CROR Noise Generation Mechanism #3: Installation Effects (& Quadrupole Noise)

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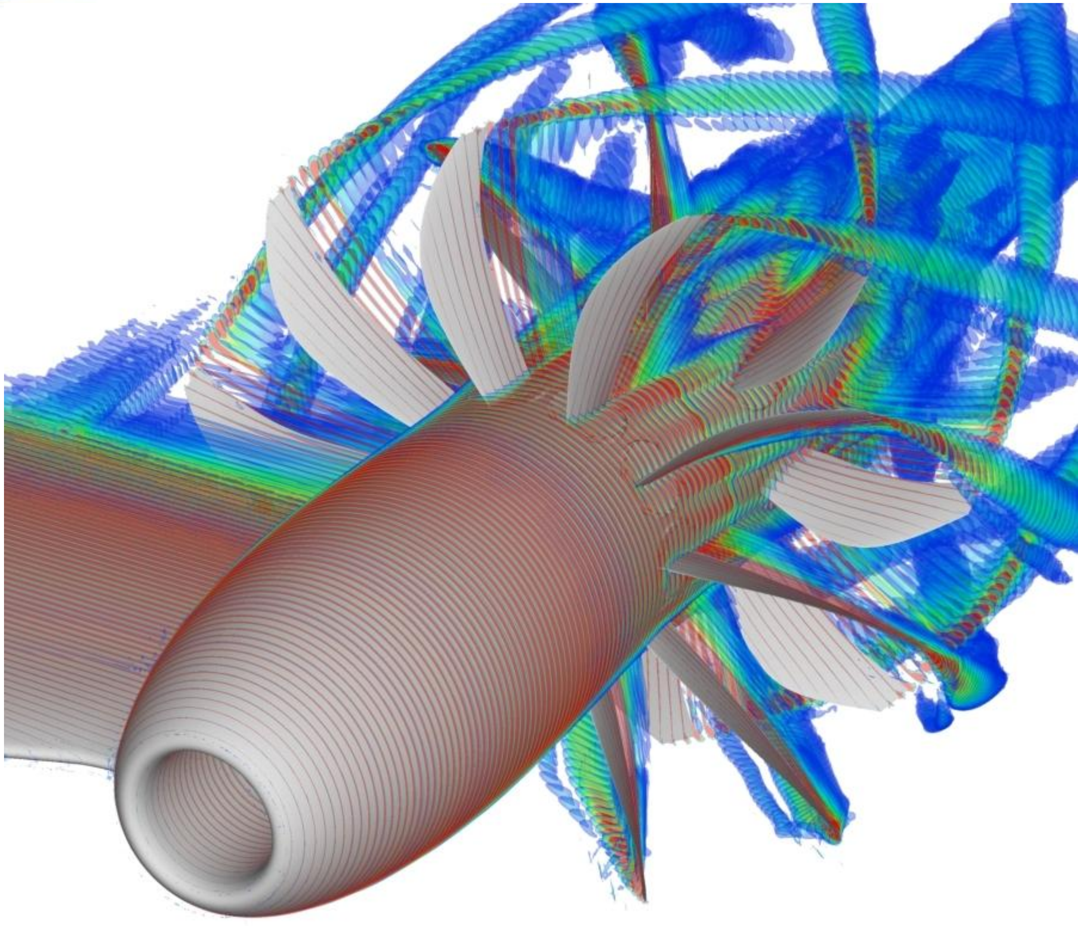

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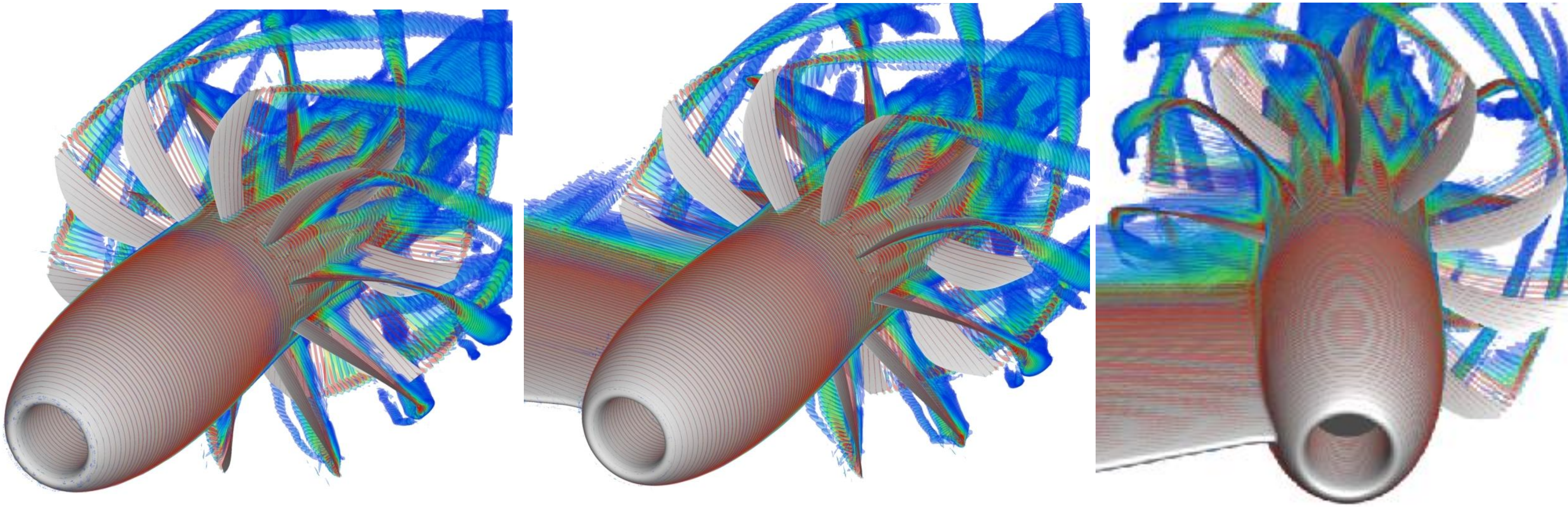
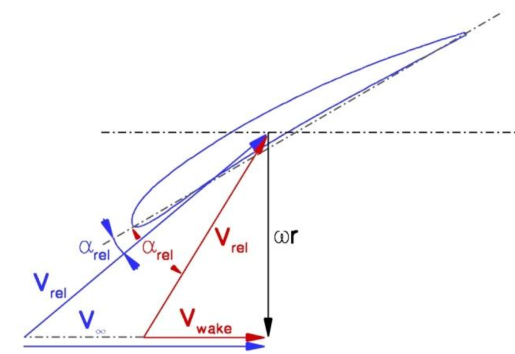
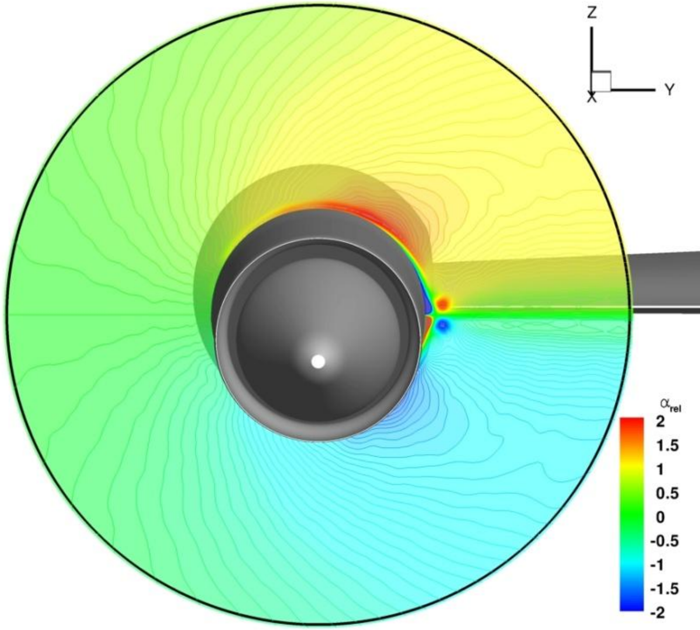
Cruise Aerodynamics:
Installation Effects Analysis



- Here: Cruise @ h=35,000ft, M=0.75 & α=0º
- Blade tip vortices and wakes dominate rotor-rotor interactions
  - Cropped aft rotor avoids front blade tip vortex impingement
- Installation creates front rotor inflow distortion, with pylon wake the dominant added source of unsteady blade and rotor loadings

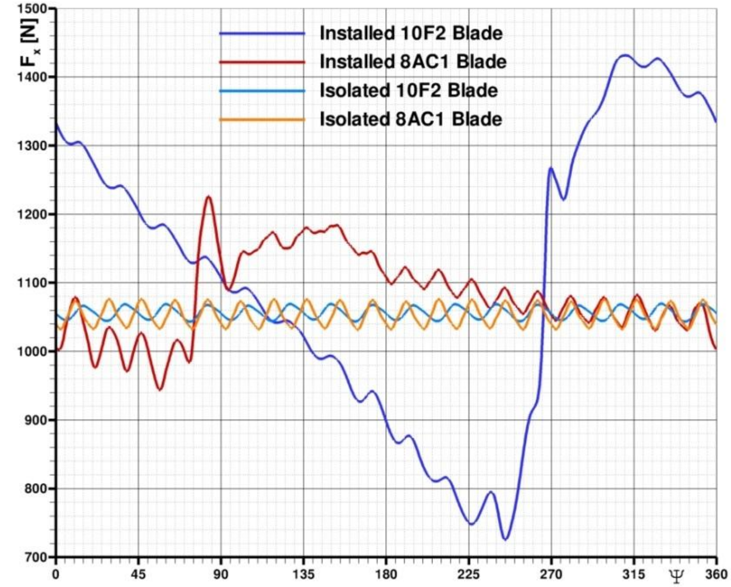


Cruise Aerodynamics: Installation Impact on Blades



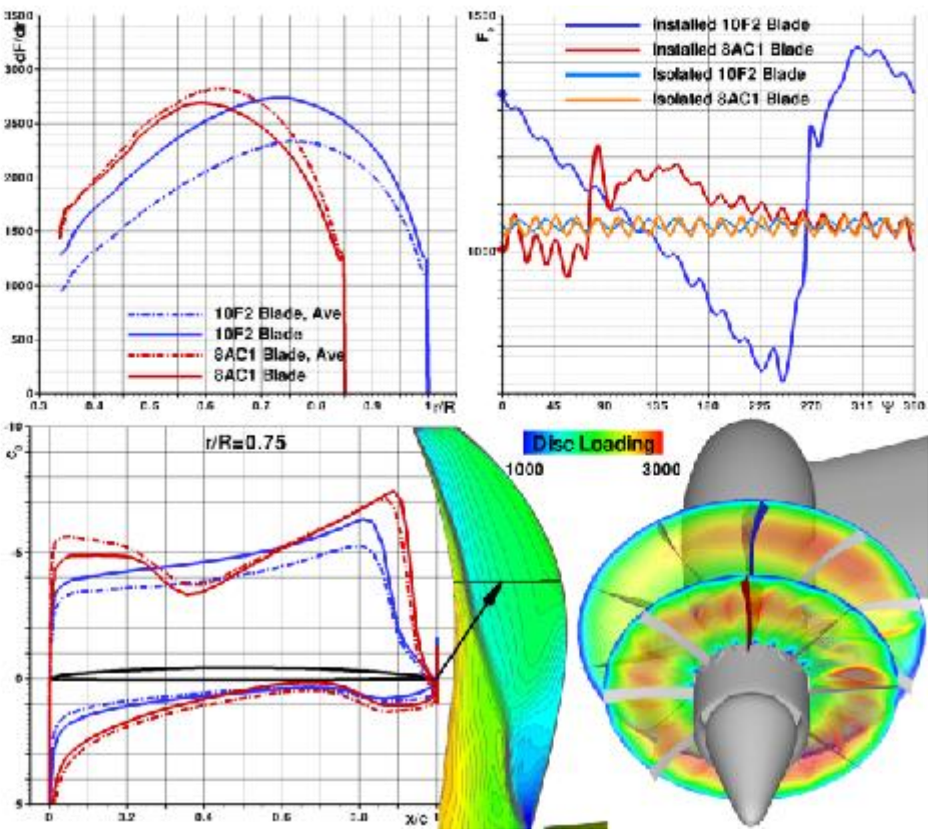
- Isolated CROR blade forces show unsteady loading cycle linked to rotor-rotor interactions
  - Aft blades affected by front blade wakes (and tip vortices)
  - Front blades affected by aft blade potential flowfield

- Installation leads to non-uniform inflow for front rotor
  - Blade effective angle of attack variations between -2º<α<2º
- Front rotor shows large amplitude loading increase due to pylon wake impingement
- Strong wake still affects aft rotor, but smaller magnitude loading increase visible
- Overlapping impact of blade-blade interactions



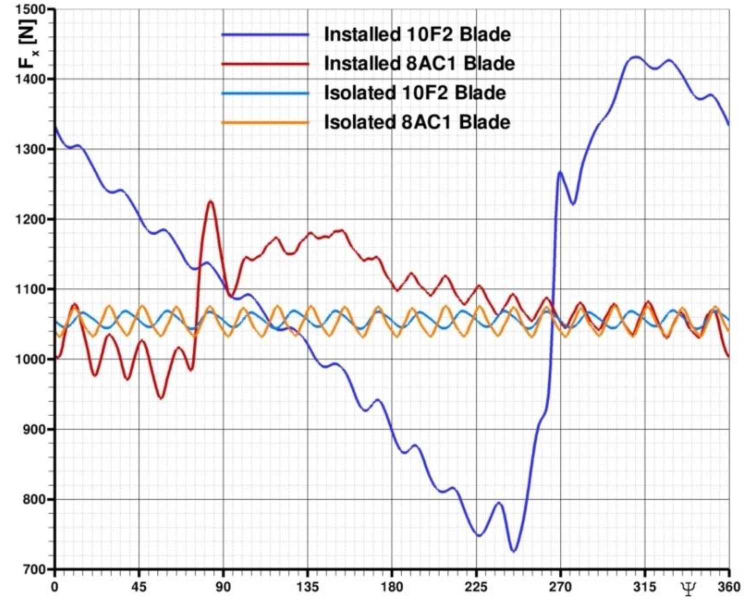
Cruise Aerodynamics:
Installation Impact on Blade Aerodynamics

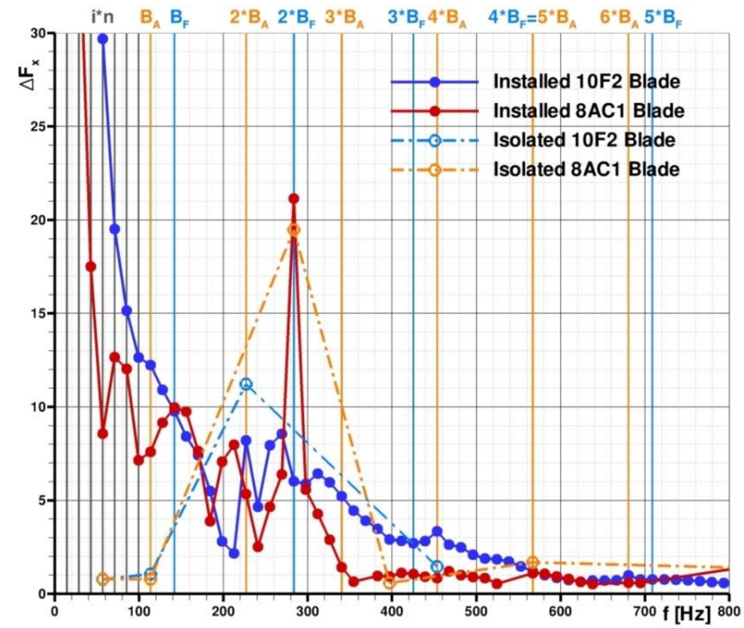
- Front blade affected by aft blade potential flow
  - Pressure fluctuation visible on pressure side
  - Full span transonic flow on blade suction side
- Aft blade shows full span unsteady loadings due to front rotor wake impingement
- Pylon wake leads to local increase in blade angle of attack
  - Strong impact on front blade
  - Notable impact on aft blade



Cruise Aerodynamics: Installation Impact on Blades

- Spectral analysis of blade loading oscillations shows dominance of pylon wake impingement at f=n
  - Front rotor amplitudes 5 times larger than seen for aft rotor
- Rotor-rotor interactions lead to blade loading oscillations at even number higher harmonics of respective other rotors BPF
  - Aft rotor blades show only small impact of installation effects versus isolated CROR
  - Front rotor blades unsteady loadings more affected by installation impact

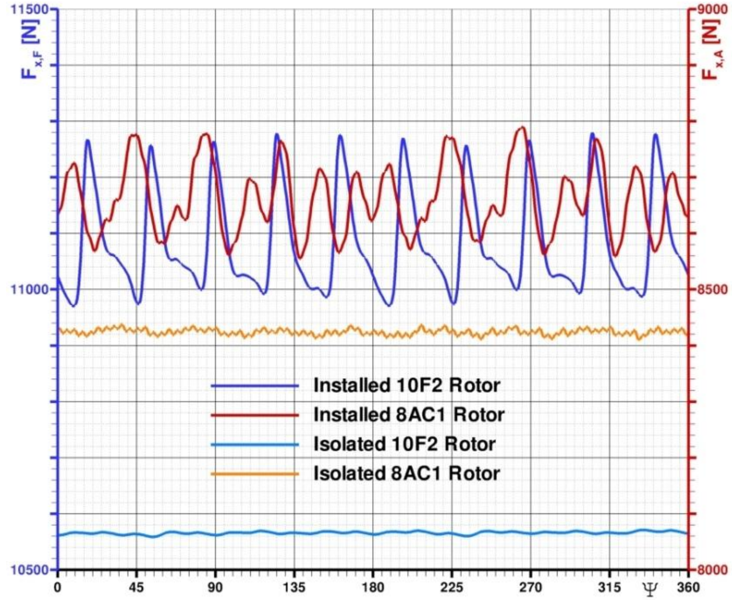


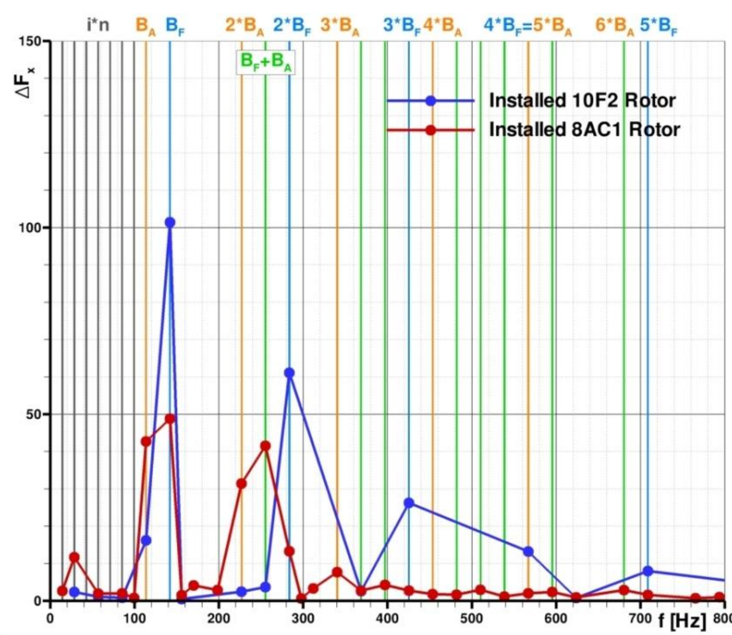


Cruise Rotor Performance

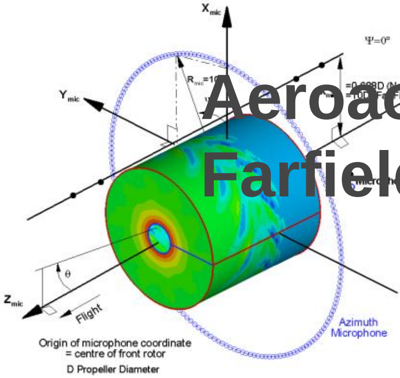
	Isolated			Installed		
	Rotor 1	Rotor 2	Total	Rotor 1	Rotor 2	Total
F_x [N]	10,566	8,424	18,990	11,082	8,660	19,742
C_T	0.4169	0.6368	-	0.4373	0.6546	-
C_P	1.9235	2.9958	-	1.9946	3.0669	-
η [%]	79.72	91.98	85.85	80.63	92.35	86.49

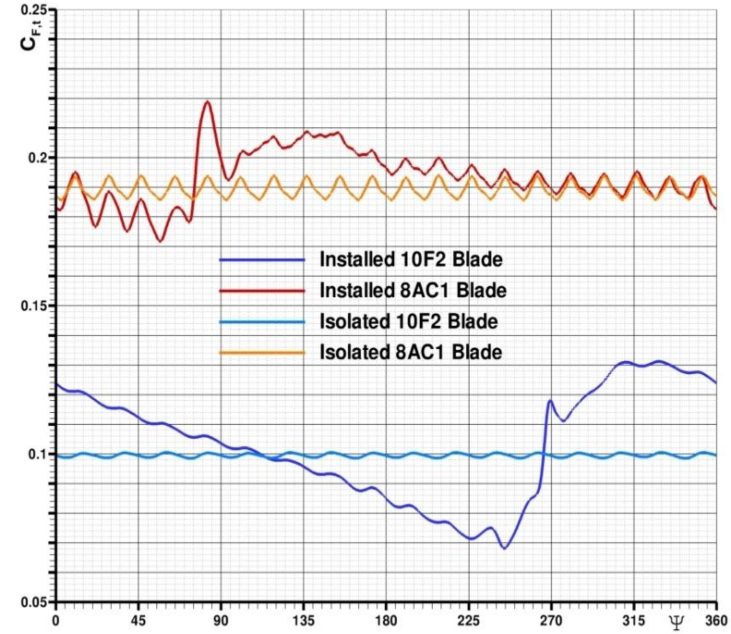
- Mean rotor performance level show achievement of 19kN thrust goal with efficiencies of η>85.85%
    - Installation leads to increased thrust and improved efficiency due to mean angle of attack increase
- Constant rotor loads for isolated CROR
- Installed CROR front rotor shows 10-cycle loading oscillation
- Installed aft rotor loading oscillation is as dependant on relative position versus front rotor blade than pylon wake impingement itself directly

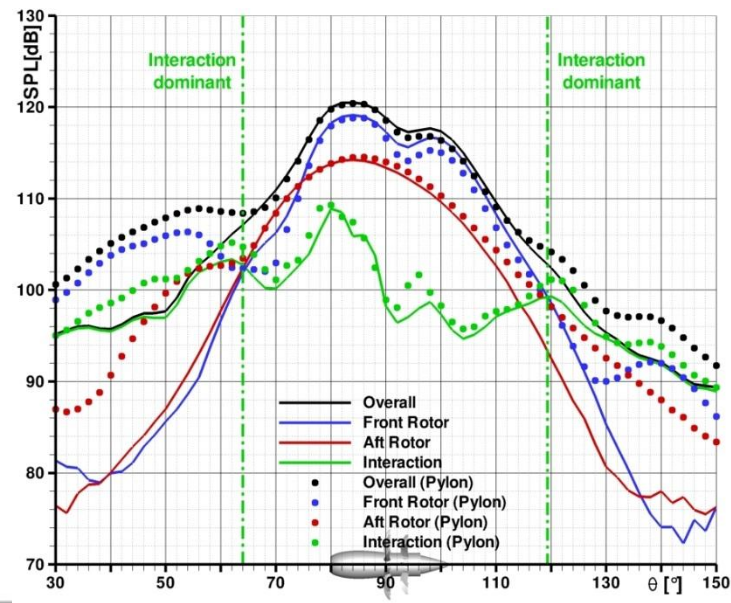




Aeroacoustic Analysis @ Cruise Farfield Noise Radiation



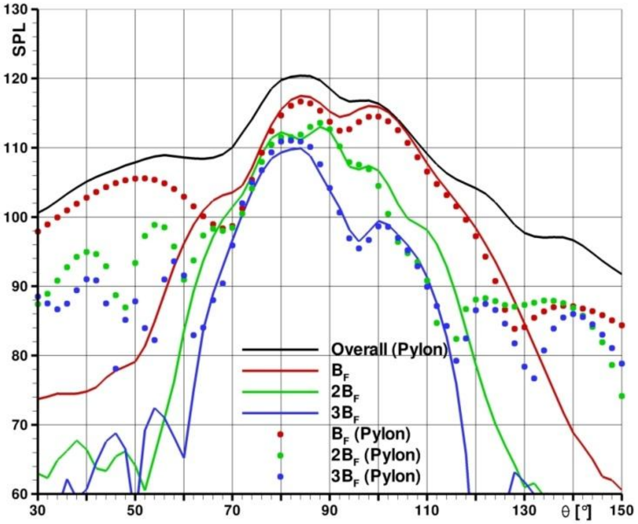


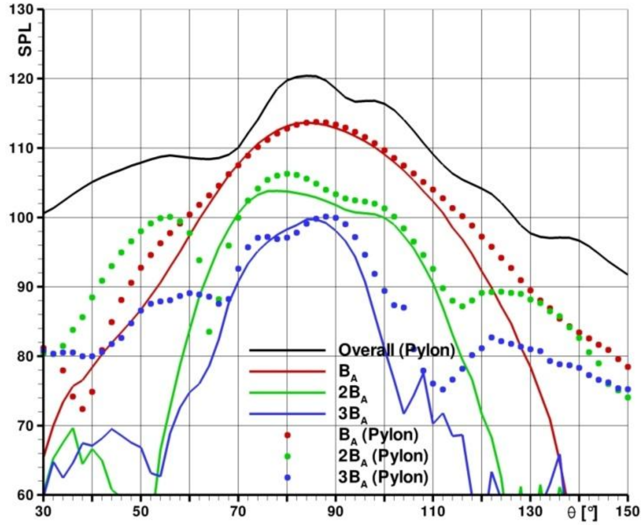


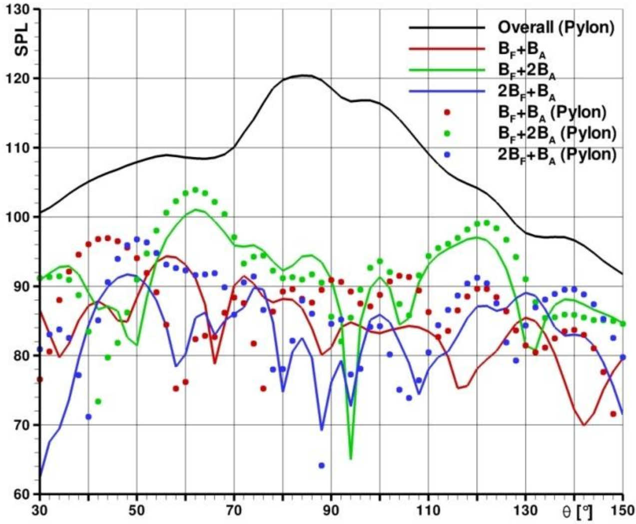
- Isolated CROR has uniform noise emissions in azimuthal direction
- Installation leads to clear non-uniform directivities, with higher noise in fuselage direction than towards the sideline

- Ground noise polar directivities show importance of interaction tones for the up- and downstream noise emissions
- Small installation impact visible near planes of rotation
  - Installed CRORs blade loadings impact steady loading noise emissions towards ground
- Strong down- and upstream installation impact, with front and aft rotor tones (and harmonics) much greater than for the isolated CROR

Aeroacoustic Analysis @ Cruise
Farfield Noise Radiation – Tone Decomposition







- Front rotor tones show significant increases due to installation effects
- Notable but not as significant increases in the aft rotor tones
- Interaction tones show only small impact of installation effects

CROR Noise Source Capturing: Requirements for CFD

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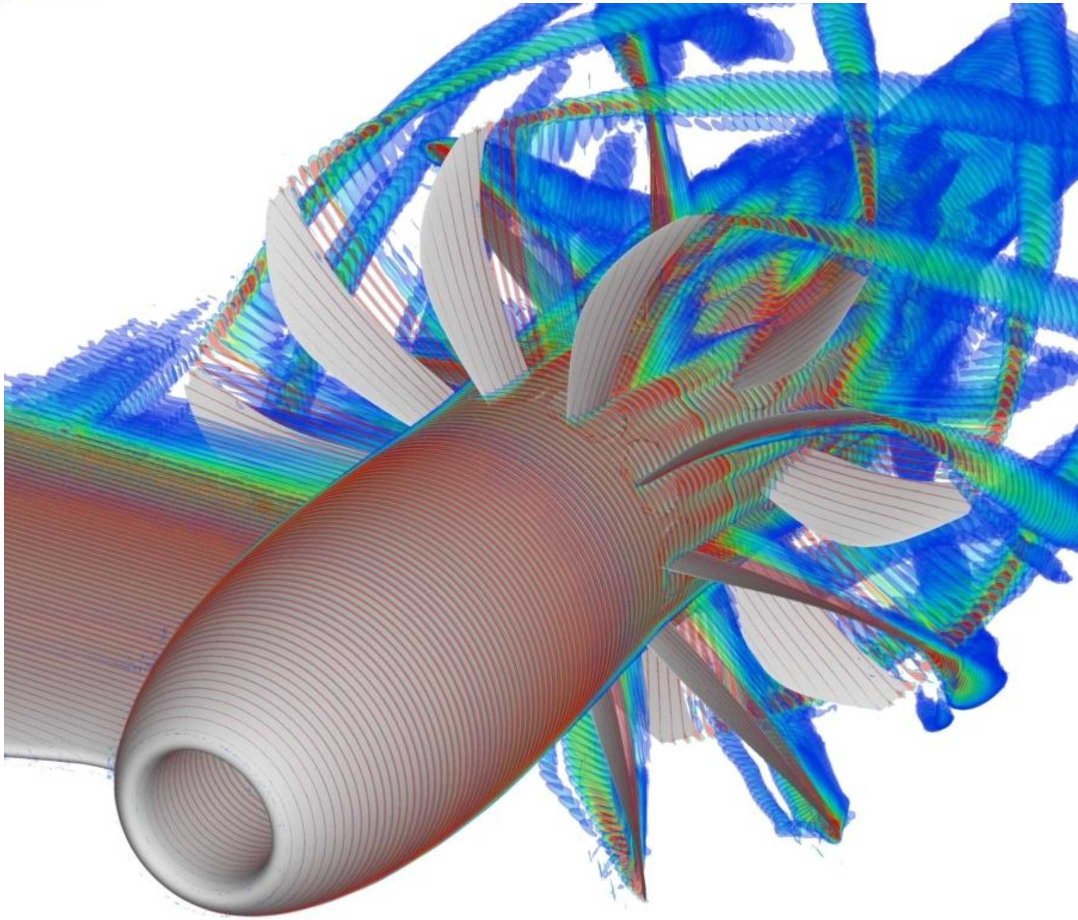

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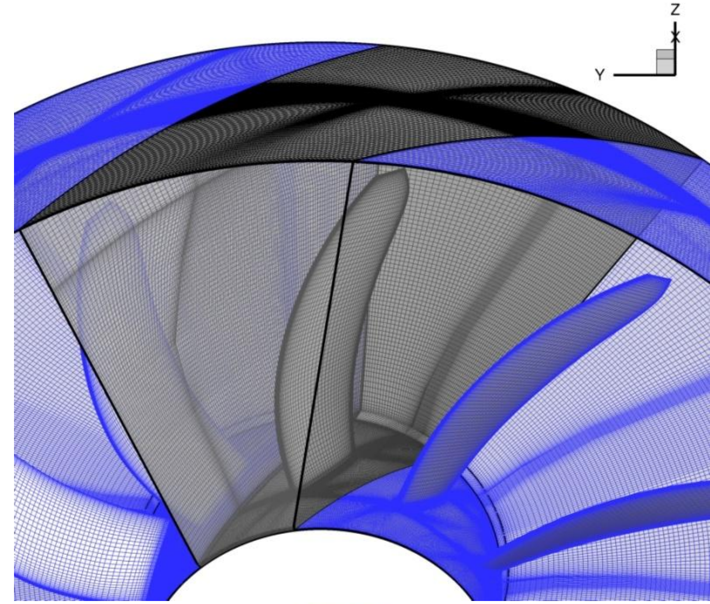
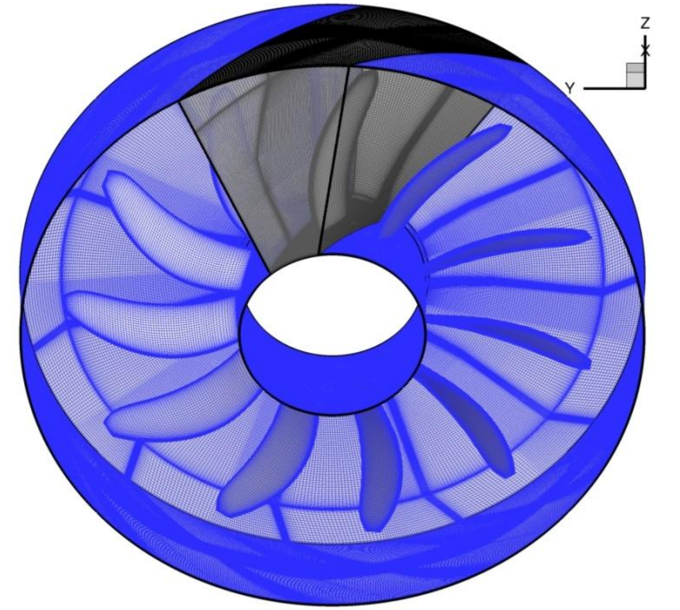
Mesh Resolution Requirements: Blade Wakes

- Work performed in the scope of JTI SFWA (Smart Fixed Wing Aircraft Project) WP2.2
- Airbus Generic CROR Configuration
- Take-Off @ SL, T=ISA+10 and M=0.23, α=0º

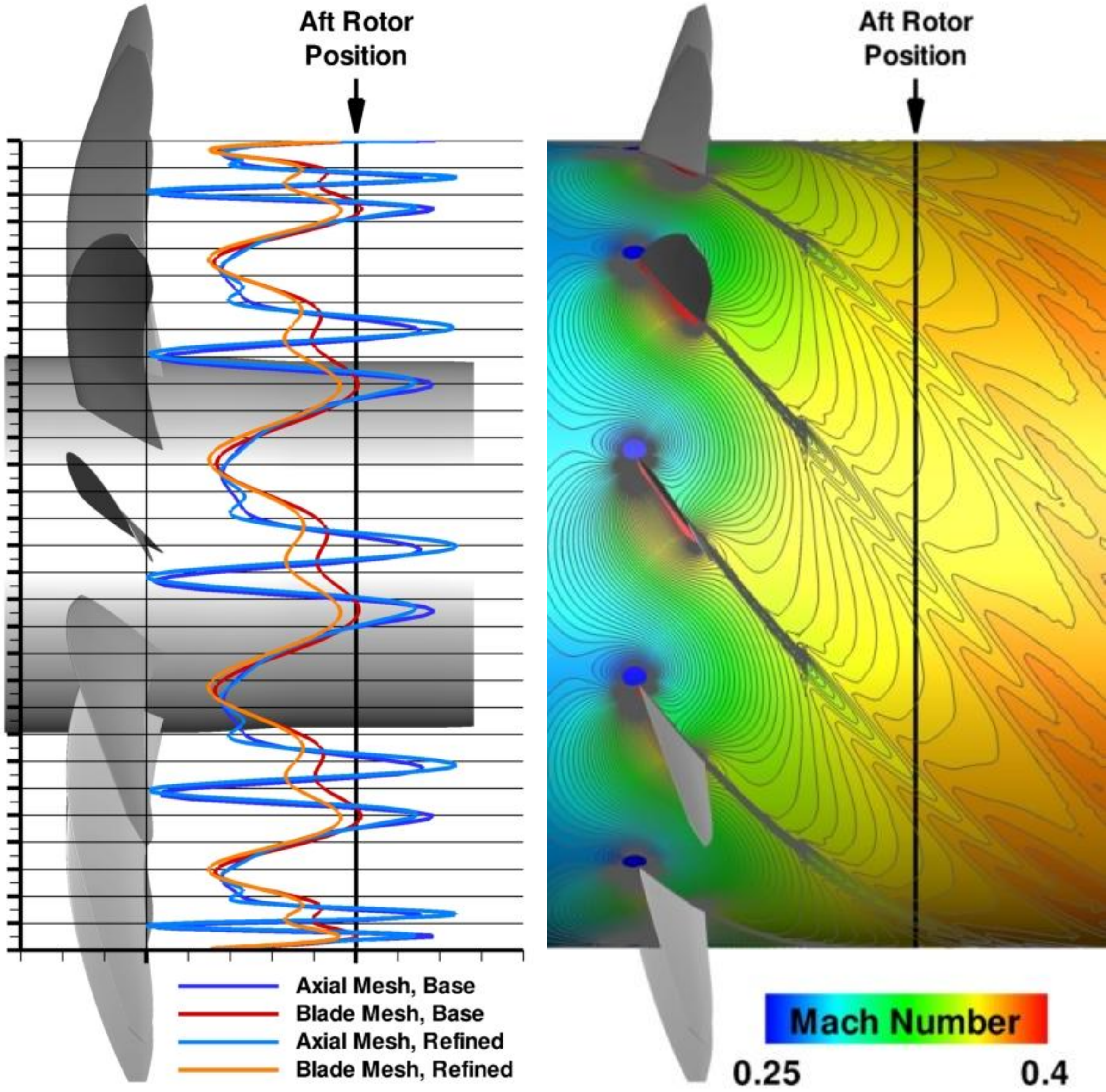
- Rotor meshes:
  - ICEM Hexa structured grids exploiting axis symmetry
  - Periodic mesh for one blade passage
  - C-O-topology for good wake resolution
  - Creation of full rotor meshes through rotation and copying of periodic blade passage meshes
- Grid resolution driven by aeroacoustic needs:
  - Focus on BPF1-5 (156.45-956.083Hz)





Mesh Influence Study

- Comparative study of influence of skewed, aft blade oriented mesh versus flow-direction oriented mesh
- Clear advantage of skew-avoidance for wake resolution
- Special attention to mesh topology and resolution is essential for proper resolution of blade wakes and thus aeroacoustics!



CROR Noise Source Capturing: Requirements for CFD-CAA Coupling

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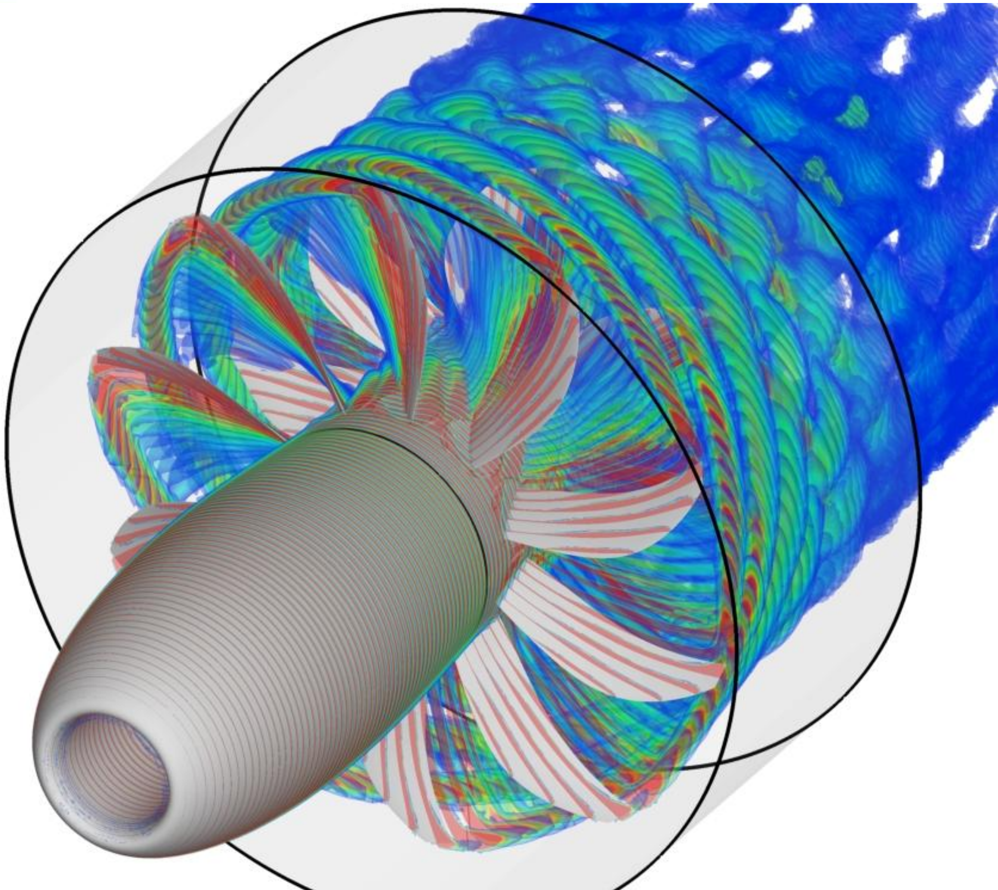

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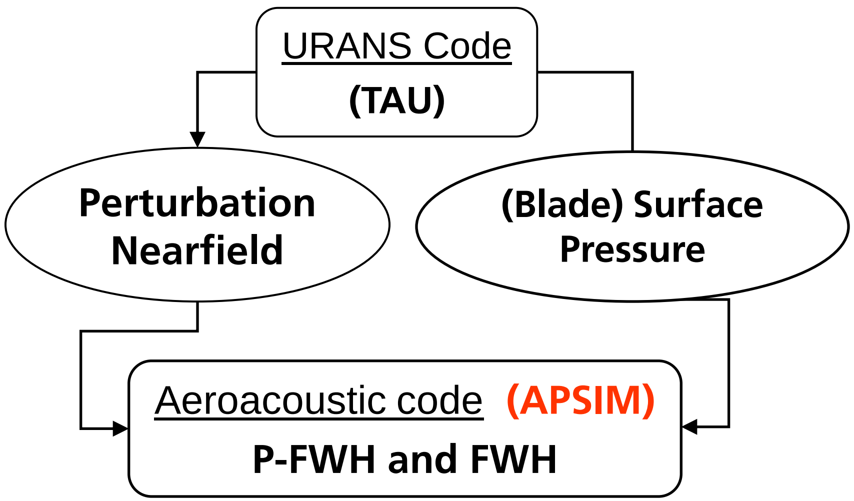
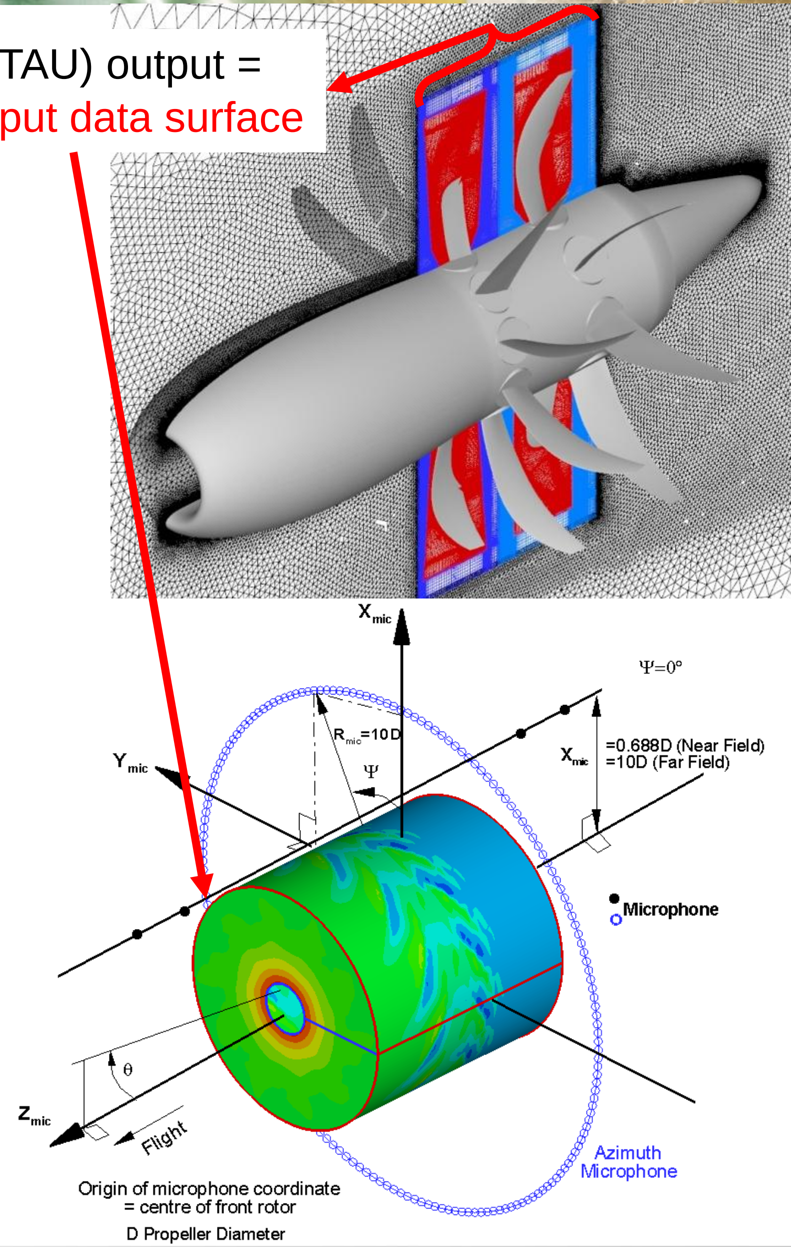
Aeroacoustic Analysis: Tools & Approach

- Noise radiation analysis using APSIM (Acoustic Prediction System based on Integral Method)
  - Rotor & Propeller Noise
  - Permeable or Impermeable FW-H



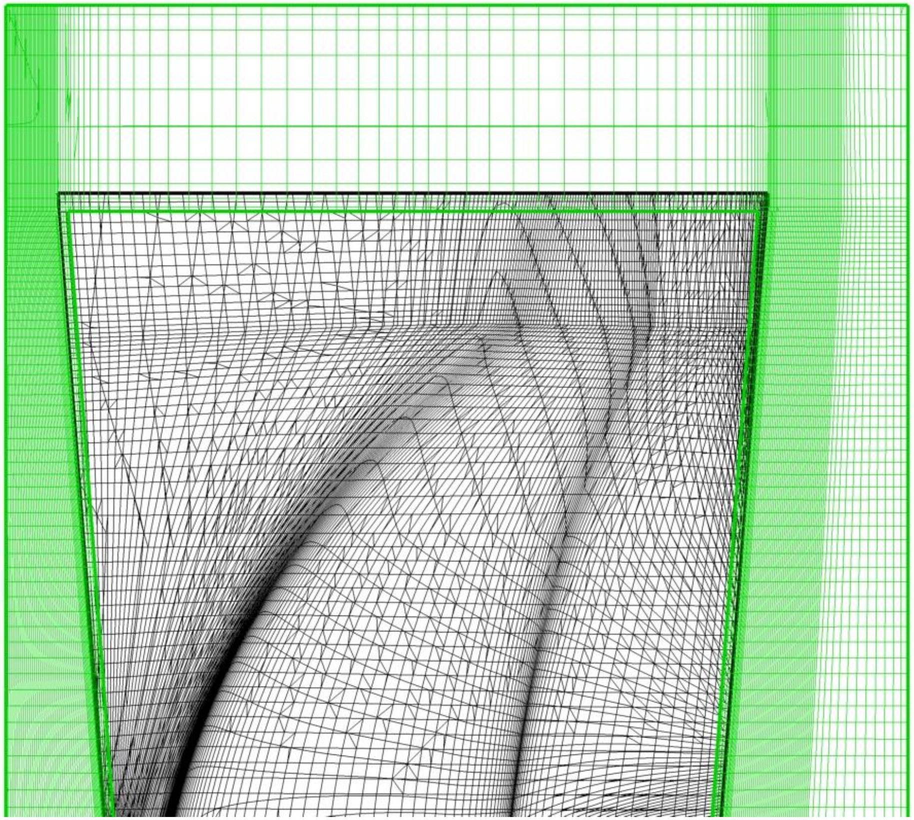
- Virtual microphones oriented around front prop center
- Nearfield mic array @ x/D=0.688 (~ pylon length)
- Farfield virtual mic array @ x/D=10
- Farfield azimuthal mic array @ r/D=10



Simulation Approach: Mesh Resolution Needs

	8F1x8A1		
	10 ppw	20 ppw	30 ppw
n [rpm]	850		
f(5*BPF) [Hz]	709		
Λ [m]	0.419		
s [mm]	41.852	20.926	13.951

- Permeable surface FW-H approach requires CFD to resolve all relevant noise (sources & frequencies of interest) up to the selected CAA input surface
- 2nd order accuracy of typical CFD solvers leads to this requirement as the main driver in mesh density
- Investigation of mesh resolution requirements for TAU simulations to capture and propagate rotor tones to Chimera boundary

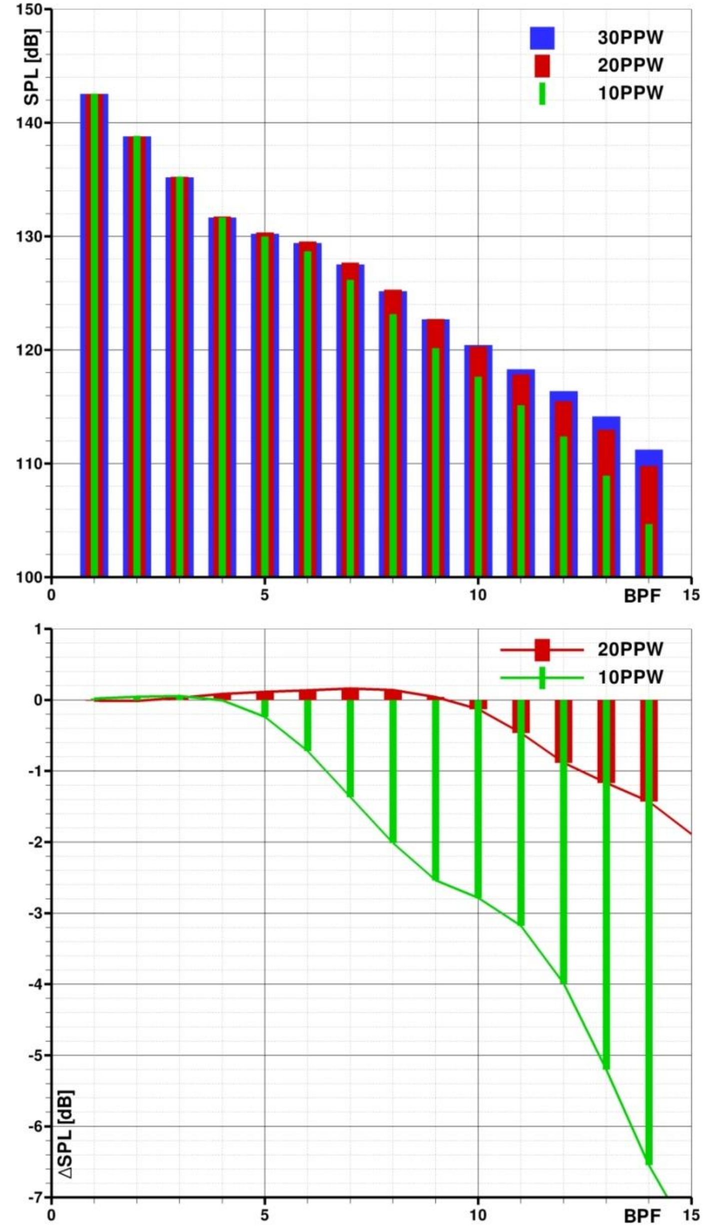


	Core engine		n_1 [rpm]	J_1	$\beta_{75,F}$ [°]
	p_t/p_0	T_t/T_0			
10F2x8AC1	1.25	2.9	850	3.678	61.95

Simulation Approach:
Mesh Resolution Requirements

- Evaluation of mesh impact on propagation of front rotor-alone tone to Chimera boundary in the plane of rotation

- Frequencies through 4*BPF well captured on all grids
- Assumption of 10ppw-requirement for adequate resolution of f=5*BPF too optimistic, 20ppw too pessimistic
  - Conclusion: TAU Simulations can provide good acoustic wave capturing (on smooth orthogonal meshes) using a conservative 15ppw



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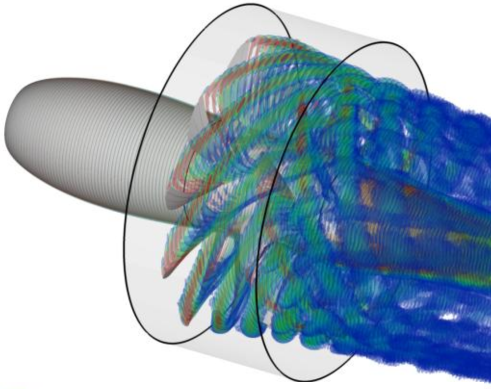
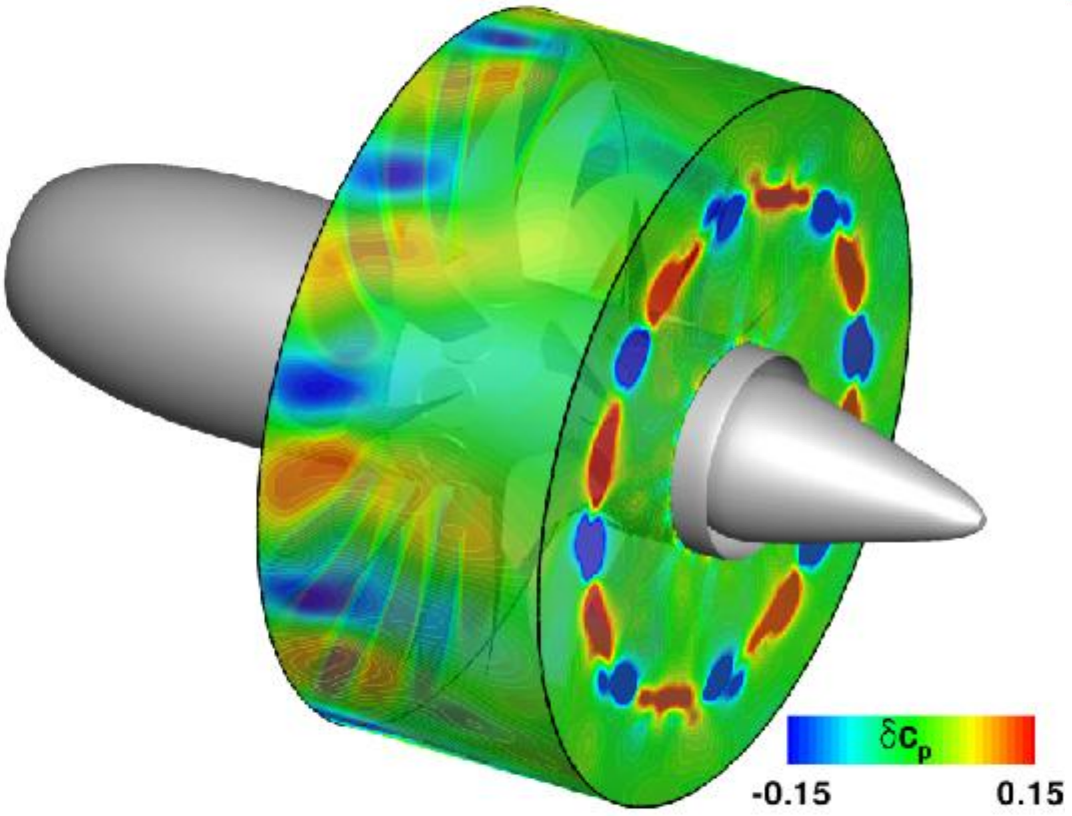
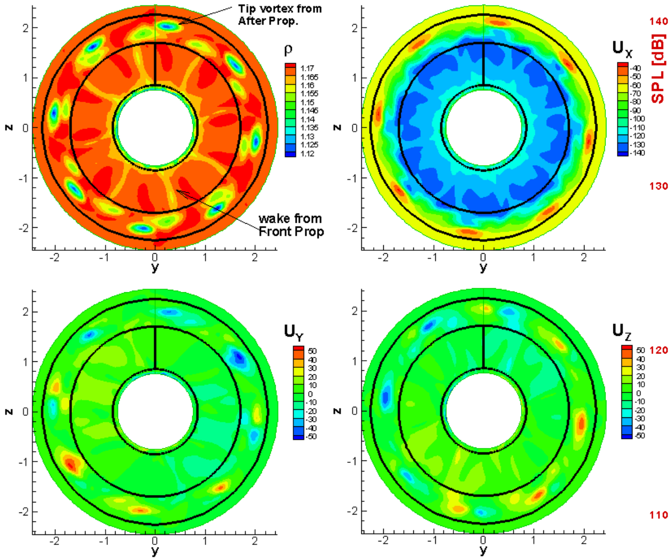
Aeroacoustic Analysis: Permeable FW-H Approach

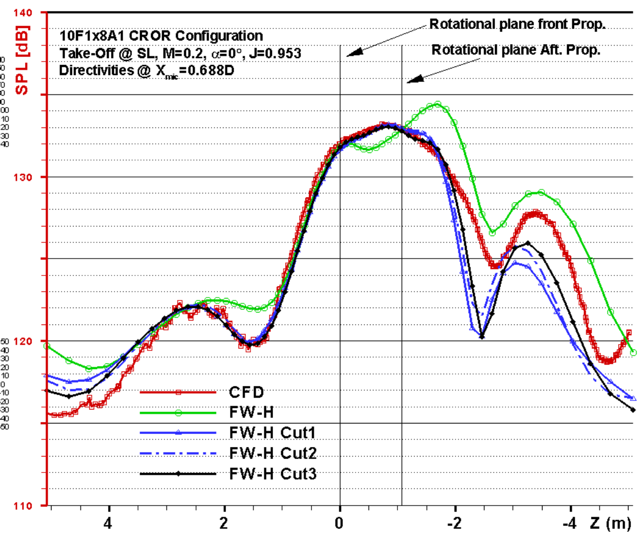
- Proper aeroacoustic wave resolution on the CFD side only half the story for permeable FW-H approach
- Impingement of strong aerodynamic perturbations(blade tip vortices, engine jets,…) on input surface known to lead to erroneous results in the farfield noise predictions

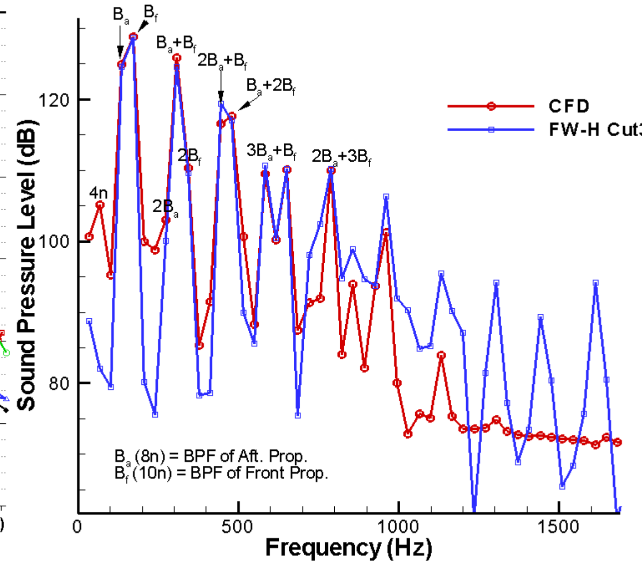




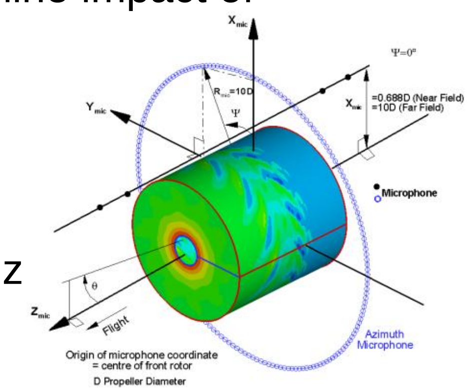
Aeroacoustic Analysis: Permeable FW-H Approach





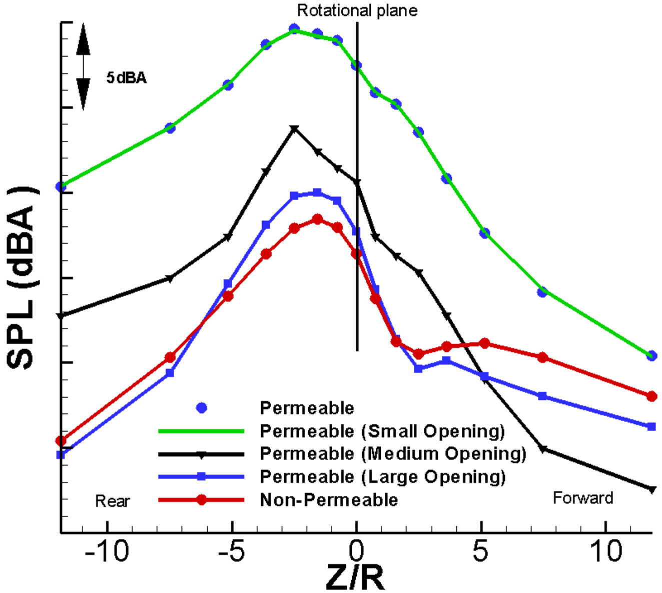


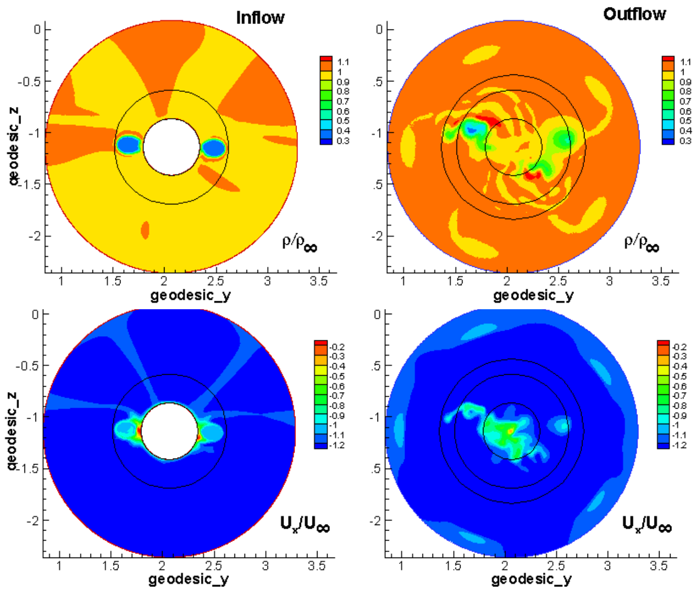
- Systematic analysis of permeable surface variations to determine impact of wake/vortex impingement on the downstream plane
- Comparison with results extracted directly from CFD
  - Mesh resolution sufficient for frequencies through $4*B_A$
  - Front rotor plane spectrum:
    - Good match between FW-H and CFD for f<800Hz
- Conclusion: Apparently no need to modify downstream plane



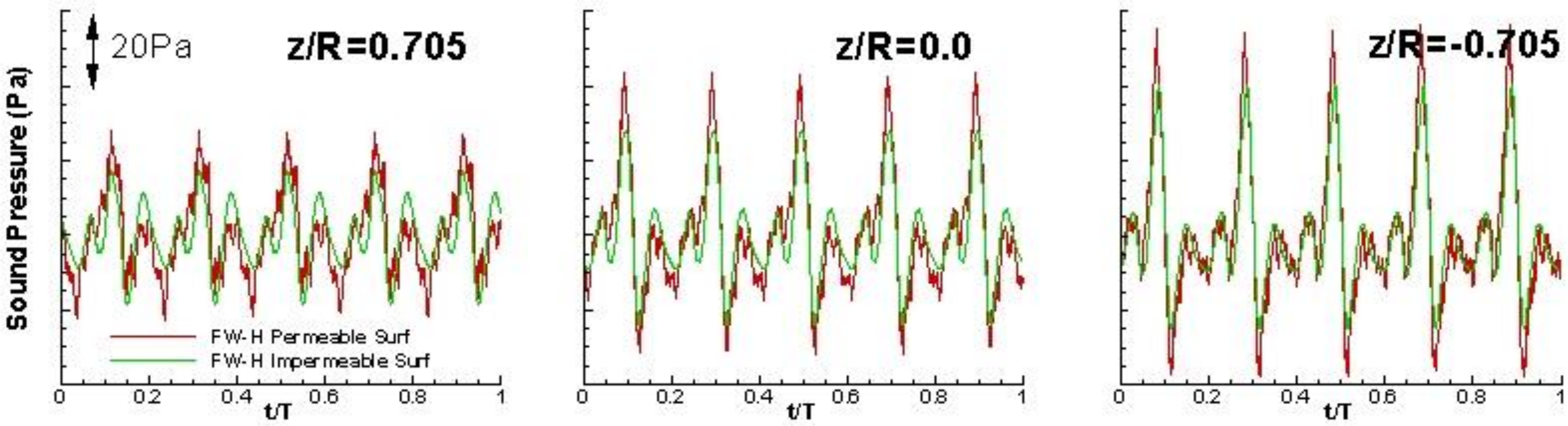
Aeroacoustic Analysis: Permeable FW-H Approach

- Porous FW-H can account for quadrupole noise emissions
  - CFD grid good up to 9*BPF
- Impingement of aerodynamic wakes & vortices known issue for porous FW-H approach
- Parametric study of surface clipping to assess PFW-H
  - No significant inflow impact
  - Spinner wake impact negligible
  - Engine jet impact important





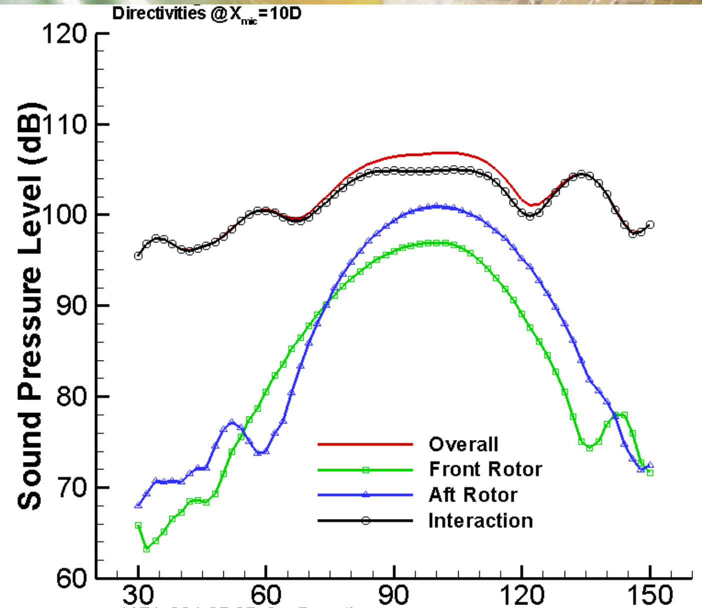
Aeroacoustic Analysis:
Permeable FW-H Approach

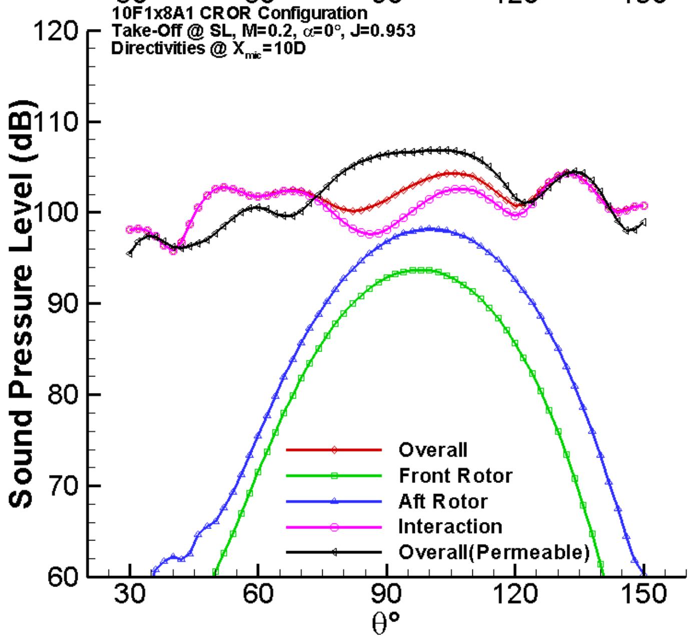


- Large-opening pFW-H versus iFW-H APSIM results of sound pressure time histories
- Generally similar development, with BPF and n*BPF components captured in both results
- Higher amplitudes and higher frequency content in pFW-H results could be quadrupole contributions and/or residual effects of wake impingement on integration surface

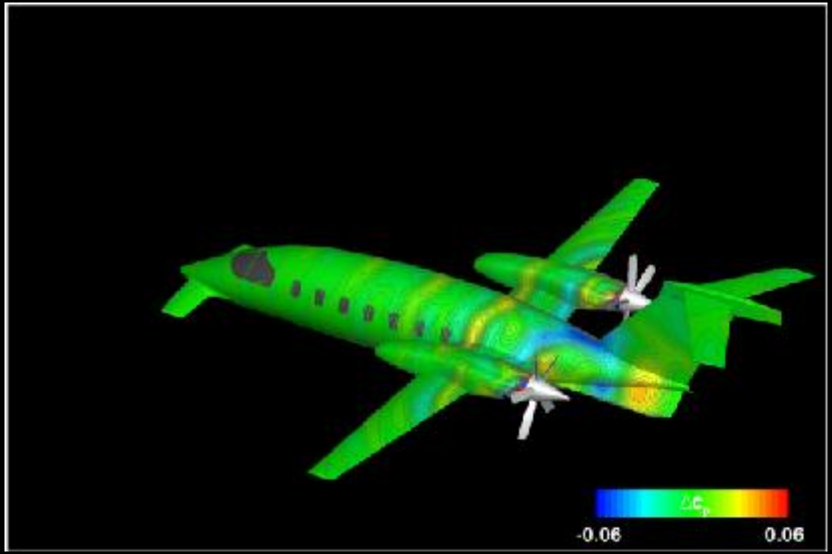
Aeroacoustic Analysis: Impermeable FW-H Approach

- Generally similar directivities as found for pFWH
  - Lower SPLs in rotor planes
  - Notable differences upstream
  - Reduced SPL difference between rotor and interaction tones near front rotor for iFWH
- Quadrupole noise seems to be an important factor at low-speed conditions
  - Increase noise levels in rotor plane directions
  - Reduced noise levels forward indicates mutual cancellation of noise sources
  - No downstream differences





Conclusions & Outlook



- Established process chain for coupled Hi-Fi TAU uRANS & aeroacoustic simulations with the DLR APSIM code allows for an in-depth analysis
- Better understanding of requirements for good quality data
- Many special considerations need to be adhered to on the CFD and CAA sides
  - WTT validation data necessary next step to clarify remaining uncertainties in numerical tools utilization for CROR analysis
- Topics not addressed:
  - Broadband noise!
  - Aeroelastics impact on blade loadings and noise!
- CFD-CAA-Potential for other important aspects:
  - Cabin noise
  - Structural fatigue