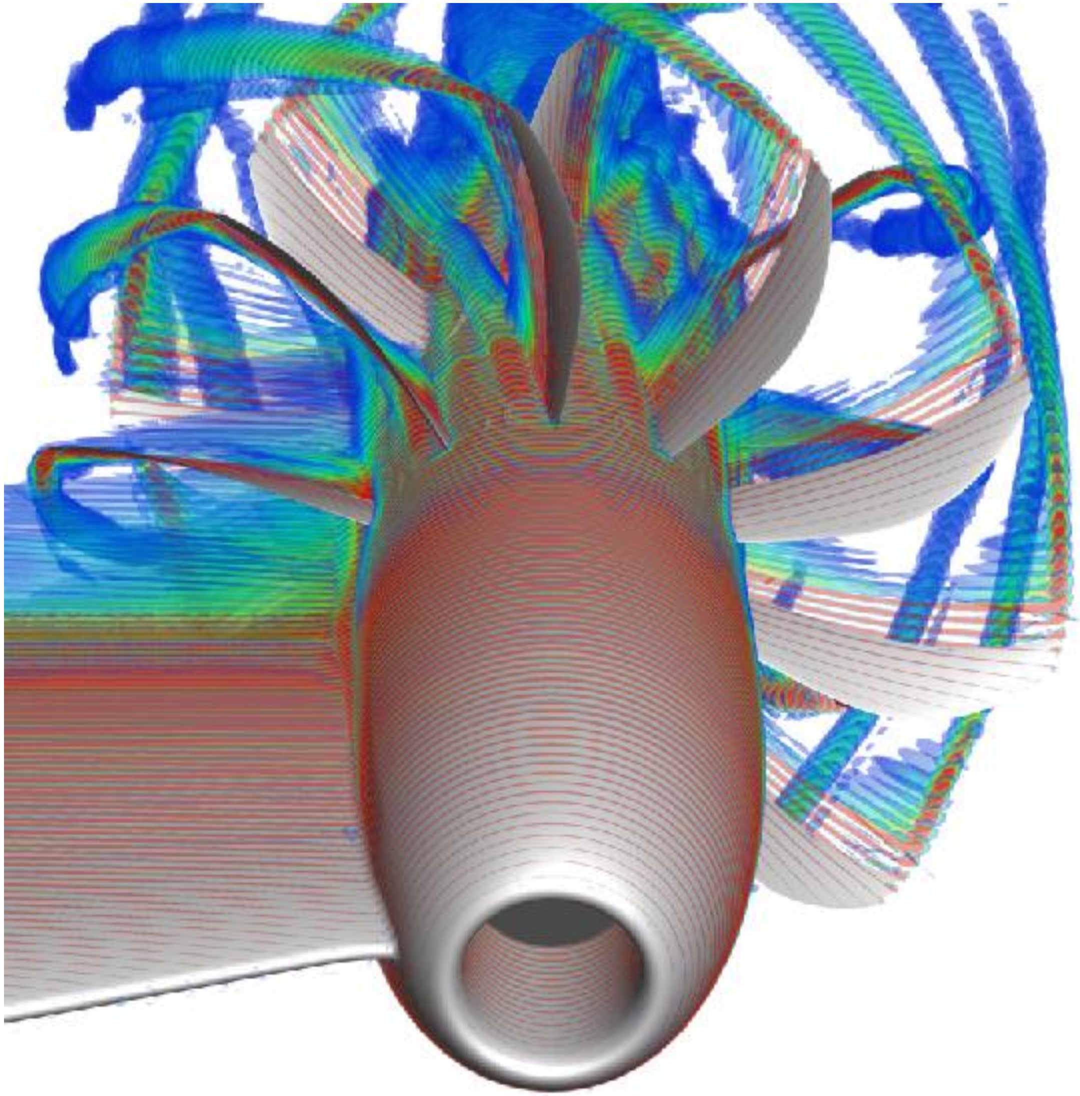
DLR-AS CROR & Propeller Noise Prediction



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14th CEAS-ASC Workshop
October 7th-8th, 2010
Institute of Aviation
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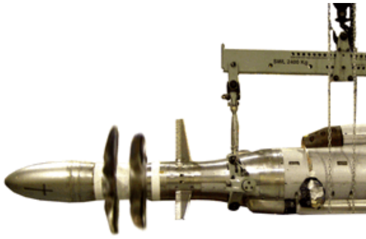
Overview

What's needed in CFD and CAA for Numerical Predictions?

- Introduction and Motivation
- DLR-AS CROR Activities Overview
- Single Rotation Propeller Simulations
  - Validation & Noise Emission Specific Activities
- CROR Simulations
  - Noise Source Identification
  - CFD & CAA Requirements
- Conclusion and Outlook

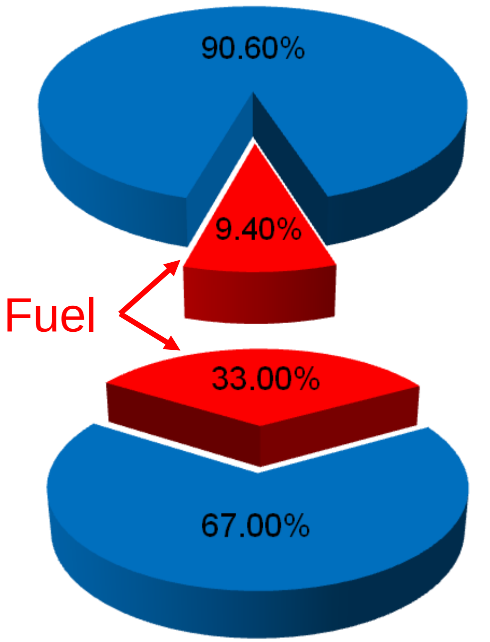
Introduction and Motivation





1998

- Cost of fuel has lead to a renaissance of the Contra-Rotating Open Rotor (CROR)
- Propfans studied in 1980s NASA/US Industry Advanced Turboprop Project (ATP)
  - Significant efficiency benefits demonstrated
  - 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: Waning of interest for airlines
- Fuel cost concerns are back: ‘08: 33%→’98:9.4% of TOC



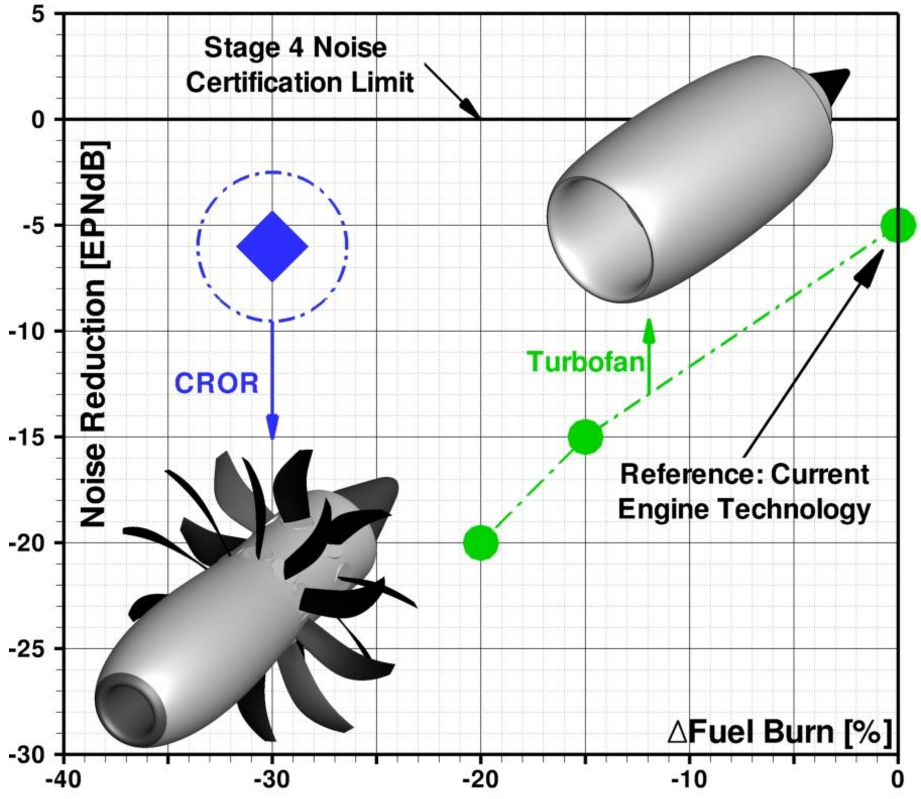
2008

Introduction and Motivation - Why CROR?

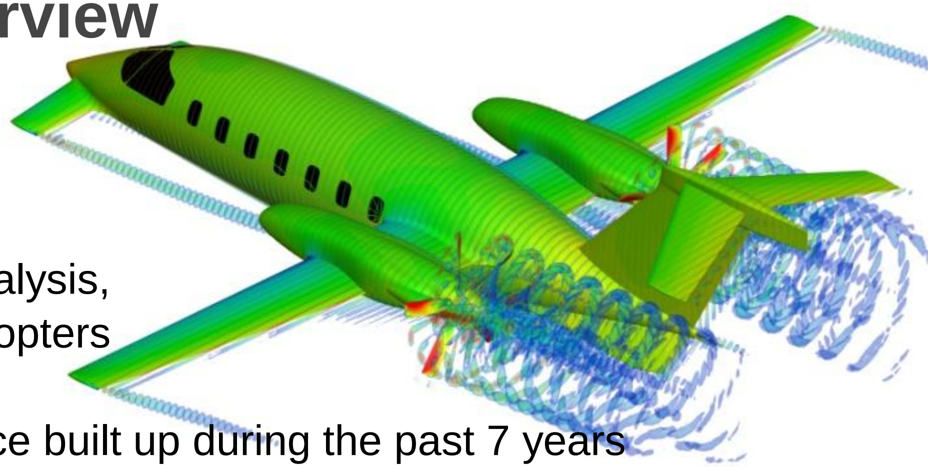
- Engine manufacturers are working on further improvements of (shrouded) turbofans, promising ~20% SFC and significant noise reductions

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

- Turbofan (TF) bypass ratio increases will eventually lead to increases in nacelle and installation drag
- CROR propulsive efficiency expected to be better than TF by a comfortable margin
- For CROR technical challenges on installation, noise and certification 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 Single Rotation Propeller-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

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 ~ 2-4 weeks wallclock

Single Rotation Propeller Simulations: Code Validation

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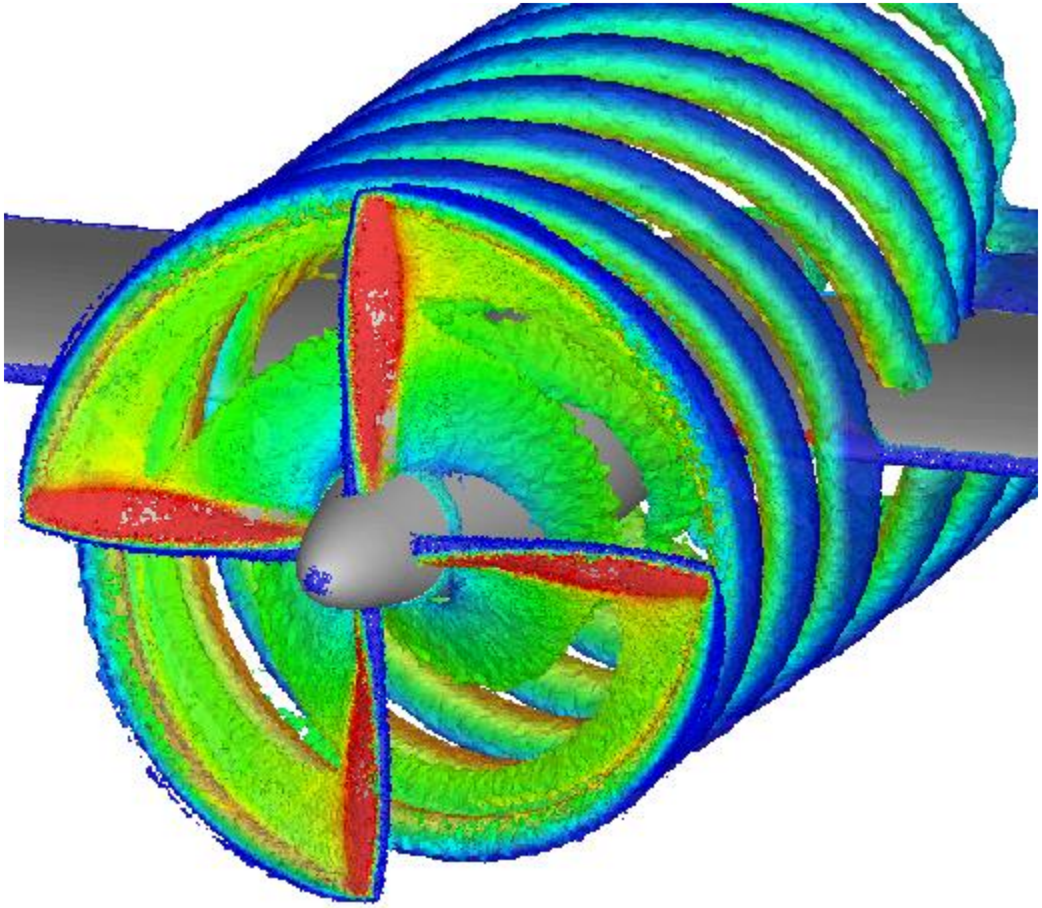

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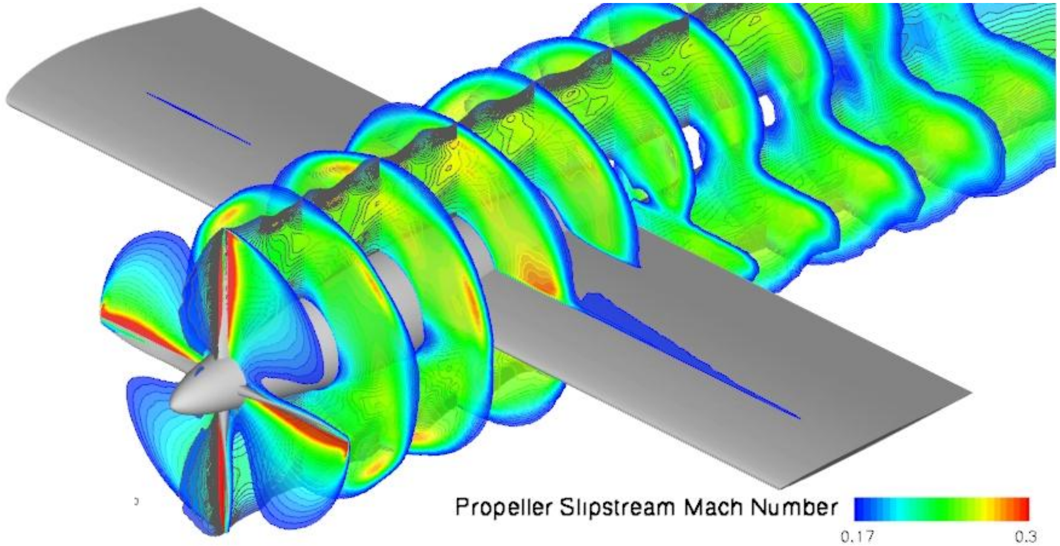
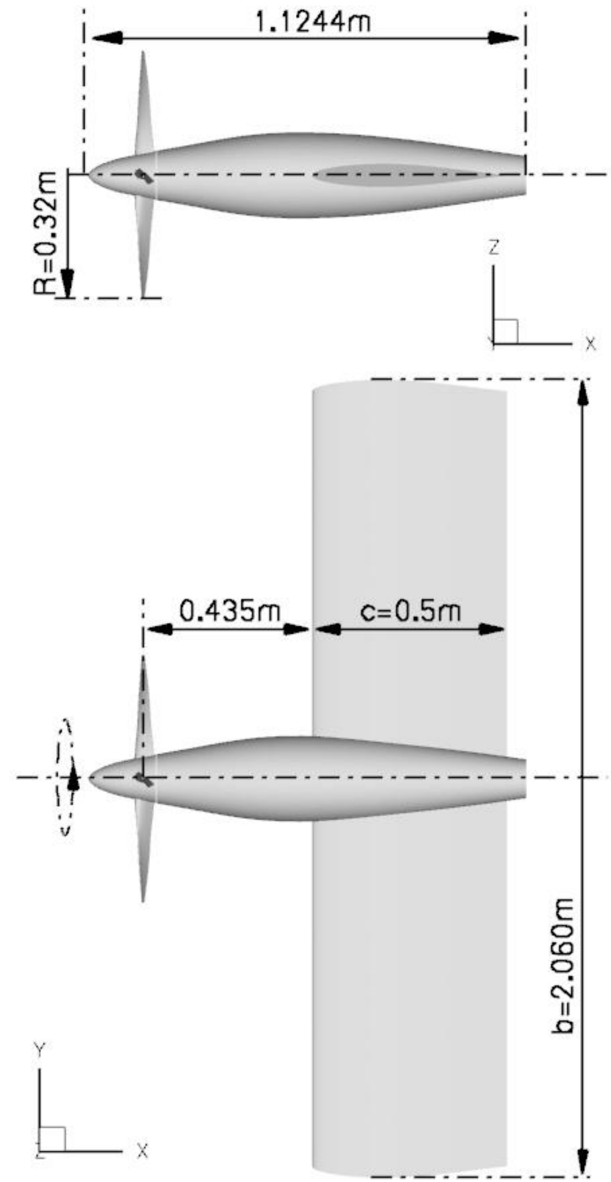
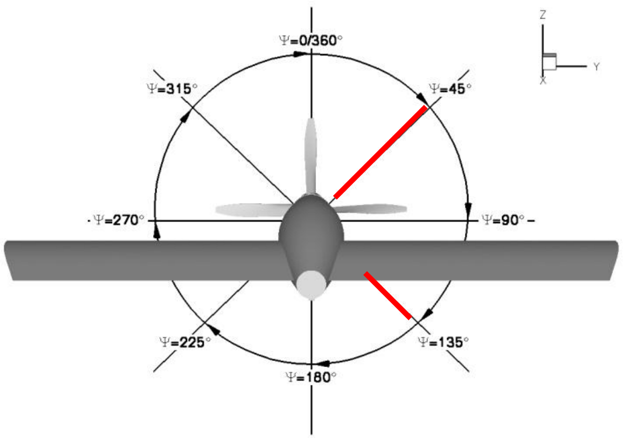
AGARD Propeller



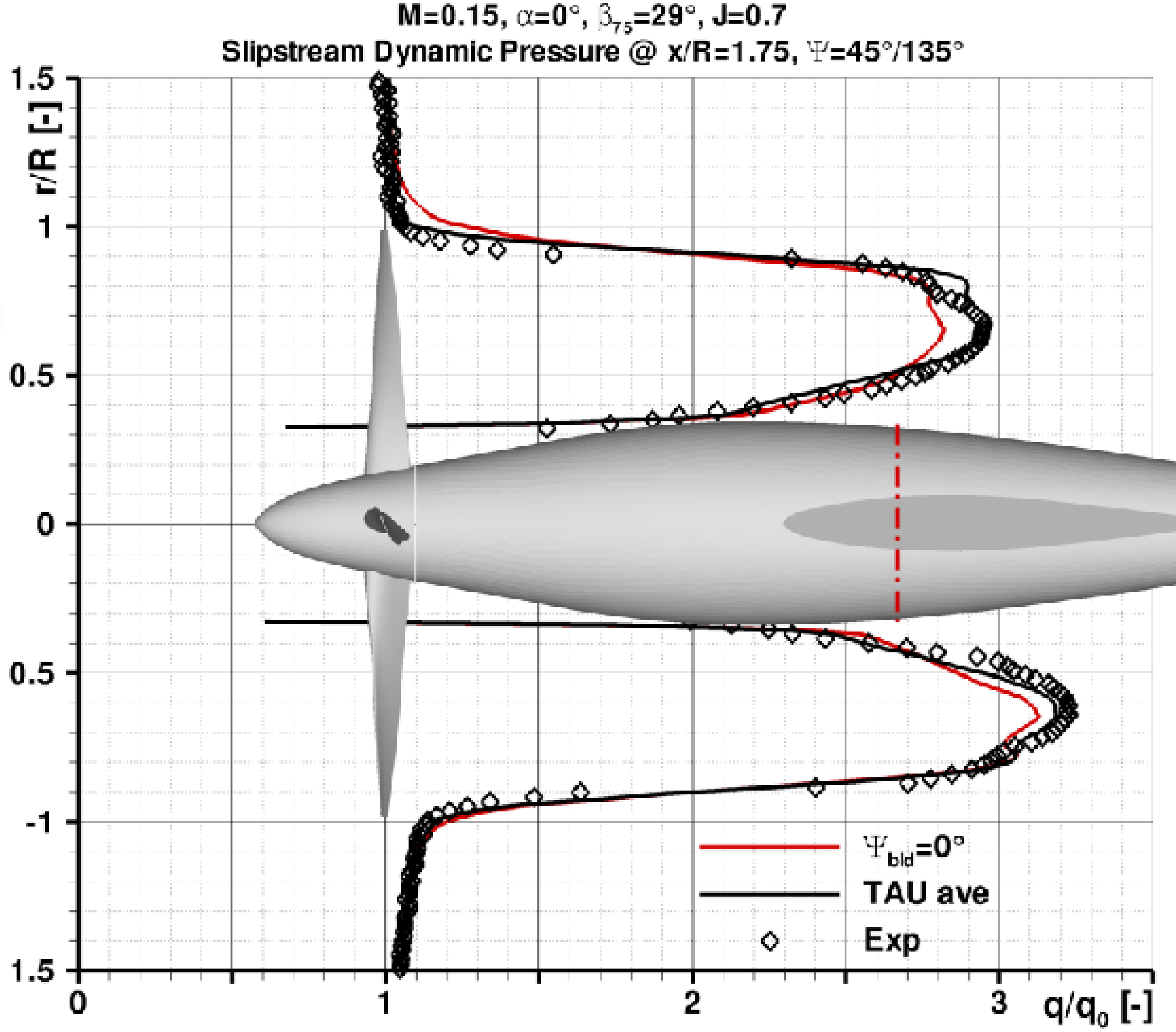


- Generic isolated and installed propeller test case @ 1:5 scale
  - 4-blade propeller for 30 seat regional transport
  - Axissymmetric nacelle
  - Untwisted wing, symmetric NACA 63(10)A-012 airfoil
- Low-speed experimental investigations in the 80s/90s
- Variation of blade pitch, α and side slip angles, advance ratios
- Measurements of slipstream development, surface pressures on wing and propeller force and moment
- Simulationen @ M=0.15, α=0º und 10º

Validation: Propeller Slipstream Development

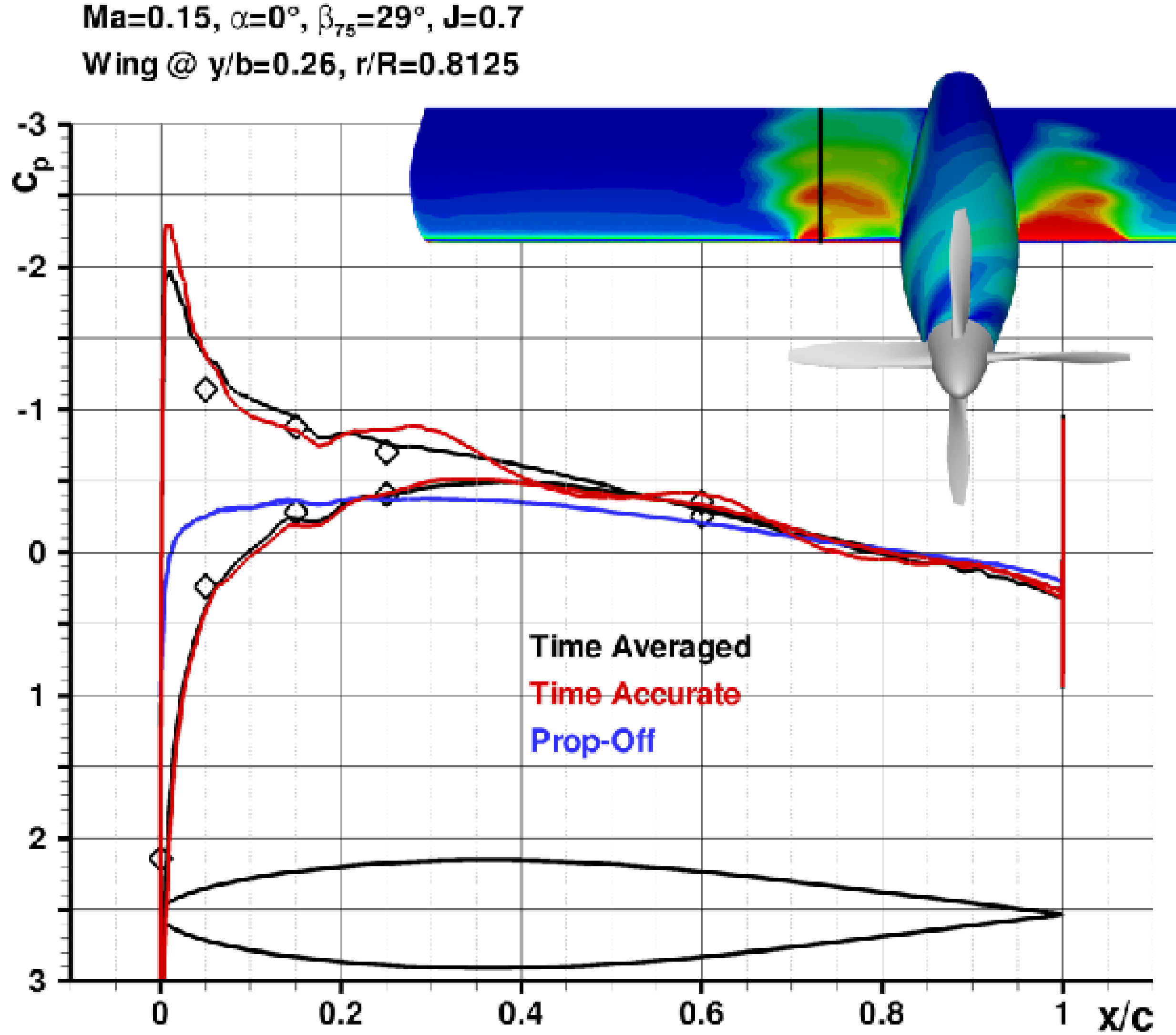


- Time averaged TAU results in very good agreement with wind tunnel data
- Unsteady fluctuations due to periodic passage of blade wakes and blade tip vortices
- Wake asymmetry due to swirl: Acceleration of flow around leading towards the right wing lower side (left wing upper side)



Validation: Propeller Slipstream Development

- Increased velocities in propeller slipstream
- Swirl leads to asymmetric flow, with positive local AOAs for the wing on the side of upward propeller rotation and negative local AOAs on the other → Locally positive or negative lift generation
- Airfoil @ r/R=0.8125:
  - Good agreement of time-averaged CFD results with wind tunnel data
  - Unsteady fluctuations due to periodic passage of blade tip vortices



Single Rotation Propeller Simulations: Noise Emission Reduction Studies in the EU CESAR Project

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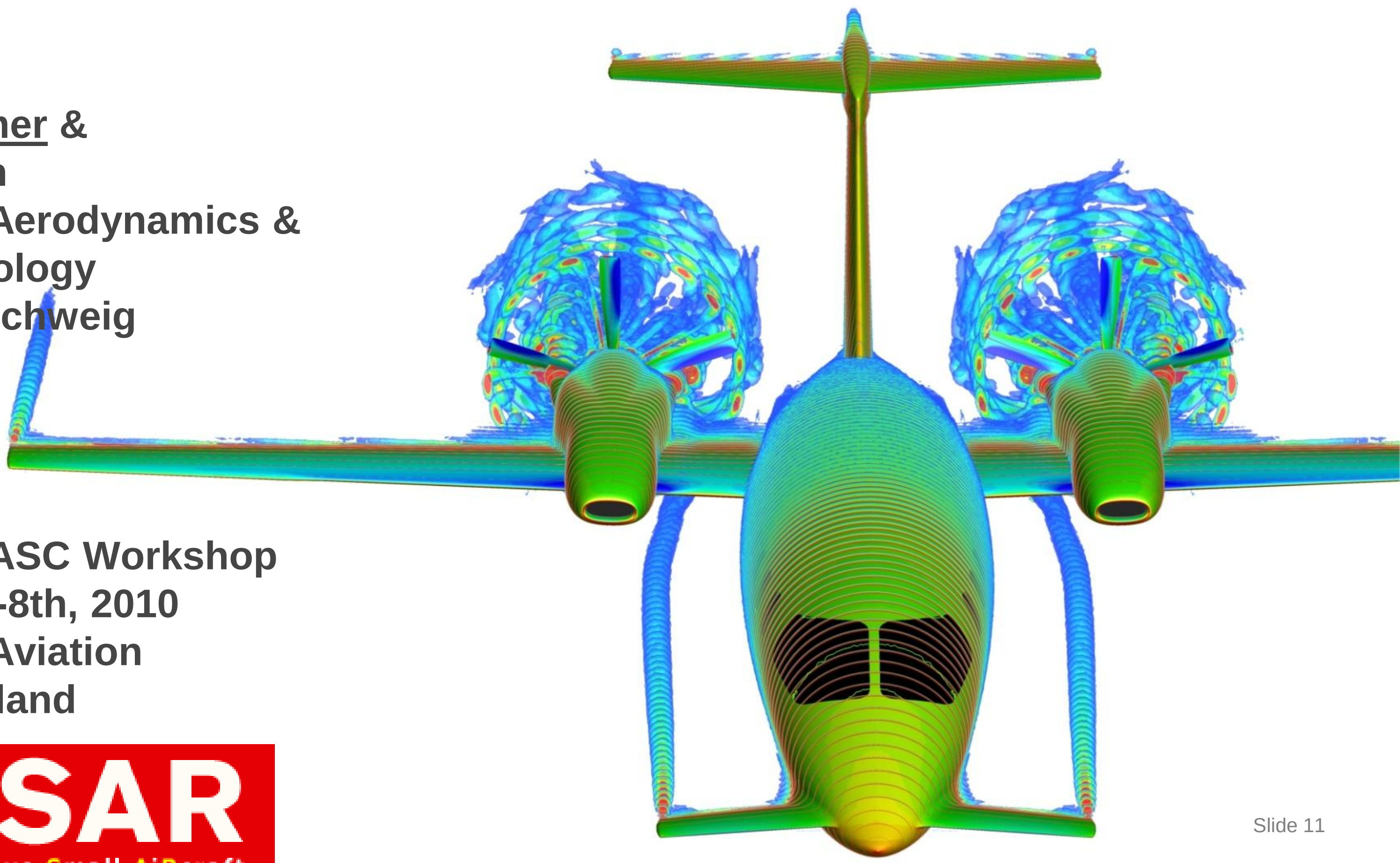
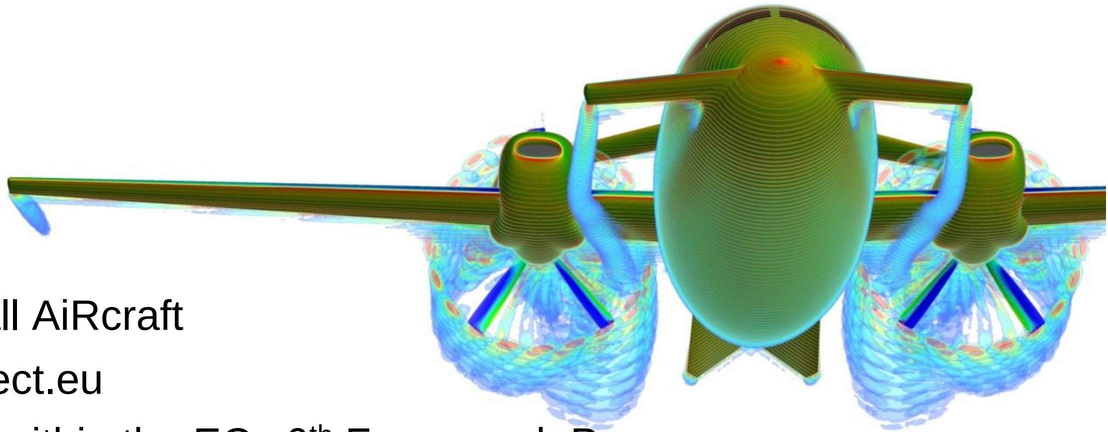


CESAR
Cost-Effective Small AiRcraft

EU 6th FP CESAR:

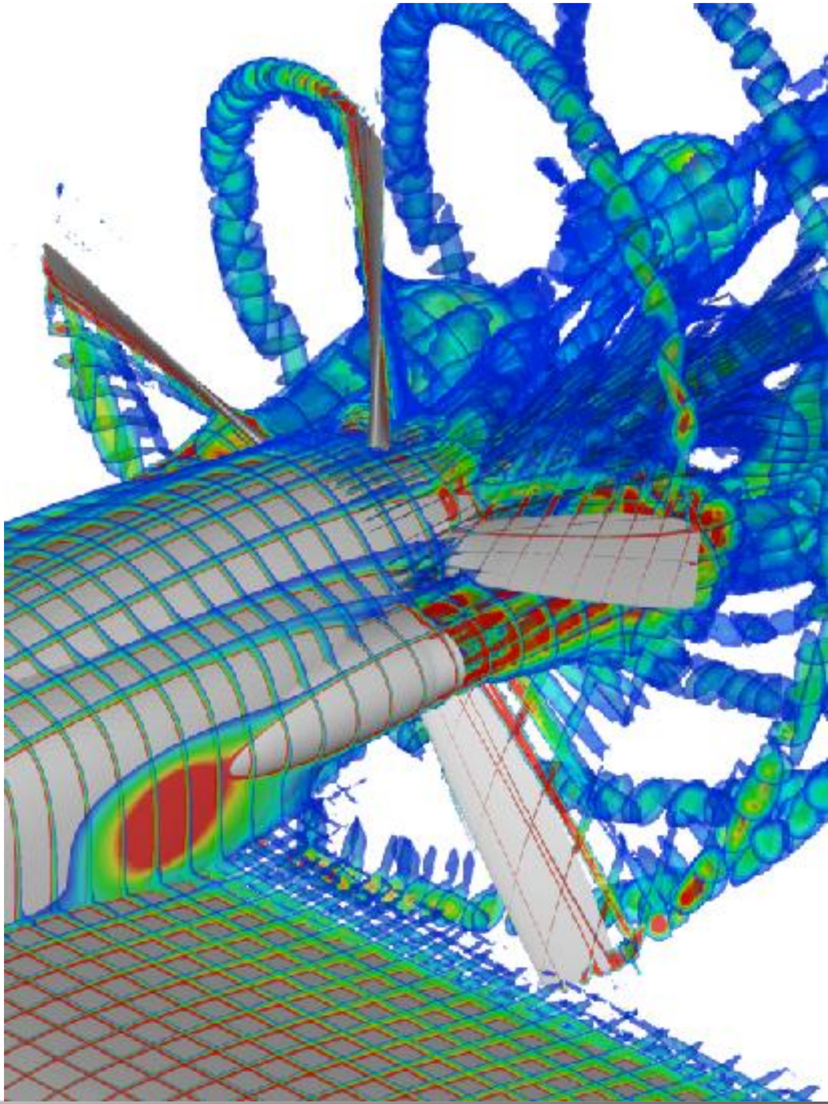


- CESAR: Cost Effective Small AiRcraft
  - http://www.cesar-project.eu
- Aerospace research project within the ECs 6th Framework Program
- Targeted at the small commercial aircraft segment
- New aircraft development concepts and selected technology advancements aimed at lowering development times and costs along with improvements in operational economics, safety, comfort and environmental impact
- 39 participating organizations from 14 countries
- Project kick-off on September 1st, 2006

- Present work performed in Piaggio Aero Industries led Task 3.3 “Environmentally Friendly Propeller Propulsion”
  - Low-noise high efficiency propeller-airframe integration
- Focus on high power setting climb case: h=400 ft, M=0.235, α=6.5º, J=1.101

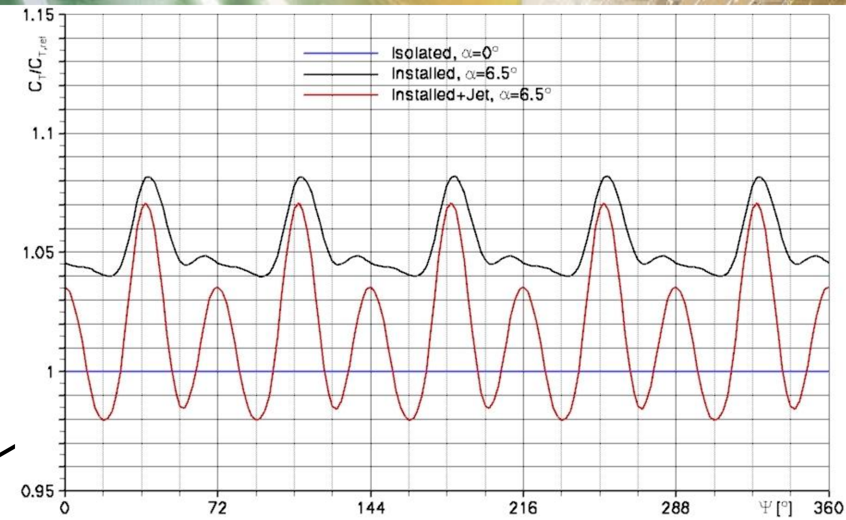
Aerodynamic Analysis: Prop-Jet-Interactions

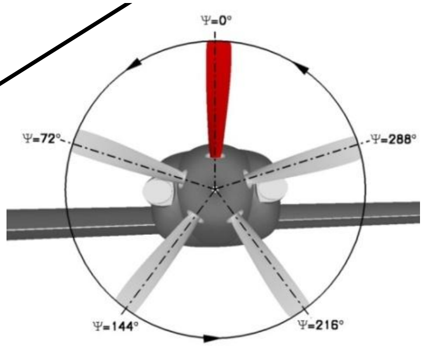
- Noise a particular concern for pusher propeller configurations, in particular for certification at low-speed take-off and approach conditions
- Close proximity of exhaust and propeller planes leads to strong mutual interactions
- Propeller blades “slice” and deflect the jets during their rotation
- Entrainment of jet in swirl of propwash

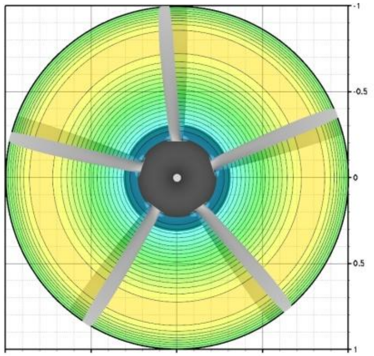


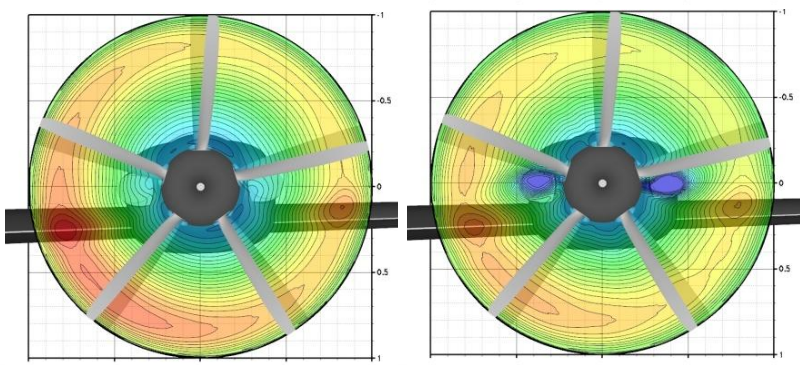
Aerodynamic Analysis: Blade & Propeller Forces

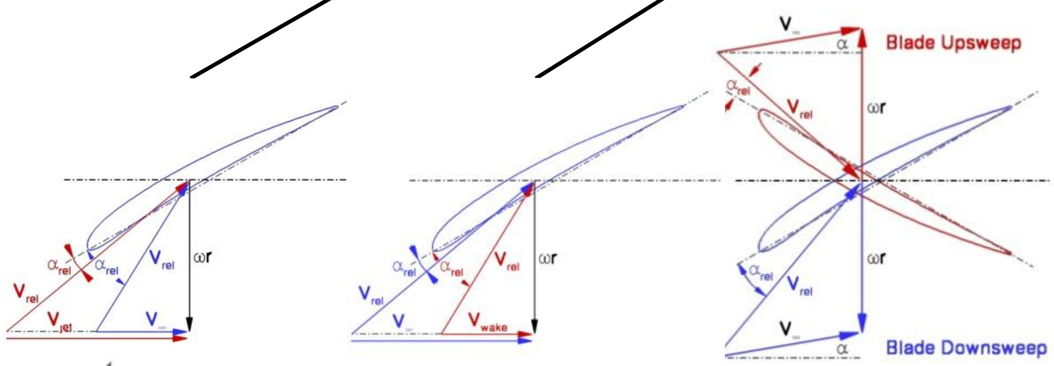
- Blade forces show overlapping impact of AoA and interaction with engine jet and wing wakes
- Pronounced periodic fluctuations for propeller force components
  - 10P for 5-blade propeller: non-synchronous passage of blades through jet and wakes on left and right side of nacelle



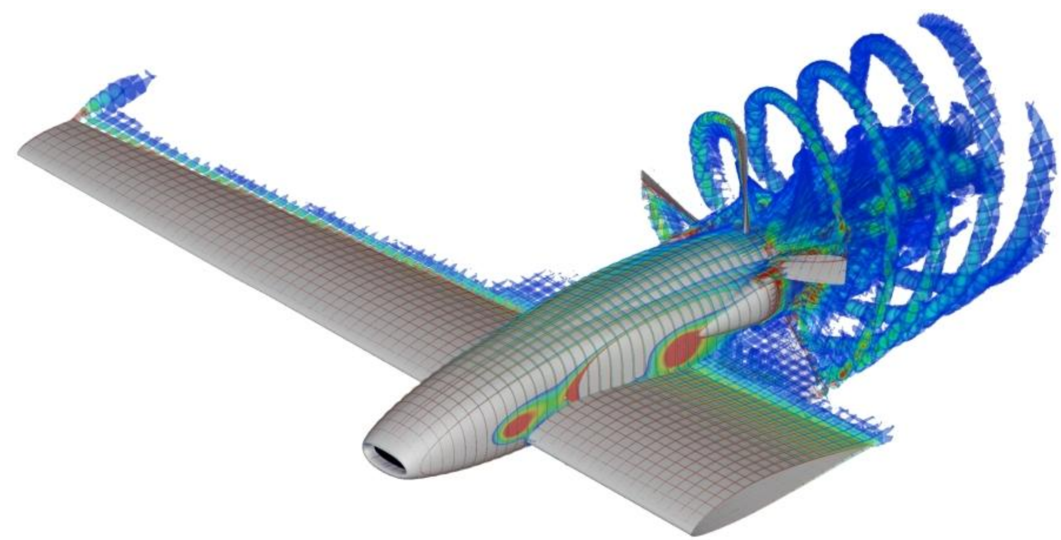




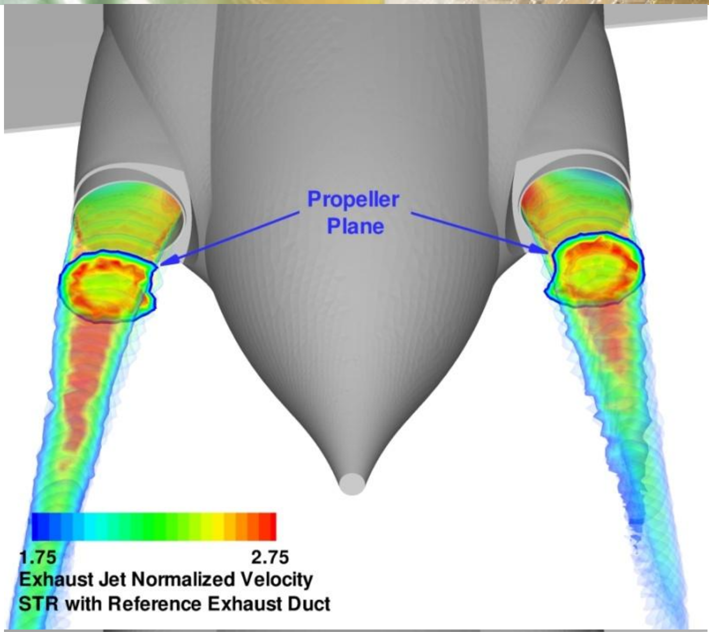


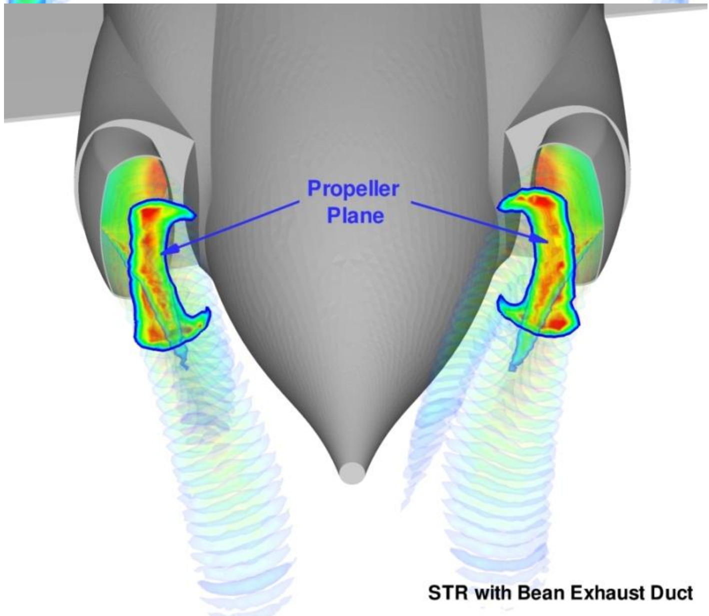


Configuration Adaptation: Bean Exhaust



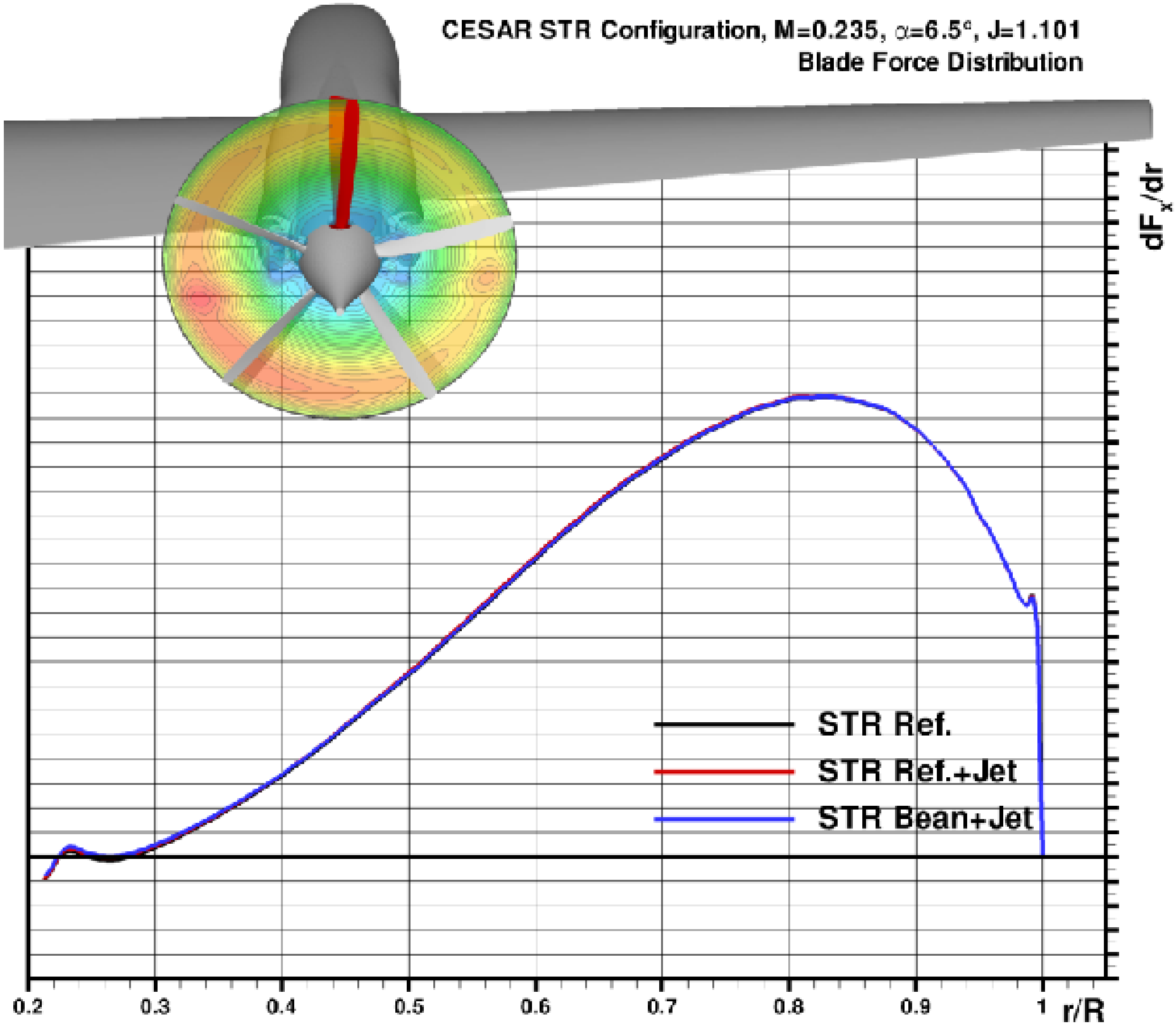
- Modular Chimera mesh approach beneficial for configuration design studies
  - Reduced remeshing requirements for the various configurations
  - Better guarantee of CFD result comparability due to re-use of many of the Chimera blocks





Configuration Adaptation: Bean Exhaust

- Blade thrust distributions indicate generally favorable bean jet effect on blade
- Reduced magnitude of thrust loss
- Reduced radial extent of affected region
- But: Increased period length of jet interaction

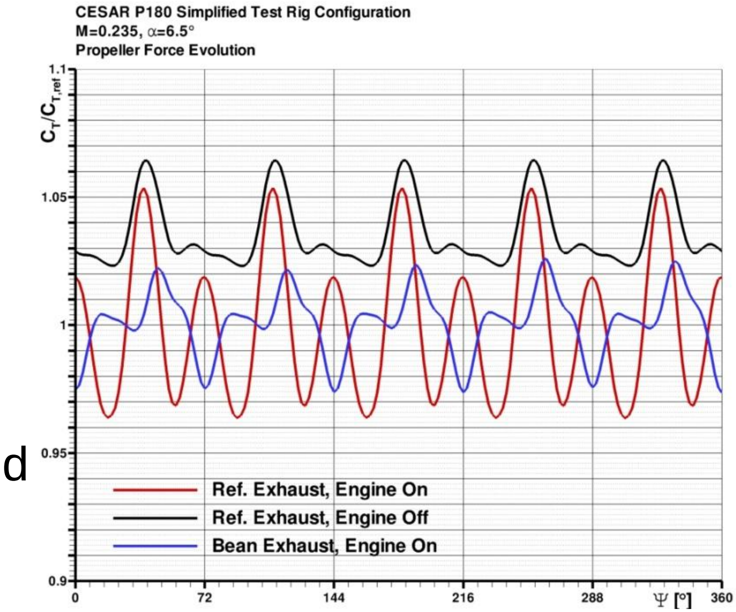


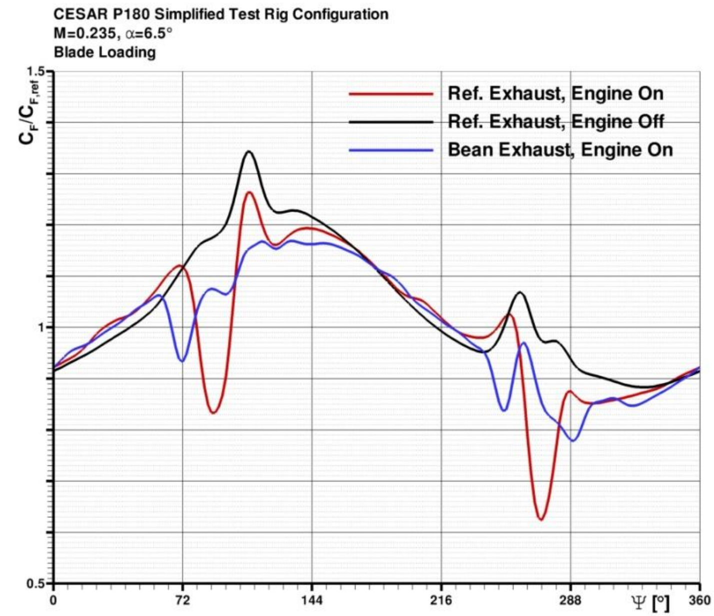
Configuration Adaptation: Bean Exhaust

- Disc loading shows reduced magnitude of thrust loss due to jet impingement
- Simultaneous occurrence of wing wake and engine jet for the bean exhaust

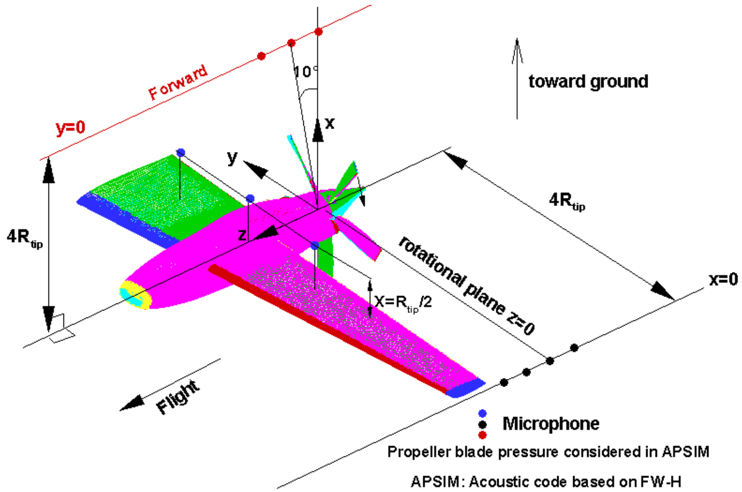
- Bean exhaust impact on mean blade loadings small, unsteady loadings strongly reduced

- Integrated propeller thrust loading fluctuations are also of lower amplitude for the bean exhaust

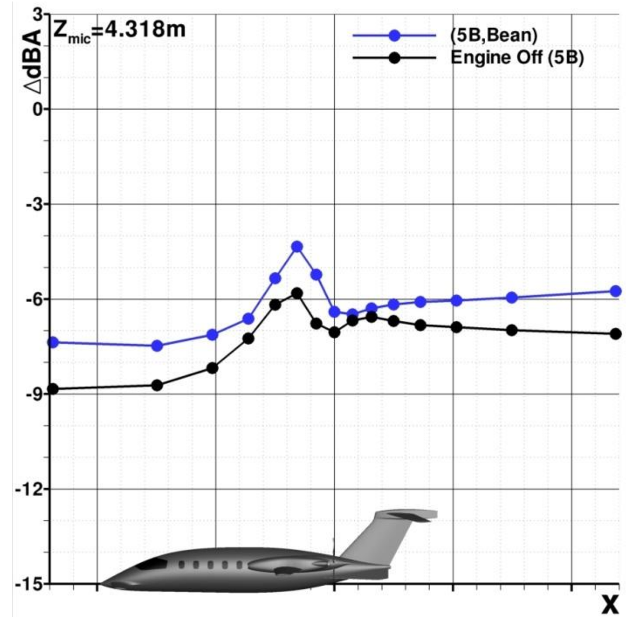


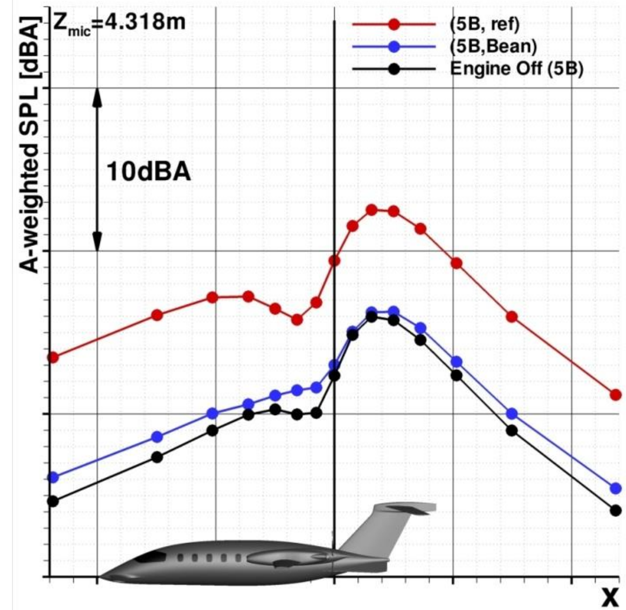


Configuration Adaptation: Bean Exhaust

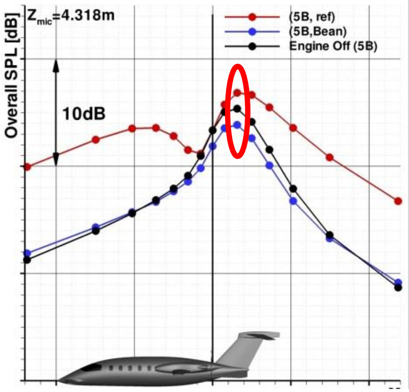


- Overall SPLs show beneficial impact of modified exhaust system on ground noise emissions
- Reduced unsteady blade loading (masked wing wake impingement) lowers noise near propeller plane
  - Peak noise reductions ~6dBA
- Reduced interaction tones improve sound radiation in axial direction
  - Noise reductions of 4-7dBA
  - Almost as good as turning the engine off

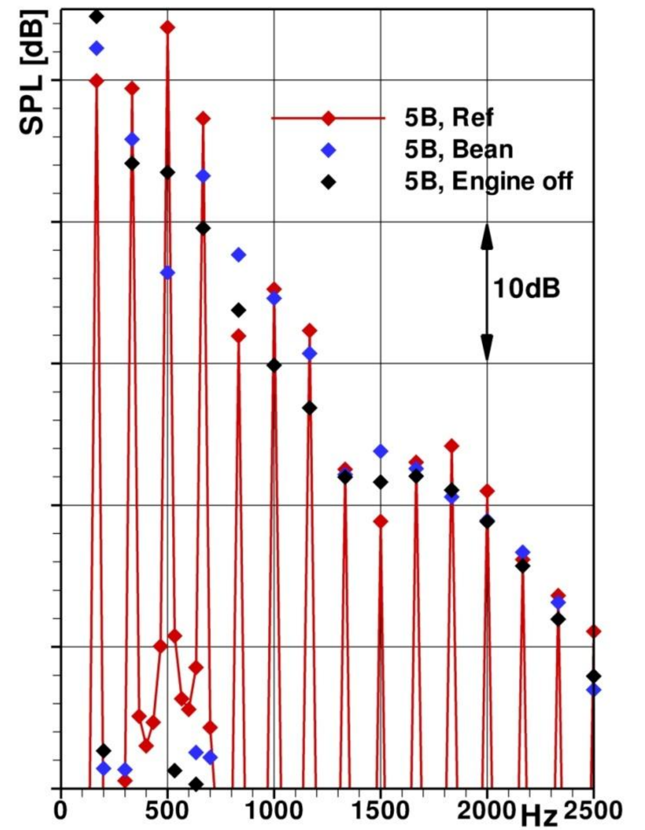




Configuration Adaptation: Bean Exhaust Spectrum @ Peak Noise



- Engine-off and bean exhaust case show higher sound power @ BPF due to higher mean blade loadings
- Levels at almost all higher BPFs are reduced versus the baseline case due to decreased unsteady loadings
  - Exception for tone @ 5BPF: More of a 5P-propeller loading cycle for bean exhaust and engine-off cases than the 10P-cycle of the baseline case
- Bean tone spectrum almost always very close to engine-off results



CROR Simulations: Coupled CFD-CAA Investigations

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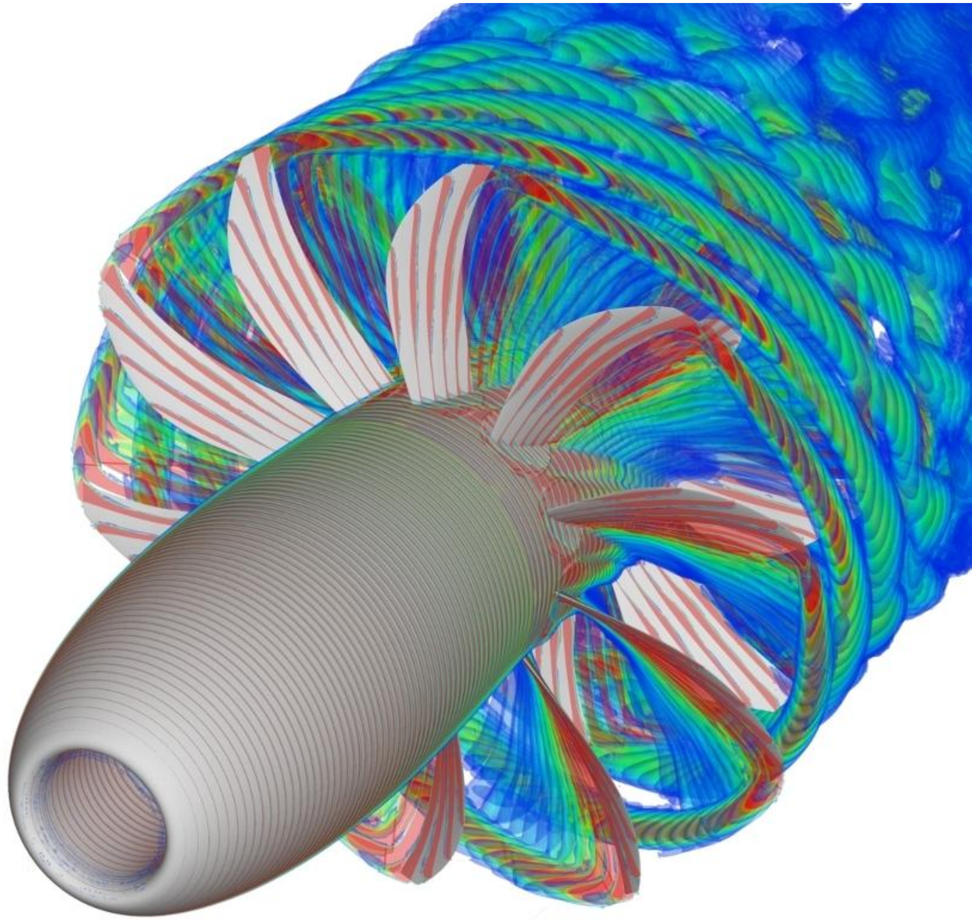

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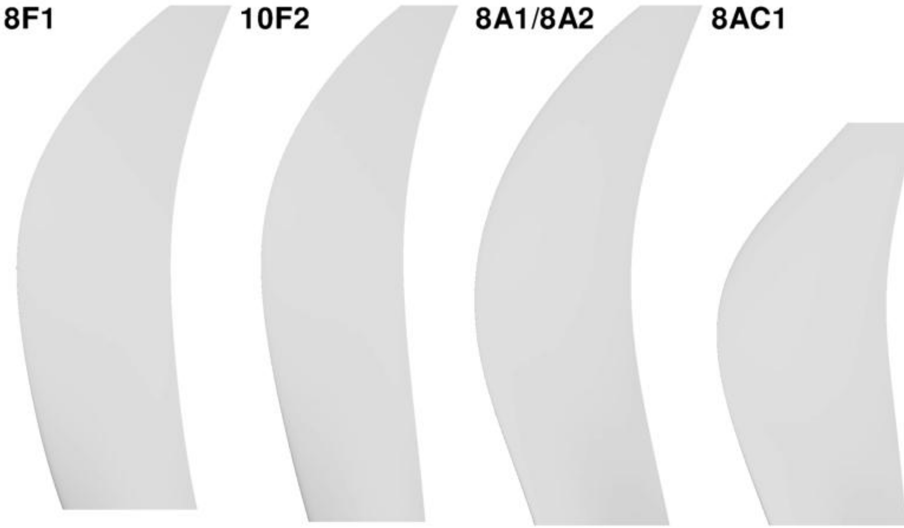
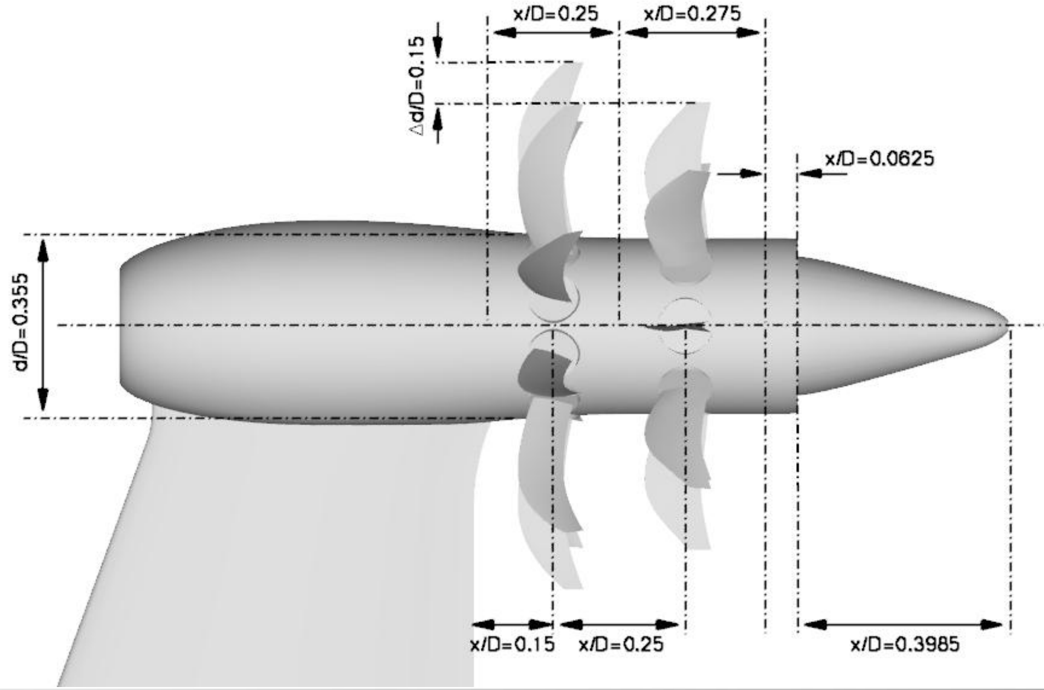
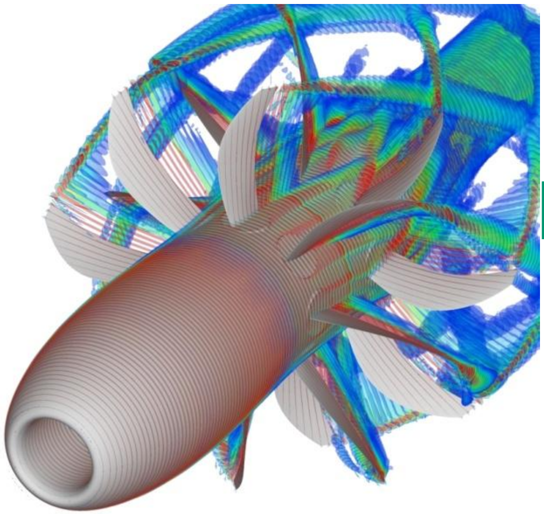
Research Geometry: Sizing, Nacelle and Pylon

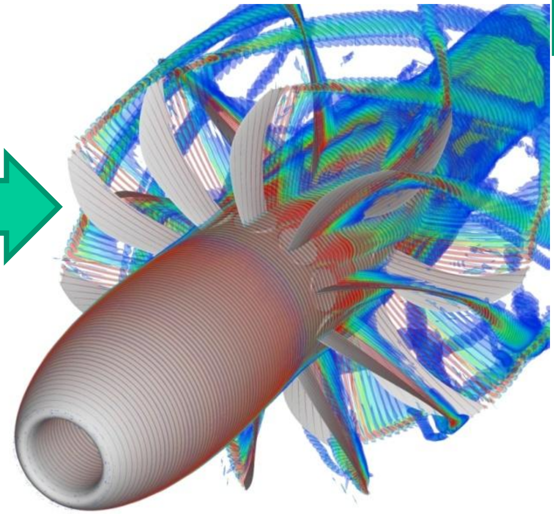
- Generic CROR to test and mature numerical methods and approaches and improve understanding
- Sized for 150-seat aircraft:
  - TO-thrust ~88kN
  - Cruise thrust ~19kN
- D=14ft/4.2672m propeller
- Family of blade designs
  - 8- & 10-blade front rotor
  - 14ft & 11.9ft 8-blade aft rotor
  - Generic pylon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

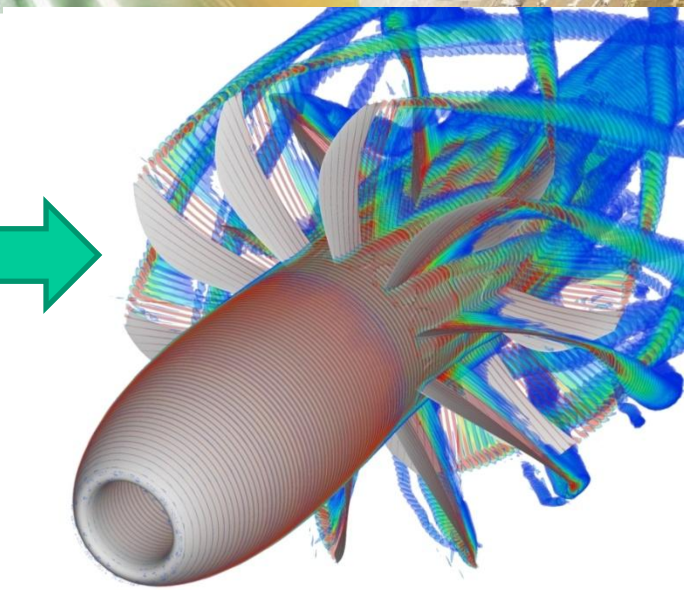


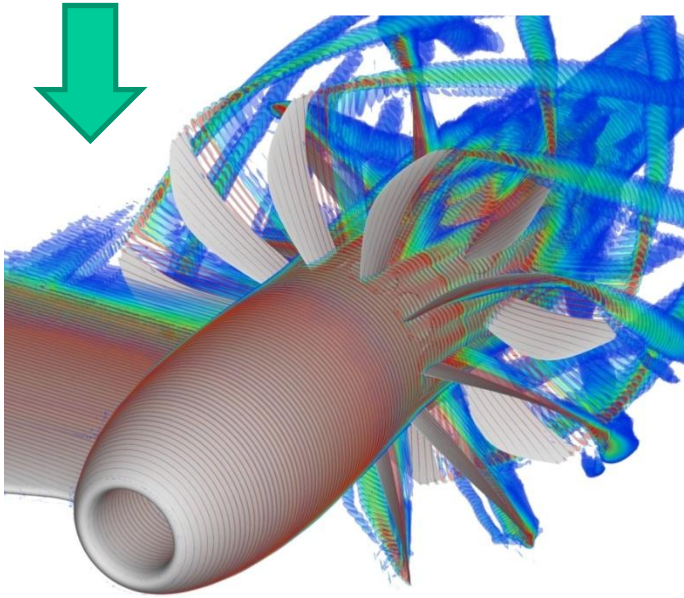


Systematic Configuration Studies







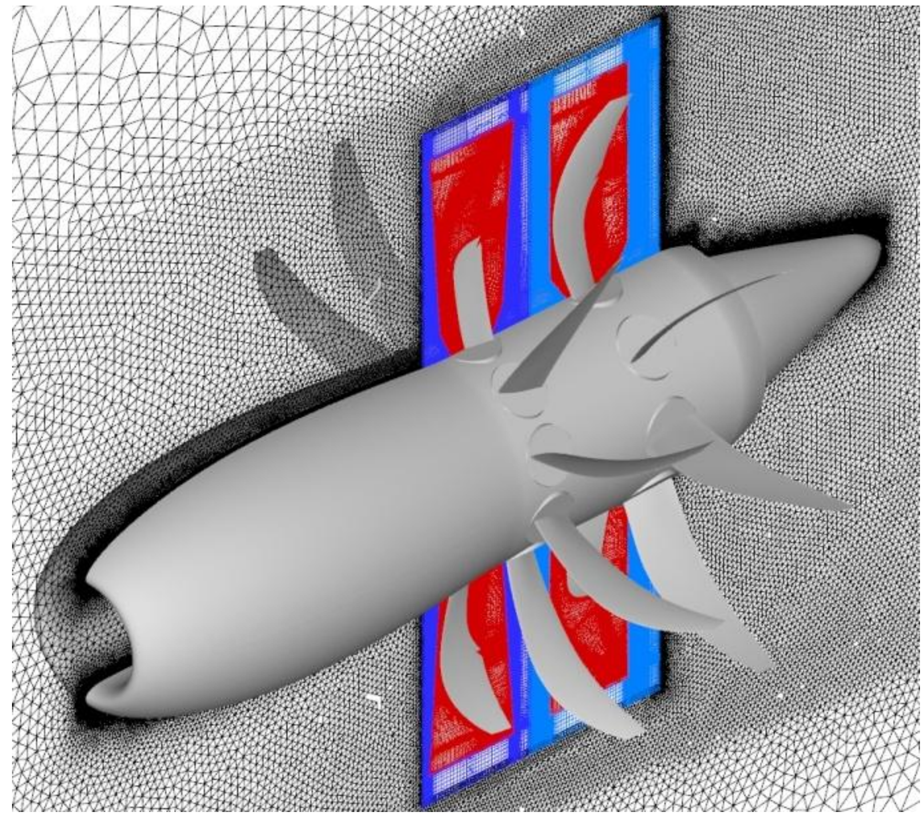


- Investigation of configuration impact on performance and noise
- Blade number variation: 8x8 to 10x8
- Aft rotor diameter reduction to eliminate tip vortex impingement
- Addition of pylon to investigate installation effect impact
- Representative performance levels:

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: 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



CROR Noise Generation Mechanism #1: Rotor-Rotor-Interaction – Blade Wakes & Potential Flow

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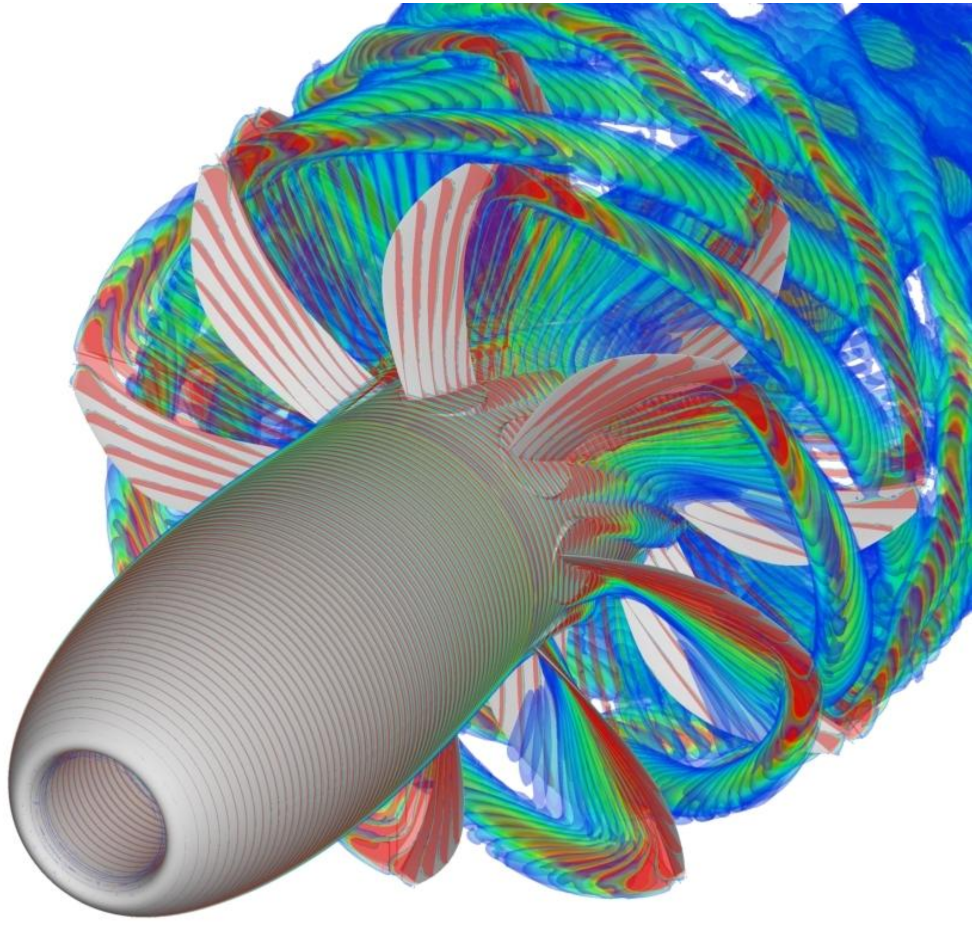

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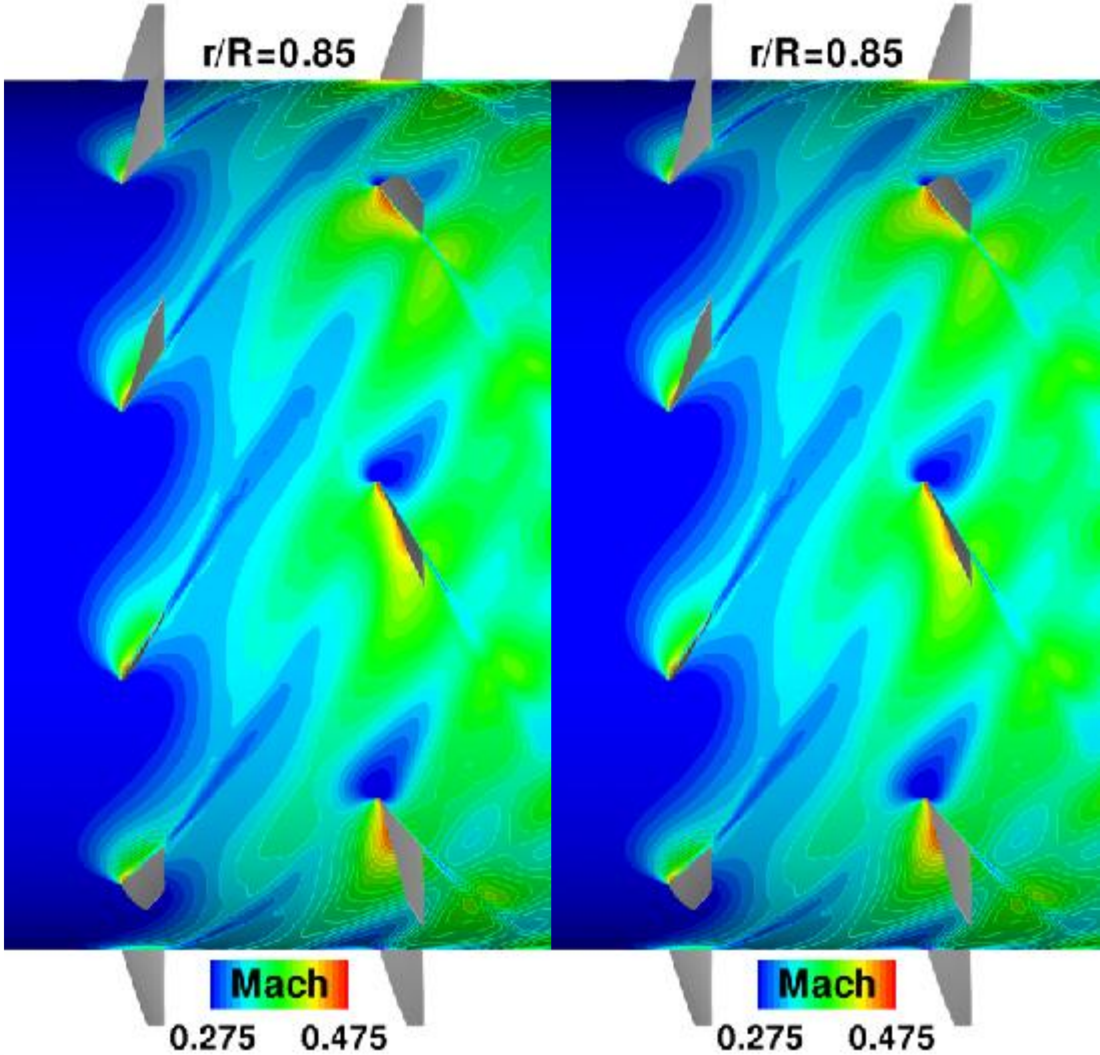
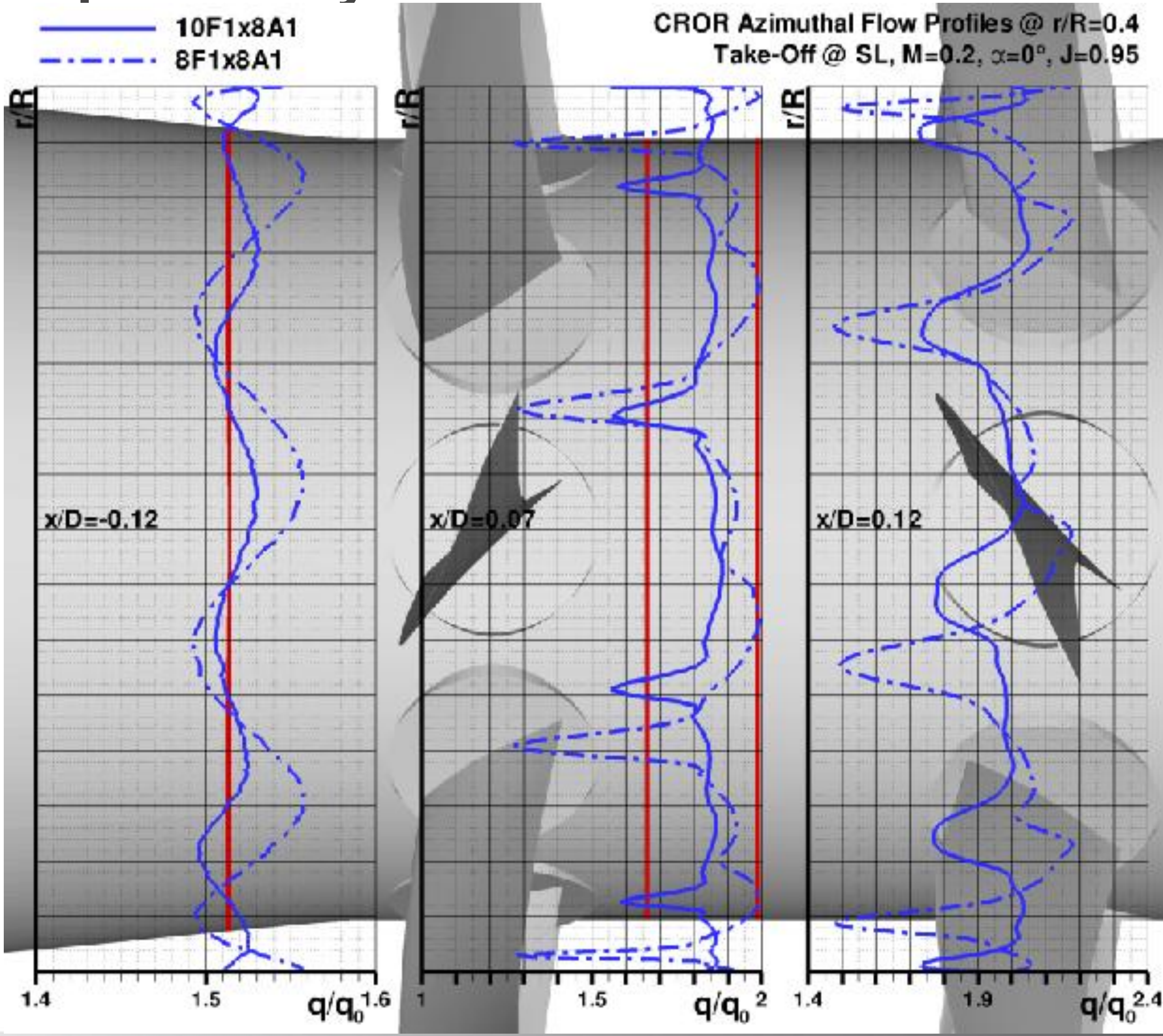
Slipstream Development: Blade Wakes @ r/R=0.85 10x8 CROR

- 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 rotor interactions:
  - Aft blades influenced by forward rotor blade wakes
  - Aft blade wakes interact with “sliced” forward blades wakes
  - 16-cycle oscillations on forward blades pressure side
  - Small Mach number fluctuations upstream of front rotor



Slipstream Development: Dynamic Pressure Profiles

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

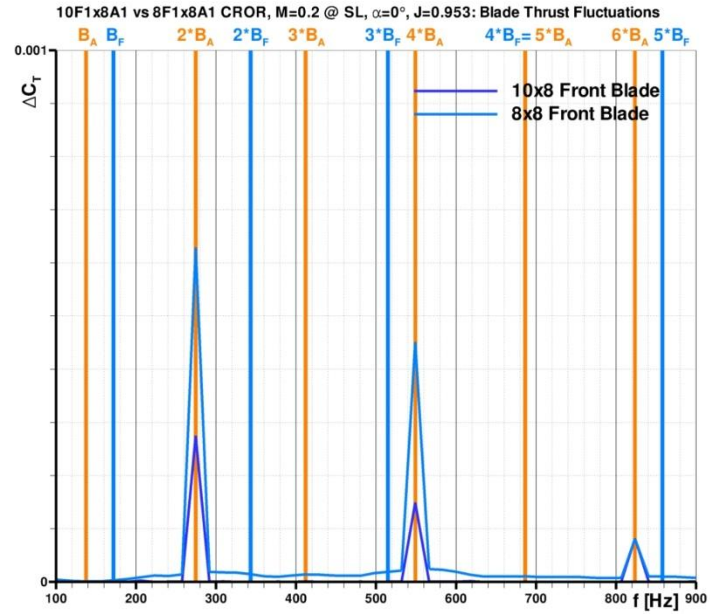


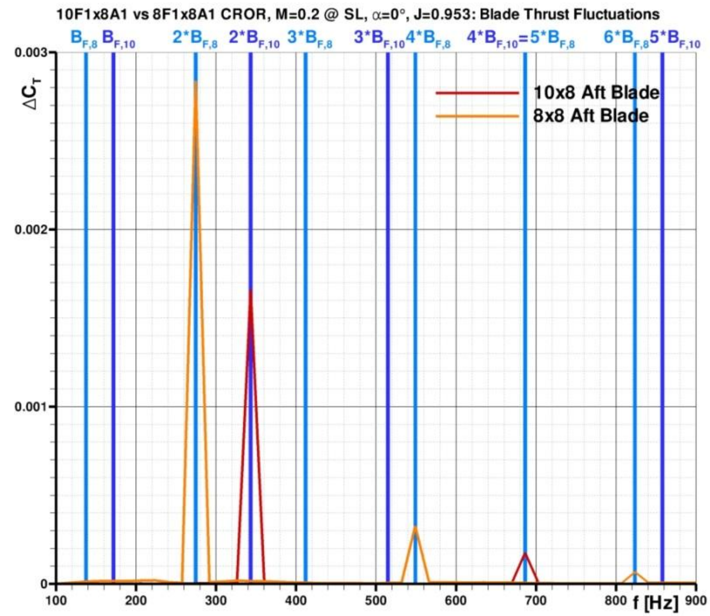
Blade & Rotor Performance

	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

- Increase of blade number in front rotor reduces individual blade mean/steady loading for both front and aft rotors at selected operating point

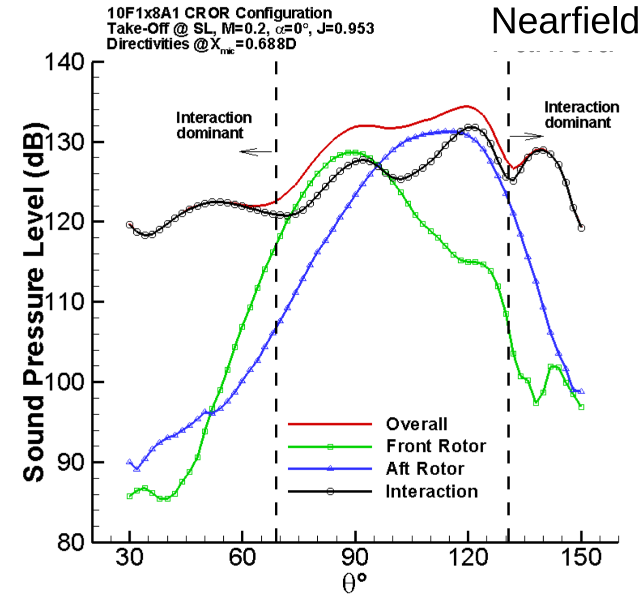
- Unsteady loading also benefits:
  - Unloading of front blade reduces aft blade fluctuation amplitudes by ~40%
  - Front blade unsteady loading reduced by ~50%

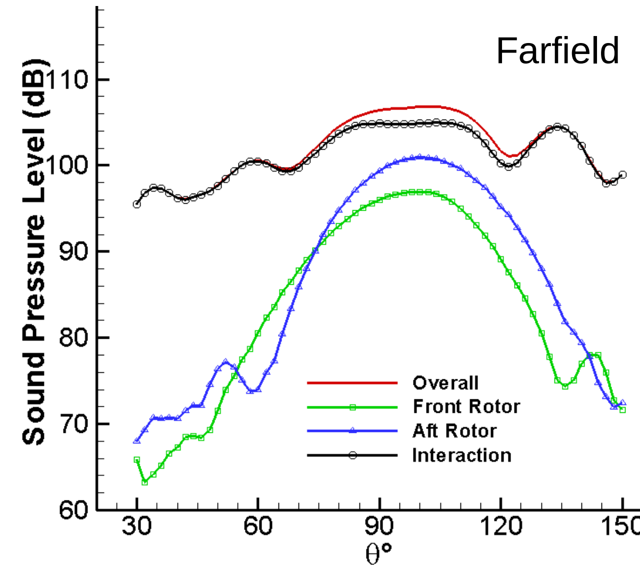




Aeroacoustic Analysis @ LS
Near- & Farfield Noise Radiation

- Highest noise levels in vicinity of rotor planes
- Noise levels higher for 8x8 at most microphone locations
- 8x8 shows 16 lobes in azimuthal directivity
  - Blade-blade interactions every 22.5º of rotation, 16 times at identical locations
- 10x8 shows constant azimuthal noise radiation
  - Blade-blade interactions every 4.5º of rotation, only twice at identical 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





CROR Noise Generation Mechanism #2: Rotor-Rotor-Interaction – Blade Tip Vortices

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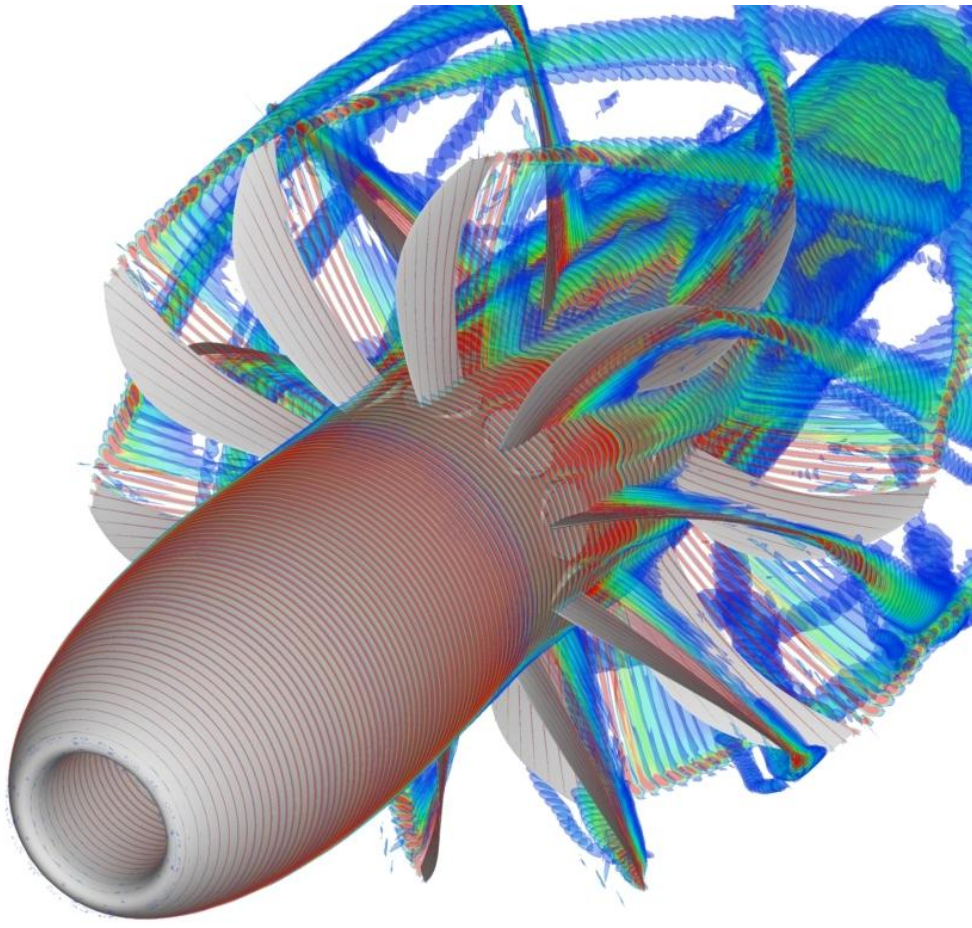
14th CEAS-ASC Workshop
October 7th-8th, 2010
Institute of Aviation
Warsaw, Poland



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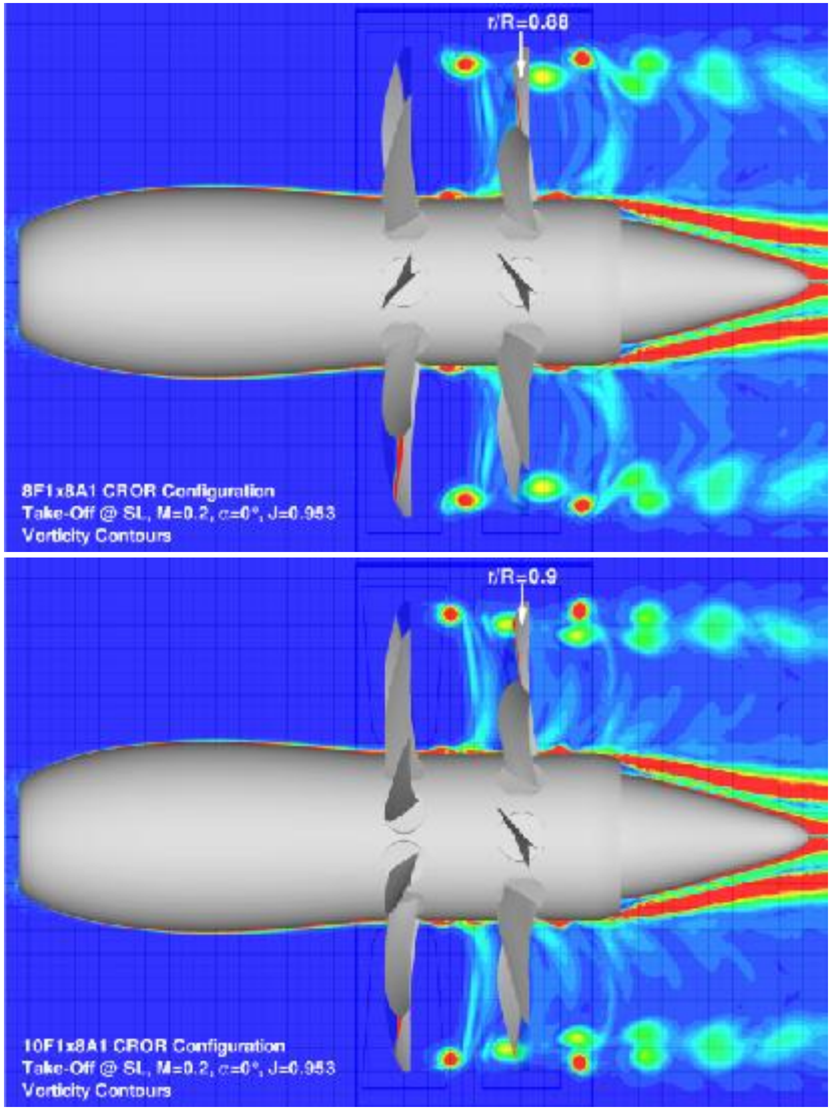
Slipstream Development: Tip Vortex Trajectory

- Investigation of front rotor tip vortex impact on aft rotor blades on noise emissions
- Comparison of vortex track for 10F1x8A1 & 8F1x8A2 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



Slipstream Development: Tip Vortex Trajectory

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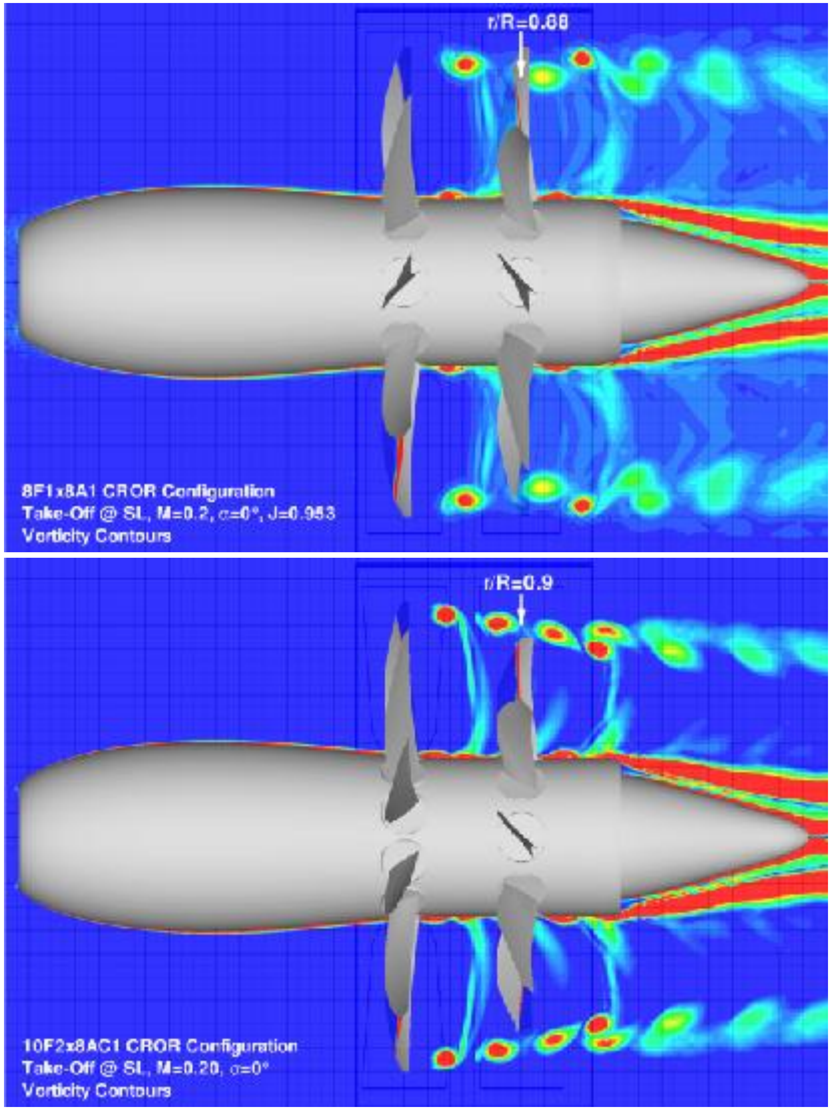
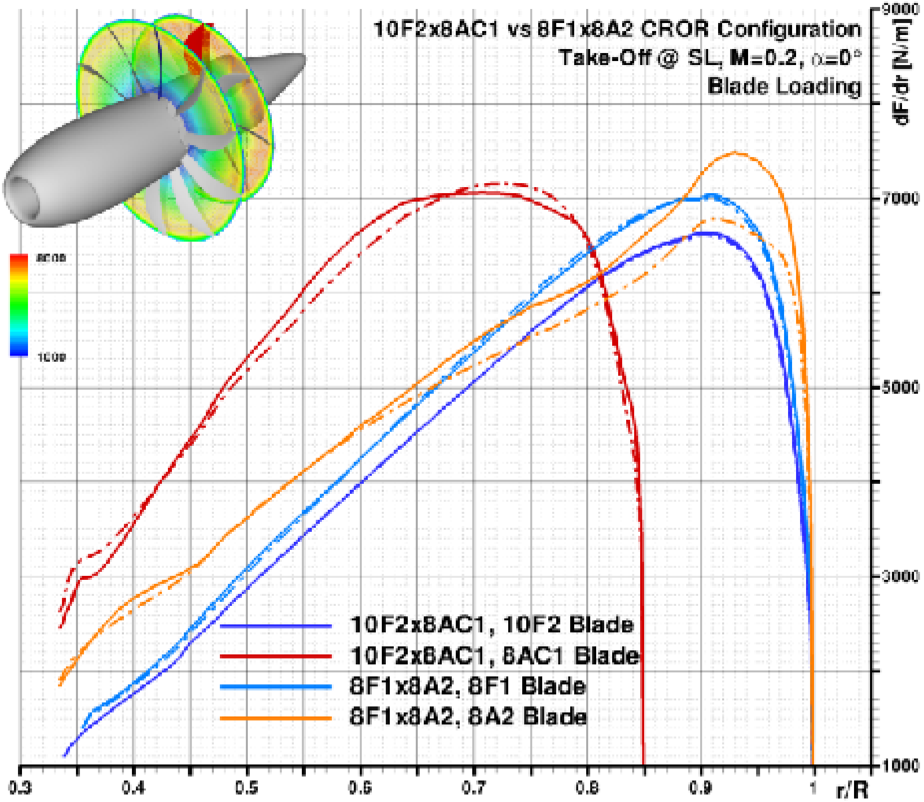
- Guide for blade design of reduced diameter aft rotor
  - 8AC1-blade has a 15%-crop in diameter
  - Direct tip vortex core impingement avoided



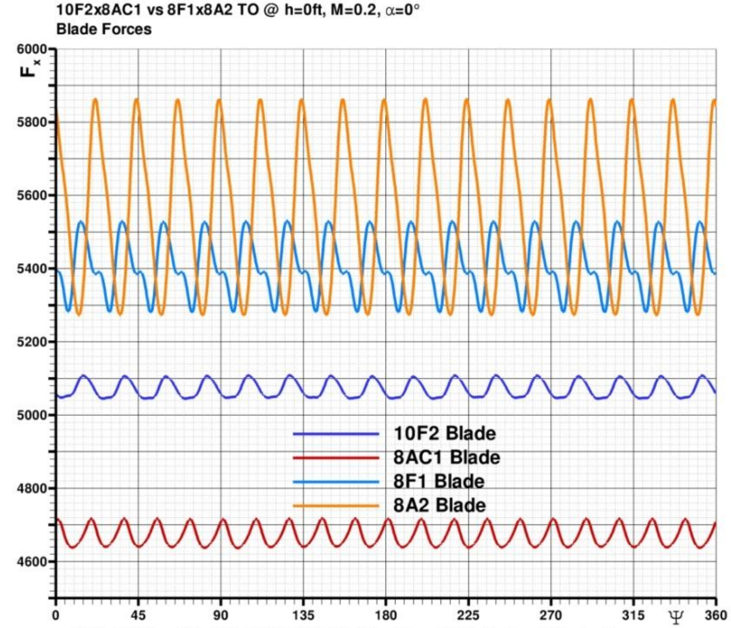
Blade Load Distributions: 8F1x8A2 vs 10F2x8AC1 CROR

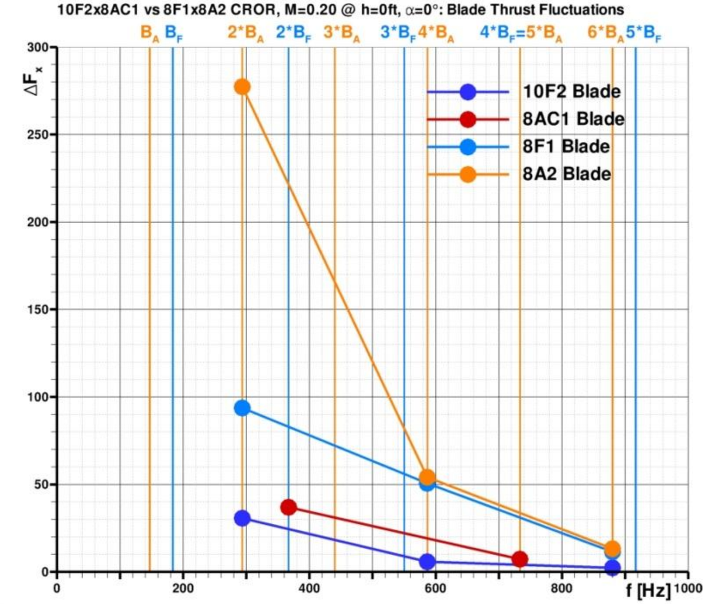
- Blades more highly loaded for 8F1x8A1
- Blades show force oscillations linked to rotor-rotor blade passage
- Front blade wakes lead to full-span fluctuations on aft blades (pronounced at hub and tip)
- Front rotor blade shows smaller oscillations due to aft rotor potential flow
- Tip vortex impact on aft blades is dominant for 8F1x8A2, almost fully avoided for the 10F2x8AC1



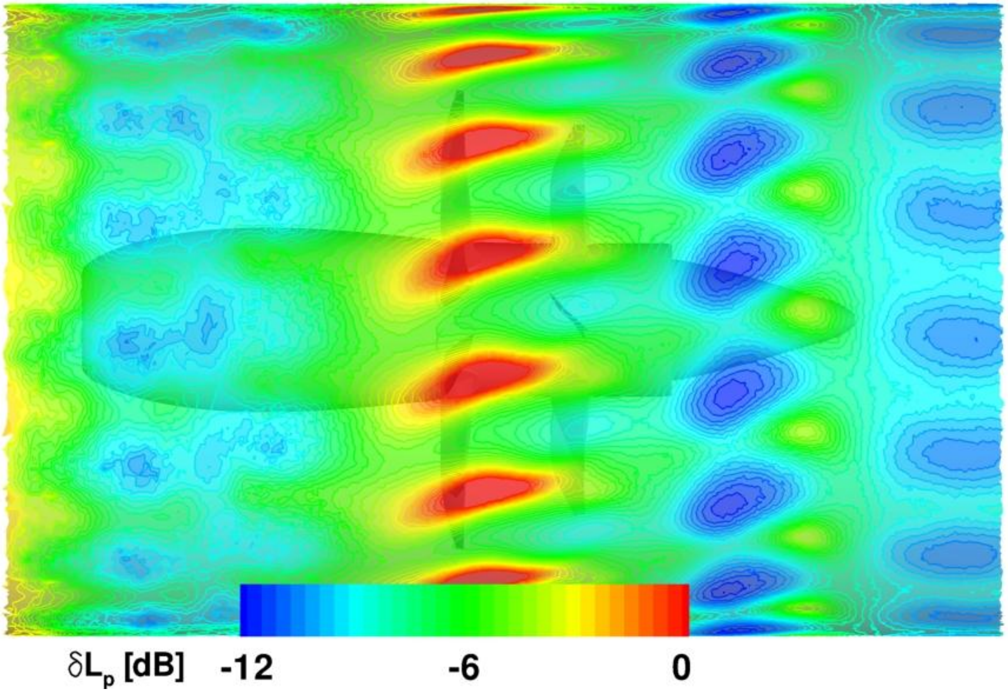
Blade Force Development
Low-Speed Conditions

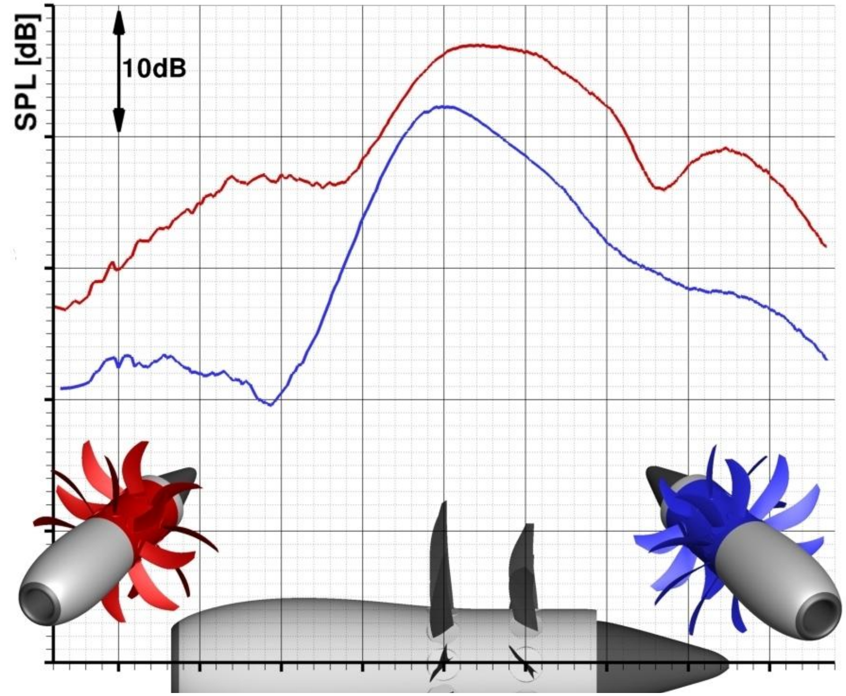
- Higher blade thrust loadings in both rotors for the 8x8 configuration
- Fluctuation amplitudes for aft blades more pronounced
- 8x8 fluctuation amplitudes greater
- Aft blades shows 16/20-cycle fluctuations (i.e. $2*B_F$)
- Front blades shows 16-cycle oscillations (i.e. $2*B_A$ but important contributions also at $4*B_A$)
- FFT Analysis of blade thrust loading:
    - Dominant $2*B_F$ fluctuations for aft blades
    - Importance of higher harmonic thrust oscillations of front blades
    - Tip vortex impingement avoidance reduces aft blade unsteady loading by ~85%





Aeroacoustic Analysis @ LS
Nearfield Noise Radiation





- Highest noise levels for both configurations in vicinity of rotor planes
- Aft rotor cropping reduces noise levels significantly near aft rotor plane of rotation
- Combination of steady & unsteady blade loading reductions for the 10F2x8AC1 CROR configuration leads to significant noise reductions
  - Strong reductions in interaction tone levels