Numerical Analysis of CROR Propulsion System Aerodynamics & Aeroacoustics at DLR

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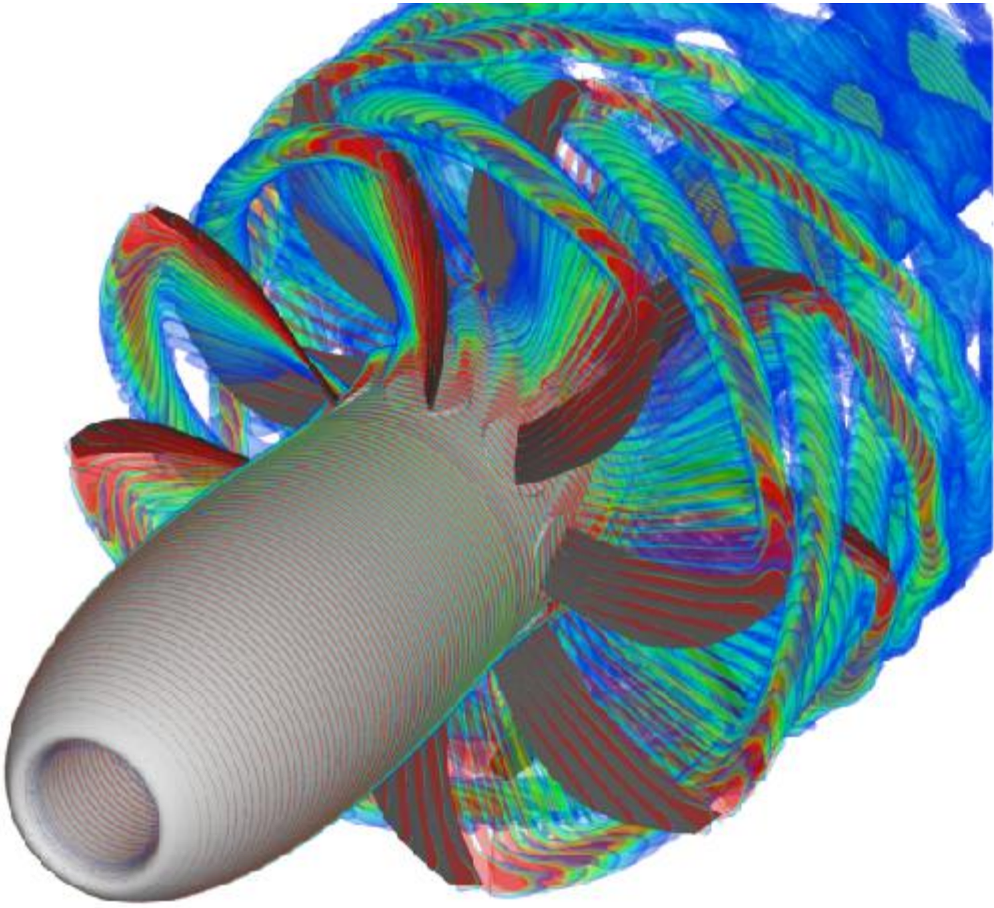

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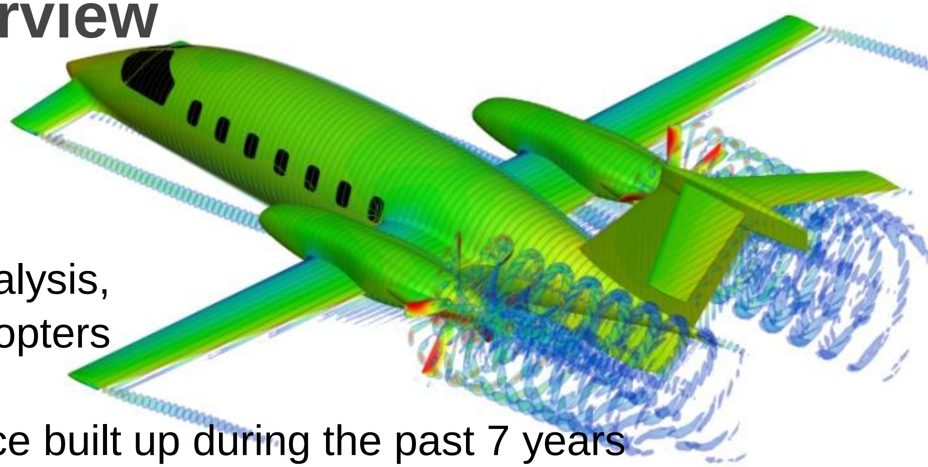
Overview

- Introduction and Motivation
- DLR-AS CROR Activities Overview
- Generic Research Geometry and Test Case Definition
- Aerodynamics & Aeroacoustics @ Low-Speed and High-Speed:
  - Numerical Tools and Approaches
  - Flow Physics Analysis and Comparison
- Conclusion and Outlook

Introduction and Motivation

- Cost of fuel has lead to a renaissance of the Contra-Rotating Open Rotor (CROR)
- Propfans studied in NASA/US Industry Advanced Turboprop Project (ATP)
  - Comprehensive research on aerodynamics and aeroacoustics, demonstrating significant efficiency benefits
  - Flight tests of prototype engines on McDonnell Douglas MD-80 and Boeing 727
  - Close to EIS in 1990s on proposed McDonnell Douglas MD-90XX & Boeing 7J7
  - Drop in fuel prices lead to waning of interest for airlines
- Concern about high fuel costs are back (‘08: 33% of TOC; ’98:9.4% of TOC)
- Installation, noise and certification issues still remain:
  - Modern methods could play vital role in realizing full potential of CRORs for EIS ~2020

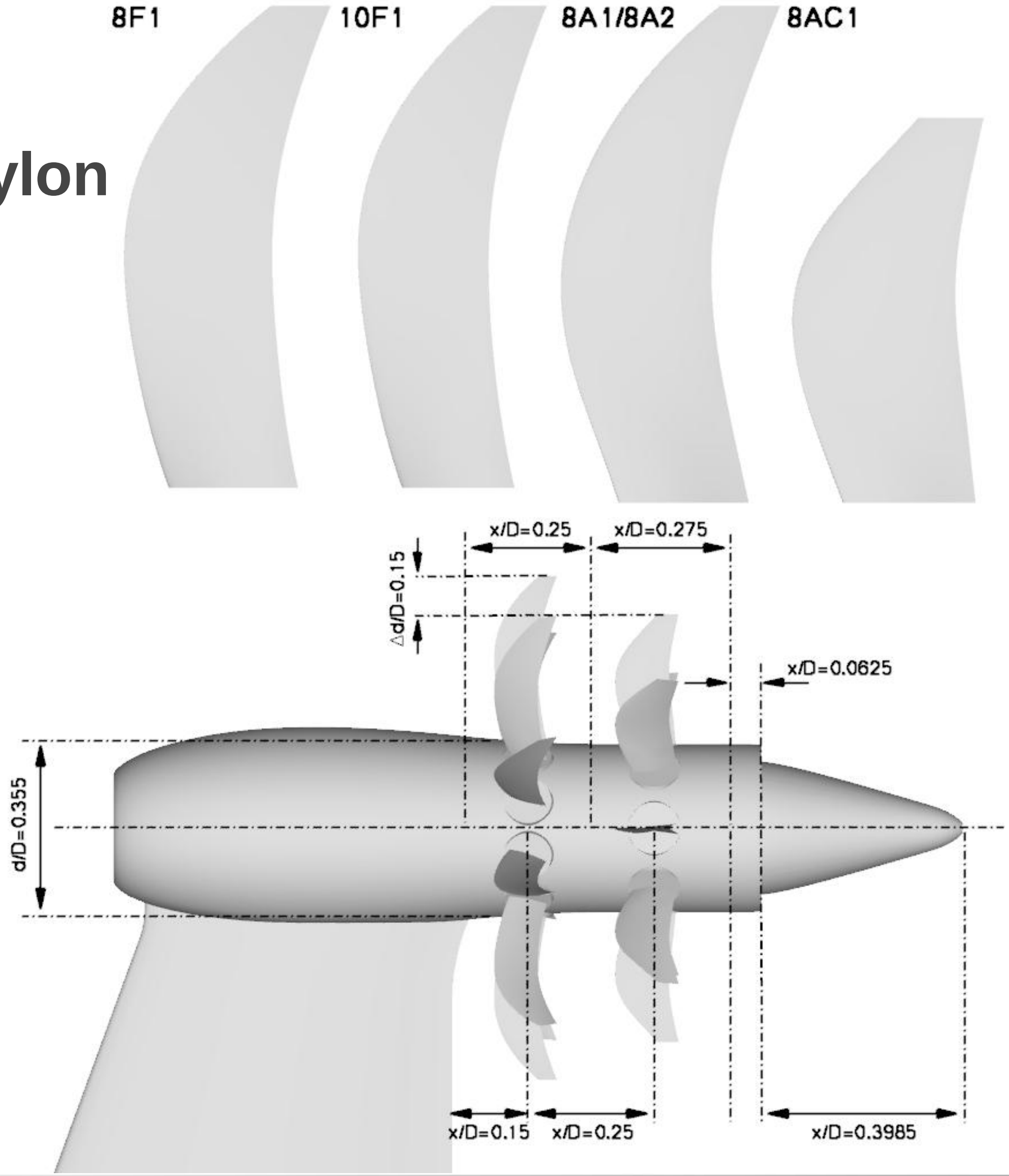
DLR CROR Activities Overview



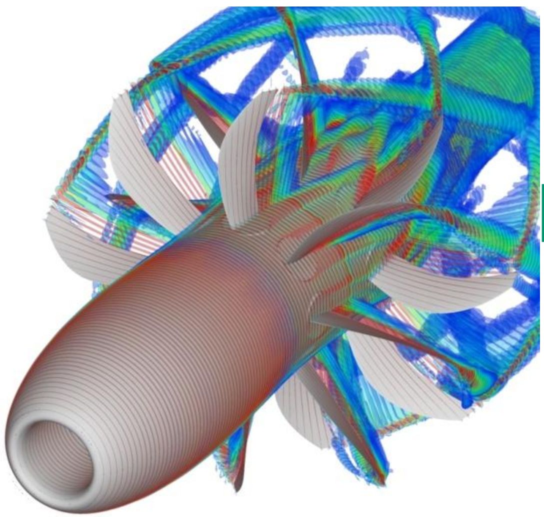
- History of experimental & numerical analysis, design & testing of propellers and helicopters
- DLR-AS CFD-based analysis experience built up during the past 7 years
  - Coupled CFD-CAA (TAU/APSIM) analysis process chain established
  - Cooperation with Industry on SRP-related topics
  - EU FP6 project CESAR (Cost Effective Small AiRcraft)
  - CROR activities since 2007
    - Generic studies based on in-house designed research configurations
    - Cooperation with & contract work for airframe and propulsion industrial partners
    - DLR-AT/AS involvement in EU FP7 project DREAM (valiDation of Radical Engine Architecture systeMs)
    - Associated Partner in CROR activities in JTI SFWA WP2.2
    - Partnership with industry in nationally funded projects

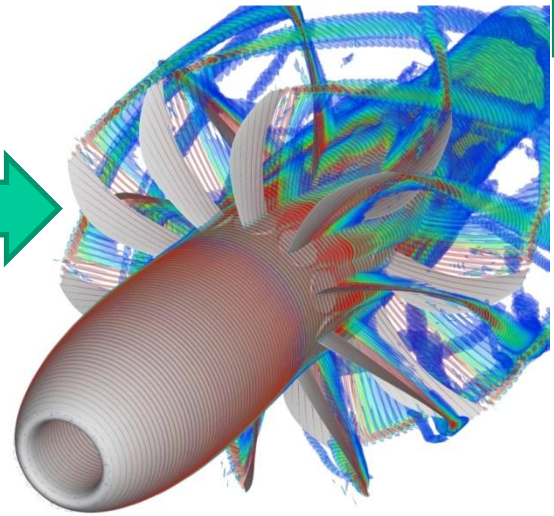
Research Geometry: Sizing, Nacelle and Pylon

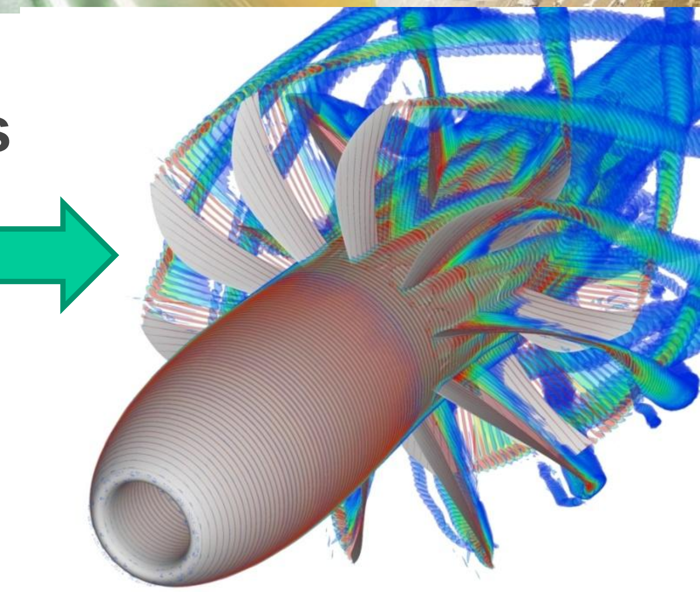
- Generic CROR to test and mature numerical methods and approaches and improve understanding
- Sized for 150-seat aircraft:
    - TO-thrust ~88kN
    - Cruise thrust ~19kN
- D=14ft/4.2672m propeller
- Family of blade designs
    - 8- & 10-blade front rotor
    - 14ft & 11.9ft 8-blade aft rotor
    - Generic pylon
- CATIA V5-CAD model and mesh generation setup for flexibility in terms of configuration variations

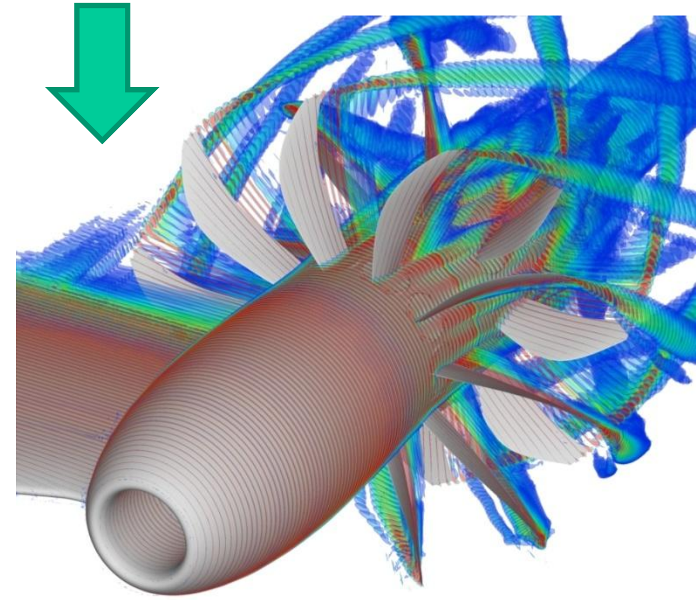


Systematic Configuration Studies







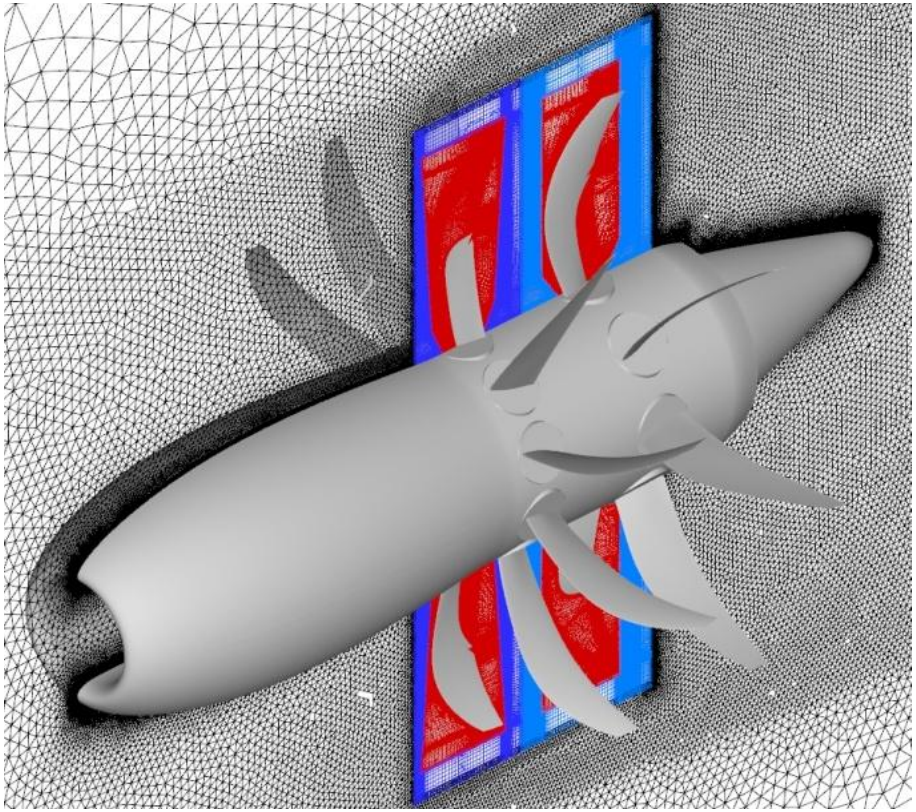


- Investigation of configuration impact on performance and noise
- Blade number variation: 8x8 to 10x8
- Aft rotor diameter reduction to eliminate tip vortex impingement
- Addition of pylon to investigate installation effect impact
- Representative performance levels:

Cruise Performance of 10F2x8AC1 CROR M=0.75 @ h=35,000ft; J_1=3.678, J_2=4.203			
	Rotor 1	**Rotor 2**	**Total**
F_x [N]	10,566	8,424	18,990
η [%]	79.72	91.98	85.85

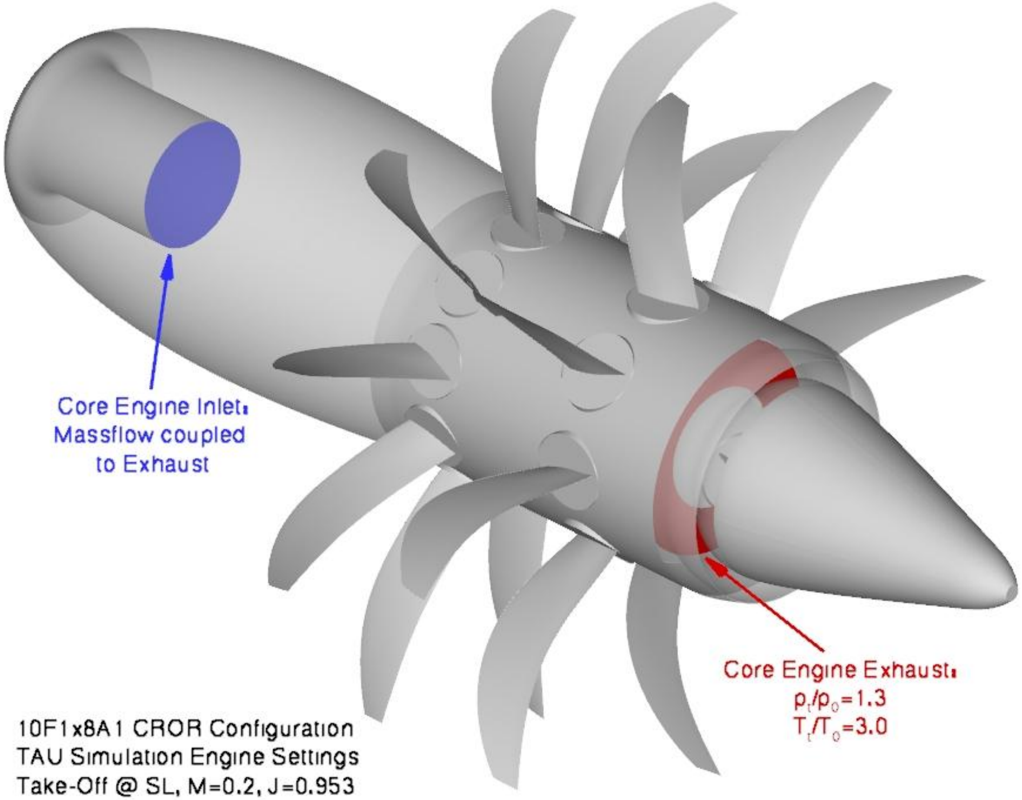
Numerical Approach: Geometry & Mesh Generation

- Unstructured/structured mesh generation with CentaurSoft Centaur and ICEM CFD HEXA
- 19-21 mesh blocks used to fully exploit flexibility of Chimera approach
- Hub PCM geometry introduced to allow flexible adjustment of blade pitch angles
- Special care taken @ Chimera boundaries and for viscous sublayer resolution
- Rotor Chimera boundary can serve as interface to aeroacoustic tools
- Total mesh sizes ~45, 000,000 nodes



Test Case Definition: Low-Speed Cases

- Take-Off @ SL and M=0.2, α=0º
- Identical propeller rotational speeds
- TAU engine boundary condition to simulate realistic inlet and jet flows
- Blade settings for a 50:50 power split



	Core engine exhaust		$n_1=n_2$ [rpm]	$J_1=J_2$	$\beta_{75,R1}$ [°]	$\beta_{75,R2}$ [°]
	p_t/p_0	T_t/T_0				
8F1x8A1	1.3	3.0	1029	0.953	37.6	36.25
10F1x8A1	1.3	3.0	1029	0.953	36.5	36.15

The DLR TAU-Code
Code Description and Simulation Approach

- Unstructured finite volume Euler/RANS-flow solver
- All standard state-of-the-art CFD techniques available:
  - Central and upwind schemes for spatial discretization
  - Scalar or Matrix dissipation
  - Multistage Runge-Kutta time-stepping, LUSGS
  - Convergence acceleration through MG, residual smoothing, local time-steps
  - 1- and 2-equation turbulence models (SAE,k-ω SST)
- Chimera grid approach & extensive motion libraries for rotating propeller computations
- Dual time stepping scheme for unsteady computations
- Efficiently parallelized for fast-turn around times through distributed computing

- Typically ~6 rotor revolutions computed on 256-384 CPUs of DLR $C^2A^2S^2E$-cluster
- Runtime ~ 14-21 days wallclock

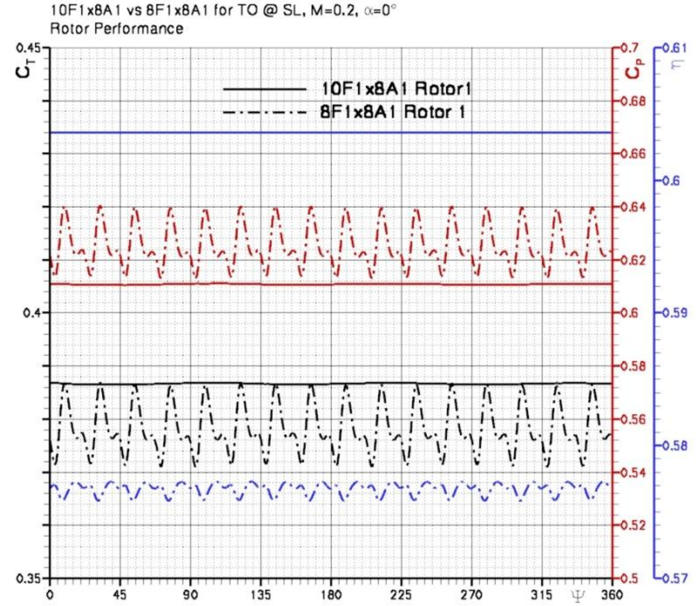
Rotor Performance

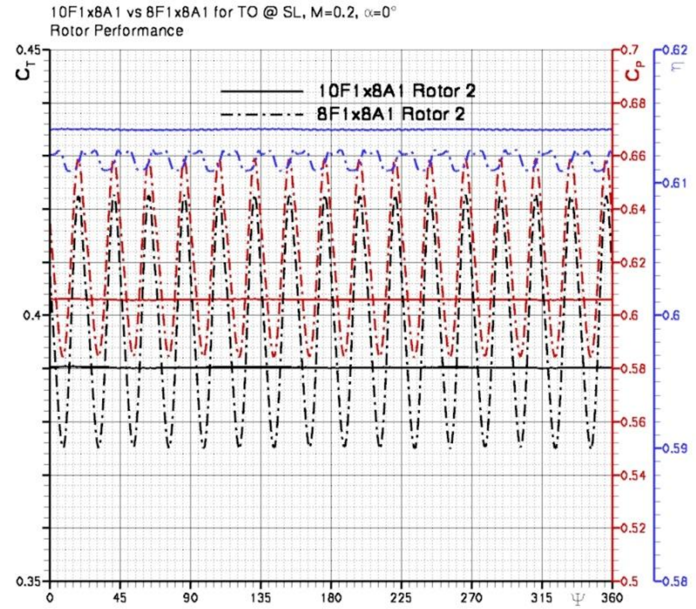
	8F1x8A1			10F1x8A1		
	Rotor 1	**Rotor 2**	**Total**	**Rotor 1**	**Rotor 2**	**Total**
F_x [N]	42,994	45,233	88,226	43,952	44,357	88,309
C_T	0.3782	0.3979	-	0.3867	0.3902	-
C_P	0.6253	0.6203	-	0.6108	0.6059	-
η [%]	57.67	61.17	59.42	60.36	61.39	60.88

- 8x8 CROR shows 16/32 cycle oscillations in rotor loads
- F_x=88.226 kN; $C_{T,1}/C_{T,2}$=0.9523; $C_{P,1}/C_{P,2}$=1.0042
- Larger amplitudes in aft rotor
- 50:50 power split leads to higher aft rotor thrust
- Better efficiency in aft rotor

- 10x8 configuration has constant rotor loads
- F_x=88.309 kN; $C_{T,1}/C_{T,2}$=0.9909; $C_{P,1}/C_{P,2}$=1.0017

- 10x8 more thrust for rotor 1, less for rotor 2 than 8x8
- 10x8 less power for rotor 1 and rotor 2





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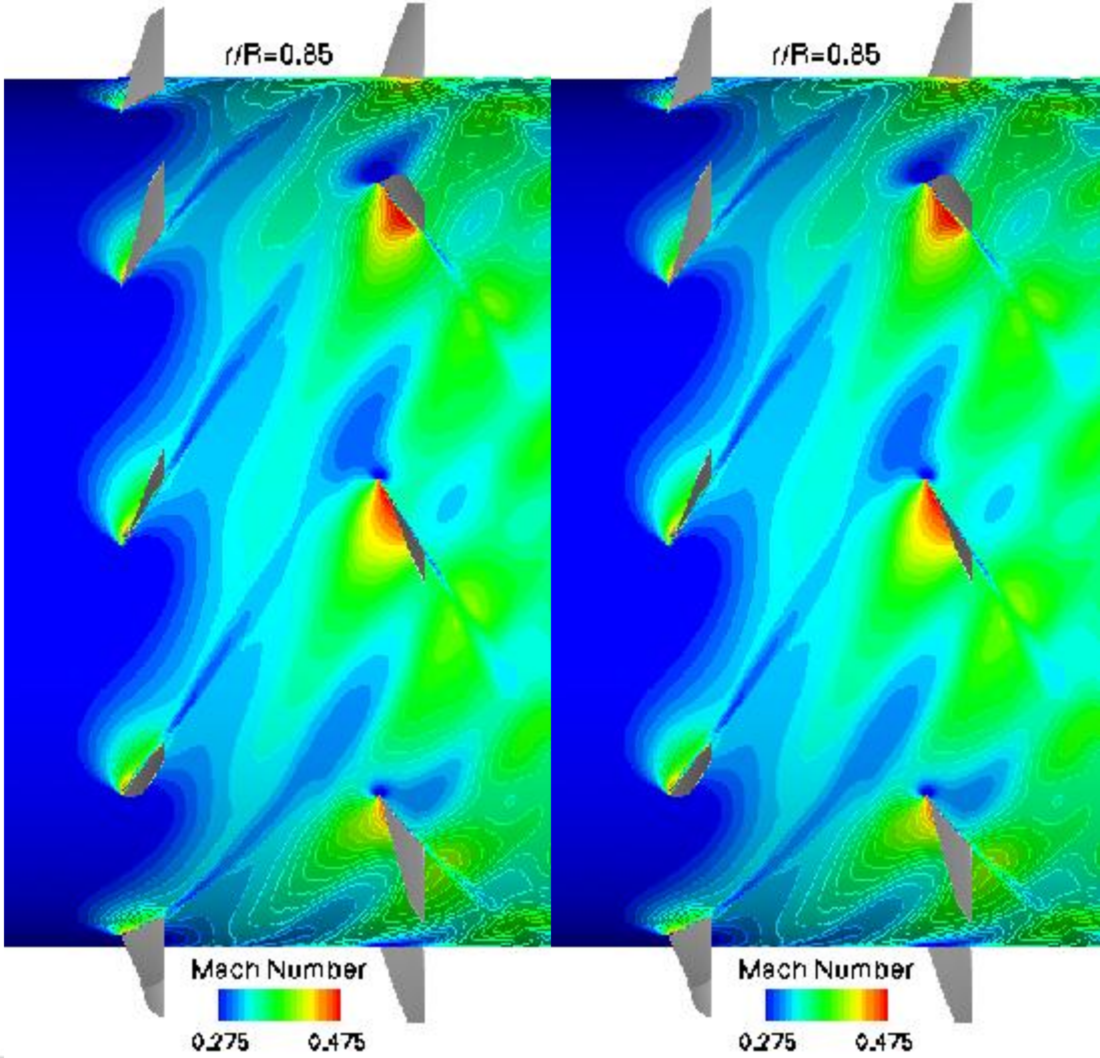
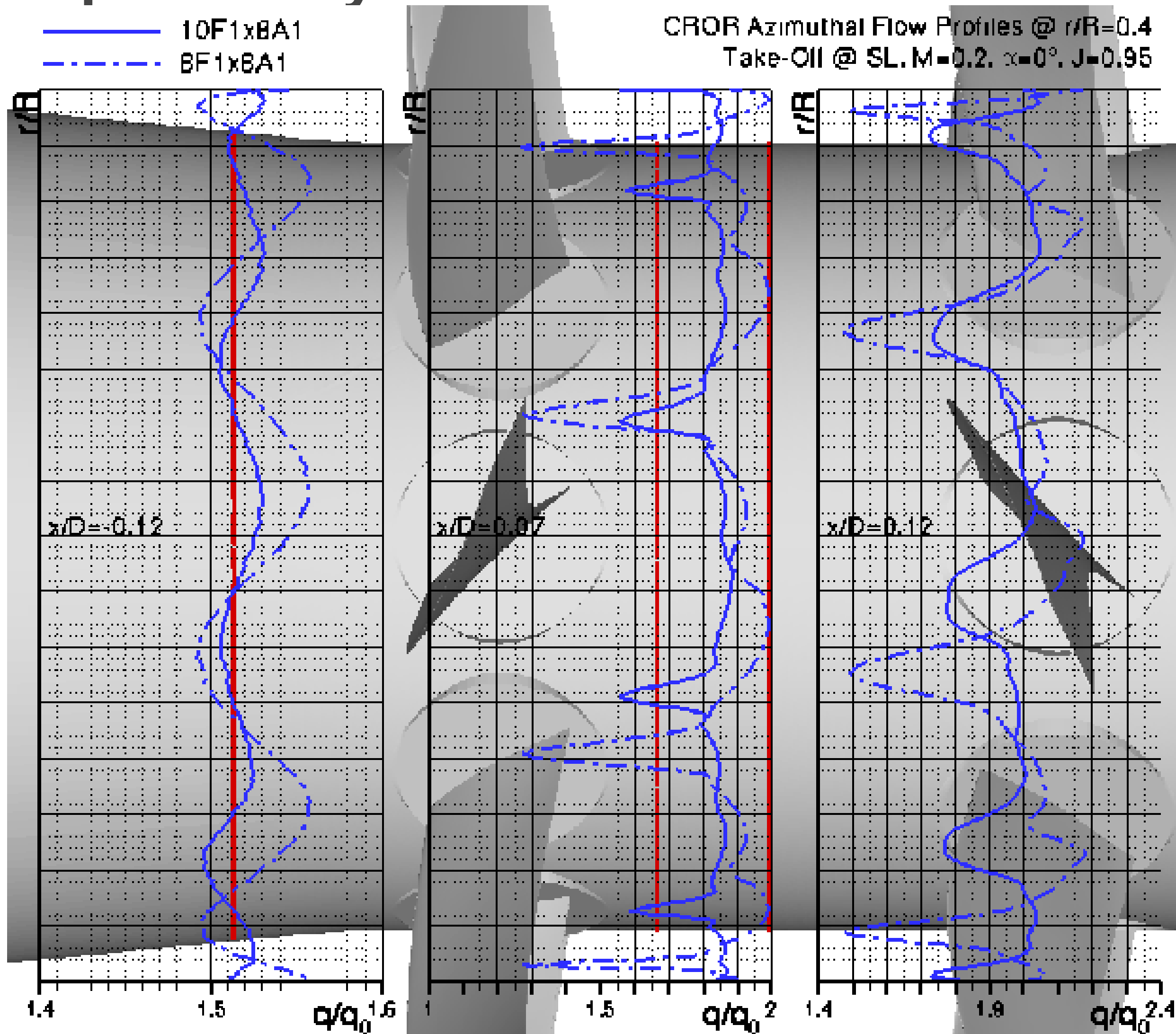
Slipstream Development: Blade Wakes @ r/R=0.85 10x8 CROR

- Strong blade wakes, quite well resolved in simulations
- Good functionality of Chimera boundary condition, with smooth transition of contour lines (blade-rotor, rotor-rotor, rotor-nacelle)
- Mutual interactions between rotors:
  - Aft blades influenced by forward rotor blade wakes
  - Aft blade wakes interact with “sliced” forward blades wakes
  - 16-cycle oscillations seen on forward blades pressure side Mach number distributions
  - Small Mach number fluctuations upstream of front rotor



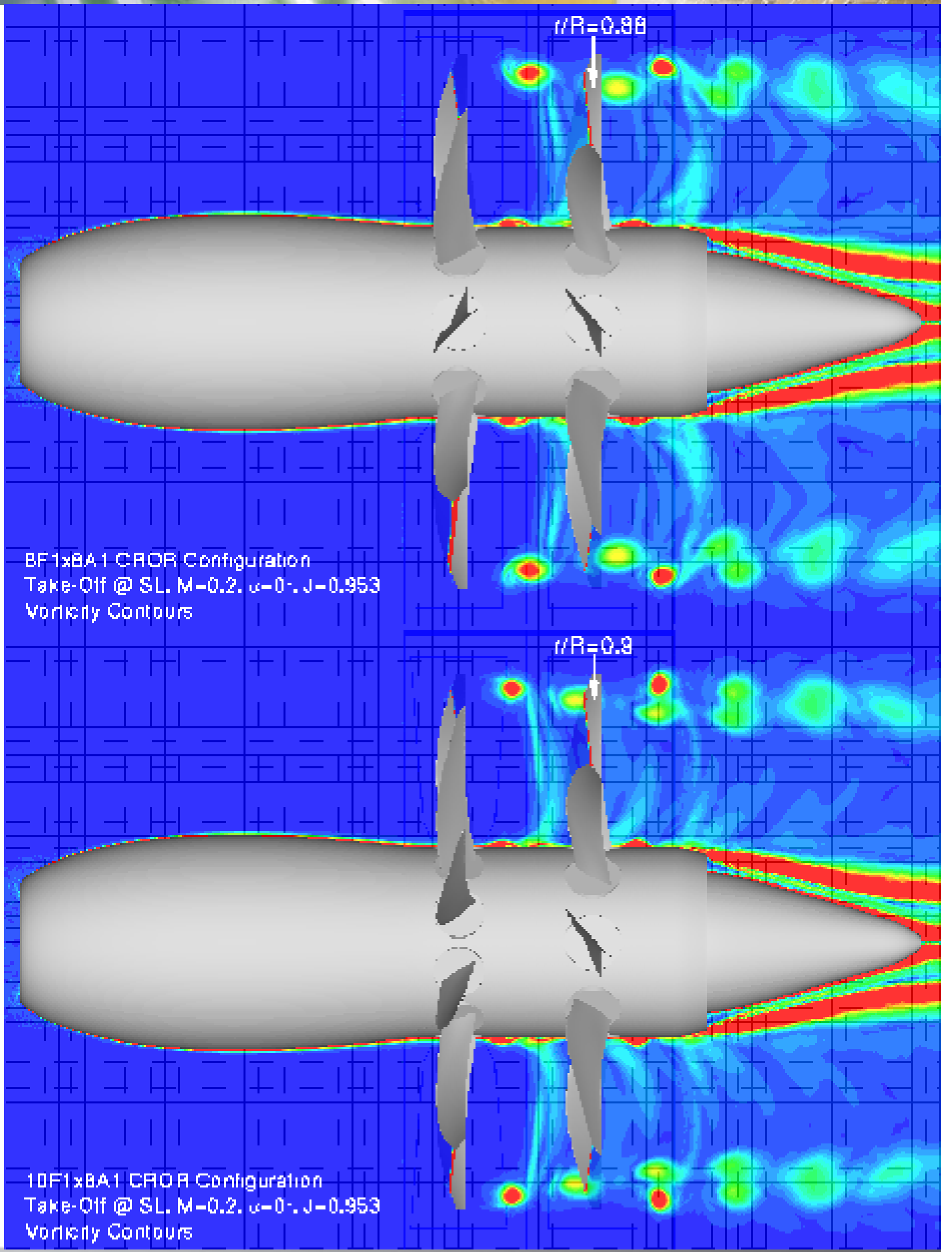
Slipstream Development: Dynamic Pressure Profiles

- 3 axial wake profiles at r/R=0.4
- Dynamic pressure increases after first and second rotor
- R1 Blade wakes:
  - Stronger for 8x8 CROR
- R1 potential flow:
  - Stronger for 8x8 CROR
- R2 potential flow seen in fluctuation of wake profiles
- Two important sources of interaction tone generations



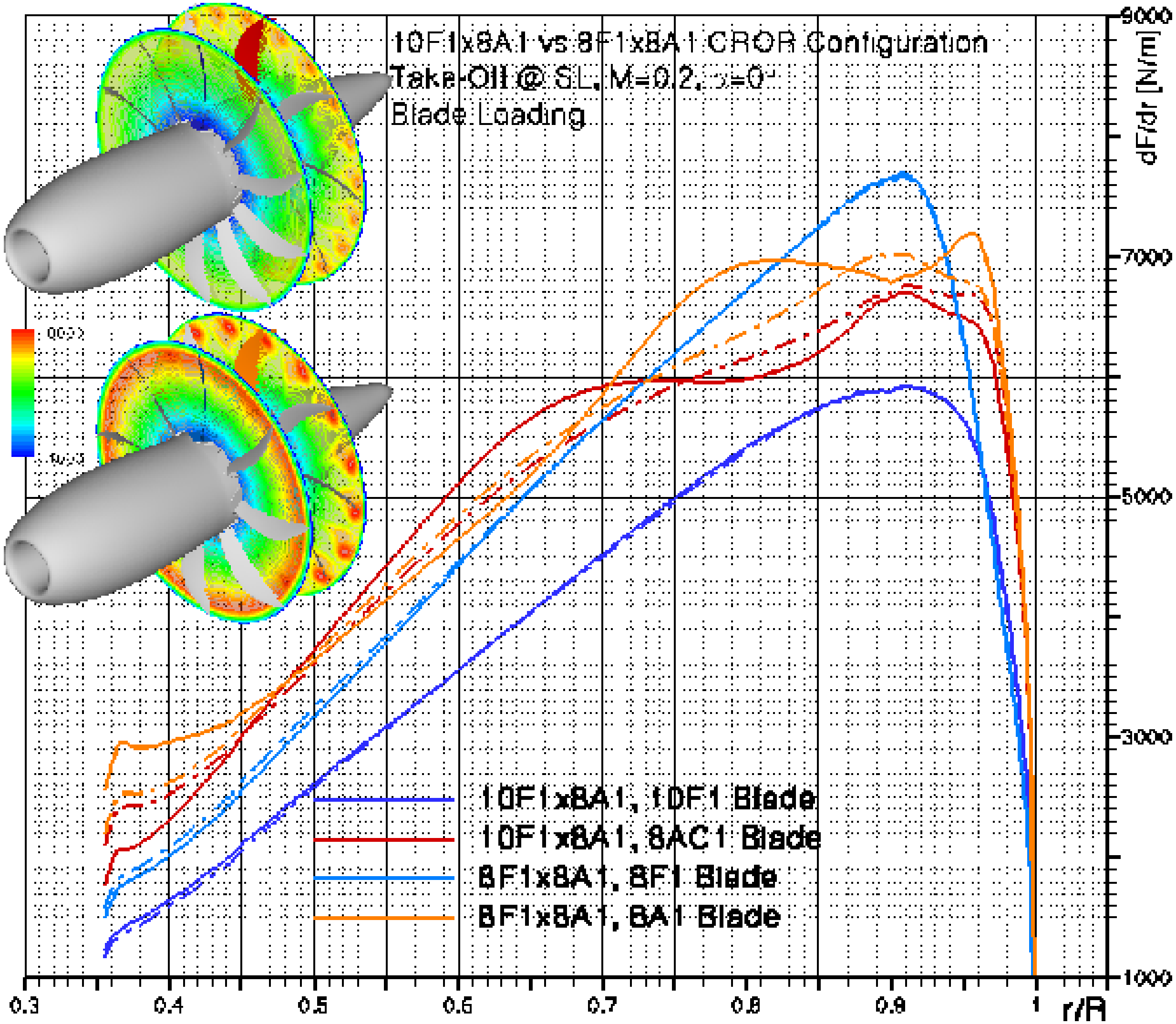
Slipstream Development: Tip Vortex Trajectory

- Investigation of front rotor tip vortex impact on aft rotor blades on noise emissions
- Comparison of vortex track for 10F1x8A1 & 8F1x8A1 CROR:
  - Stronger front rotor slipstream contraction for the 8x8 CROR due to higher blade loadings
  - Vortex impact on aft rotor occurs @ r/R=0.9 for 10x8 and r/R=0.88 for 8x8
- Guide for blade design of reduced diameter aft rotor
  - 8AC1-blade has a 15%-crop in diameter



Blade Load Distributions: 8F1x8A1 vs 10F1x8A1 CROR

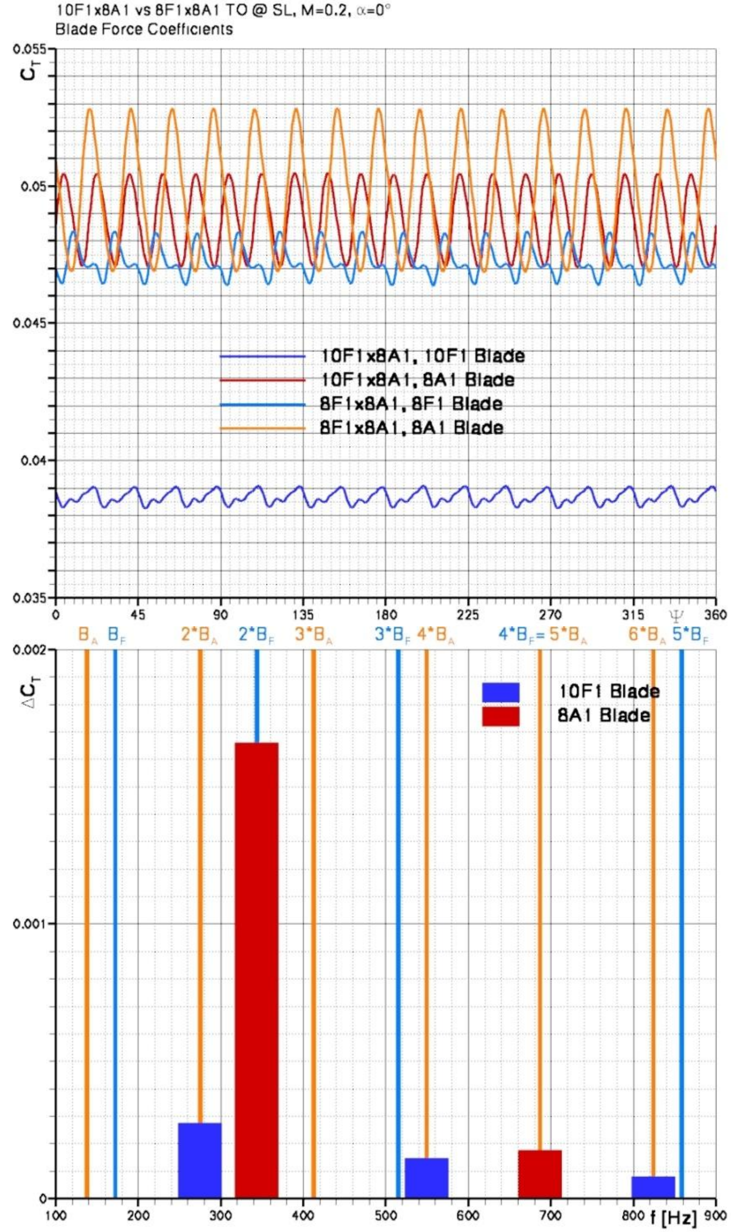
- Different blade load distributions , higher in R2 in each case
- Blades more highly loaded for 8F1x8A1
- Blades show force oscillations linked to rotor-rotor blade passage
- Front blade wakes lead to full spanwise fluctuations on aft blades (pronounced at hub and tip)
- Rotor 1 blade shows smaller oscillations
- Tip vortex impact on aft blades is dominant



Blade Force Development
Low-Speed Conditions

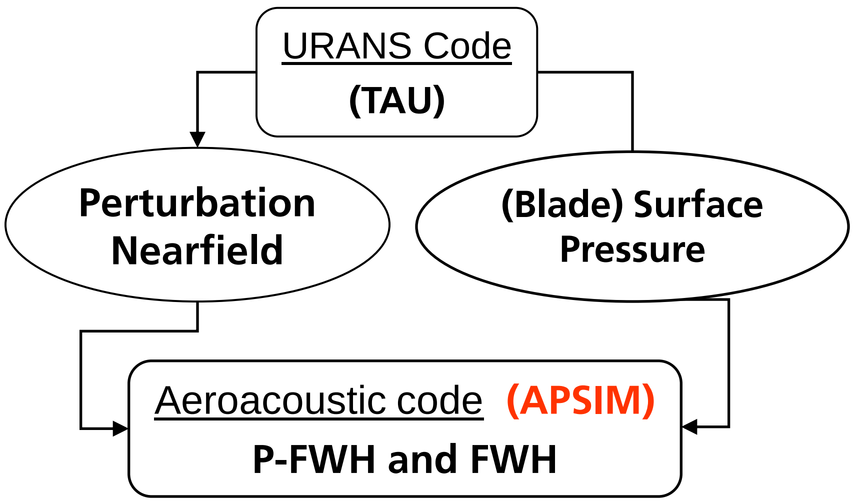
- Higher blade thrust loadings in both rotors for the 8x8 configuration
- Higher aft blade loadings in each case
- Fluctuation amplitudes for aft blades more pronounced
- 8x8 fluctuation amplitudes greater
- Aft blades shows 16/20-cycle fluctuations (i.e. $2*B_F$)
- Front blades shows 16/32 cycle oscillations (i.e. $2*B_A$ and $4*B_A$)

- FFT Analysis of blade thrust loading:
  - Dominant $2*B_F$ fluctuations for aft blades
  - Importance of higher harmonic thrust oscillations of front blades

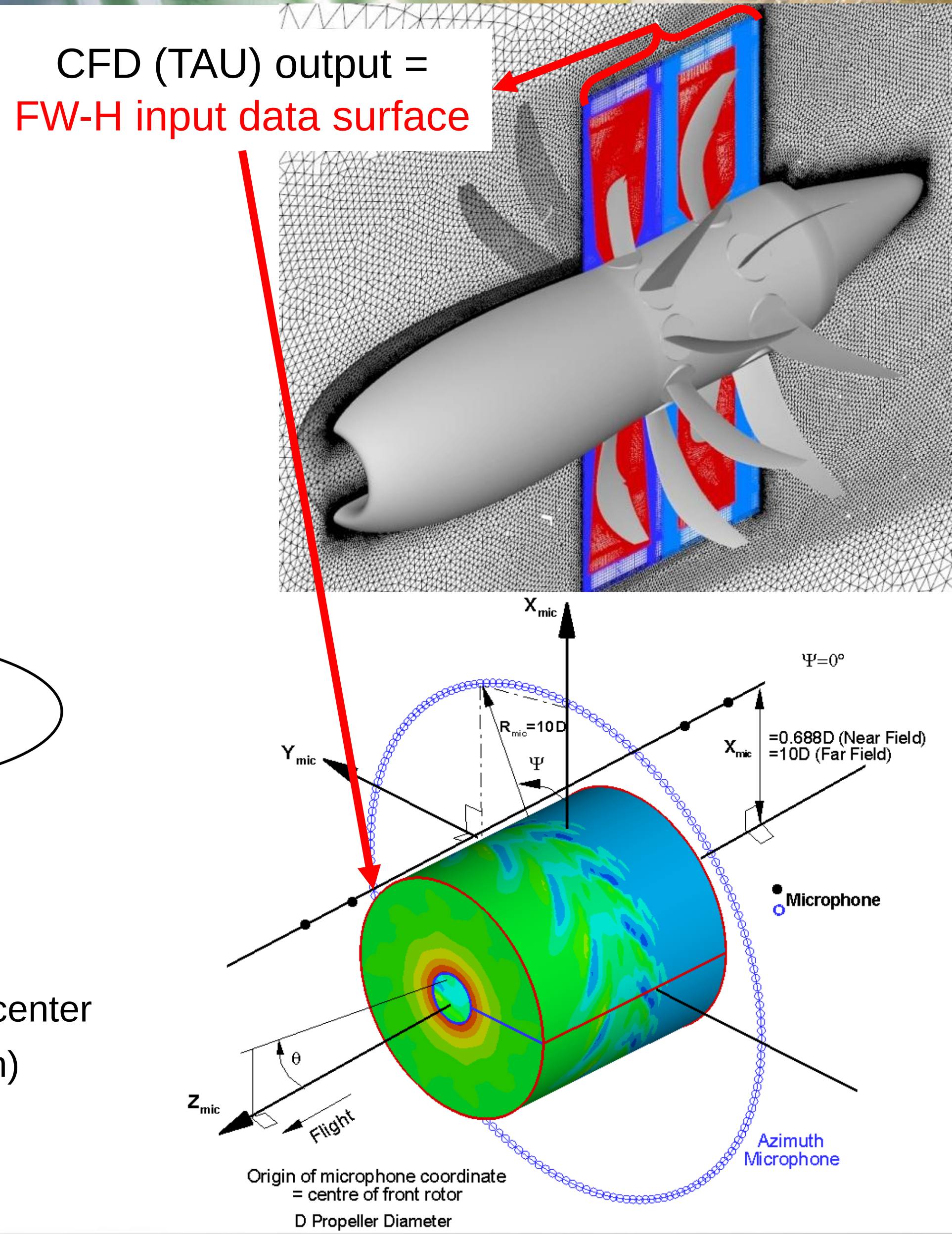


Aeroacoustic Analysis: Tools & Approach

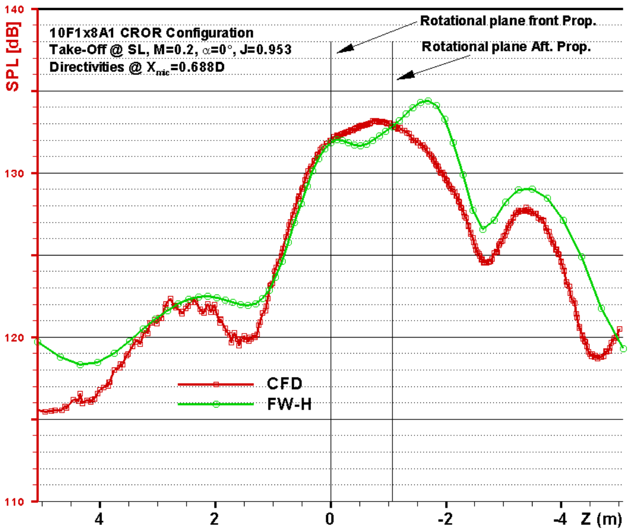
- Noise radiation analysis using APSIM (Acoustic Prediction System based on Integral Method)
  - Rotor & Propeller Noise
  - Permeable or Impermeable FW-H

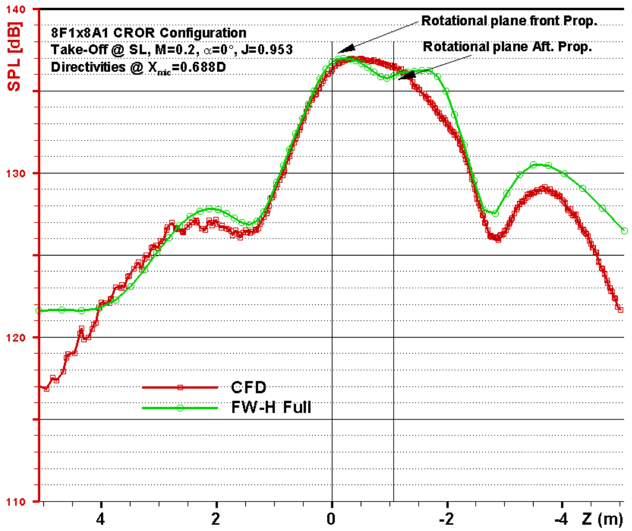


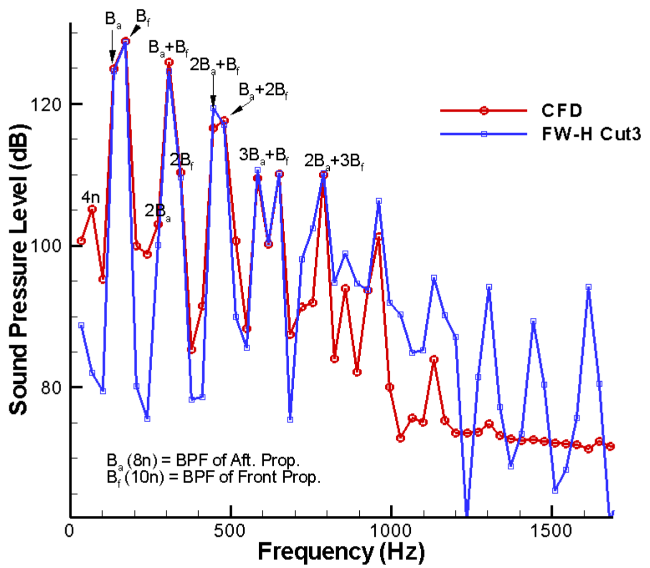
- Virtual microphones oriented around front prop center
- Nearfield mic array @ x/D=0.688 (~ pylon length)
- Farfield virtual mic array @ x/D=10
- Farfield azimuthal mic array @ r/D=10



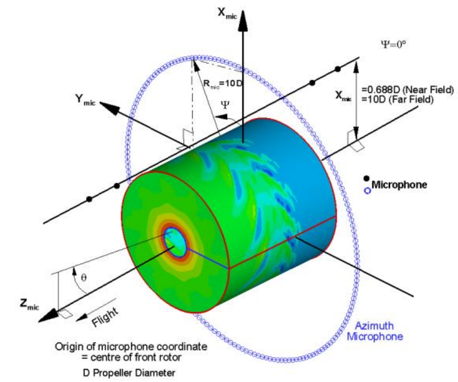
Aeroacoustic Analysis: Permeable FW-H Approach
Nearfield Noise Radiation @ LS







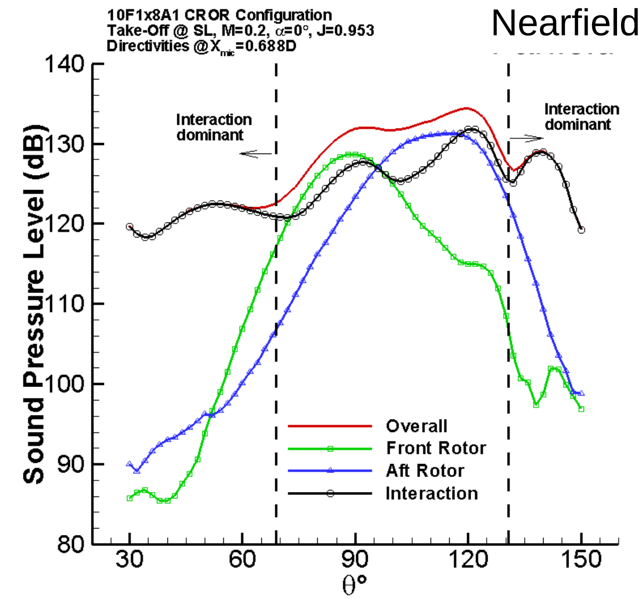
- Characteristic noise radiation signature known from literature
  - Max. noise due to rotor-alone tones near rotor planes (mono- & dipole)
  - Slightly higher noise near aft rotor due to higher loading & interactions
  - ~5dB peak noise difference between 10x8 and 8x8 configuration
- Front rotor plane spectrum:
  - Good match between FW-H and CFD for f<800Hz
  - Strong rotor fundamental tones and 1st & 2nd order interaction tones

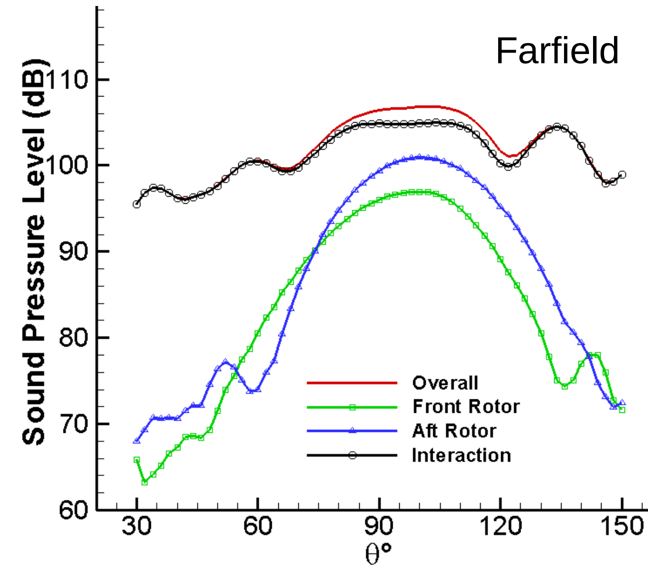


Aeroacoustic Analysis @ LS
Near- & Farfield Noise Radiation

- Highest noise levels for both configurations in vicinity of rotor planes, with peaks closest to aft rotor
- Noise levels higher for 8x8 at most microphone locations

- 10x8 near-field directivity decomposition:
  - Rotor tones dominate in vicinity of planes of rotation
  - Interaction tones very important for polar angles towards the rotational axis
- 10x8 far-field directivity decomposition:
  - Interaction tones are major noise source
  - Rotor tone levels in farfield reduced more notably than interactions tones





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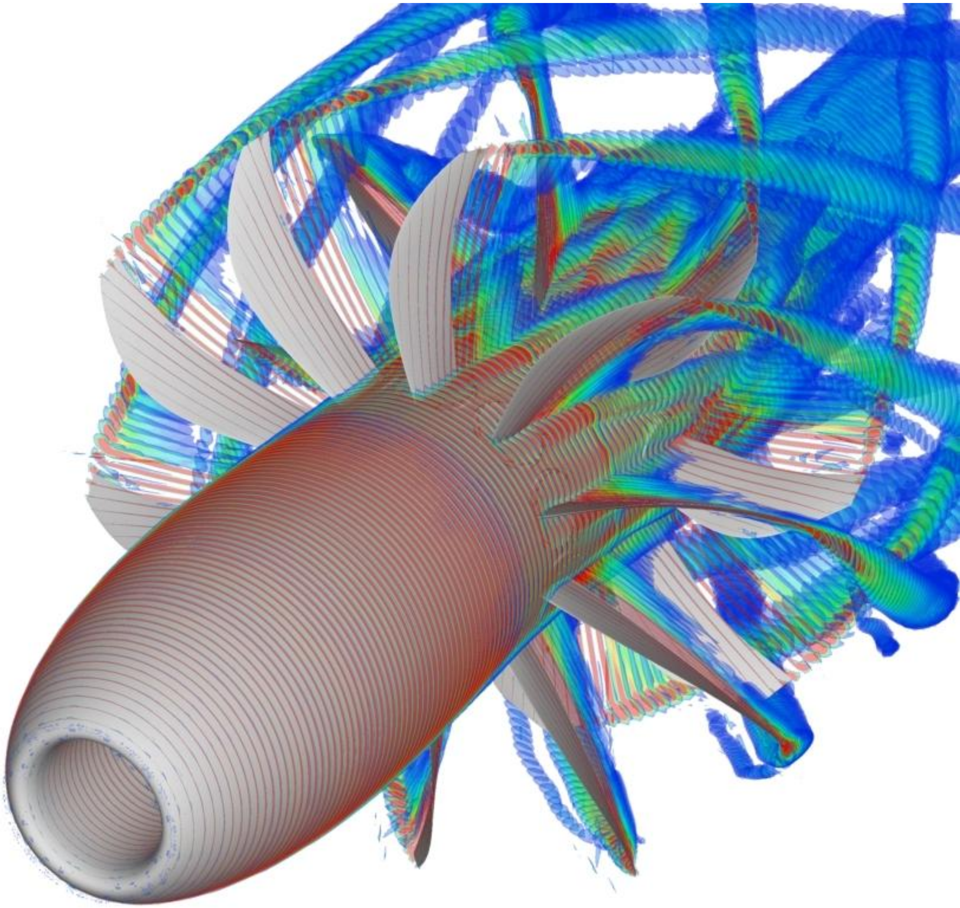

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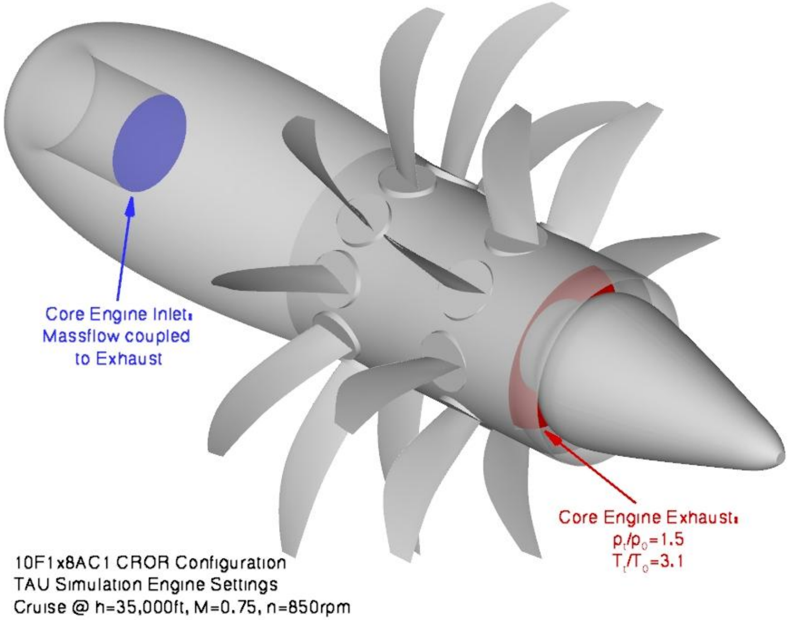
Test Case Definition: Cruise

- Cruise @ h=35,000ft, M=0.75 & α=0º
- Identical propeller rotational speeds
- TAU engine boundary condition to simulate realistic inlet and jet flows
- Blade settings for an equal blade power absorption for the 10F1x8A2 configuration (i.e. power split of 1.25:1/56:44), identical disc power loading for the 10F2x8AC1 (1.45:1/x59:41)

- 10F2x8AC1 CROR:
  - F_x=18.990 kN
  - $C_{P,1}/C_{P,2}$=1.4471
- 10F1x8A2 CROR:
  - F_x=19.103 kN
  - $C_{P,1}/C_{P,2}$=1.2488

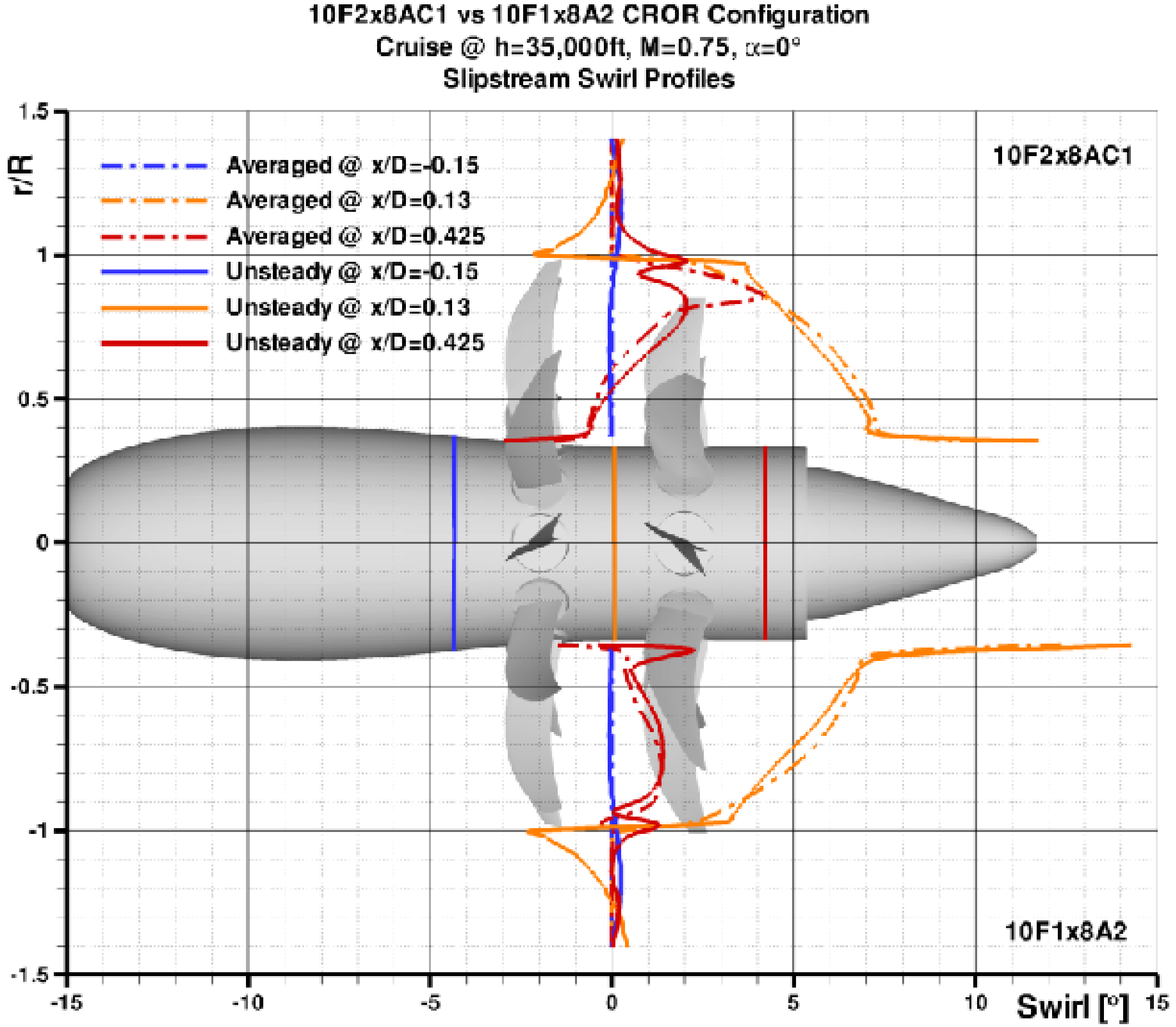


	Core engine		$n_1=n_2$ [rpm]	J_1	J_2	$\beta_{75,R1}$ [°]	$\beta_{75,R2}$ [°]
	p_t/p_0	T_t/T_0					
10F1x8A2	1.5	3.1	850	3.678	3.678	61.95	58
10F2x8AC1	1.5	3.1	850	3.678	4.327	61.95	63.05

	10F1x8A2			10F2x8AC1		
	Rotor 1	Rotor 2	Total	Rotor 1	Rotor 2	Total
F_x [N]	9,972	9,131	19,103	10,566	8,424	18,990
C_T	0.3934	0.3603	-	0.4169	0.6368	-
C_P	1.8381	1.4719	-	1.9235	1.1031	-
η [%]	78.73	90.03	84,38	79.72	91.98	85.85

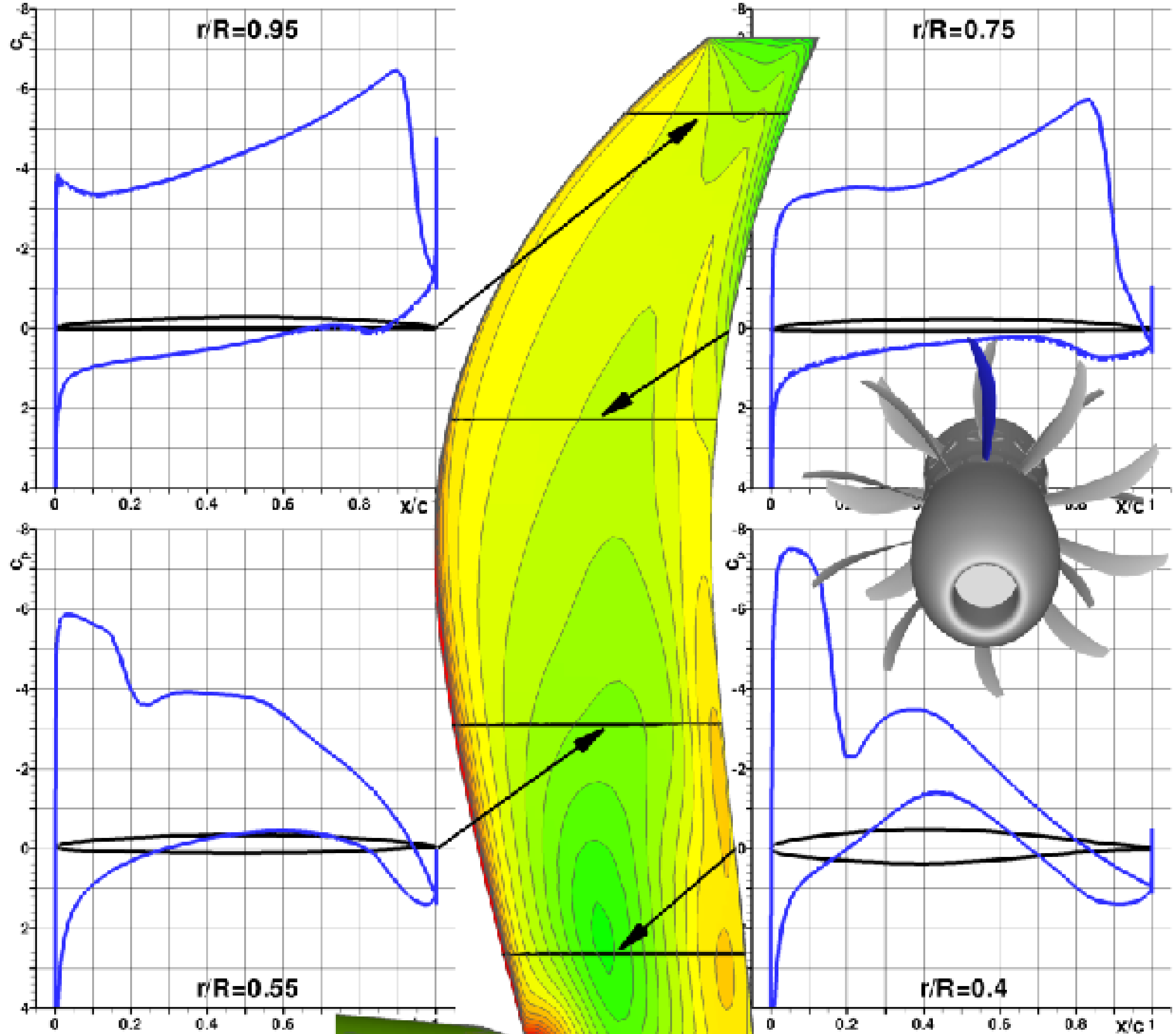
Slipstream Development: Swirl Recovery

- Comparison of swirl for 10F2x8AC1 & 10F1x8A2 CROR:
  - Good swirl recovery for both configurations
  - Similar front rotor loadings result in similar slipstream swirl distribution
  - Cropped aft blade “misses” tip swirl recovery



Blade Pressure Distributions 10F2x8AC1

- Front blade is affected by aft blade potential flow field
- Notable pressure fluctuation visible on pressure side, in particular near the tip
- Full span transonic flow on blade suction side
  - Shock @ x/c~0.2 near the root
  - Shock near TE towards the tip
  - No notable impact of unsteady blade-blade interactions on front rotor transonic flow (shock strength & location constant)



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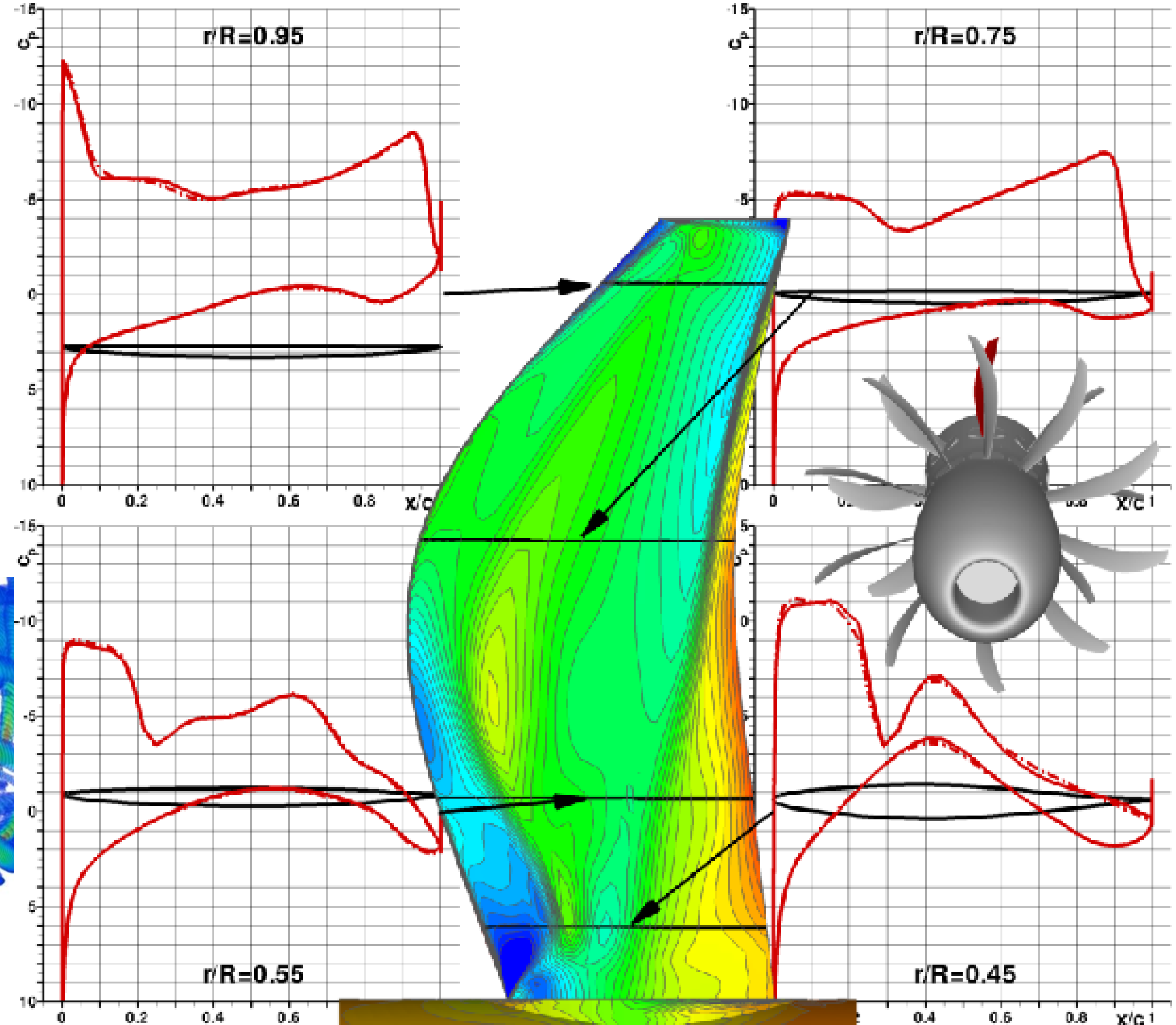
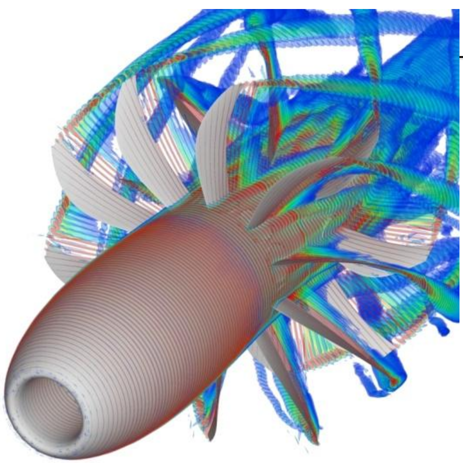
Blade Pressure Distributions
10F2x8AC1

- Aft blade is strongly affected by front rotor blade wakes
- Pressure and suction side show 20-cycle oscillations
- Apparent residual influence of front rotor tip vortex passage over blade tip
- Strong hub fluctuations due to PCM/blade root vortex



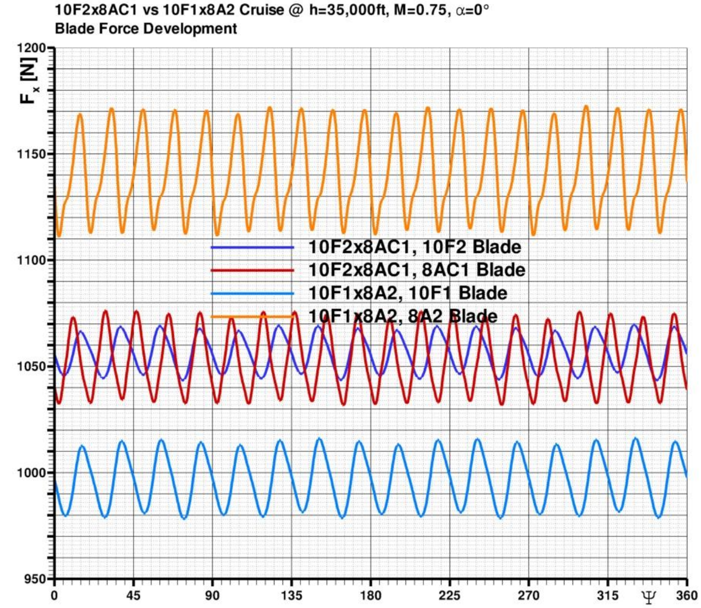


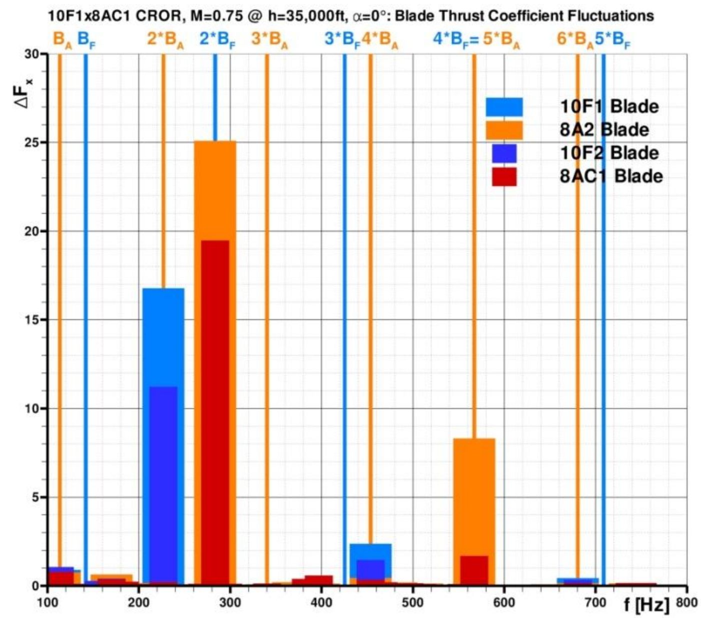
Blade Force Development
Cruise Conditions

- Fluctuation amplitudes for aft blades more pronounced in each case
  - Larger amplitudes for 10F1x8A2 CROR due to tip vortex impingement

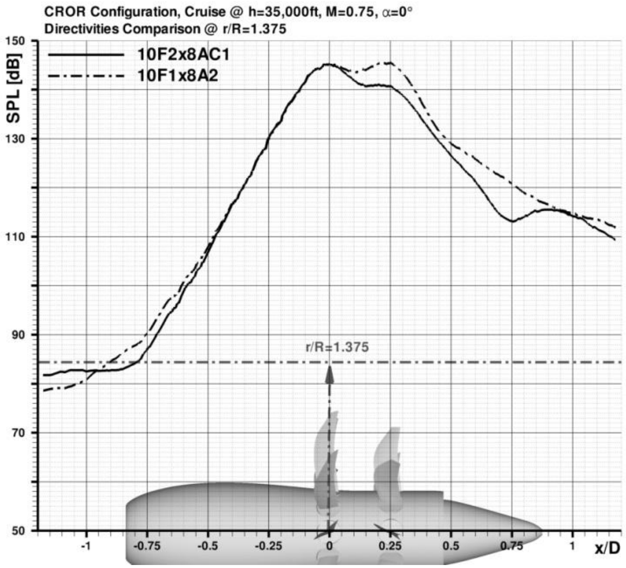
- Aft blades show 20-cycle fluctuations, i.e. @ 2*B_F
  - Larger amplitudes for 10F1x8A2 CROR due to tip vortex impingement

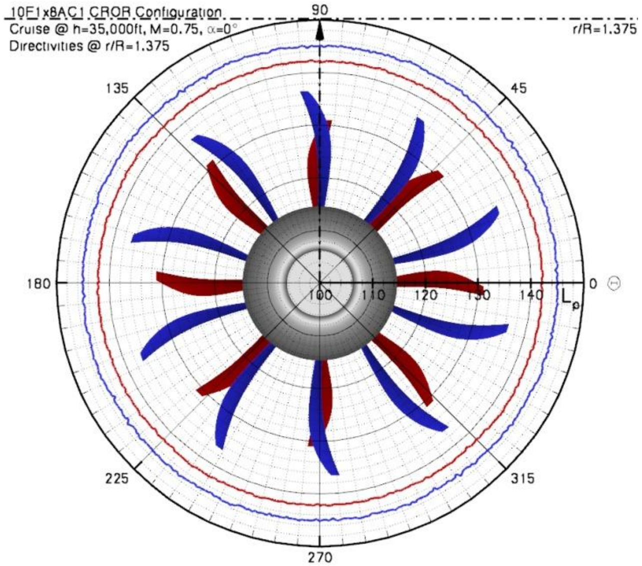
- Front blades show 16-cycle oscillations, i.e. @ 2*B_A
  - Slightly larger amplitudes for 10F1x8A2 CROR due to full-span potential flow impact of aft rotor blades

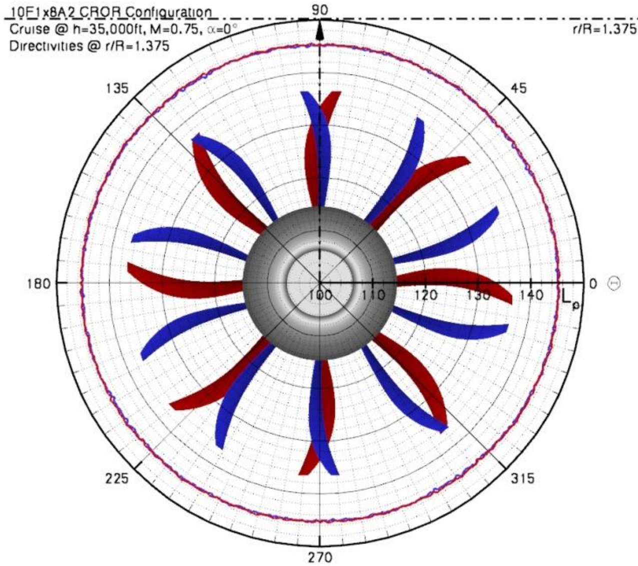




Aeroacoustic Analysis:
Nearfield Directivities

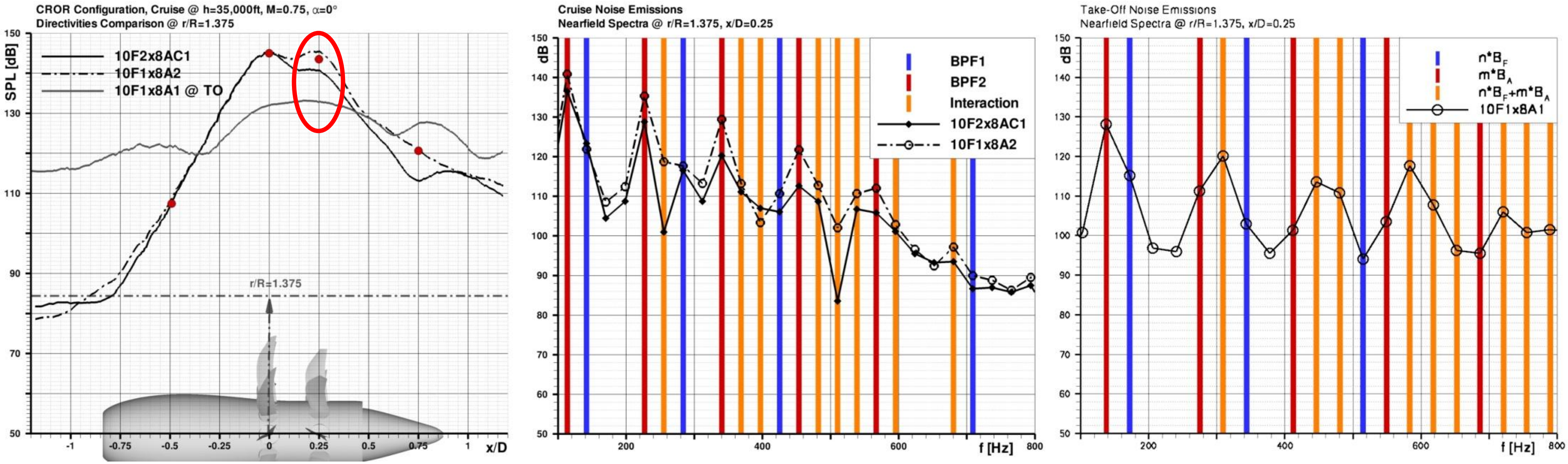






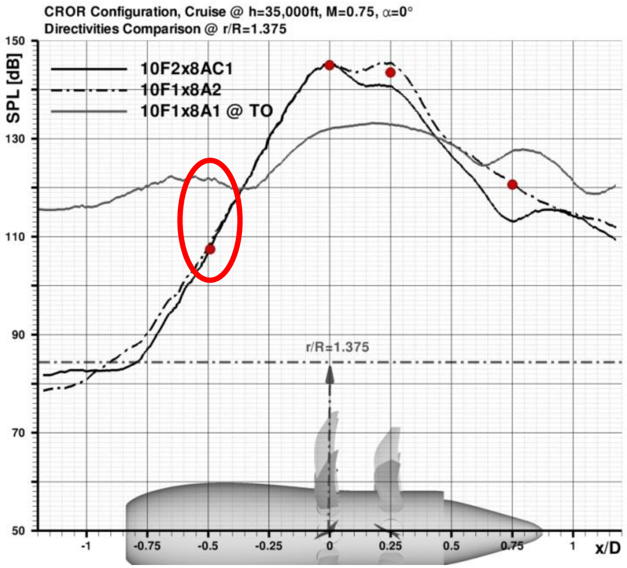
- Front rotor plane shows similar OASPLs for both configurations
  - Mean loadings near-identical → Mono- and di-pole noise similar
  - Only small differences in unsteady loadings → Unsteady loading noise similar
- Slightly higher OASPLs for 10F1x8A2 CROR in aft rotor plane
  - Unsteady loading noise dominates steady loading noise

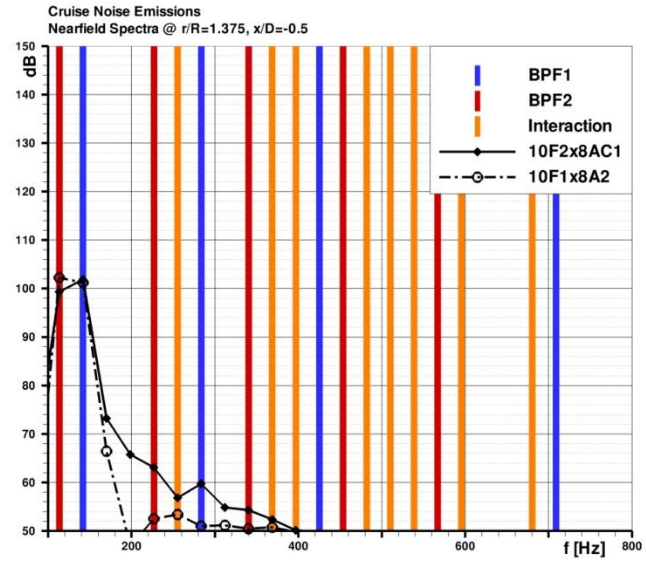
Aeroacoustic Analysis:
Nearfield Noise Spectra @ x/D=0.25

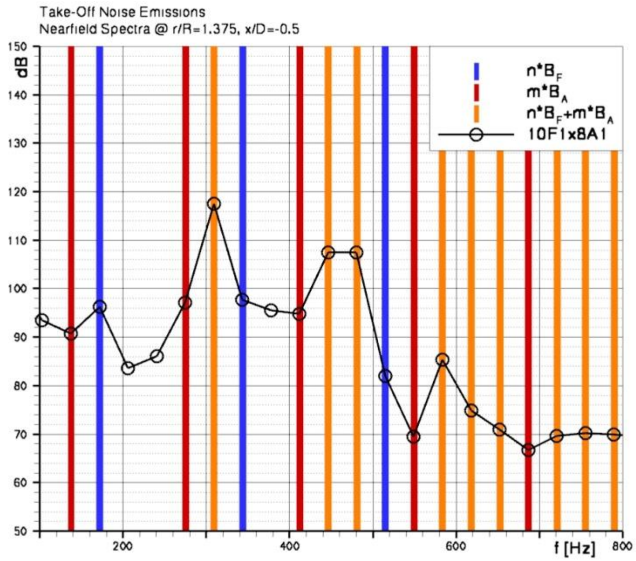


- Aft rotor plane noise emissions dominated by B_A and its higher harmonics
  - Slightly higher SPL @ $n*B_A$ for 10F1x8A2
- At low-speed conditions spectrum in the aft rotor plane also shows importance of interaction tones

Aeroacoustic Analysis:
Nearfield Noise Spectra @ x/D=-0.5



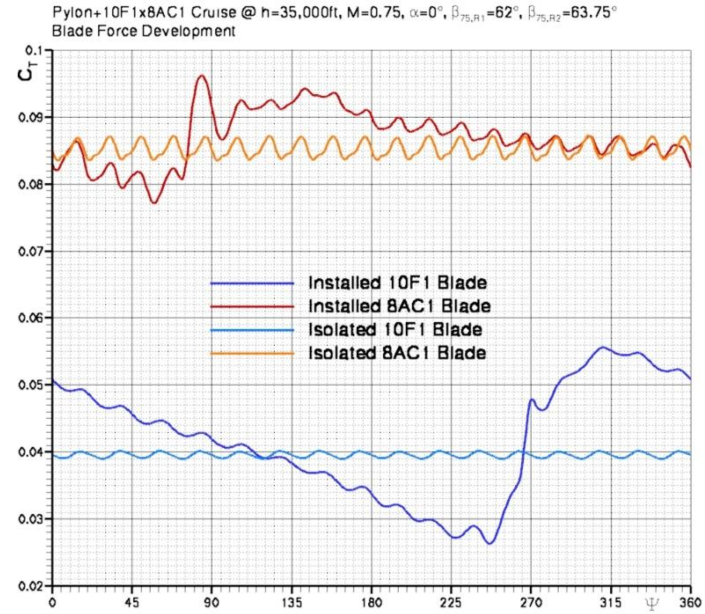


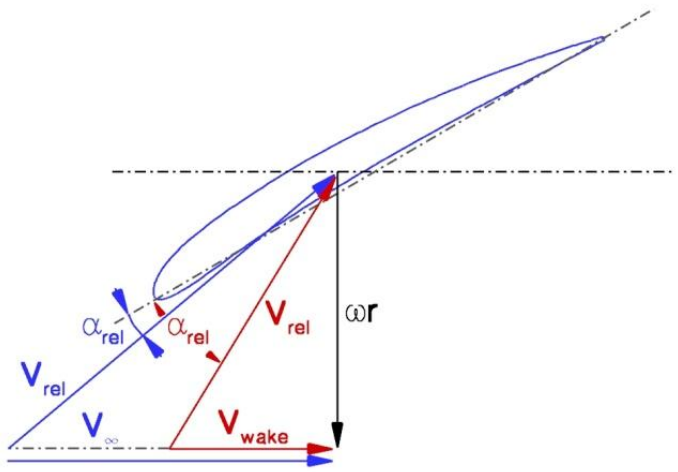


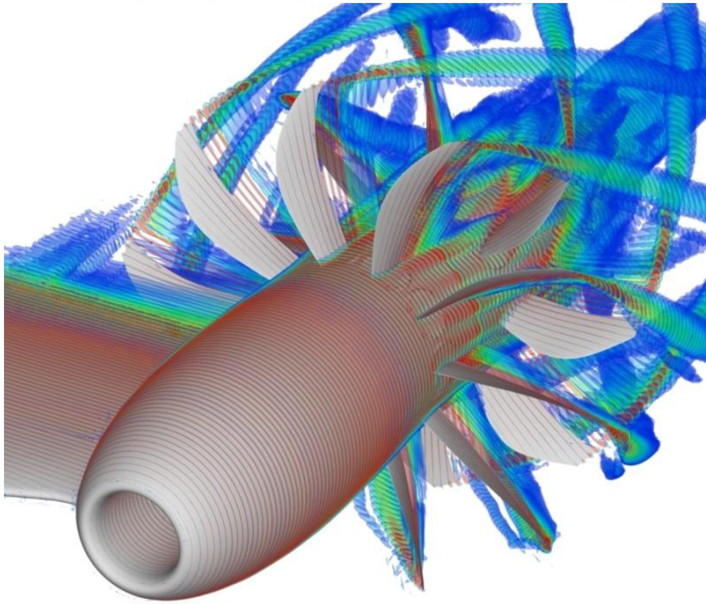
- Forward noise radiation at cruise limited to rotor BPF contributions
  - Slightly higher SPL @ B_A for 10F1x8A2
- Much richer spectrum and higher levels throughout at low-speed conditions
  - Interaction tones dominate

Installation Impact @ Cruise: Blade Forces

- Installation impact for identical blade settings as the isolated case leads to increased mean loadings
- Azimuthal variations of blade loadings due to local interaction with pylon wake
  - Wake increases the effective blade angle of attack







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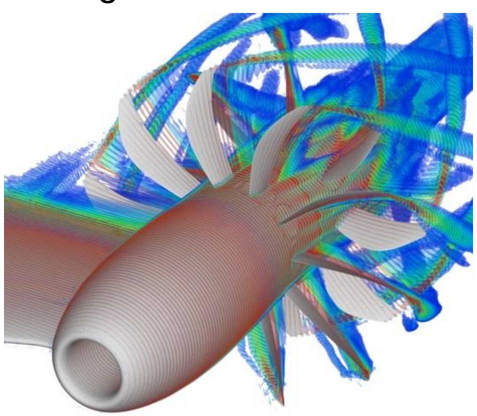
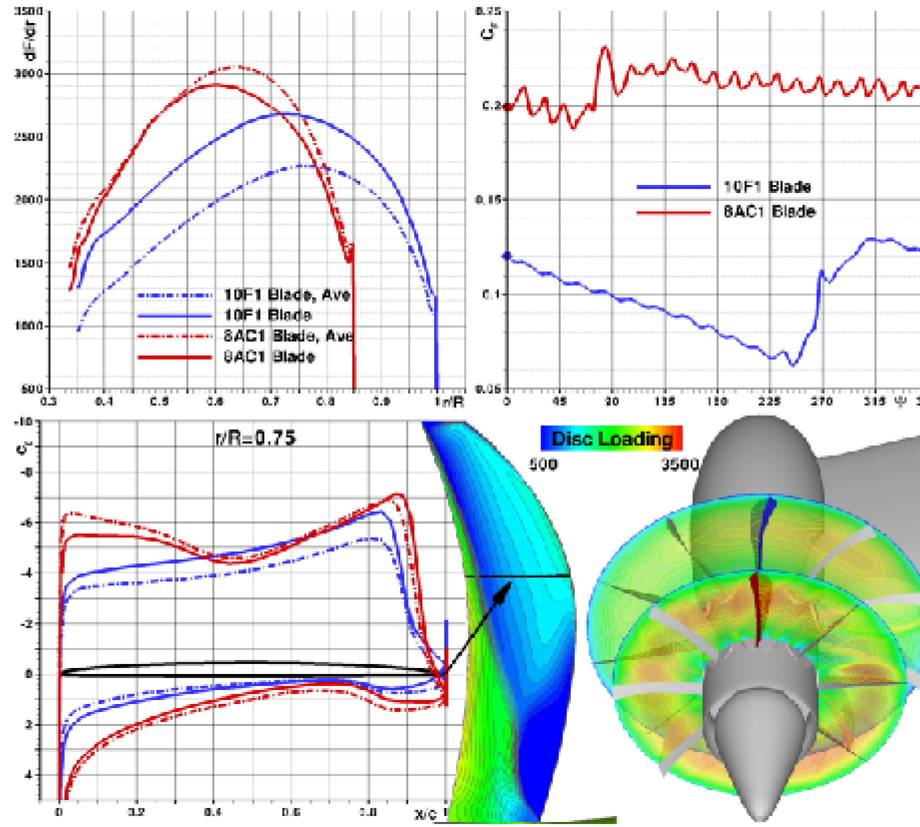
Installation Impact on Blade Pressure Distributions 10F1x8AC1

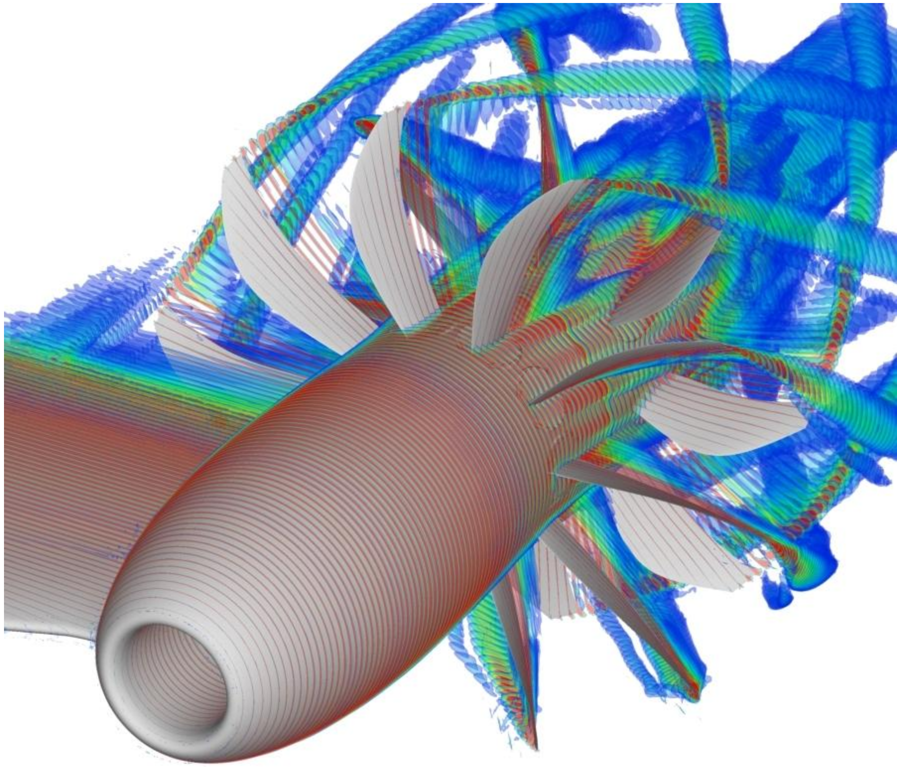
- Front blade affected by aft blade potential flow
- Notable pressure fluctuation visible on pressure side, in particular near the tip
- Full span transonic flow on blade suction side
- Pylon wake leads to local increase in blade angle of attack
  - Strong impact on suction side transonic flow
  - Global effects are azimuthal blade loading variations





Conclusions & Outlook

- Established process chain for coupled Hi-Fi TAU uRANS & aeroacoustic simulations with the DLR APSIM code allows for an in-depth analysis, enhancing understanding of complex interactions
- Better understanding of requirements for good quality data
- Outlook on planned future activities:
  - CROR configuration/operating point studies, 1P-Loads & installation effects
  - Passive and active noise control technologies: Pylon and front rotor blade trailing edge blowing; front rotor blade trailing edge serrations (DLR-AT)
- Perspective:
  - Maybe Hi-Fi CFD and CAA can contribute to making Open Rotor work this time around



Numerical Analysis of CROR Propulsion System Aerodynamics & Aeroacoustics at DLR

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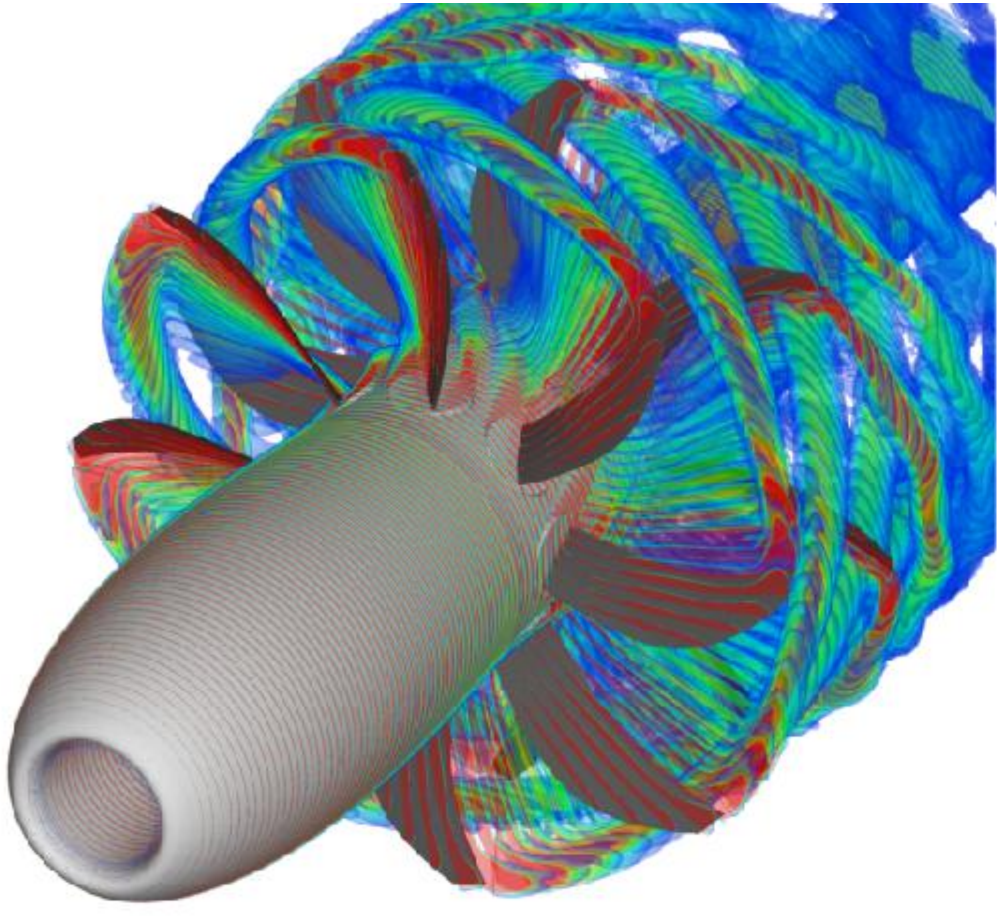

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