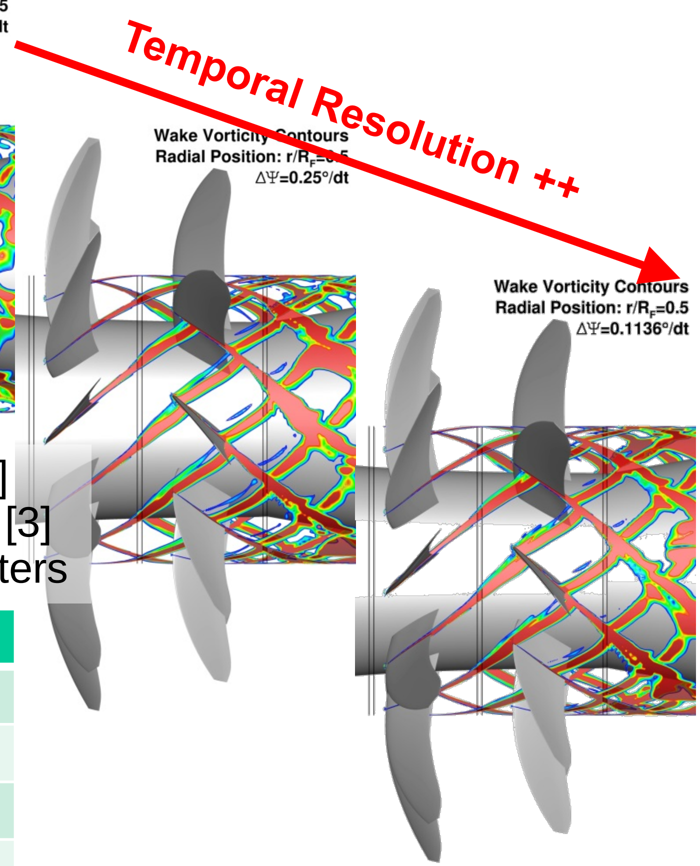


	Coarse	Medium	Base	Opt	Pylon
Farfield	2x10^{6}	6x10^{6}	15x10^{6}	13x10^{6}	7x10^{6}
Nacelle	10x10^{6}	32x10^{6}	76x10^{6}	74x10^{6}	55x10^{6}
Sting	2x10^{6}	8x10^{6}	19x10^{6}	18x10^{6}	14x10^{6}
Front Rotor	5x10^{6}	19x10^{6}	43x10^{6}	36x10^{6}	
Aft Rotor	7x10^{6}	23x10^{6}	54x10^{6}	44x10^{6}	
Total	26x10^{6}	88x10^{6}	207x10^{6}	185x10^{6}	154x10^{6}

[3] 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.

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



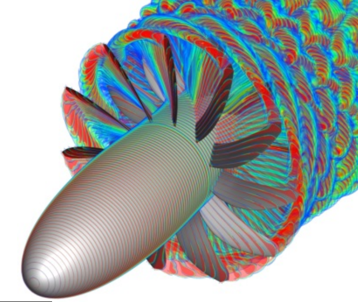


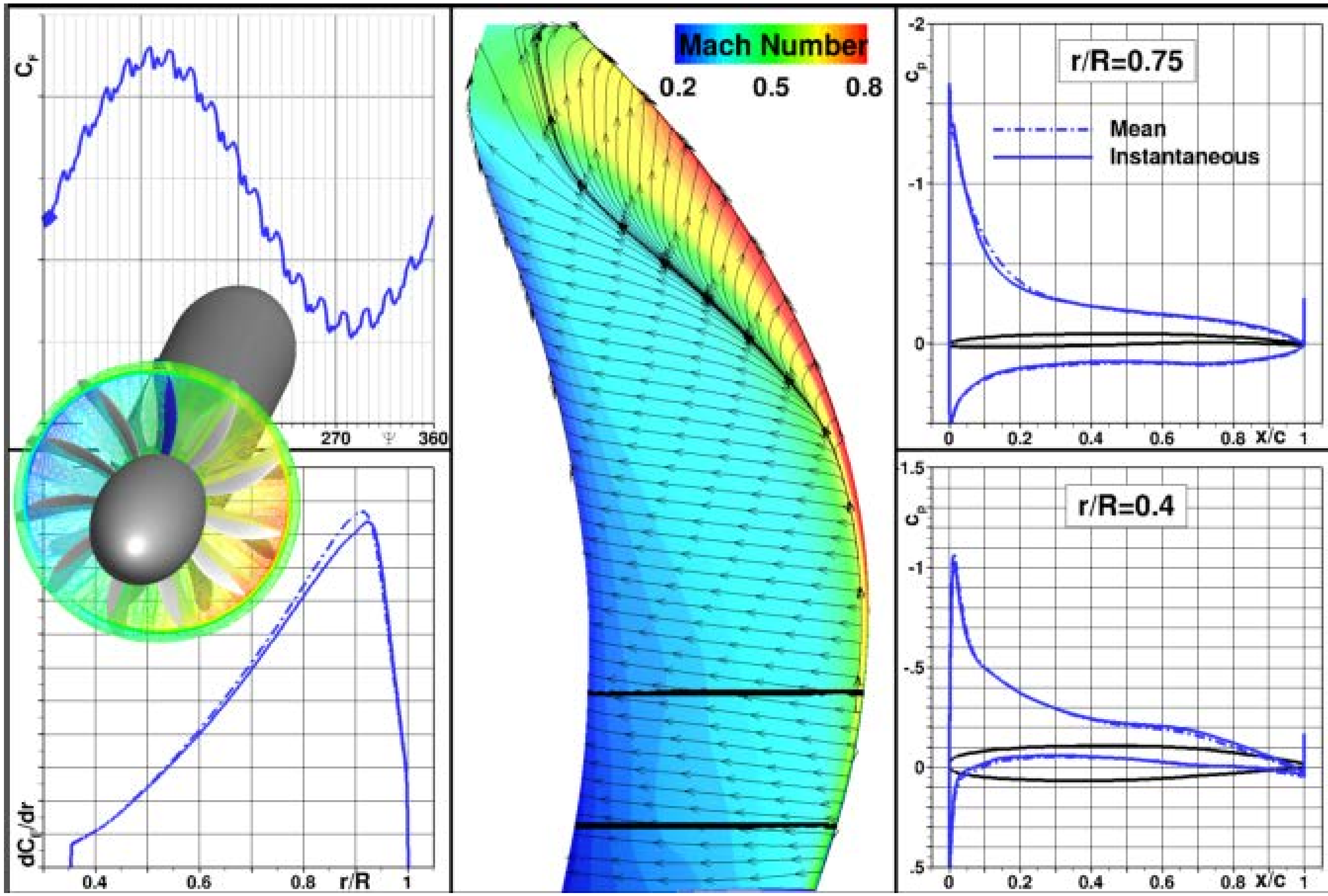
- Dependance of solution quality on spatial resolution [3]
- Dependance of solution quality on temporal resolution [3]
  - Simulation matrix to study impact of both parameters

	Coarse	Medium	Base	Optimized
ΔΨ/Δt	360p	360p	360p	360p
	720p	720p	720p	720p
	792p	1188p	1440p	1386p
	1584p	2376p	1584p	2772p
	-	-	3168p	-

[3] 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
AoA-Effect – Front Blade





Optimized Mesh, 2772p

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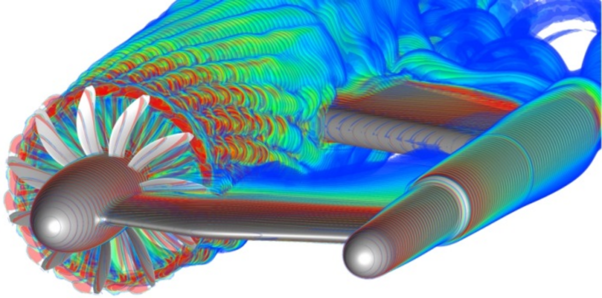
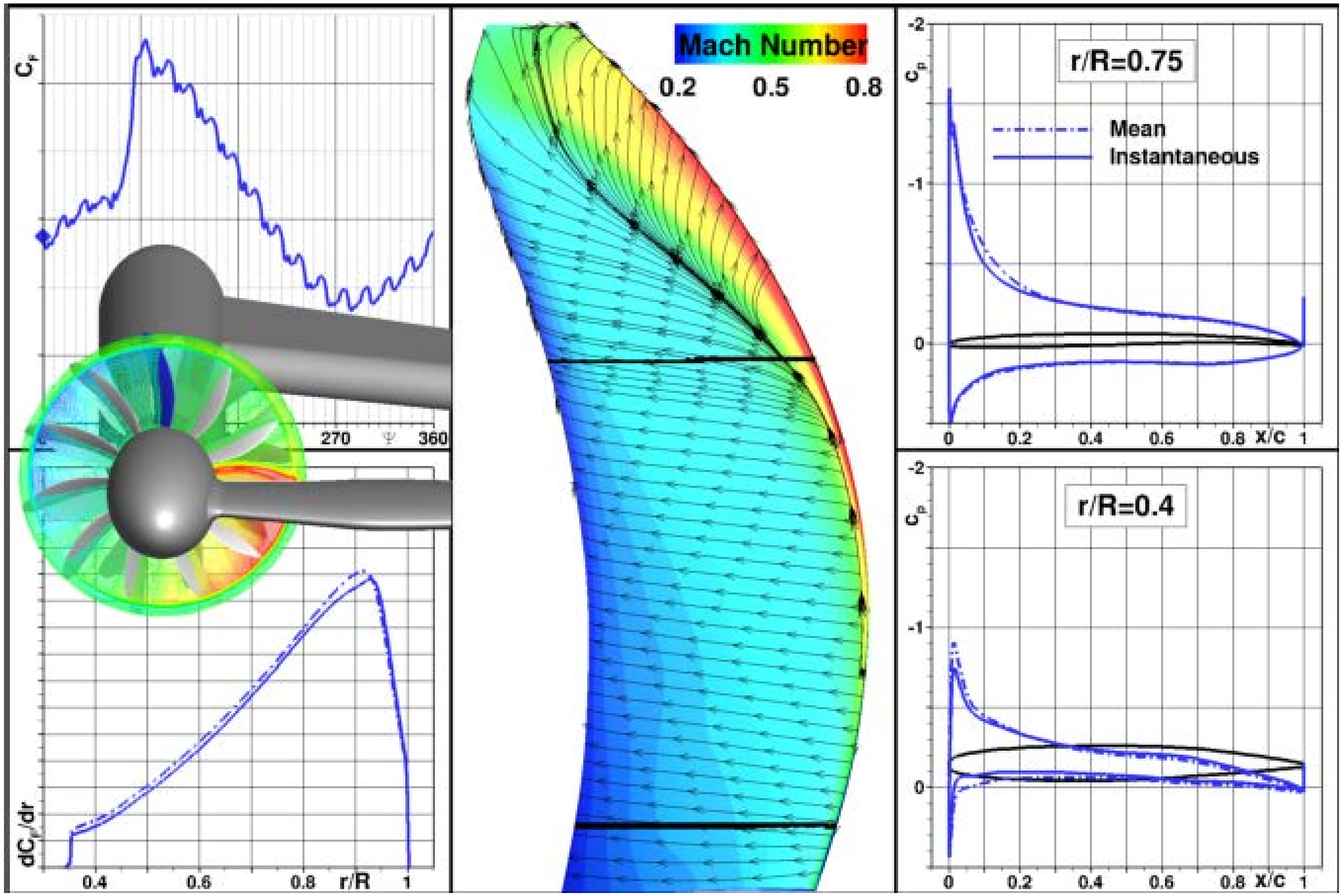
Aerodynamic Analysis: Pylon-Effect – Front Blade





Optimized Mesh, 2772p

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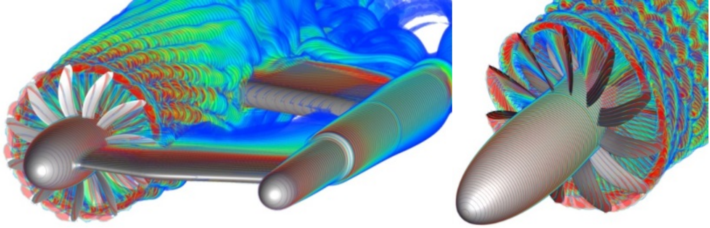
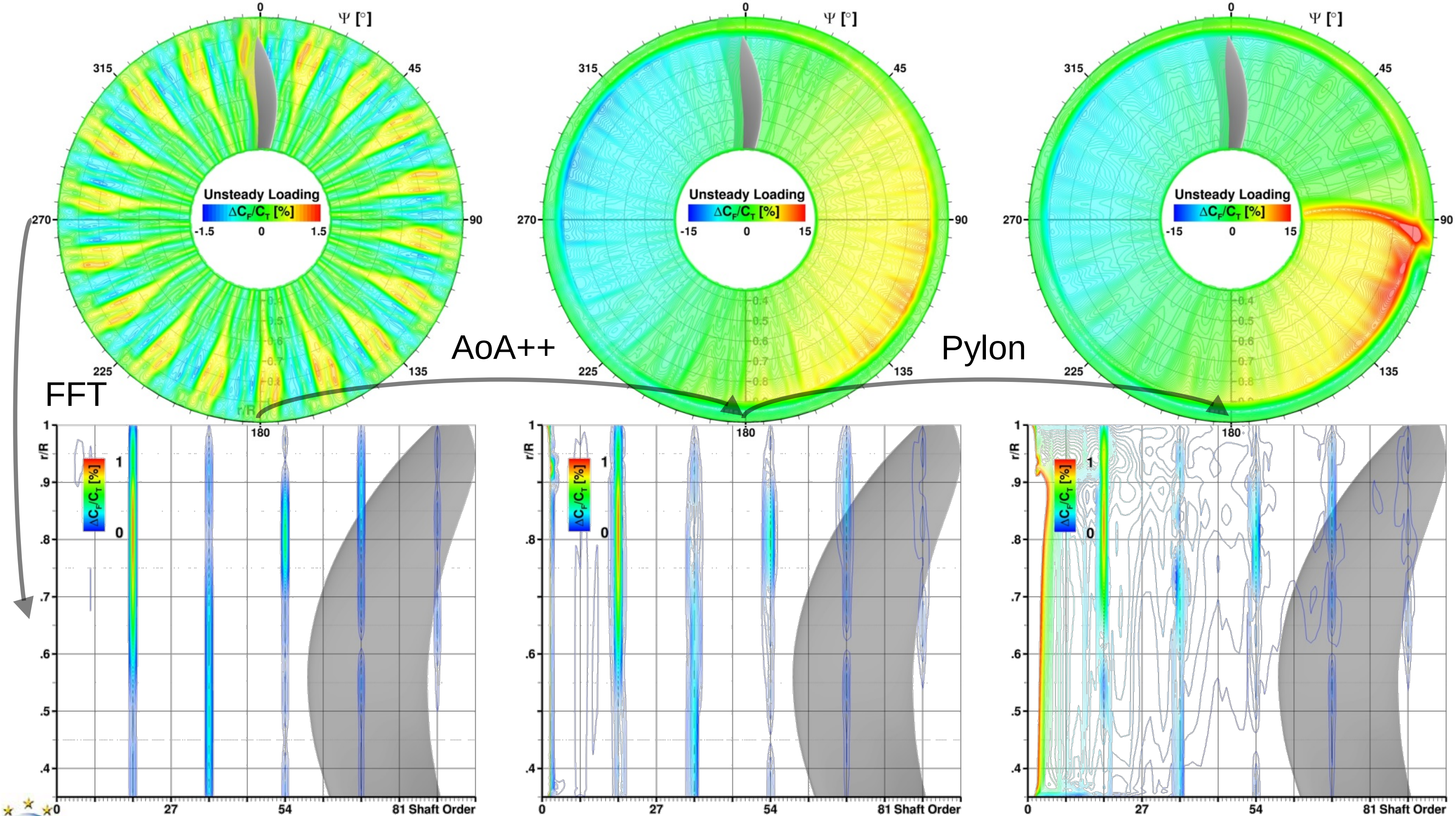
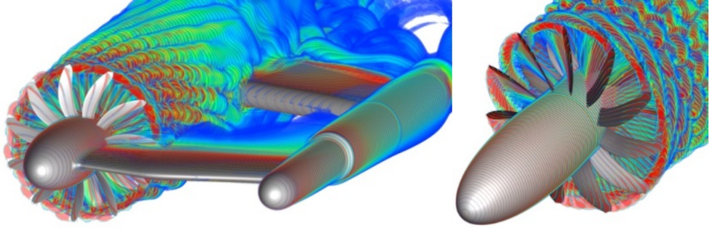
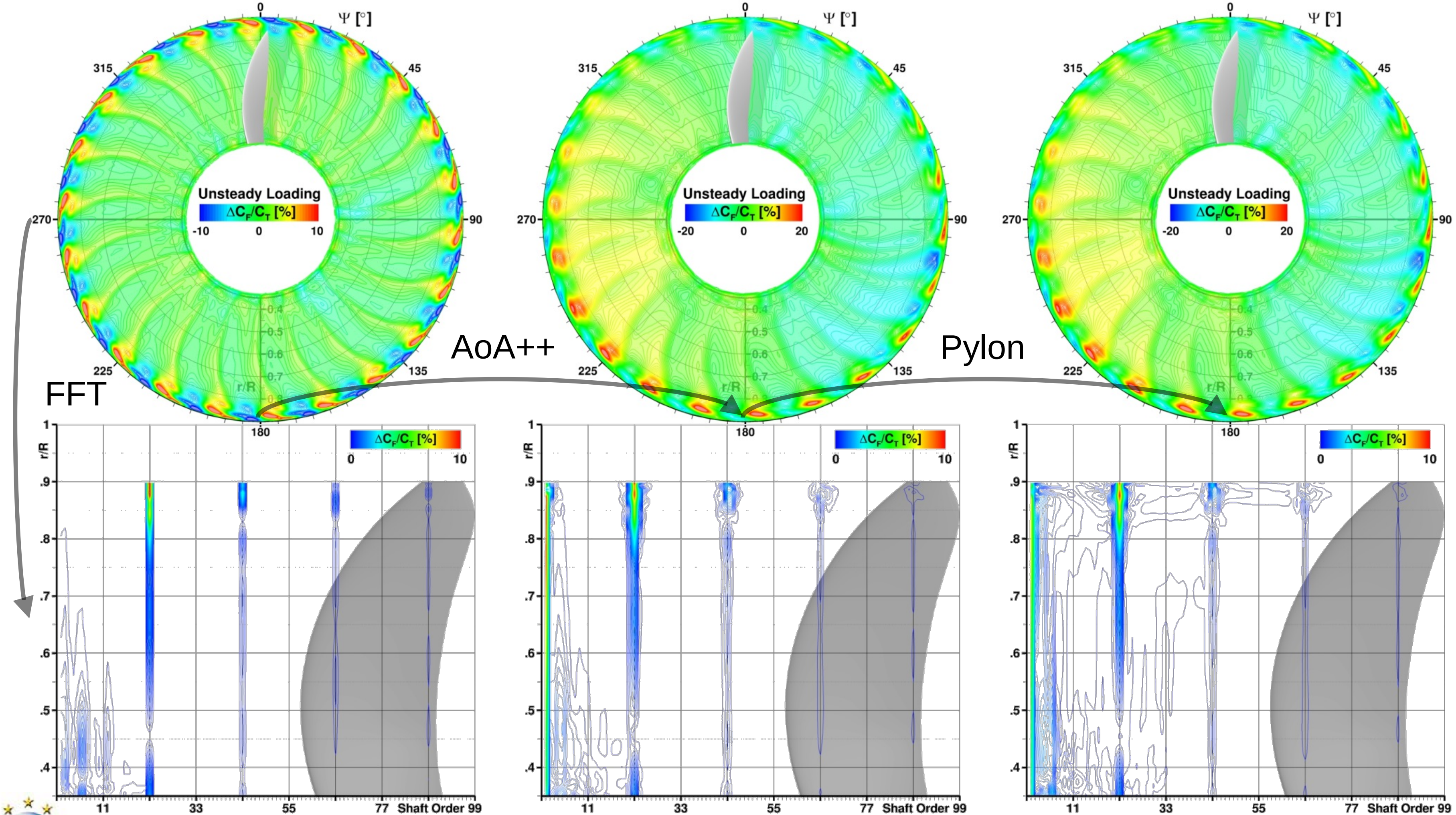
Aerodynamic Analysis: Installation Effects @ Front Blades





Aerodynamic Analysis: Installation Effects @ Aft Blades

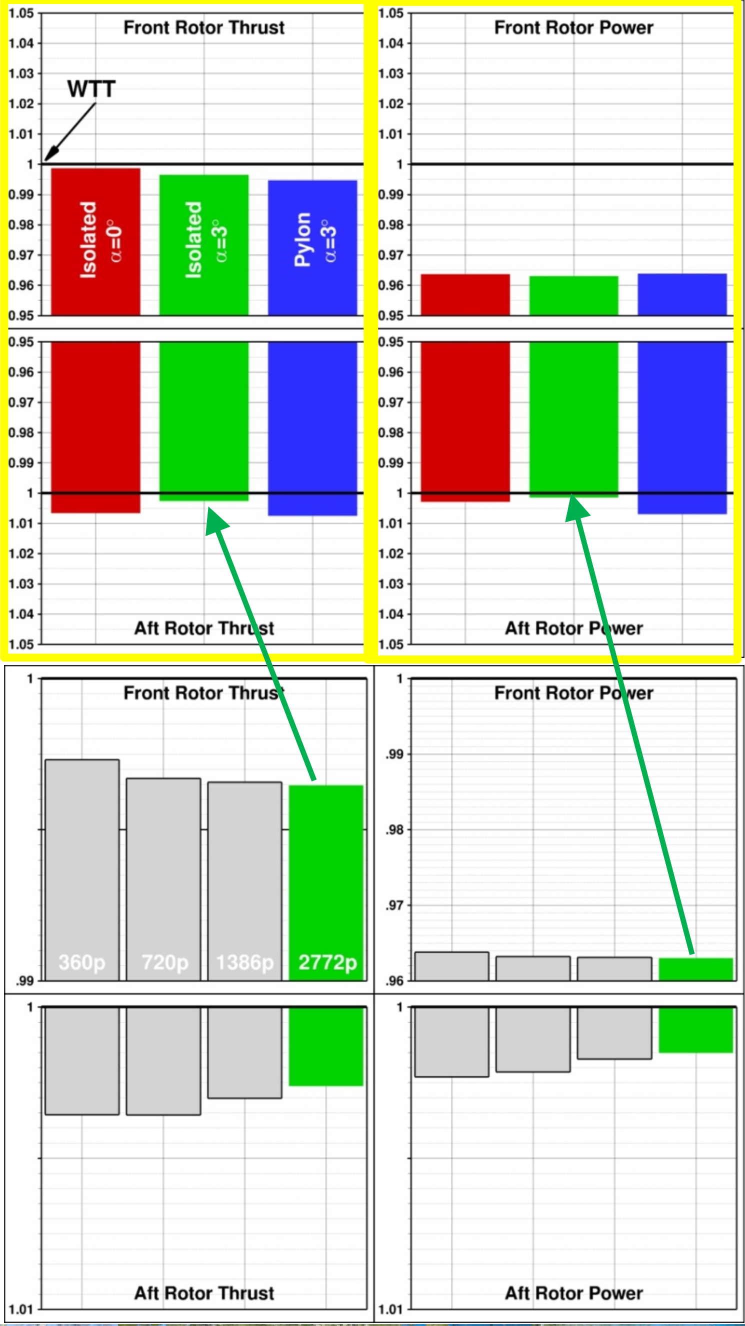




Aerodynamic Analysis: Mean Performance - Validation

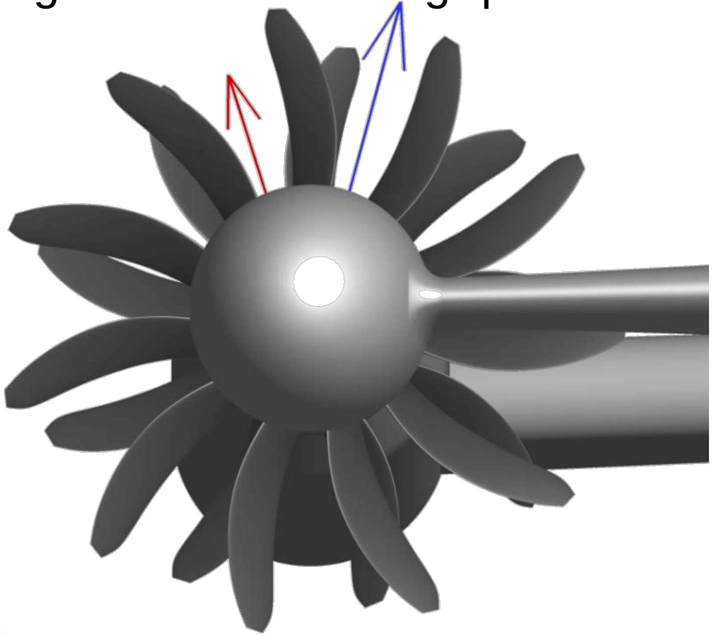
		Isolated α=0º	Isolated α=3º	Pylon α=3º
Front Rotor	T/T_{WTT}	0.9986	0.9967	0.9947
	P/P_{WTT}	0.9637	0.9629	0.9639
	η/η_{WTT}	1.0406	1.0384	1.0342
Aft Rotor	T/T_{WTT}	1.0066	1.0026	1.0073
	P/P_{WTT}	1.0029	1.0015	1.0071
	η/η_{WTT}	1.0079	1.0046	1.0024

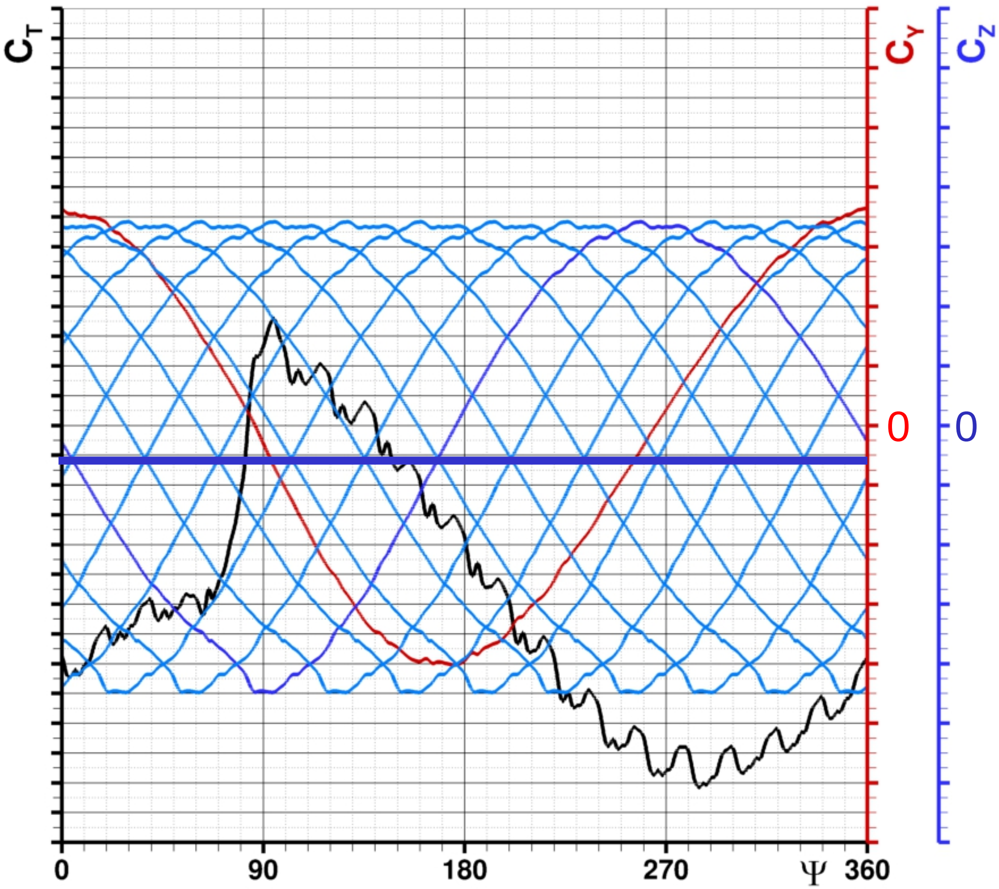
- Very good match with WTT data
- Predictions of
  - Thrust to within <1% accuracy - **consistently**
  - Power at <1%/<4% accuracy - **consistently**
  - Practically no impact of temporal resolution



Aerodynamic Analysis: 1P-Loads
Mean Performance - Validation

- Non-uniform inflow leads to loads acting in the planes of the rotor
- Example: Vertical 1P-load of the front rotor for the pylon case
- 1P loads impact engine-airframe structural integration design and flight control/handling qualities

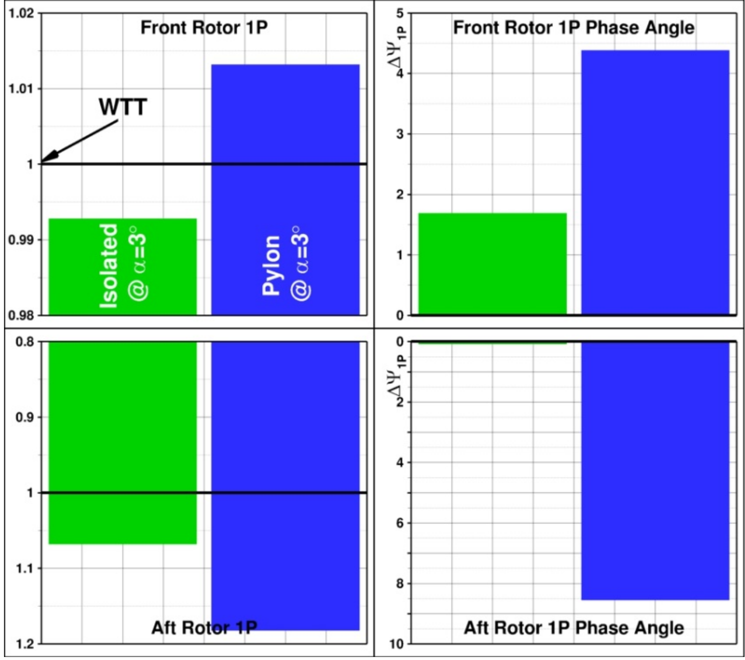




Front rotor vertical load development

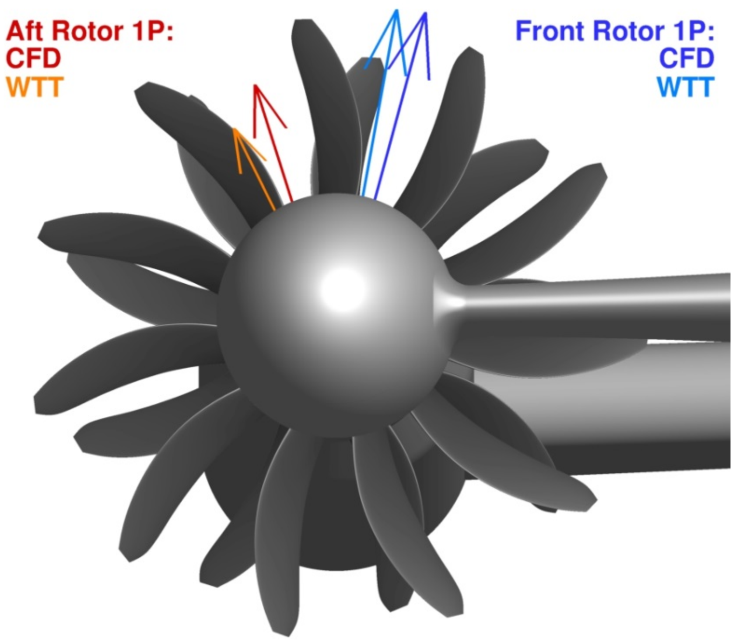
Aerodynamic Analysis: 1P-Loads Mean Performance - Validation

		Iso α=3º	Pylon α=3º
Front Rotor	$F_{1P}/F_{1P,WTT}$	0.9928	1.0132
	$\Delta\psi_{1P} = \psi_{1P} - \psi_{1P,WTT}$	1.6908º	4.3841º
Aft Rotor	$F_{1P}/F_{1P,WTT}$	1.0683	1.1827
	$\Delta\psi_{1P} = \psi_{1P} - \psi_{1P,WTT}$	0.0848º	8.5569º

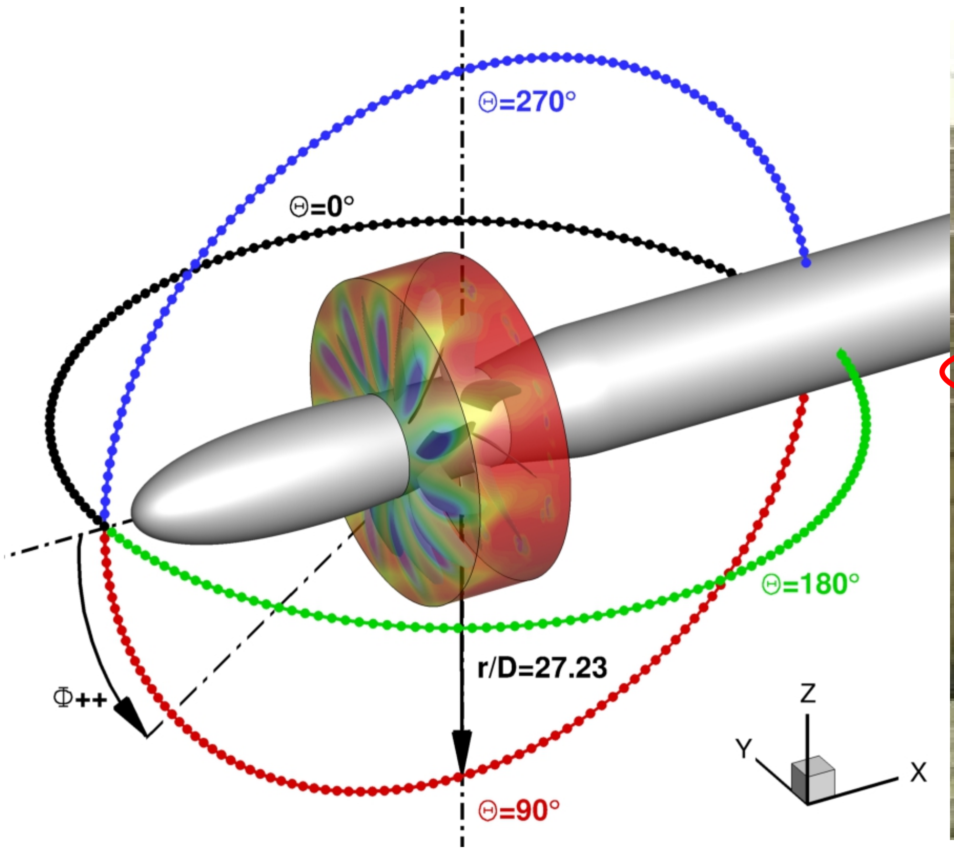


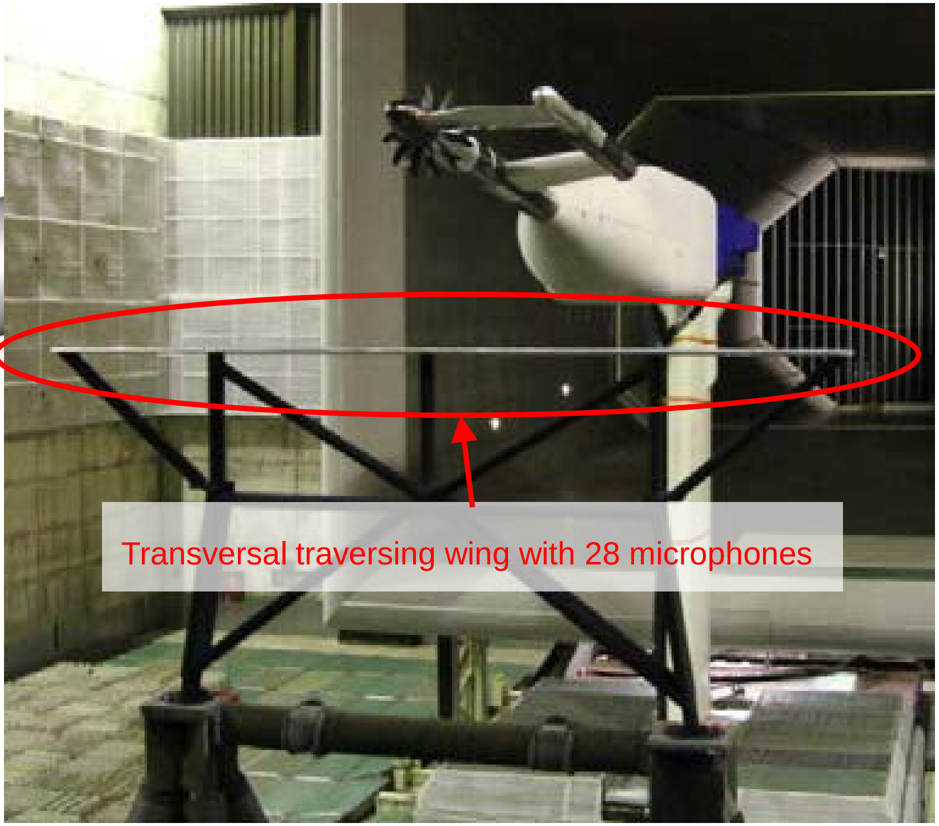
- Very good prediction accuracy for front & acceptable accuracy for aft rotor for isolated CROR at α=3º:
    - 1P-load magnitude predicted to <1%/~6%
    - 1P-phase angle shows deviation of ~1º

- Slightly larger deviations in 1P-predictions for semi-installed CROR at α=3º:
    - 1P-load magnitude predicted to <1%/~18%
    - 1P-phase angle shows deviations of ~4º/~8º



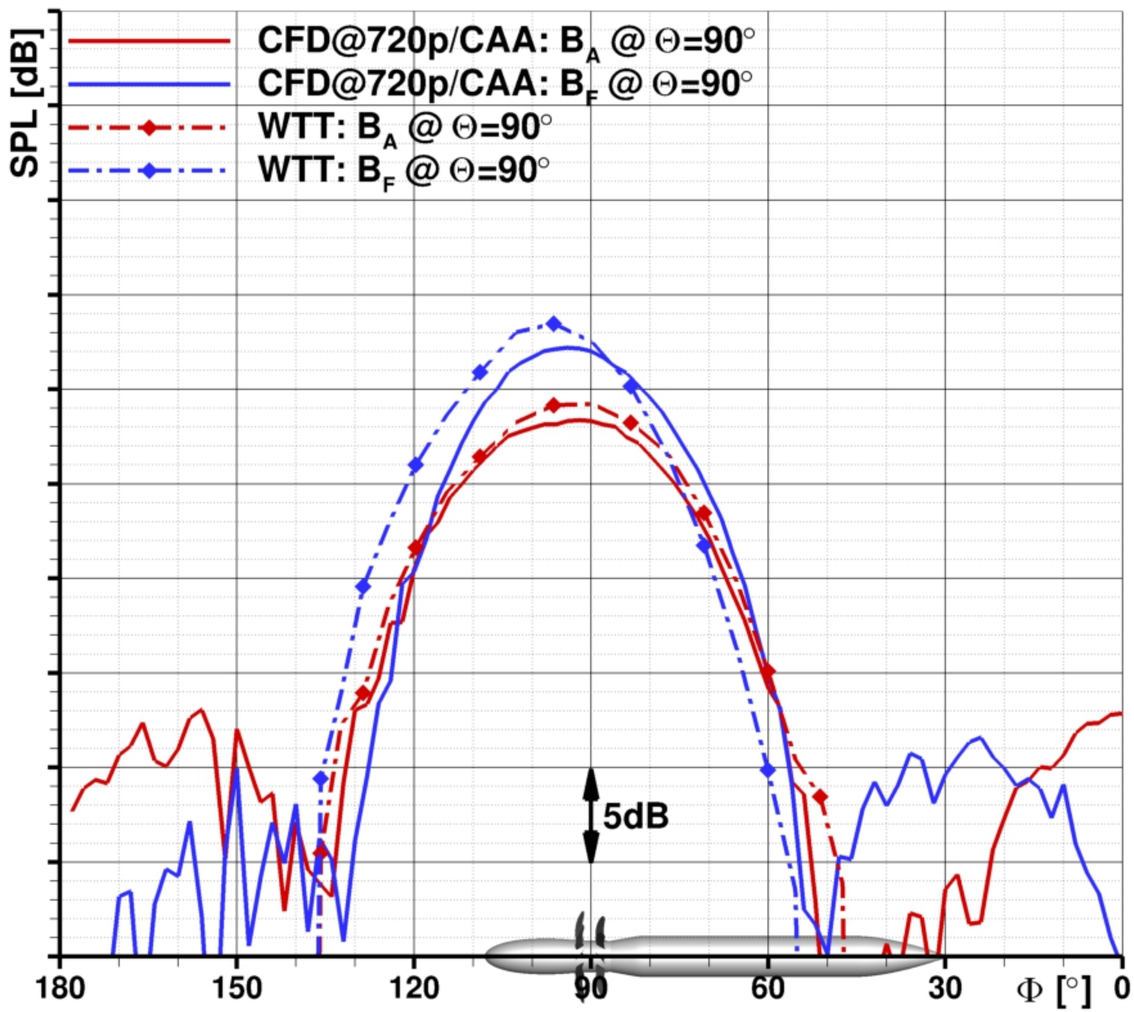
Aeroacoustic Analysis: Validation Data and Specifications

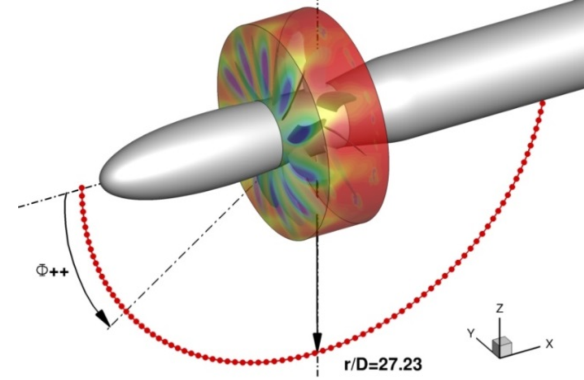




- Validation of numerical results with acoustic data from DNW-LLF WTT
- In-flow traversing microphone array gives azimuthal directivity information

Aeroacoustic Analysis: Rotor Tones
Impact of CFD Temporal Resolution



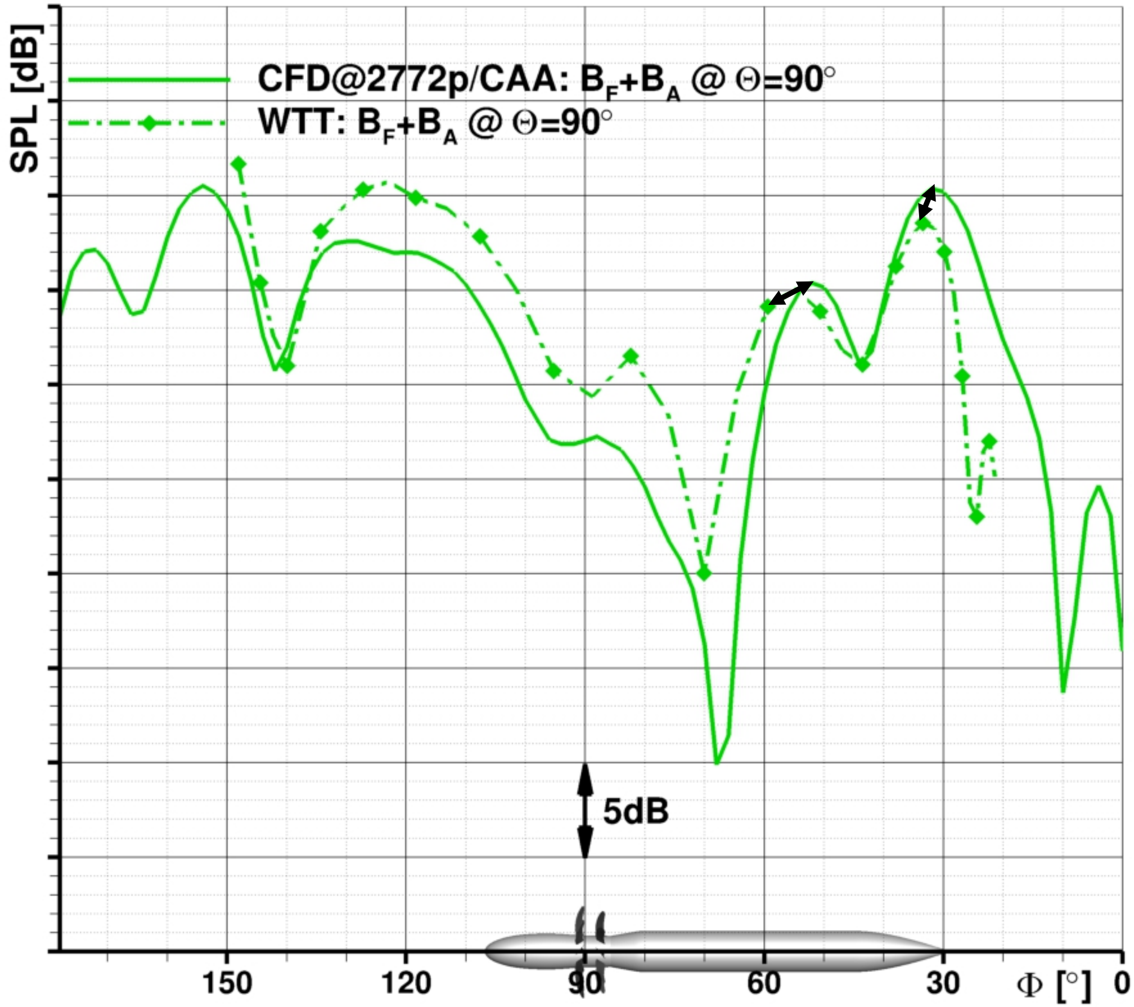


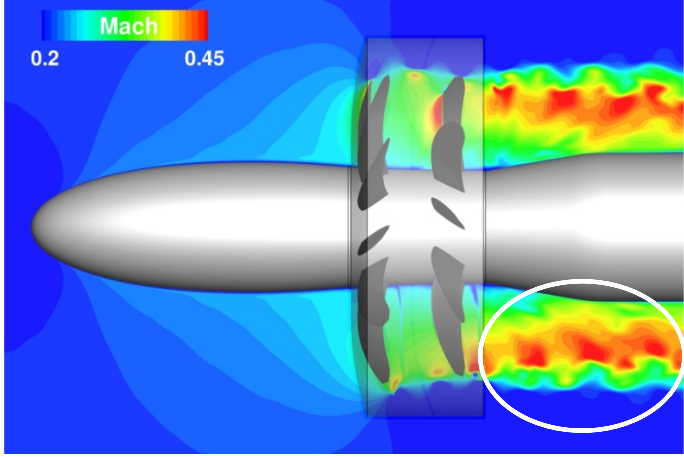
- **Isolated CROR @ α=3º**

- APSIM+-runs using uRANS input at **several temporal resolutions (720p & 2772p)**

- Very good prediction of rotor tones, Δ~1dB
- Deviations versus WTT data generally increase with CFD data at lower resolution of 720p
  - 720p most likely an inadequate temporal resolution

Aeroacoustic Analysis: 1F+1A Tone Impact of CFD Temporal Resolution

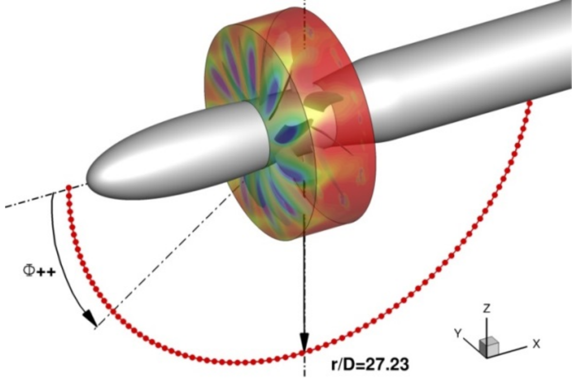


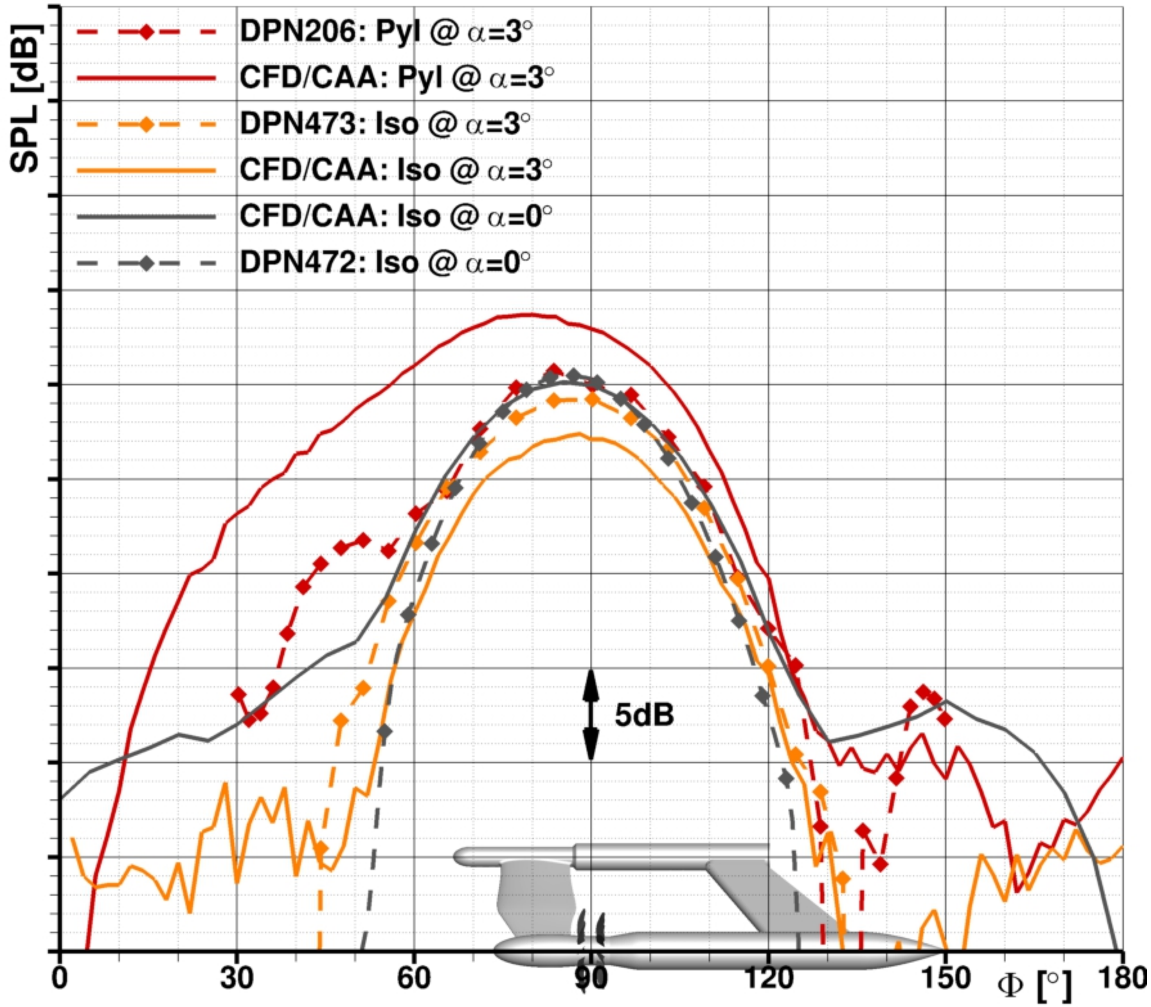


- APSIM+-runs using uRANS input at **several temporal resolutions (720p & 2772p)**

- Good prediction of 1F+1A interaction tone directivity
- Small but evident improvement with higher CFD temporal resolution, Δ~1-2dB
- Shift in downstream directivity lobes in CFD/CAA: Probable impact of neglected non-linear propagation in propeller slipstream

Aeroacoustic Analysis: Aft Rotor Tone Installation Effect

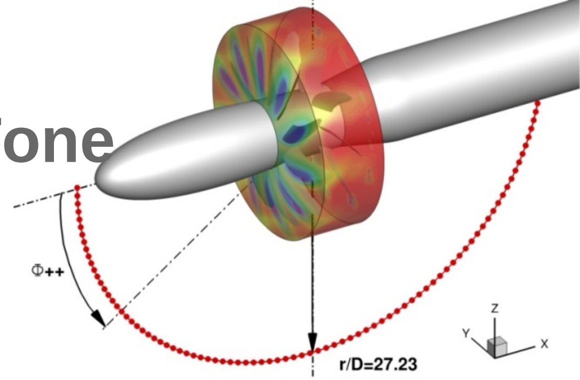


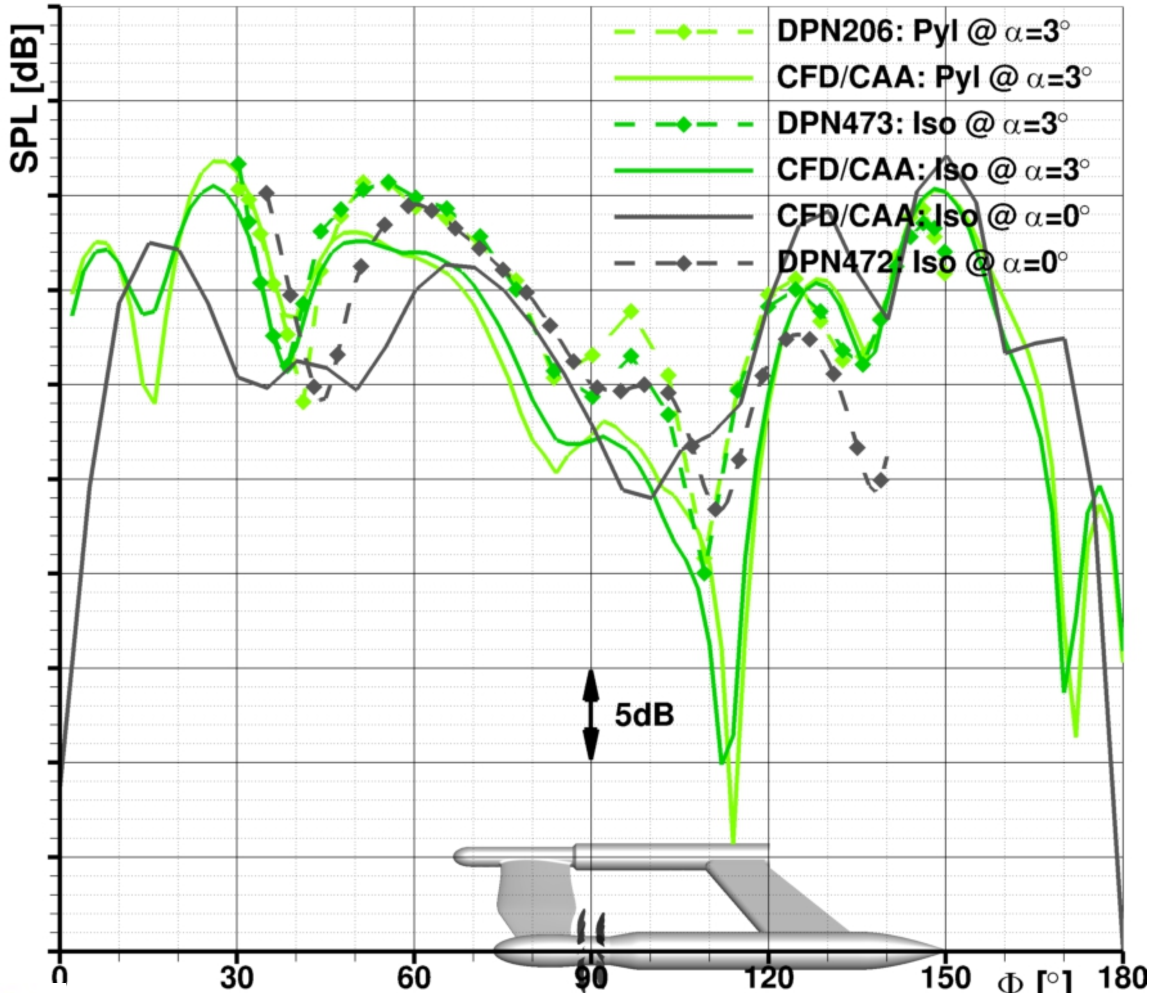


- APSIM+-runs for **all cases** using uRANS input at **highest temporal resolution (2772p)**

- Good prediction of aft rotor tone for isolated CROR at α=0º
    - Scatter due to aft blade unsteady flow separation
- Trend of incidence effect well predicted & good agreement with WTT data, Δ~1-2dB
- Trend of pylon effect well predicted, reasonable agreement with WTT in terms of magnitude

Aeroacoustic Analysis: First Interaction Tone Installation Effect





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

- Reasonable prediction of interaction tone for isolated CROR at α=0º
- Very good agreement with WTT data for incidence case
- Small AoA impact , with trends generally well reflected
- Good match for pylon case directivity, with trends of pylon effect (practically none) well predicted

Conclusion & Outlook

- **Good prediction of aerodynamic & aeroacoustic installation effects**, in line with WTT
- **Good maturity of CFD/CAA-approach** for the analysis of performance and noise
- In parallel to research in the frame of SFWA, these tools have been applied to full CROR-powered aircraft configuration analysis in support of airframer design activities

- **So where are we in 2016 with CROR**
  - In a low-cost fuel environment?
  - With a need for a likely rather radical aircraft configuration change and remaining technological challenges in an industry that is risk averse?
  - Where neo's and MAX's are just entering the market with low(er)-risk but still quite impressive aircraft level fuel burn improvements?

- In 2016, SNECMA will **ground test a CROR demonstrator engine** in Clean Sky
- Need to address an engine and aircraft level fuel burn discrepency
  - CROR engine sfc shows potential double digit advantage versus turbofan
  - But: Focus aircraft configuration for presumed lowest risk CROR integration suffers weight penalty due to empennage installation, long pylon, blade release shielding, …
- Support of Airbus-led configuration analyses for CROR **economic viability studies** in the frame of follow-on activities in **Clean Sky 2** project(s) with plans for FTD support in place

Application of Active Flow Control Technology to Enable Efficient UHBR Turbofan-Powered Aircraft Configurations

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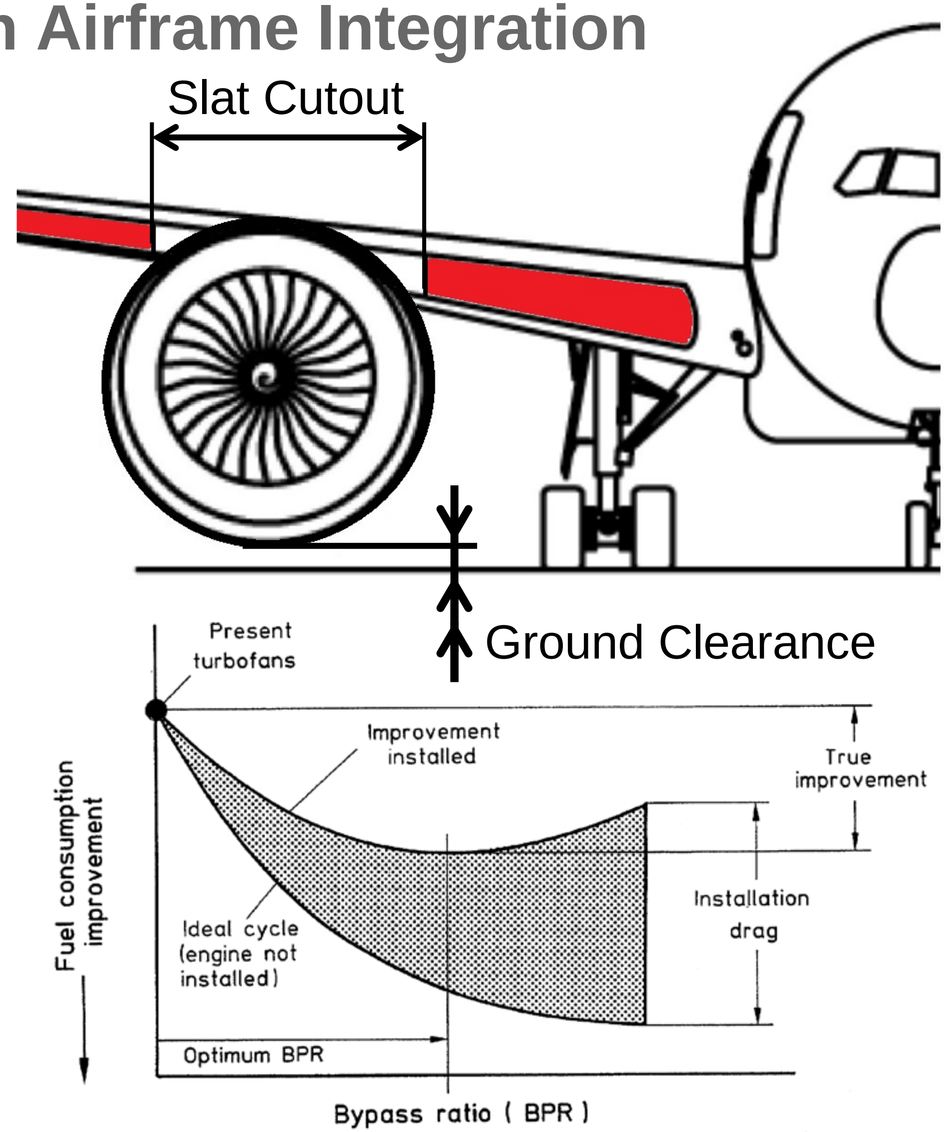
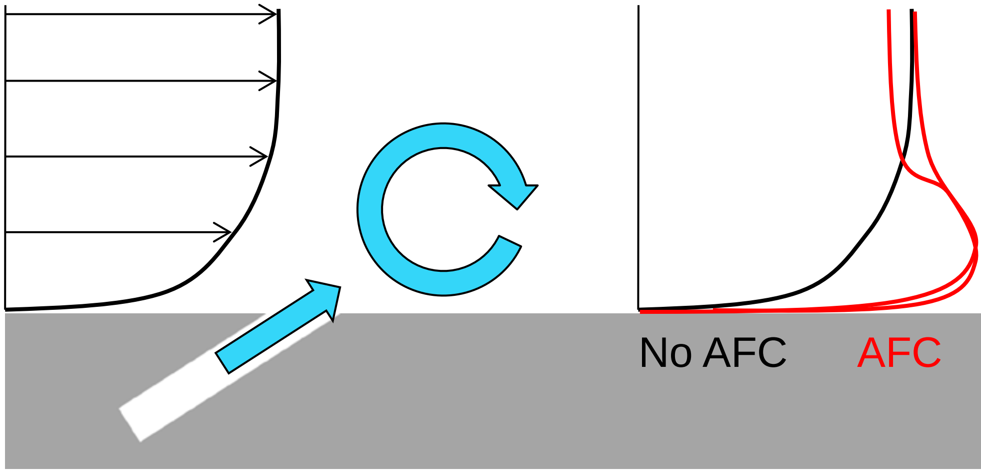
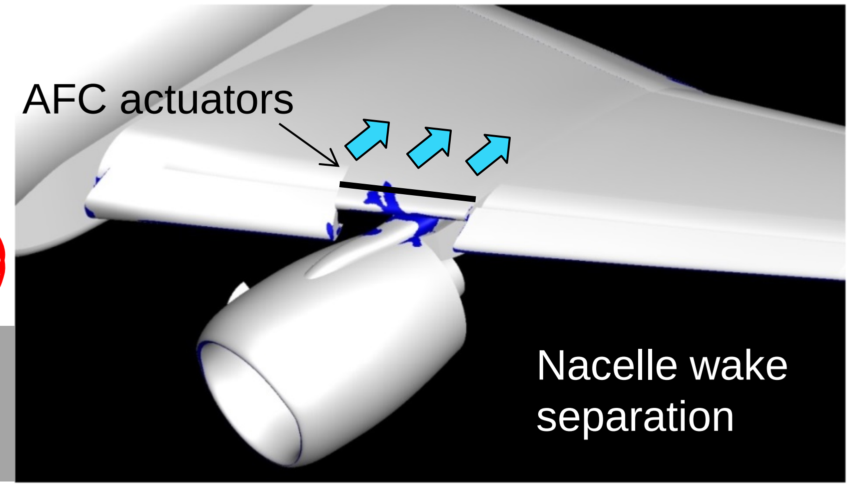
Introduction & Motivation: Challenges of UHBR Turbofan Airframe Integration

- Engine level SFC improvements through BPF increases don‘t always translate directly to improved aircraft level fuel burn due to weight, nacelle & installation drag penalties
- Challenging trade-off for large TF engine integration in underwing installation
    - Nacelle & Interference drag & aerodynamic interactions, pylon/system weight, ground clearance and landing gear height & weight
- Most likely scenario: Very close coupling of engine & wing
    - Biggest potential penalty could be the need for a large slat/leading edge device cutout with adverse impact on low-speed high-lift flight performance
- Aerodynamic performance may be recovered through the application of active flow control (AFC) technology

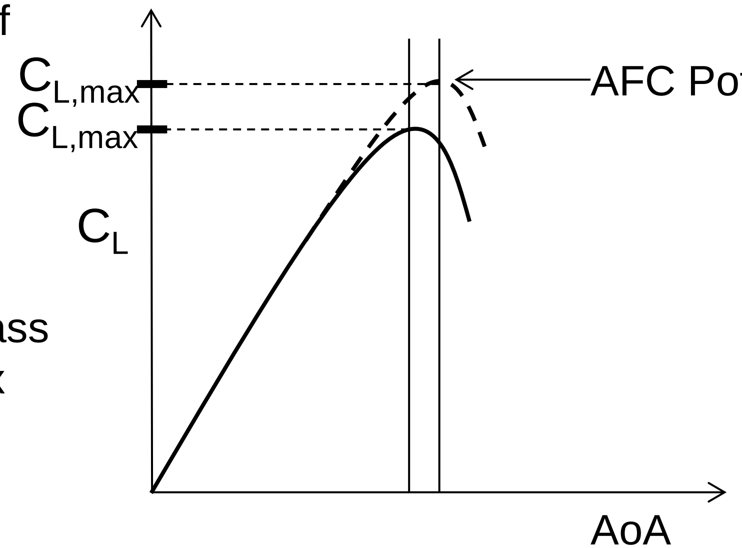


Introduction & Motivation:
AFC Basic Principles & UHBR Integration Application





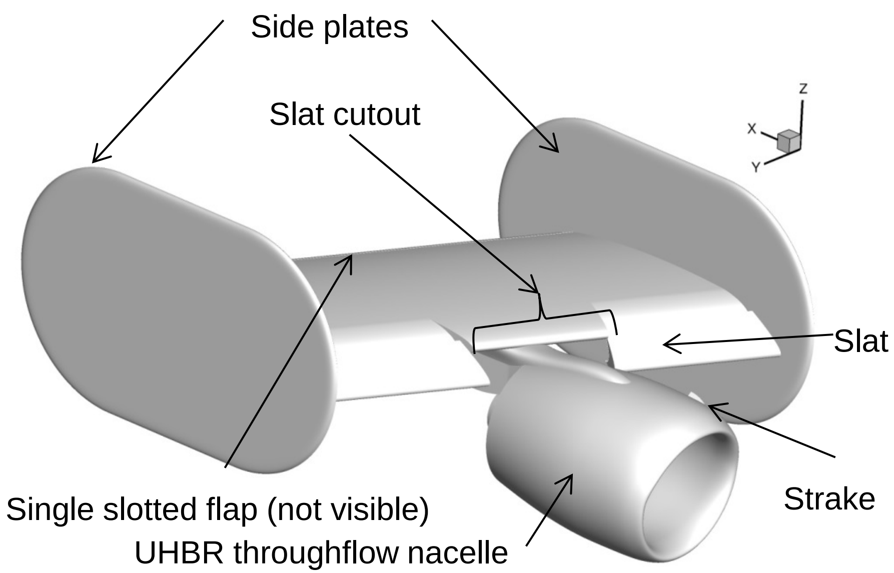
- AFC has long been studied for a broad range of application scenarios to remedy numerous aerodynamic issues
    - Separation control
    - Circulation control to enhance lift
    - Transition control
- Pulsed blowing approaches enable reduced mass flow requirements through exploitation of vortex induced mixing for similar effects as seen for constant blowing



EU FP7 AFLoNext TS3:
CFD & WTT Studies of AFC for Engine Integration

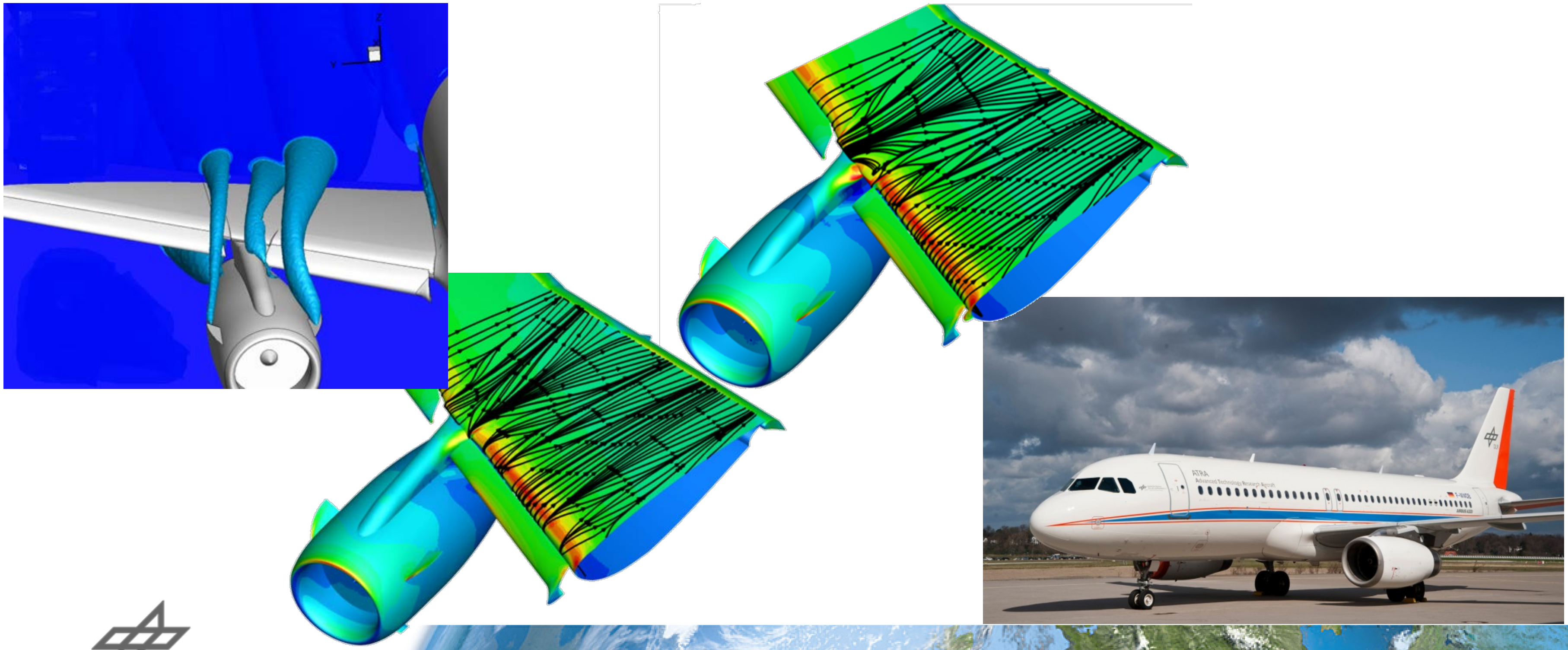
- **A**ctive **Flo**w Loads & Noise control on **next** generation wing
- EU funded studies for various AFC applications, 2013-2017
- TS3: Technologies for local flow separation control applied in wing/pylon junction
    - Goal: Maturation through TRL 4 of AFC for this application
    - Focus on overall AFC system and integration with the airframe
    - Practically full-scale wind tunnel test at TsAGI (1/1.5 scale)
    - DLR work focused on aerodynamic design of the AFC system

- Focus configuration:
- 2.5D model with representative through-flow UHBR nacelle
- Based on DLR F15 configuration: b=5.2m, c=3.29m and sweep of 28°



AFC as an Enabler for UHBR Turbofan Integration: Outlook: EU Clean Sky 2 Studies

- Synergistic and continued work currently under way to further mature the application of AFC for UHBR engine intergration facilitation in the frame of the EU Clean Sky 2 program
- Full system view, extension to 3D full aircraft application („retrofit“ and design for AFC configurations) and planned culmination in flight test demonstration



DLR Contributions to the Development of Engine-Airframe Integration Concepts for Environmentally Acceptable and Economically Viable Transport Aircraft

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