10th Overset Composite Grids and Solution Technology Symposium

NASA-Ames Research Center

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CFD/CSD Coupling and Trim of the SMART Rotor

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Mark Potsdam, *Aeroflightdynamics Directorate (AFDD)*
Mark Fulton, *AFDD*

Arsenio Dimanlig

Science and Technology Corp.

Aviation and Missile Research, Development and Engineering Center (AMRDEC)
Moffett Field, CA

MOTIVATION

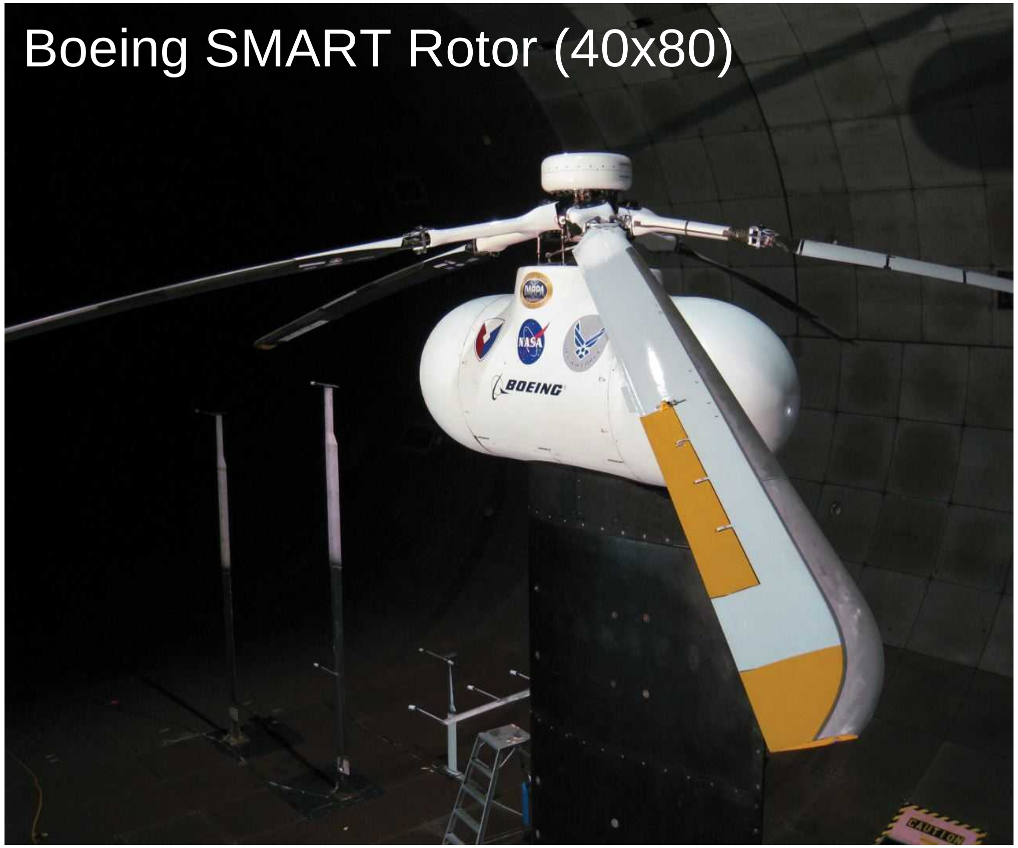
- Army S&T aeromechanics technology objectives
  - Improved rotorcraft characteristics
  - Aeromechanics modeling, accuracy & productivity improvement

Lift to drag ratio	+ 8%
Maximum blade loading	+24%
Vibratory response	-30%
Detection distance	-50%

- Army rotorcraft CFD
  - Development of CFD software analysis tools
    - HPCMO HI-ARMS Institute / CREATE-AV
  - High performance computing
    - Rotorcraft aerodynamics problems require state-of-the-art high-performance computers
  - Cutting-edge research and application to DoD aircraft
    - Improve design process by complementing existing design methods

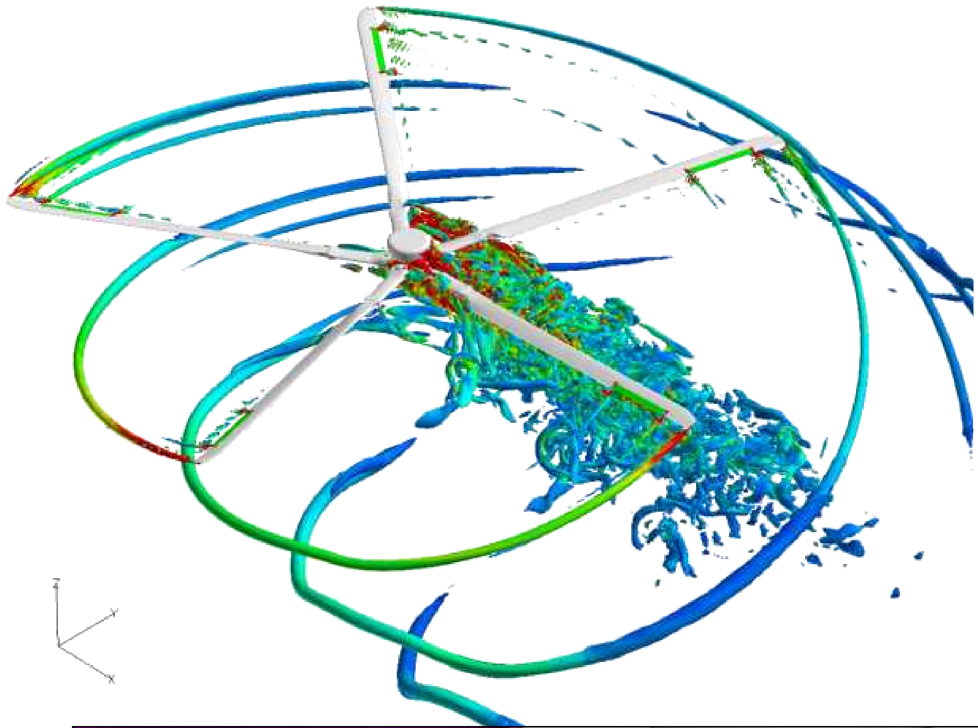
ACTIVE ROTOR CONCEPT

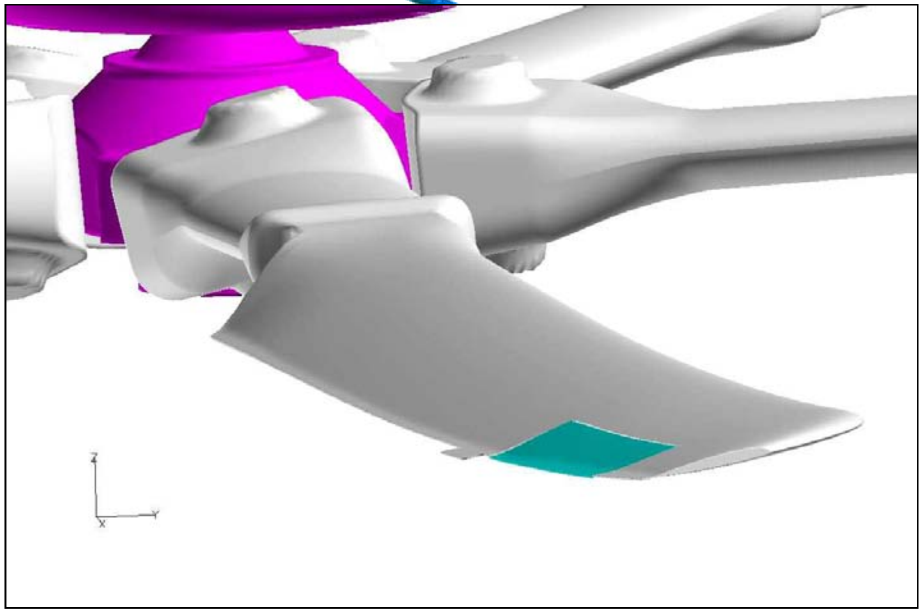
- Benefits of performance, vibration, and noise advancements
  - Improved range, payload, speed, maneuverability
  - Improved component life
  - Reduced maintenance
  - Improved community acceptance
  - Decreased acoustic detectability



MODELING CHALLENGES

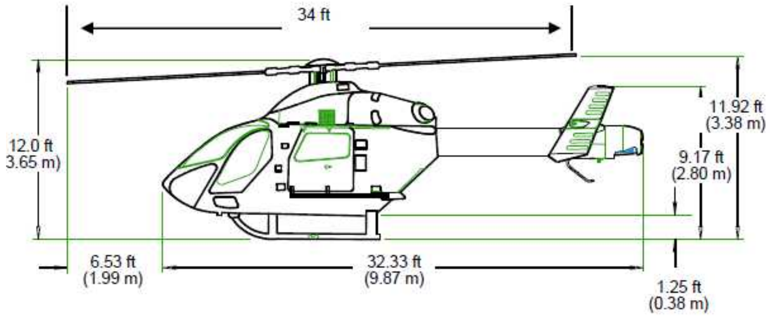
- Unsteady, interactional aerodynamics
- Complex, high-fidelity geometry
- Large range of flow velocities
  - Hover, cruise, maneuver
  - Low subsonic to supersonic
- Disparate length and time scales
  - Rotor, wake, vortices, viscous layers
- Wake modeling
  - Minimize numerical dissipation and convect over long distances
- Turbulence modeling
- Multidisciplinary coupling



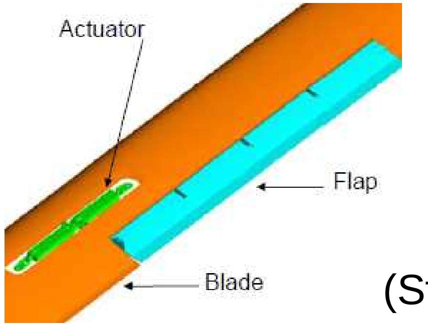


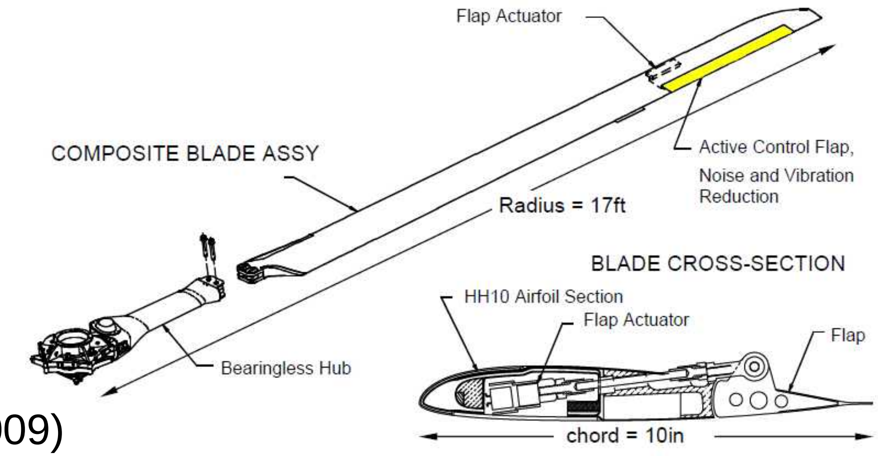
ROTOR CONFIGURATION

- Boeing Smart Material Actuated Rotor Technology (SMART) rotor
  - Full-scale, 5-bladed, flapped MD900 bearingless rotor
    - 16.9 ft radius, 10 inch chord, parabolic tip
    - 18% span piezoelectric flap (74 - 92% R), 35% chord
    - 0.62 hover tip Mach number
- Objectives to demonstrate reductions in
  - Noise: in-plane, blade-vortex interaction (BVI)
  - Vibration
  - Power: cruise - 123, 155 kts (μ = 0.30, 0.38)



MD900 HELICOPTER

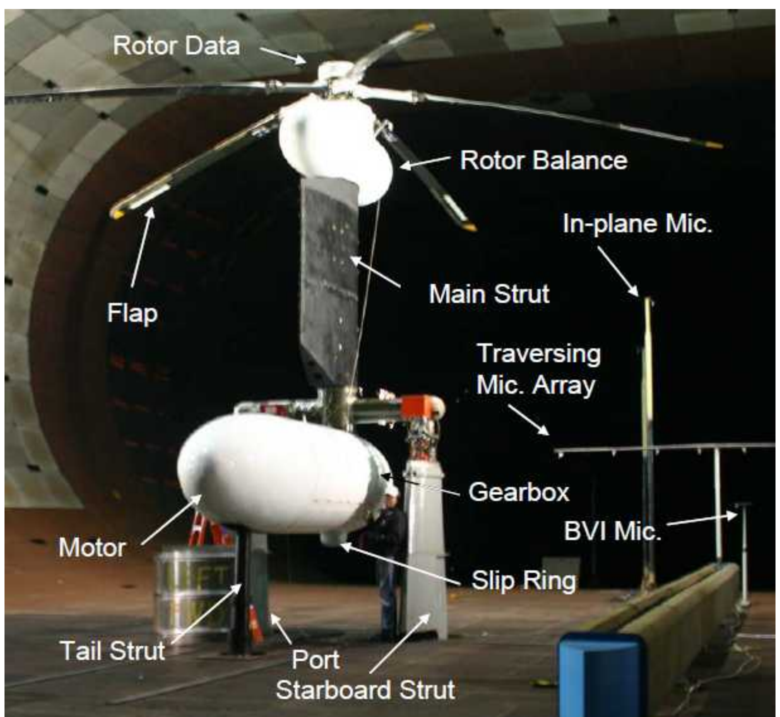


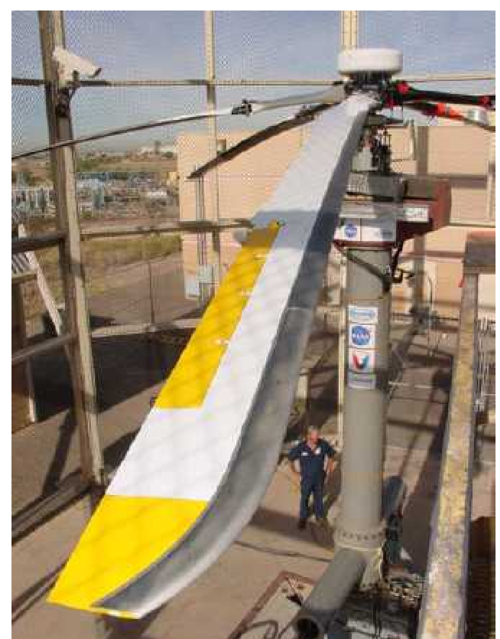


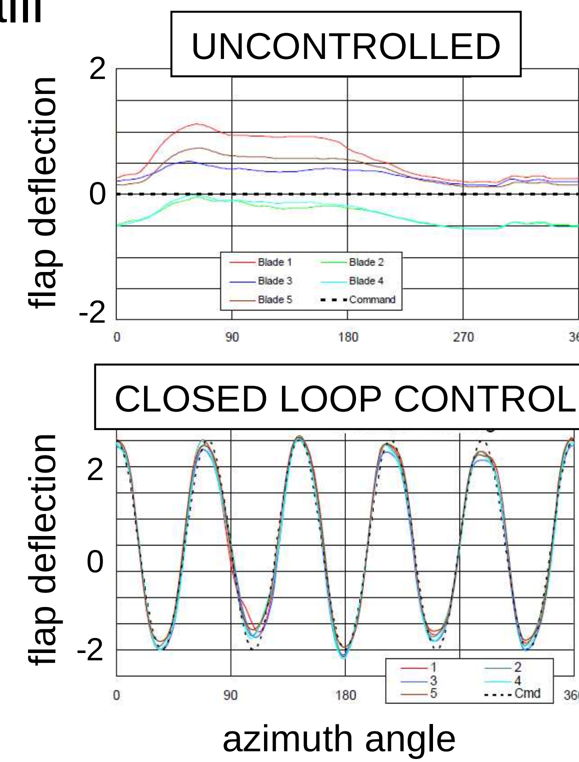
(Straub 2009)

WIND TUNNEL TEST

- DARPA/BoeingNASA/Army test in the DoD National Full-Scale Aerodynamic Complex 40- x 80-Ft Wind Tunnel (NASA Ames)
  - Database of blade and pitch link structural loads, control positions, rotor forces and moments, BVI and in-plane microphones ?(no surface pressures)
  - Papers by Straub, Hall, JanikaRam, Sim, and Kottapalli at 2009 AHS Forum





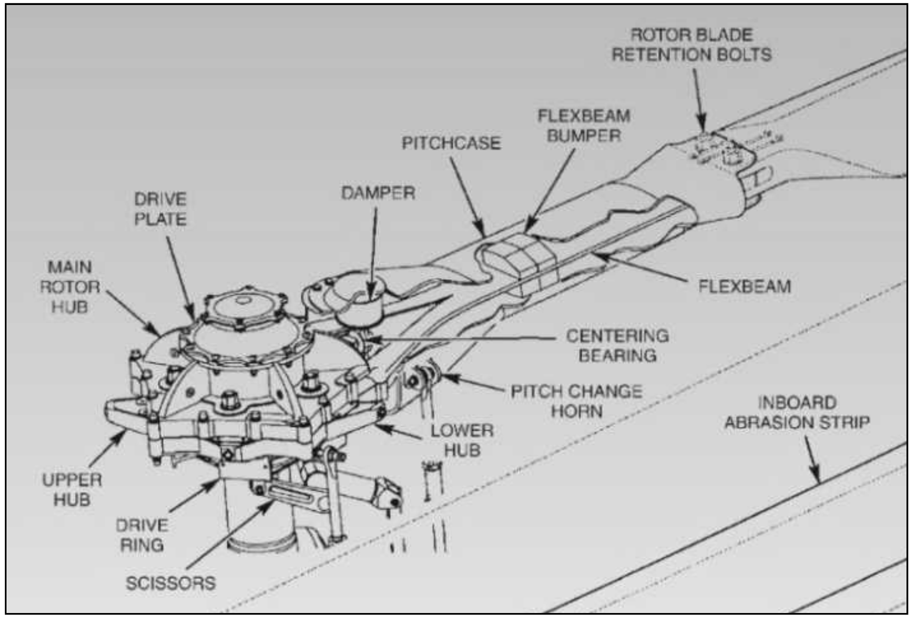


closed loop flap control

(Straub/Hall 2009)

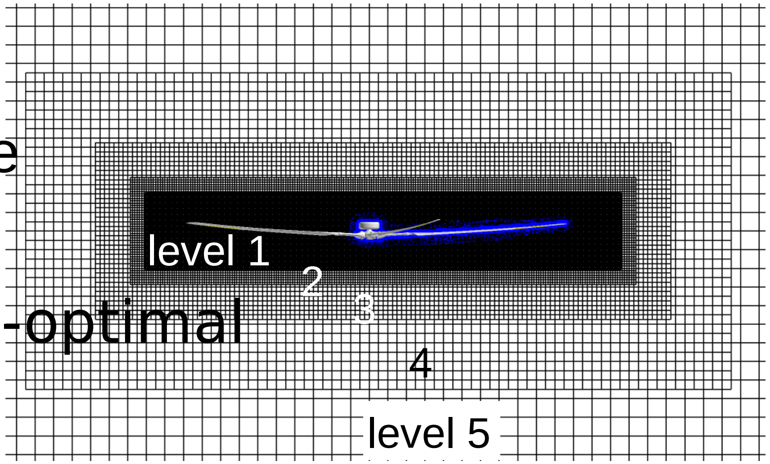
CSD MODEL

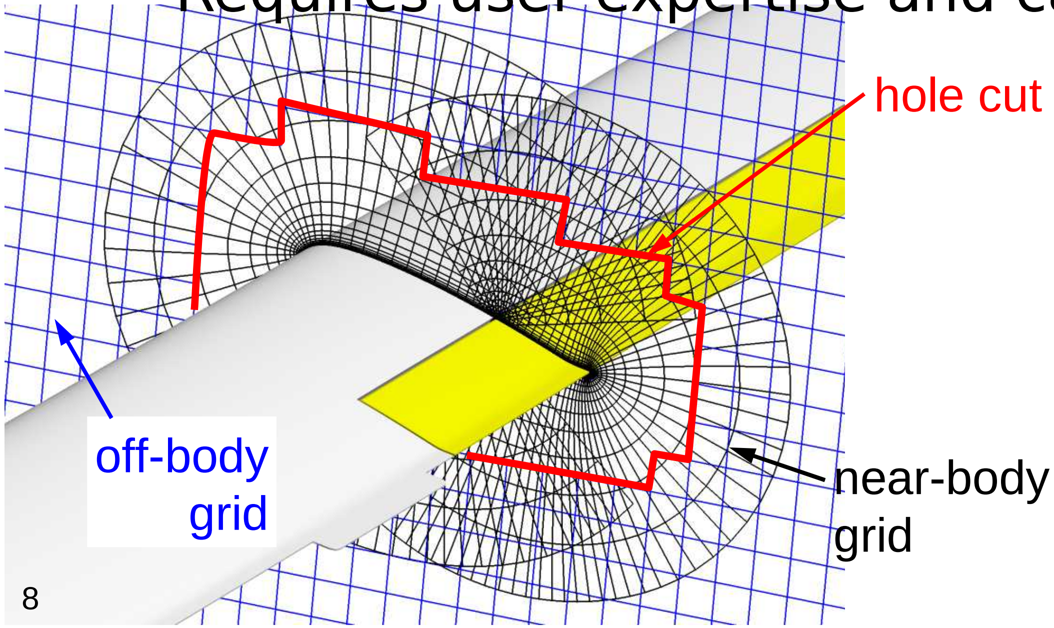
- CAMRAD II
  - State-of-the-art multidisciplinary rotorcraft comprehensive analysis (CA) performs structural dynamics and trim
  - CFD/CSD coupling replaces CA aerodynamics
  - Important to ensure CFD and CSD geometric consistency
- Aerodynamic model
  - Blade element lifting-line aerodynamics with airfoil table lookup (Mach, α, δ_f)
  - 20 aerodynamic panels with continuous flap
  - Free wake (CA) or uniform inflow (CFD/CSD)
- Structural model
  - Boeing SMART rotor properties (NASA/Boeing)
  - 10 non-linear beam finite elements:
    - Axial, lead-lag, flap, torsion and DOFs
    - Dual load path blade root (flexbeam/pitchcase)
  - *Elastic trailing edge flap* with 5 hinges
  - Compliant pitch links
  - 18 modes used
  - *Numerical conditioning issues*

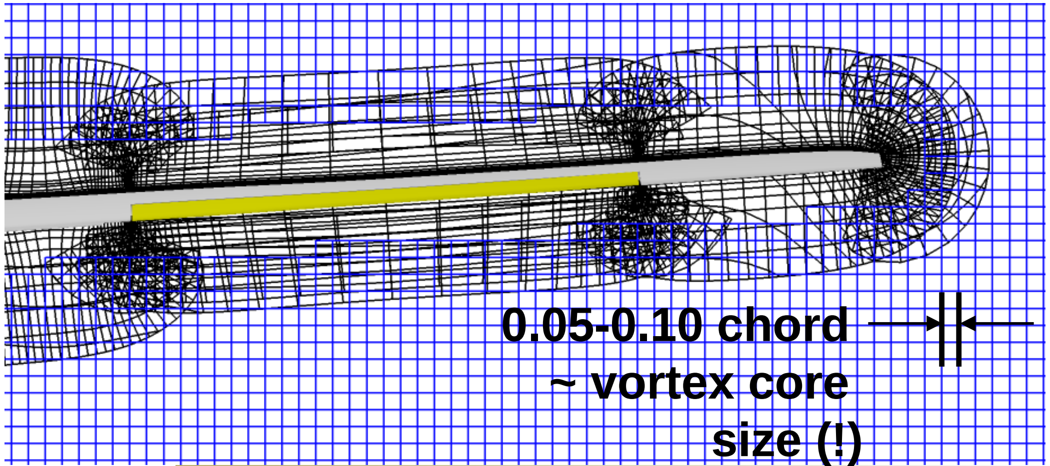


CFD METHODOLOGY

- OVERFLOW 2.0aa (NASA/Army)
  - Near-body, off-body overset grid paradigm
- Body-fitted, stretched curvilinear "near-body" grids
  - Structured grid generation is labor intensive for complex configurations
- Automatic, multi-level, Cartesian "off-body" grids
  - Efficient, accurate, automated, and adaptable
- Subroutine-activated domain connectivity
  - Requires user expertise and can be sub-optimal

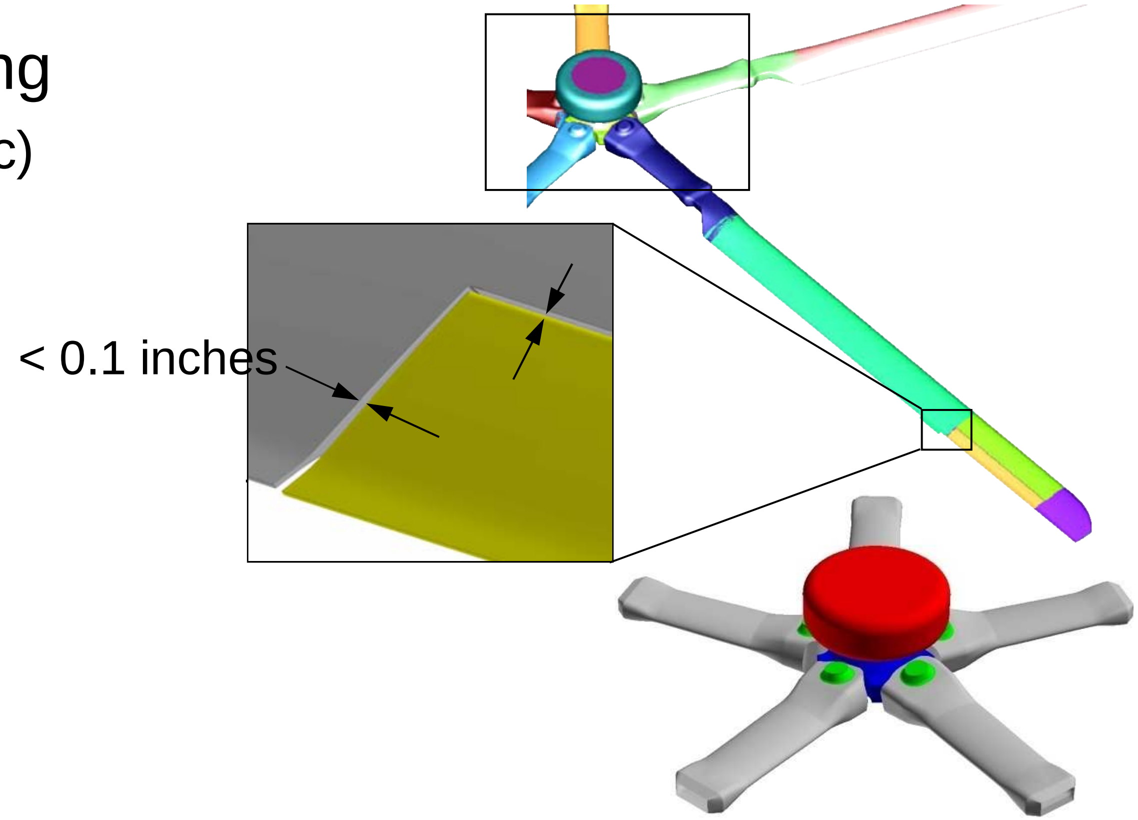


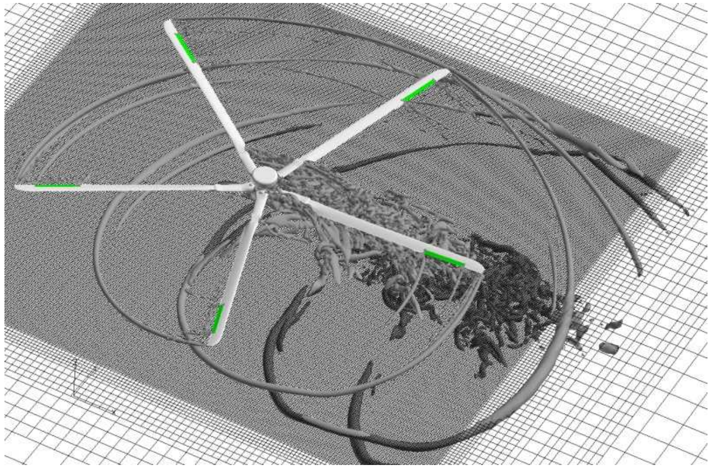




CFD MODEL

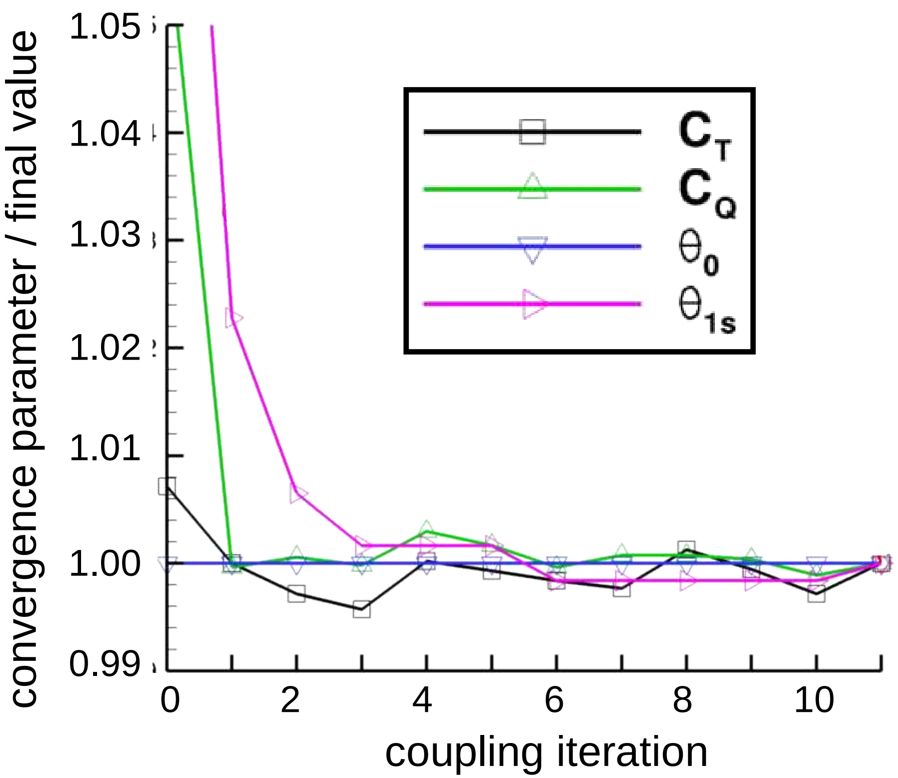
- High-fidelity geometric modeling
  - Pitchcase, blade and flap (elastic)
  - Hub and instrumentation fairing
  - *Discrete flap gaps*
- Grid generation
  - Baseline (coarse) grid
    - 17 million grid points
      - 820,000 points per blade
      - 75% off-body
    - 12% chord wake spacing
  - Fine grid with 66 million points
- Numerical scheme
  - 3rd-order spatial central-difference scheme with matrix dissipation
  - 2nd-order temporal scheme with subiterative dual-time stepping
  - 0.25° time step (RPM?)





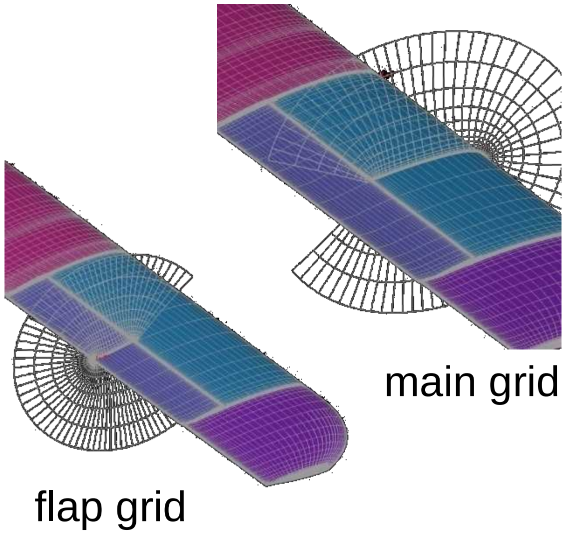
CFD/CSD COUPLING CONVERGENCE

- Loose coupling exchanges periodic forces/moments
- "Dual rotor" concept, main and flap treated as separate "rotors" in CFD
- Modifications for multiple grids per blade
- Convergence on controls, forces/moments, and airloads

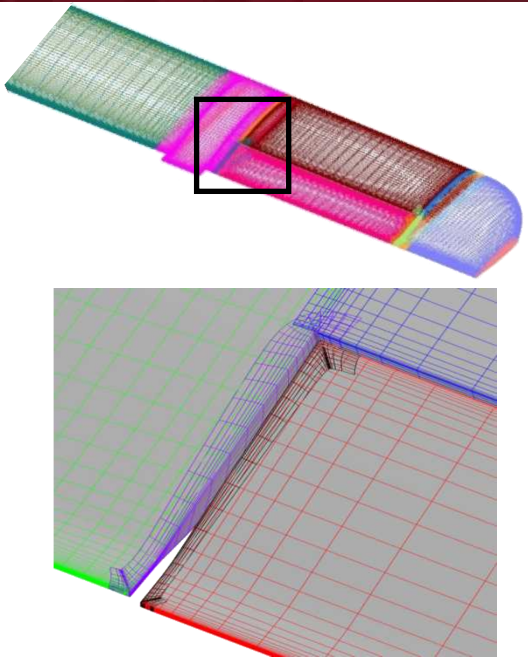


HOLE CUTTING AND CONNECTIVITY

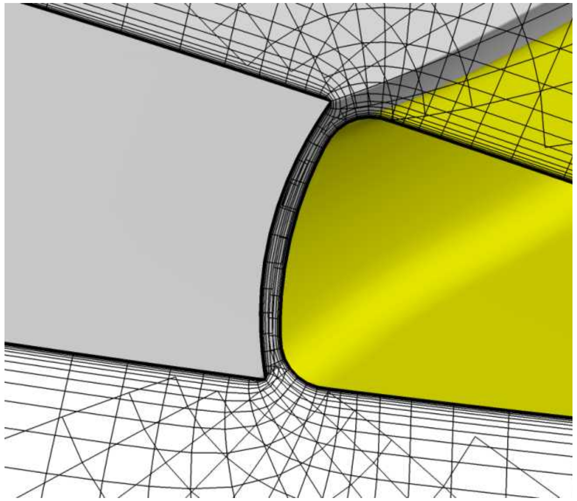
- Complex and expensive grid connectivity using object xrays
  - Tight tolerances to avoid collisions
  - Must be performed every step
  - Xrays do not handle disparate geometric fidelity very well
  - Poor donor compatibility possible
- Resolutions
  - Parallelized
  - Elasticized
  - Attention to details
  - Reduced memory
  - Cost reduced to < 20% flow solver step
  - Now in OVERFLOWv2.2



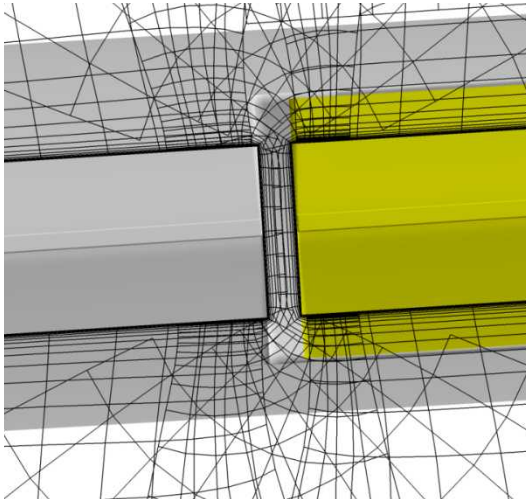
overset volume grids



overset surface grids

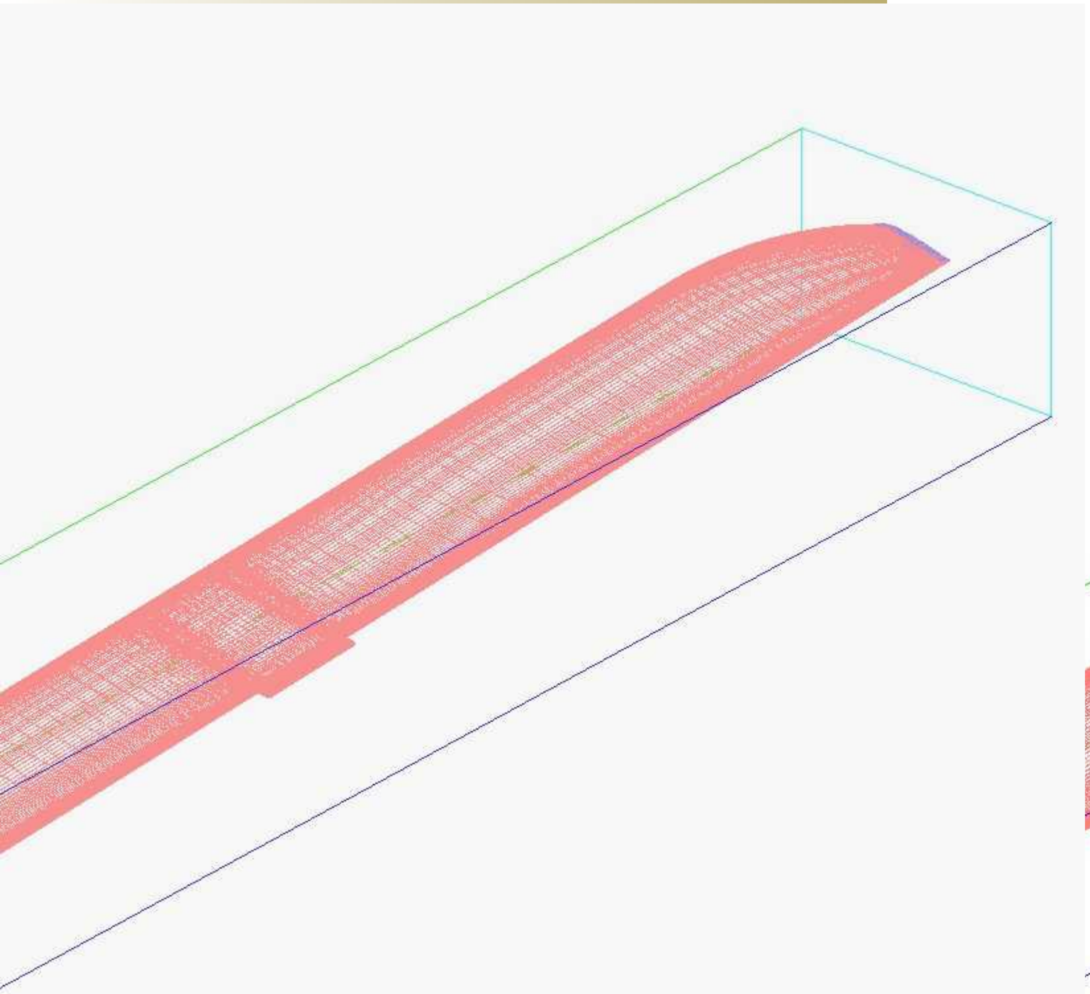


chordwise flap gap

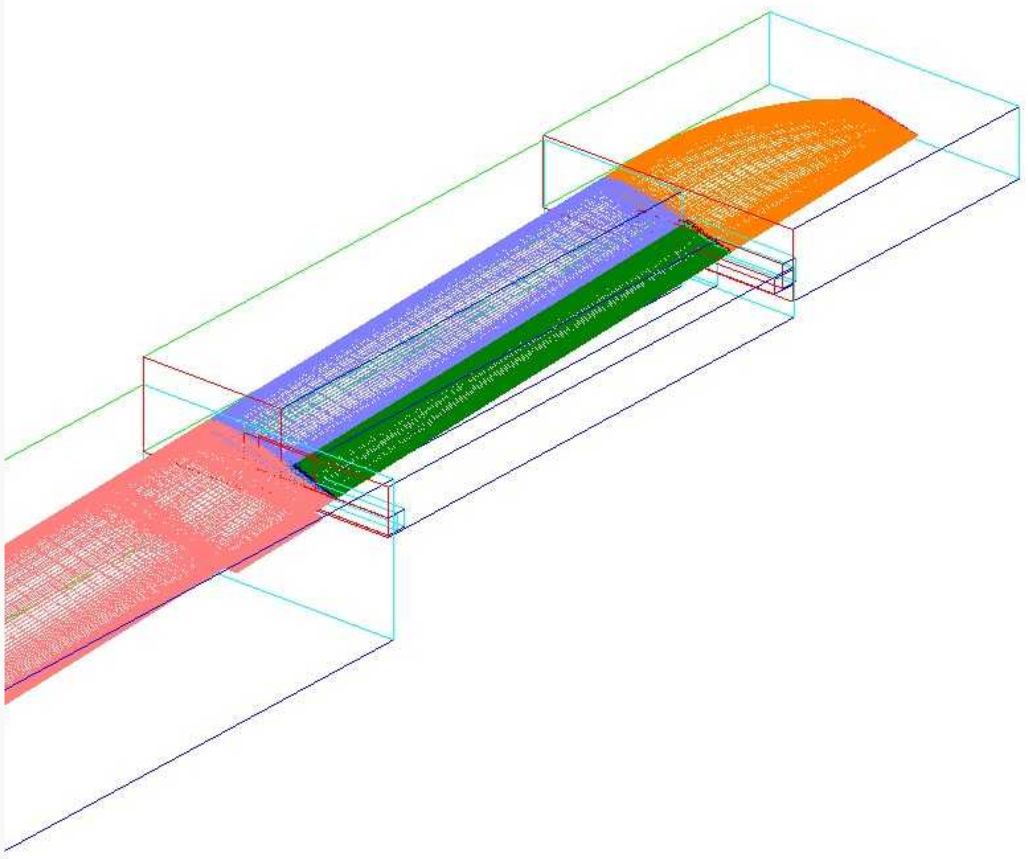


spanwise flap gap (rear view)

XRAY STRATEGY-OVERALL



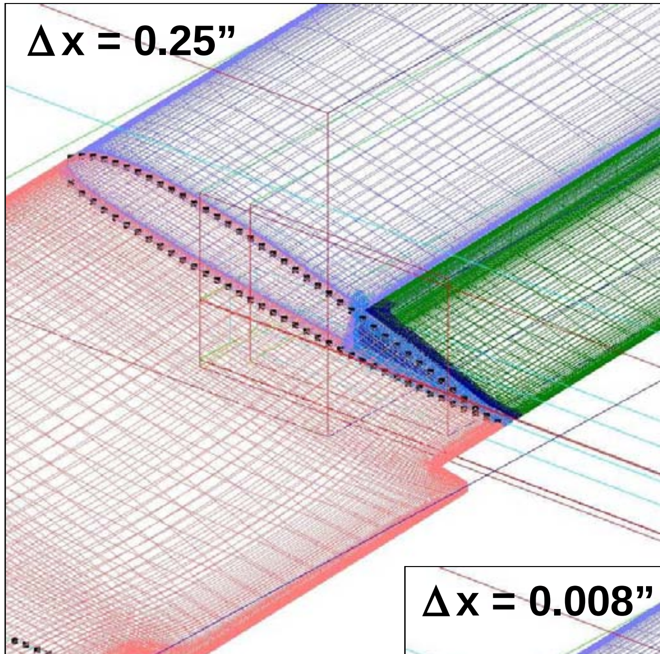
Single Blade - Single XRay
10MByte Xray file size



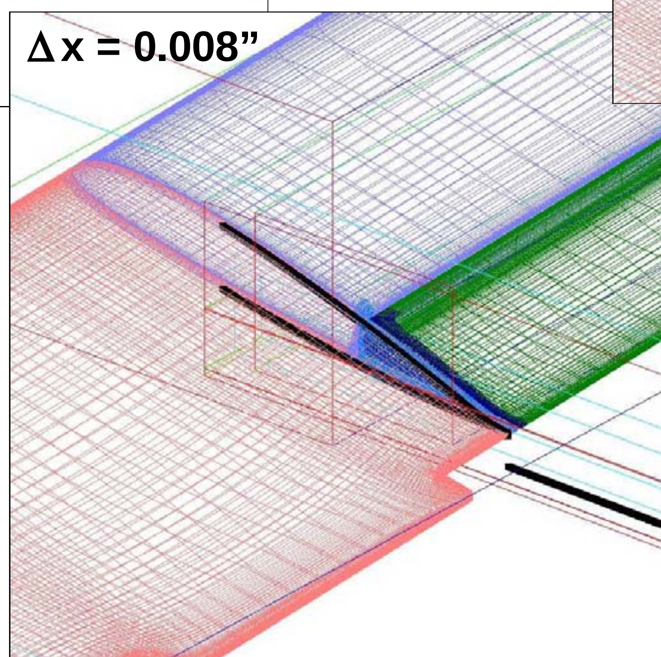
Blade and flap - 10 XRays
185MByte Xray file size

Coarse and fine grids have to use the same XRAYS

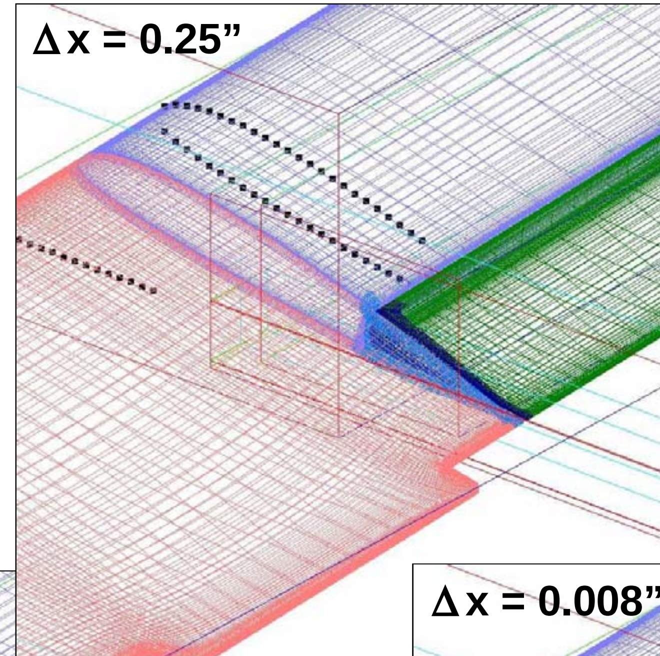
XRAY STRATEGY- GAP DETAIL



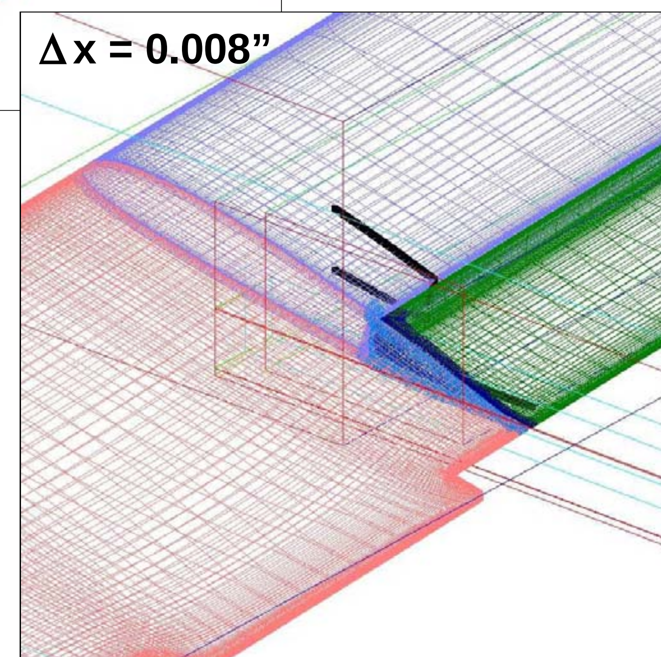
395 x 77



103 x 1376

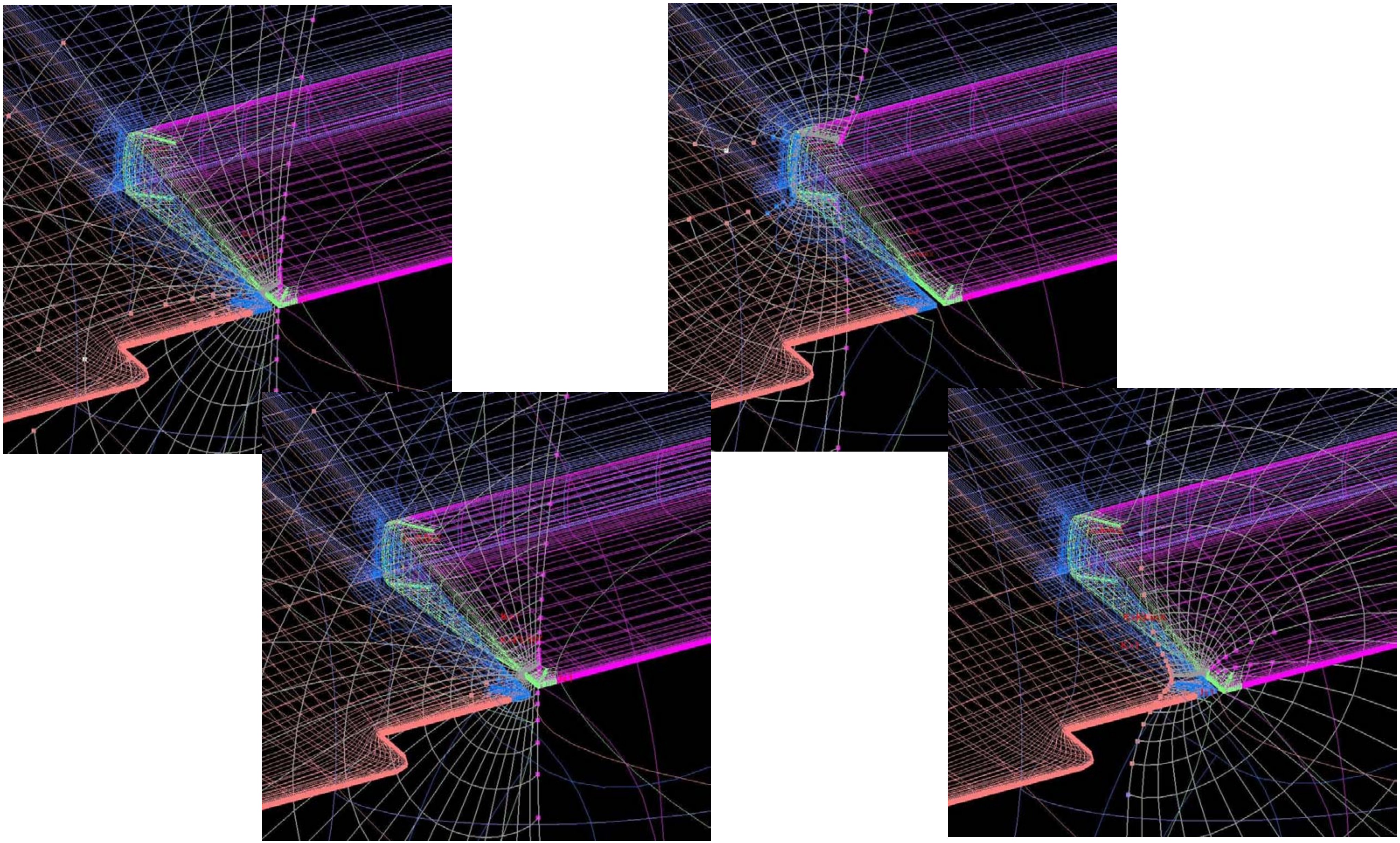


147 x 43



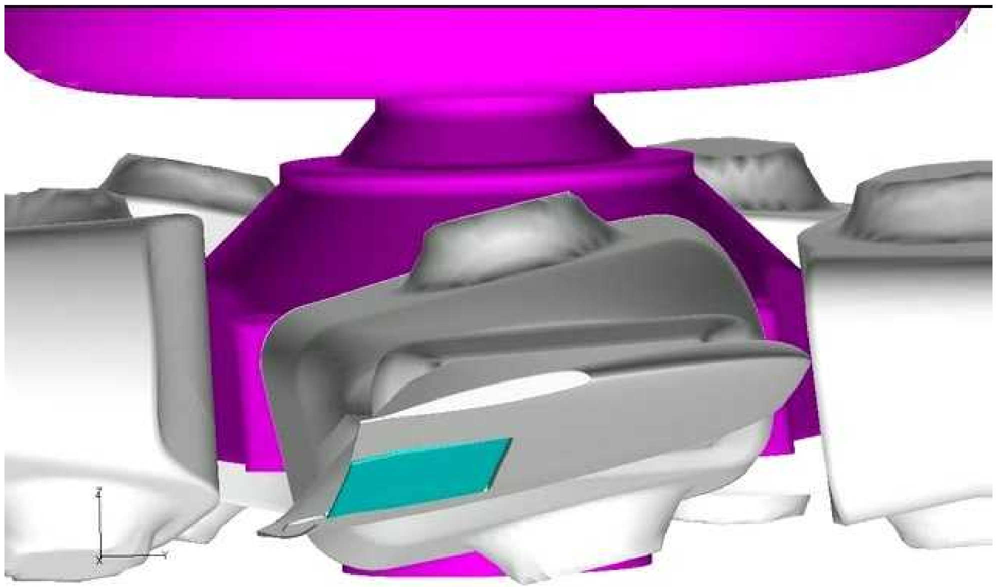
1831 x 221

ORPHAN POINTS



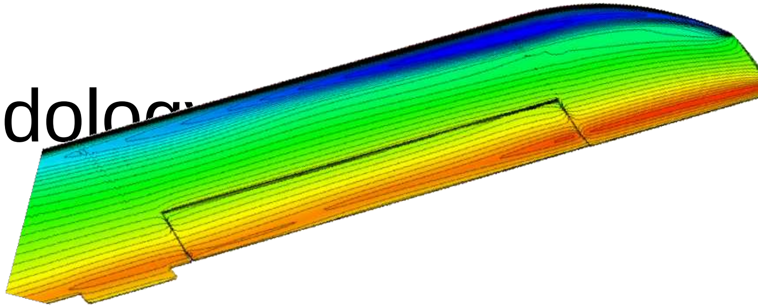
EARLY ATTEMPTS

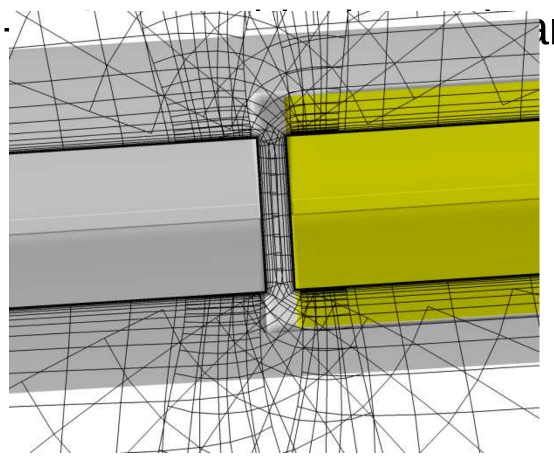
- What could possibly go wrong!?

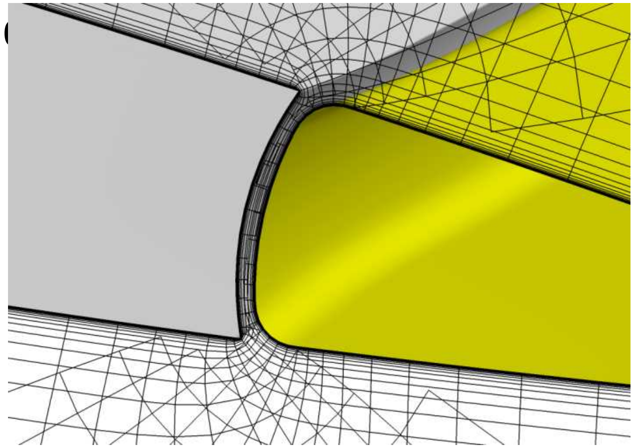


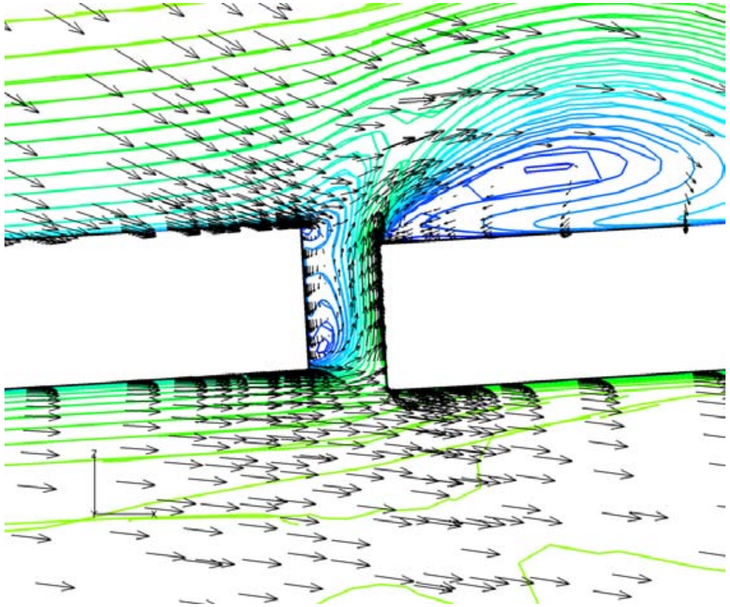
FLAP GAP DETAILS

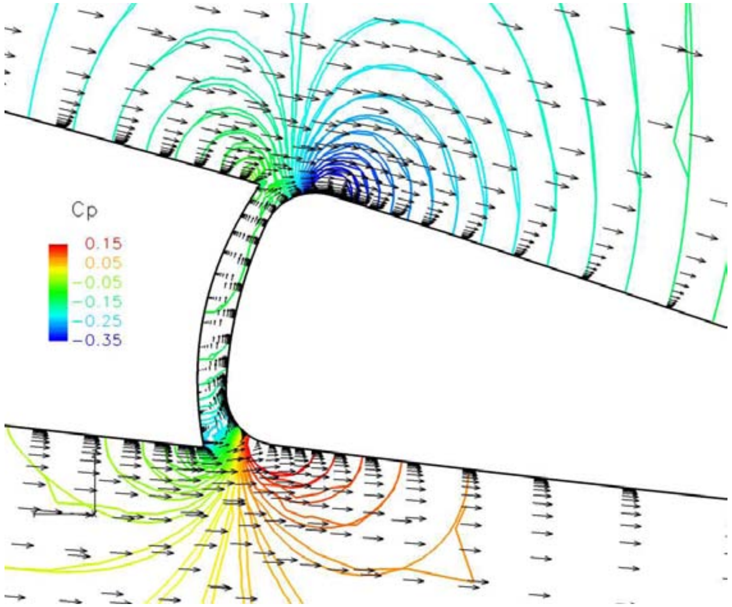
- Complex, 3D flow in flap gaps
- Major challenge for overset grid methodolog
  - and

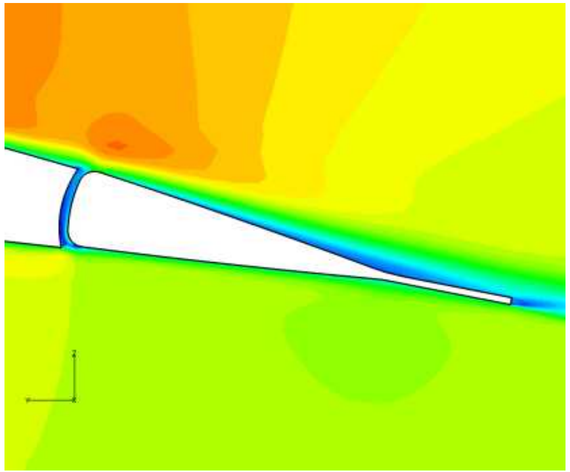












spanwise gap

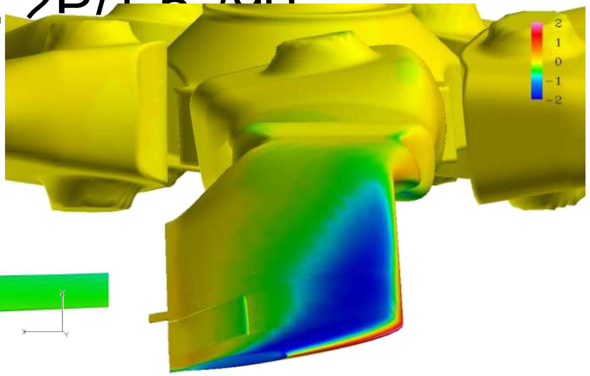
chordwise gap

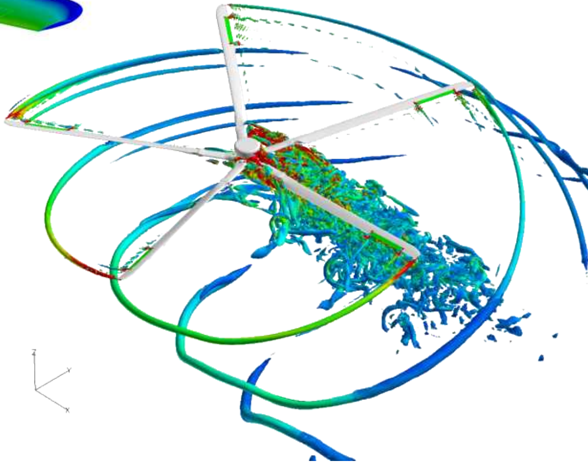
COMPUTATIONAL COST

- Coupling every 2/5 rev for 7 iterations (4 revs)
- Baseline coarse grid
  - 128 processors of a Cray XT5
  - 4.2 hours per rotor revolution
  - Coupled solution in ~16 hours
- Fine grid
  - 320 processors
  - 16 hours per rotor revolution

ANALYSIS AND RESULTS

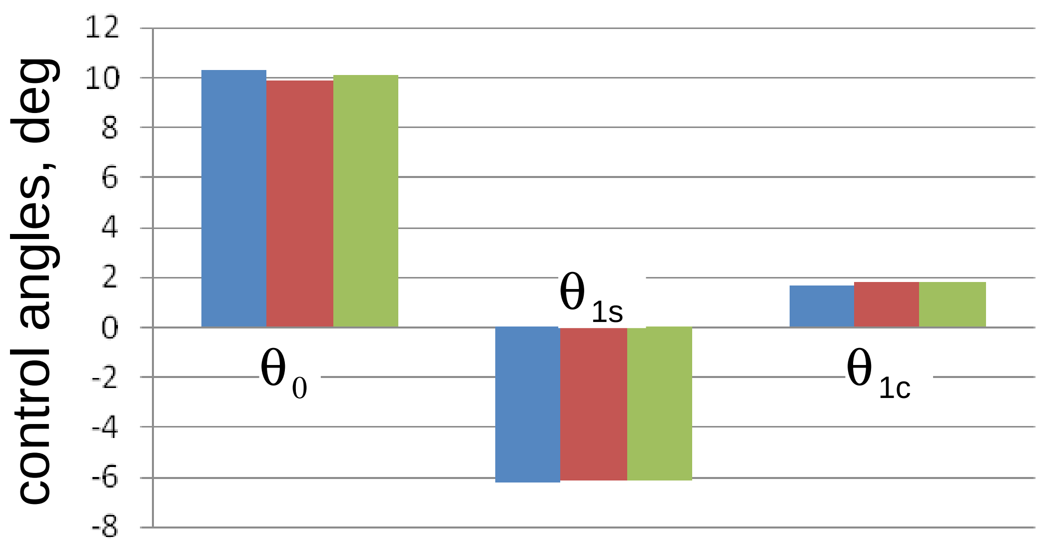
- Baseline flight conditions
  - C_T/σ = 0.075, 123 kts, 0.30 advance ratio, α_s = -9.1º (nose down)
  - Trim conditions: thrust, zero flexbeam cyclic flapwise bending moment
    - Retrim at each flap input
  - Flap inputs: frequency, amplitude, and phase – e.g. 2P/1.5°/90°
    - Frequency: 0, 2, 3, 4, and 5/rev
    - Amplitude: nominal 1.5° flap deflection
    - Phase angle sweep in 30° increments
- Multidisciplinary investigations
  - Airloads and structural loads
  - Aerodynamics and flow physics
  - Performance
- Comparison with CAMRAD II and experimental results
- Most results use the coarse CFD grid



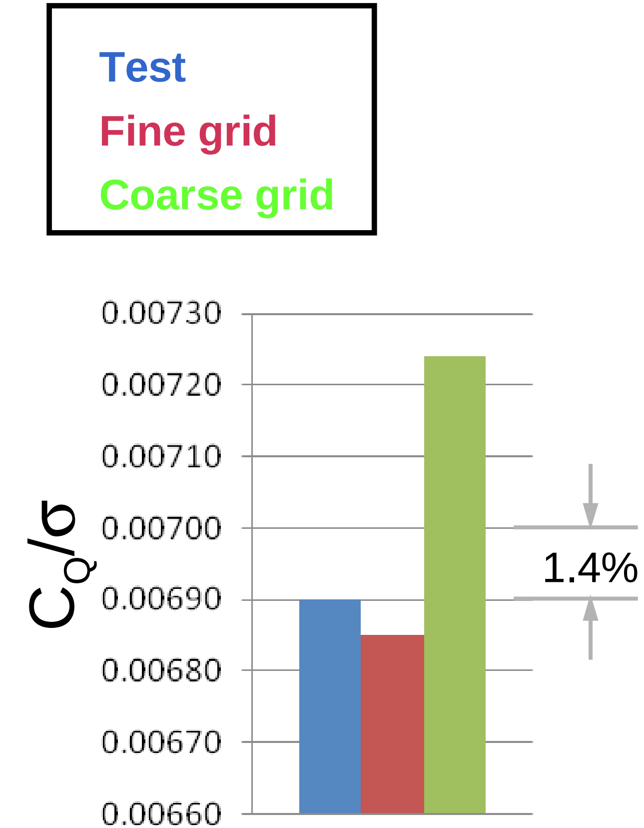


PERFORMANCE

- No flap deflection SMART configuration
- Good agreement with test for pitch control angles and (fine grid) torque
- Consistent comparison with experimental force data buildup (including hub)



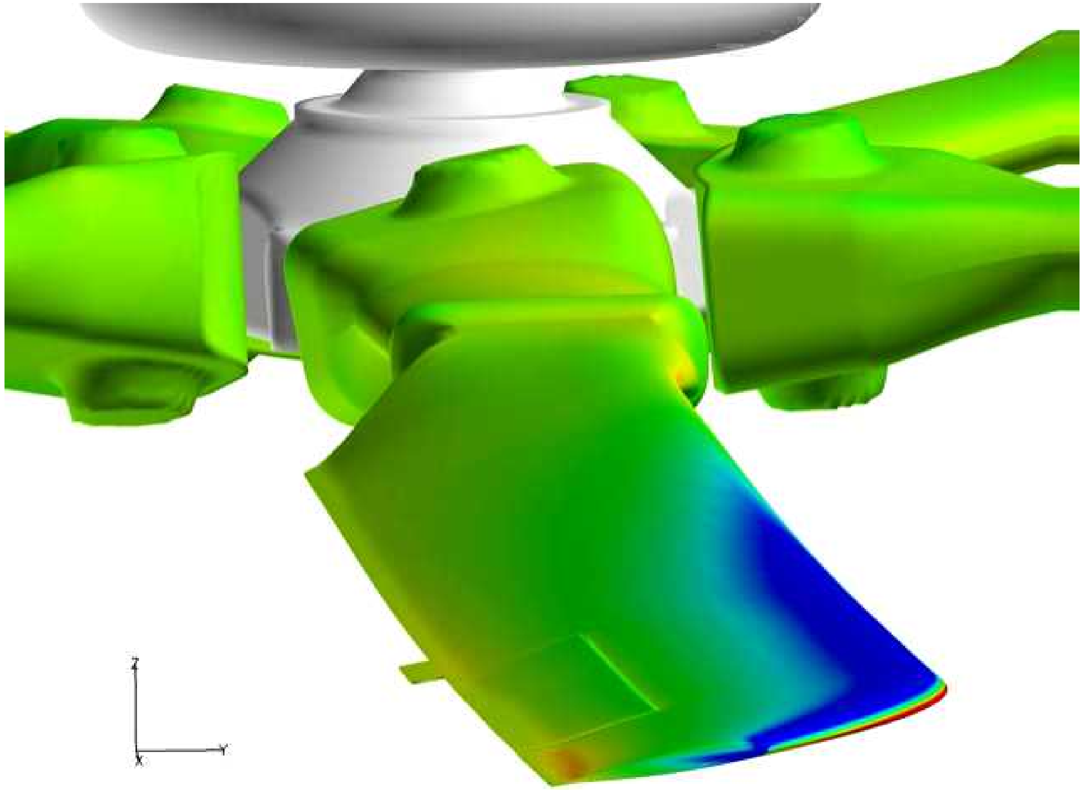
trim control angles



rotor torque

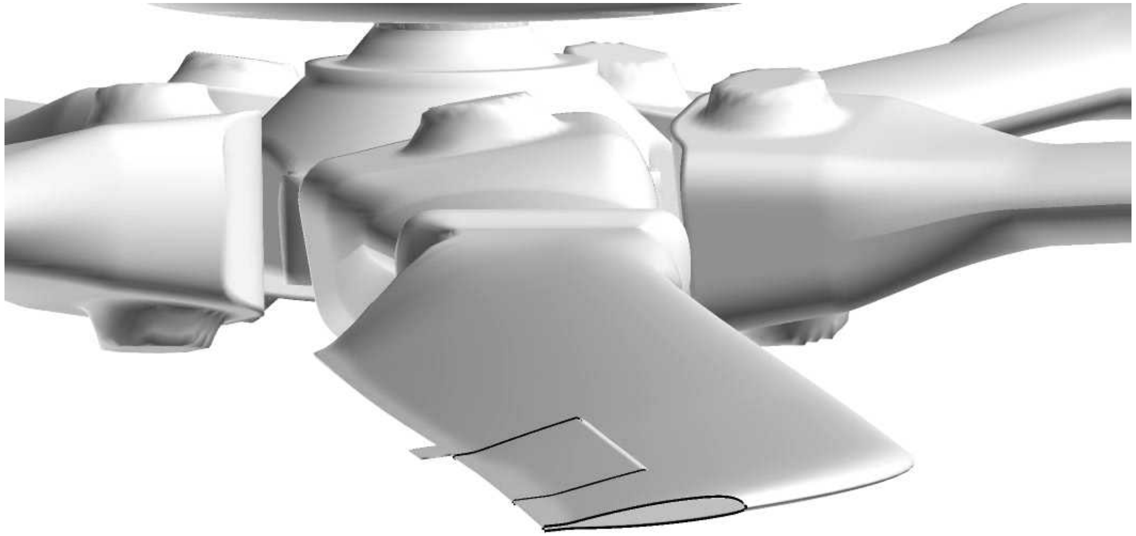
ZERO-FLAP DEFLECTION

- **Complex fluid-structure interactions**
- **Blade-fixed reference frame**

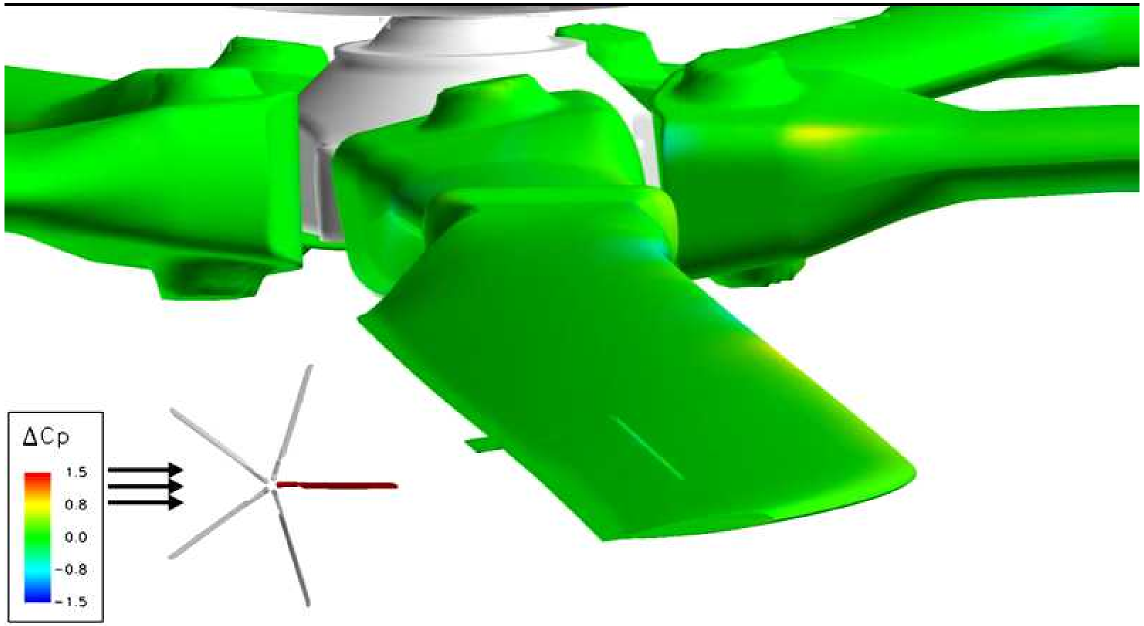


FLAP INPUTS

- Moment flap mechanism
- 5P/1.5°/180°

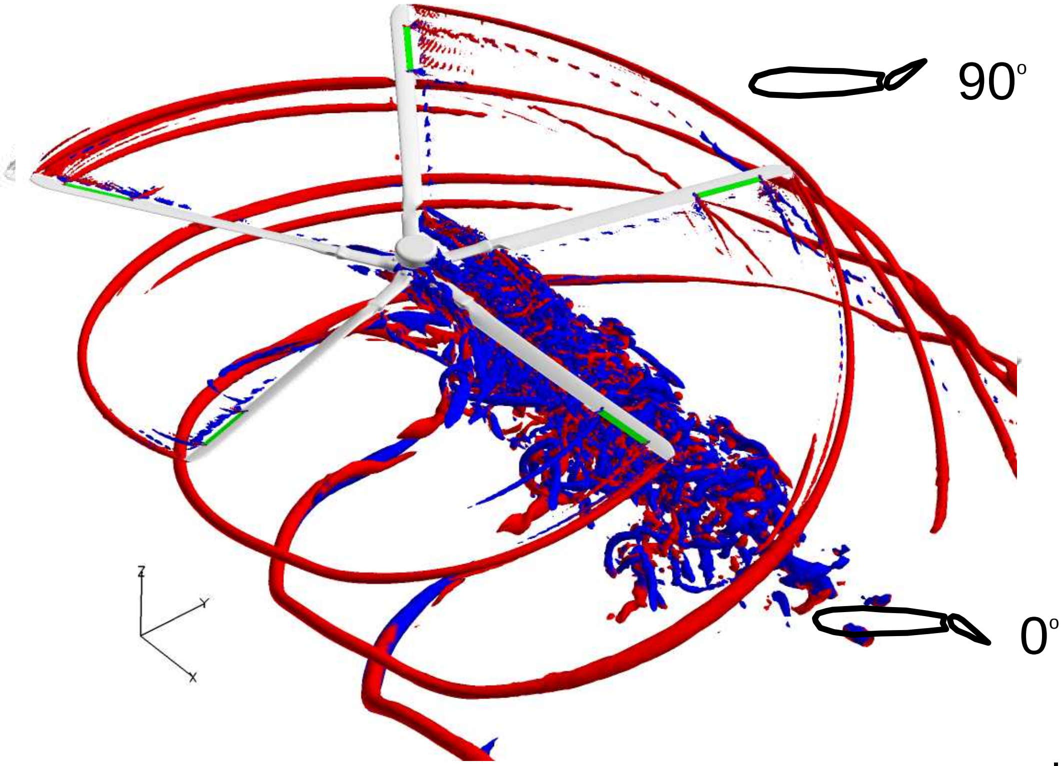


- Incremental motions (exaggerated) and pressures from the baseline



- Detailed wake visualization and interactions
  - Blade tip and flap end vortices
  - Hub wake
  - Super-vortex roll-up

2P/1.5º/90º

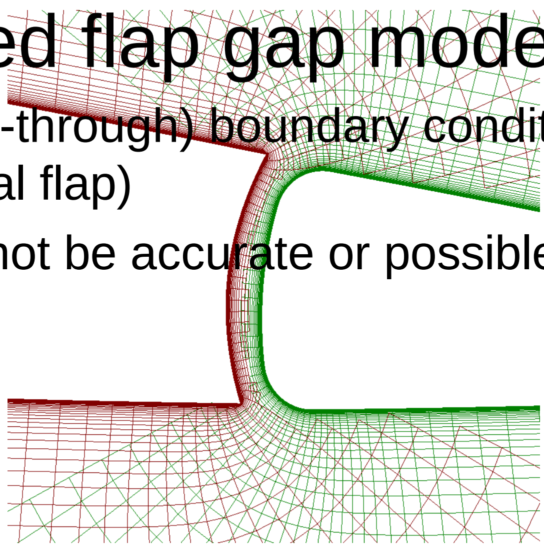


colored by sense of vorticity

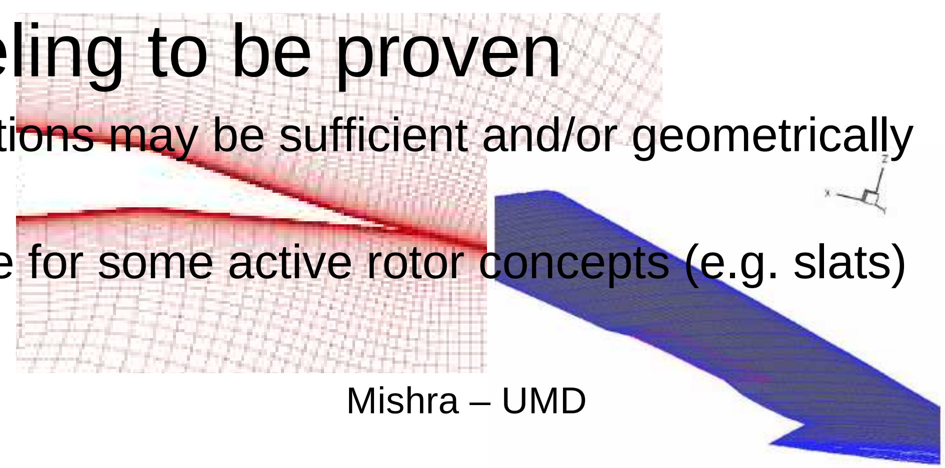
Q criterion

LESSONS LEARNED RECOMMENDATIONS

- The SMART flapped rotor is a challenging configuration for current state-of-the-art CFD, CSD and CFD/CSD coupling tools
  - Considerable user expertise required
  - Need for automated and optimized CFD domain connectivity procedures
  - Need for CSD templates for complex configurations
- Modeling the flap gaps is a time consuming, detail-oriented task
  - Consistency in the fluid-structure interface required
- Need for detailed flap gap modeling to be proven
  - Simplified gap (flow-through) boundary conditions may be sufficient and/or geometrically realistic (e.g. integral flap)
  - Simplification may not be accurate or possible for some active rotor concepts (e.g. slats)



gap modeling



Mishra – UMD

integral flap, gap approximation

ACKNOWLEDGEMENTS

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