Development of A High-Fidelity Multidisciplinary Design Optimization Framework for Rotorcraft Applications

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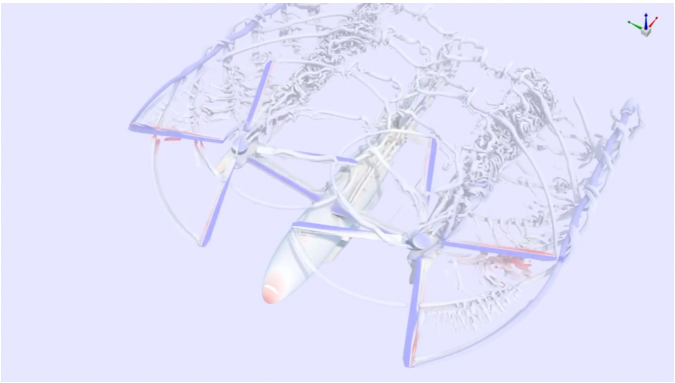
Outline

- Background & Overview
- Coupled CFD/CA Solvers
- Multidisciplinary CFD/CA Sensitivity Analysis Framework
- System Verification and Validation
- Demonstration of Multidisciplinary, Multipoint Design Optimization
- Concluding Remarks

Background

- Computational fluid dynamics (CFD) tools
  - High-fidelity, first-principle approach
  - Major simulation tools for aerodynamics
  - Large-scale simulations performed in supercomputing environment
  - Widely applied to rotorcraft simulations
  - Understanding of complex rotor flows and interactions
  - Insights to optimize design
- Rotorcraft aeromechanics requires multiple disciplines
  - Aerodynamics – airloads, rotor performance
  - Structure/multibody dynamics – blade deflections, trim, stability
  - Aeroacoustics – rotor noise and propagation
  - Flight dynamics, etc.



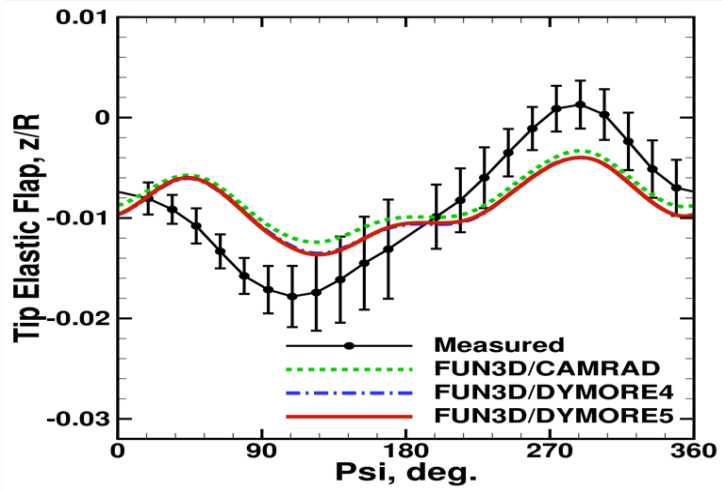
Urban Air Mobility
Air Taxis with Side-By-Side Rotors
Video Credit: NASA ARC / T. Sandstrorm

NASA Ames NAS Pleiades Facility

Background

- Coupling of aerodynamics and structure dynamics accounts for complex fluid structure interactions
  - Helicopter blades highly flexible – rigid blades not representative
  - Blade elastic motions of torsion, flap, and lead-lag coupled with rigid motions (e.g., high harmonic pitch controls)
  - Blade loading and structure responses vary and interact dynamically
- Rotorcraft comprehensive analysis (CA) tools encompass various models
  - Varying levels of fidelity, low cost
  - Widely used in rotorcraft industry
  - Rely on low-fidelity aerodynamics model (e.g., lifting line theory) – insufficient for resolving three-dimensional flow/compressibility

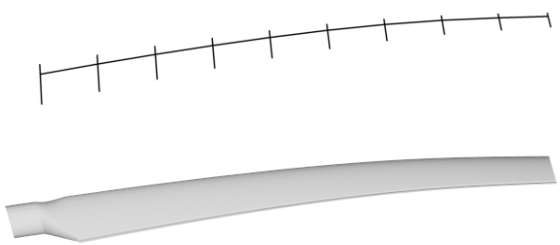
Main Rotor Blade Motions
Mil Mi-8 Flight Test
Video Credit: Technical Test Centre and Faculty of Mechanical Engineering, Belgrade



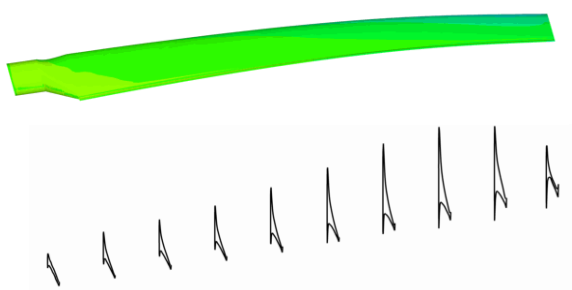
HART-II Rotor Blade Tip Elastic Flap

Overview

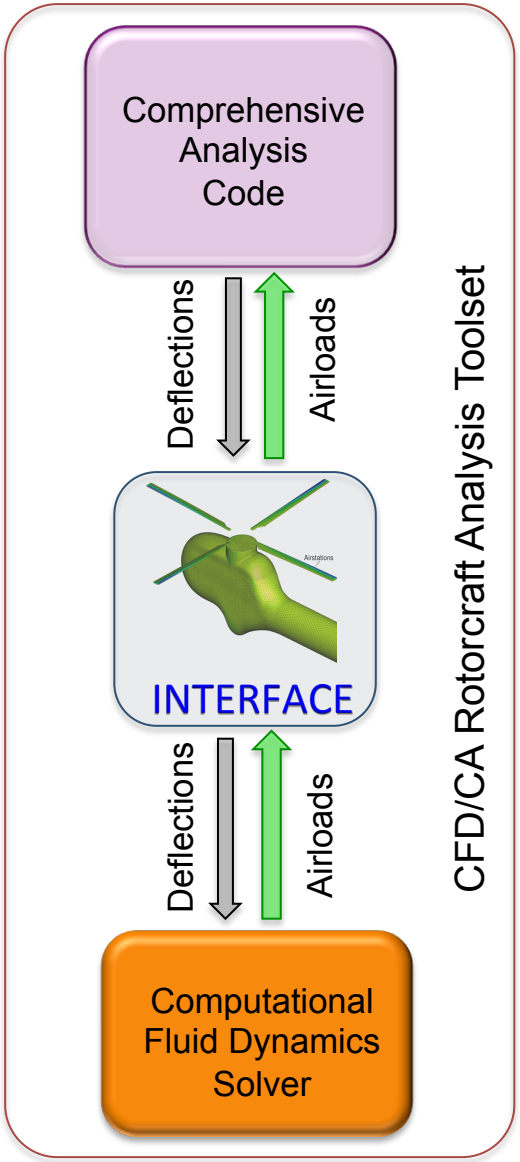
- High-fidelity rotorcraft analysis – state of the art
  - Couple CA with CFD to replace low-fidelity aerodynamics model
  - Exchange CFD airloads and structural responses
- Required CFD capabilities
  - ✓ Robust and efficient time-dependent flow solver, turbulent flow modeling
  - ✓ Overset grids to allow large relative motion
  - ✓ Surface deformation, mesh elasticity, dynamically deforming meshes
  - ✓ Interfaces to CA code for coupling, fast data transfer



CA ⟶ CFD



CFD ⟶ CA



Coupled CFD/CA Solvers

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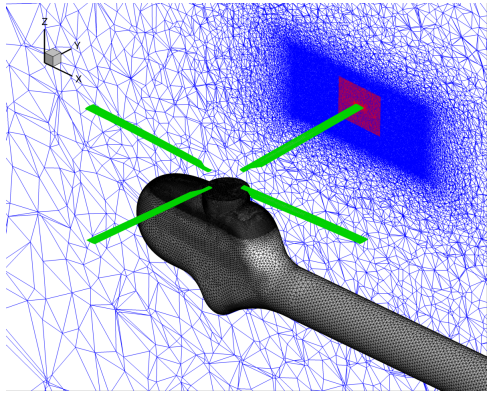
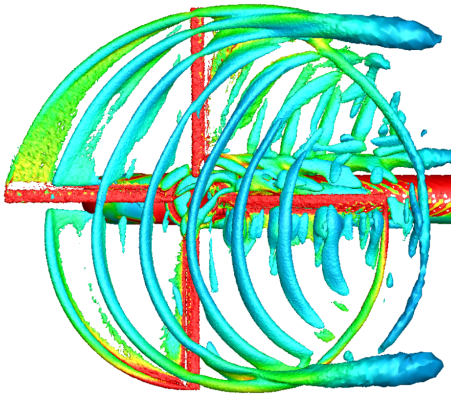
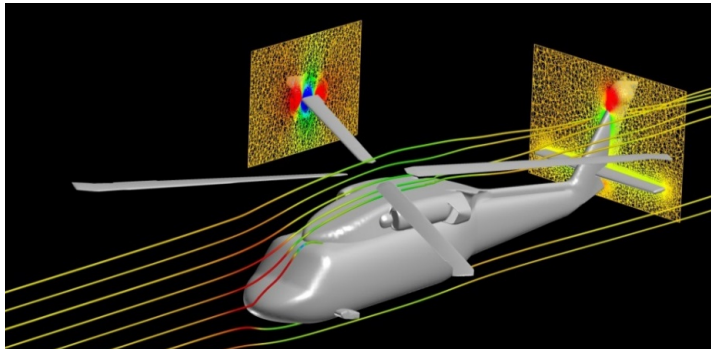
FUN3D Model

- Unstructured-grid, node-centered, finite-volume, CFD solver developed by NASA Langley
- Dynamically deforming, overset grids
- Interfaces for CFD/CA simulations





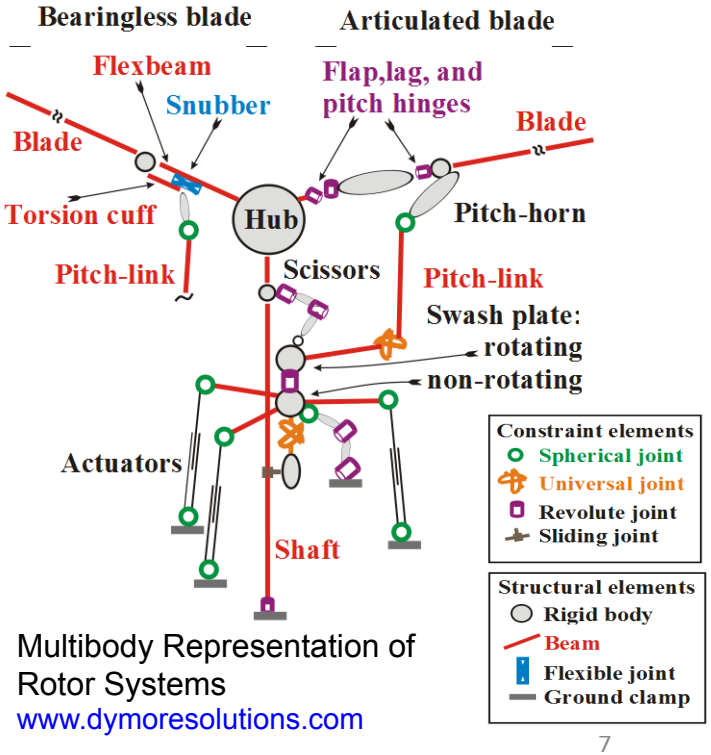
FUN3D solver used for rotorcraft applications



DYMORE5 Model

- Established nonlinear flexible multibody dynamics CA code, open source
- Production-level, low cost
- Local-frame motion formulism and parallelization

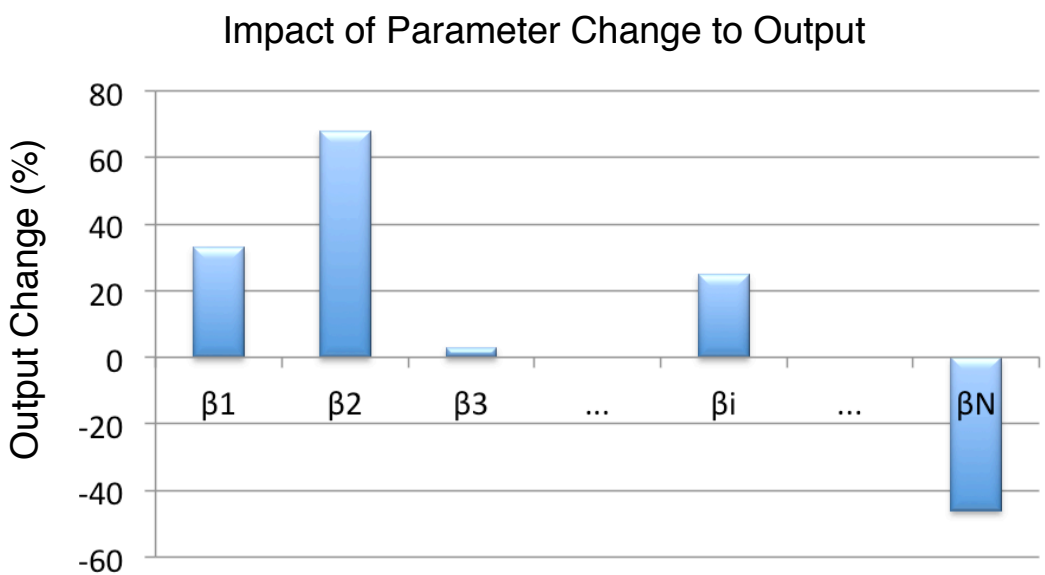
O(10^3) degrees of freedom

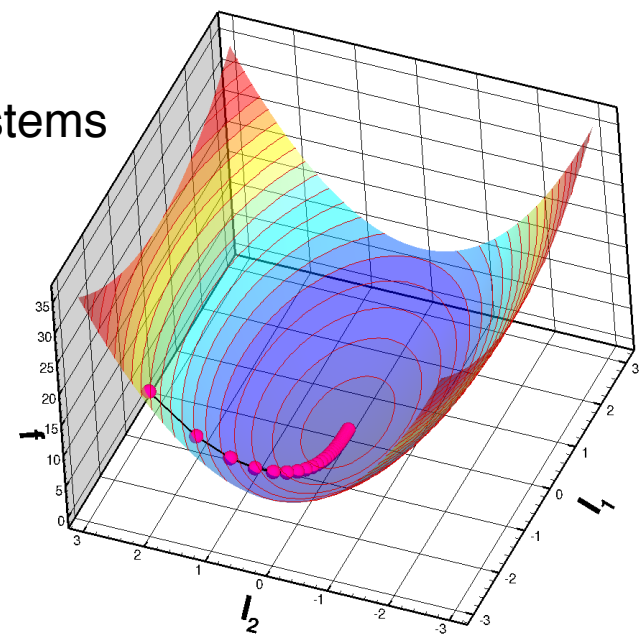


Multibody Representation of Rotor Systems
www.dymoresolutions.com

Sensitivity Analysis (SA)

- Determines how input variables impact output of interest
  - Also known as *"what-if"* analysis
  - What inputs causing most/least influence to output – prescreening process
  - Direction of input change to improve output
  - Guidance toward optimum
  - Uncertainty quantification
  - Model development – calibrating, simplifying systems

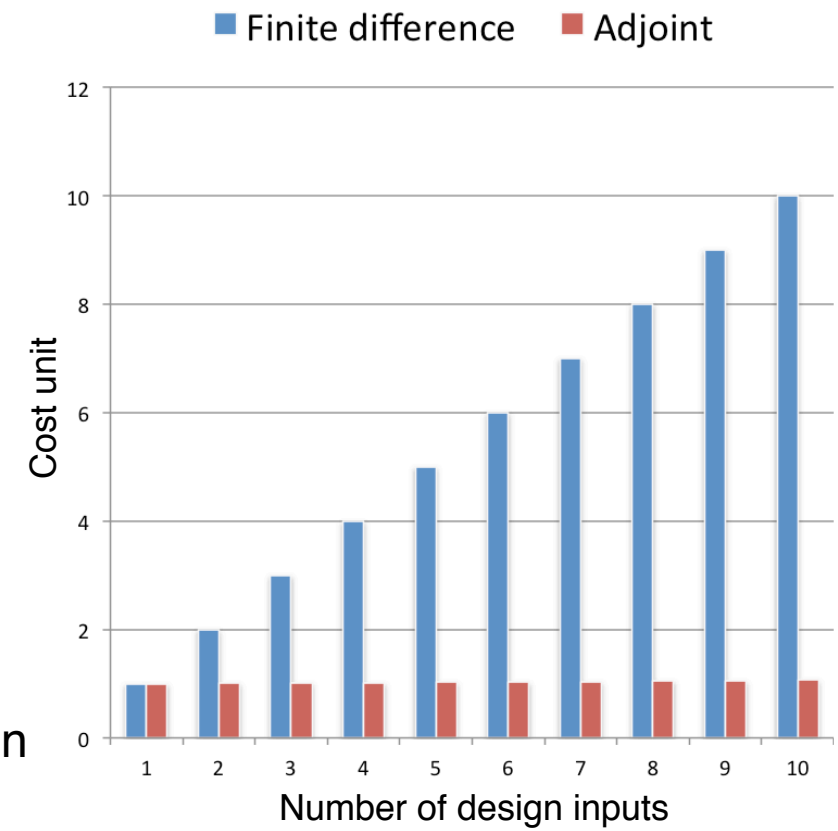




Example of Using Sensitivity to Seek Functional Minimum

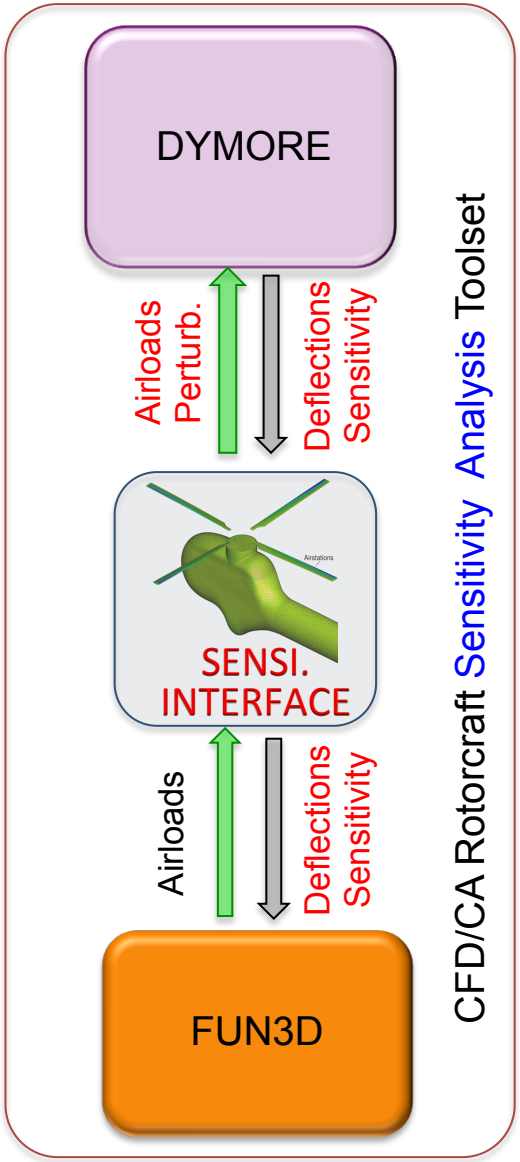
Approaches to SA

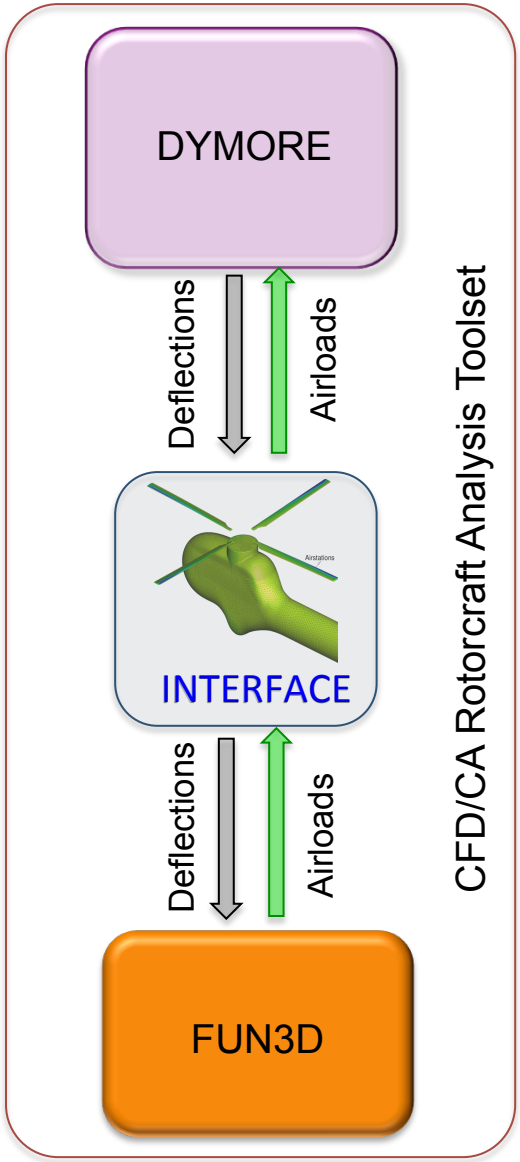
- Finite difference method
  - Perturb input variables one at a time and analyze relative change in output
  - Simplest, minimum source code modifications
  - Computational cost depends on number of inputs
  - Suitable for "*black-box*" systems with "*light*" computations – SA can be conducted in *parallel*
  - Not affordable for high-fidelity CFD
- Adjoint method
  - Linearize system and transpose
  - Cost does not depend on number of inputs, similar to one analysis
  - Efficient for design with large number of input/design variables and few outputs
  - Widely used in aircraft shape optimization



SA for Multidisciplinary CFD/CA System

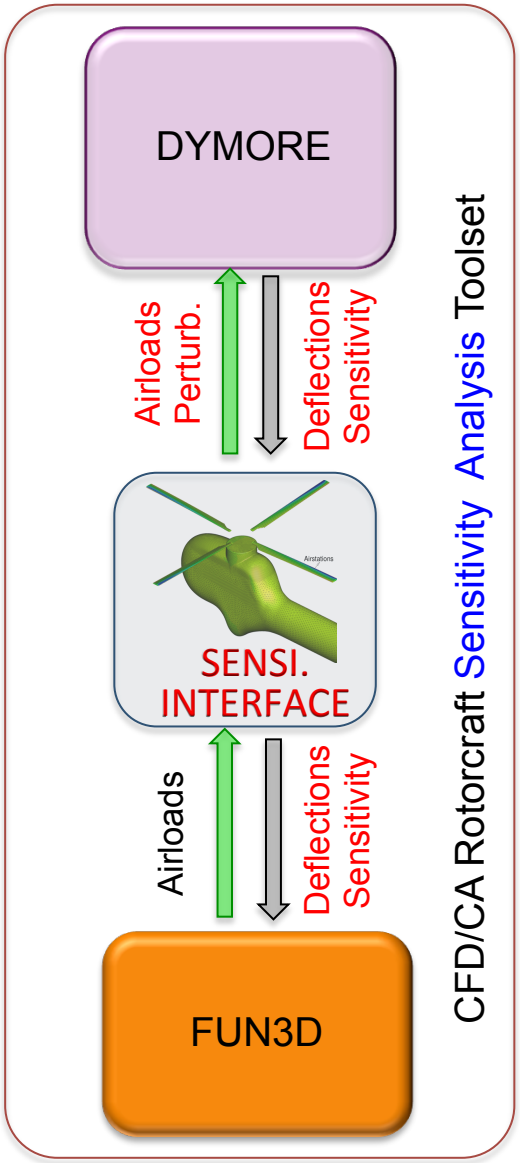
- Develop integrated SA for coupled CFD/CA system
  - Disparity in CFD and CA computational costs
  - Adjoint method for "*heavy*" system – CFD
  - Finite-difference method for "*light*" system – CA
  - Extended interface transfers perturbed airloads from CFD to CA and deflection sensitivities from CA to CFD
  - Complete discretely consistent adjoint system is ideal



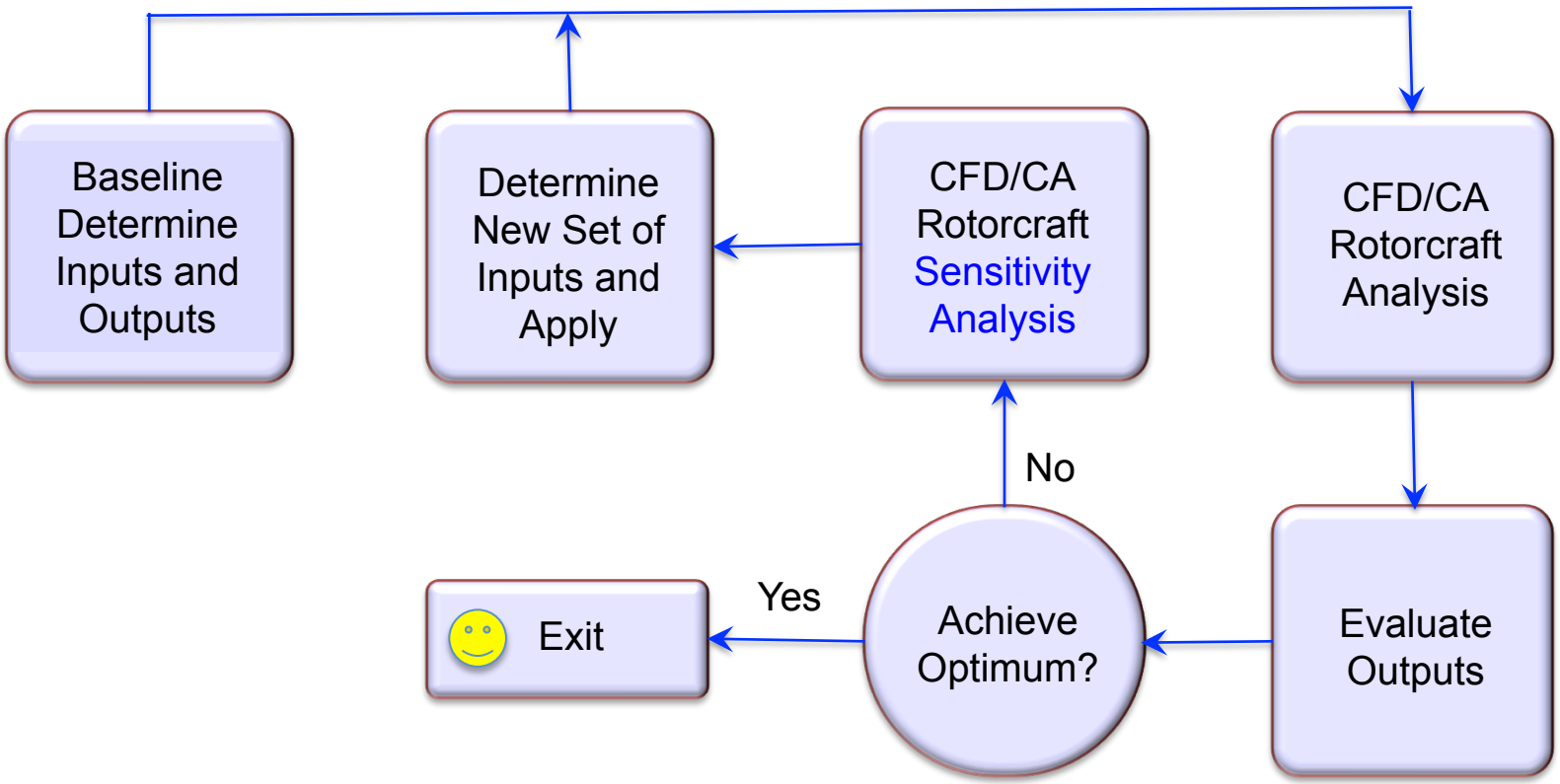


SA for Multidisciplinary CFD/CA System

- What kind of sensitivities does the coupled system account for?
  - *CFD flow* sensitivities from unsteady, turbulent flow
  - *CFD grid* sensitivities from overset and dynamically deforming meshes reflecting structural deflections
  - *Structure* sensitivities from various structural elements such as beams, mechanical joints, springs, dampers, etc.
  - *Integrated, mathematically rigorous system*
- What types of input variables can be enabled for design optimization?
  - Geometry *shape* design variables – blade planform, twist, thickness, camber, etc.
  - *Kinematics* design variables – pitch controls
  - *Global* design variables – AOA, shaft tilt, etc.



Multidisciplinary Design Optimization



- *Input* variables are parameters that can be changed by designer
- *Outputs* are design objective and constraints such as rotorcraft-specific functional of interest, e.g., rotor power, figure of merit, thrust, moments, etc.
- This framework can be used to perform single- or multi-point design optimization

System Verification and Validation

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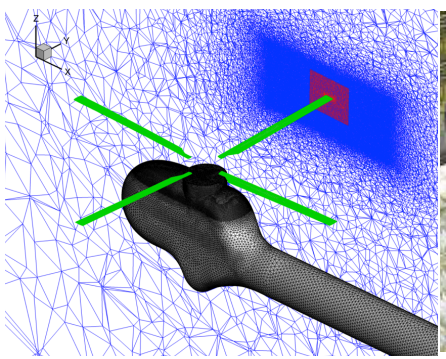
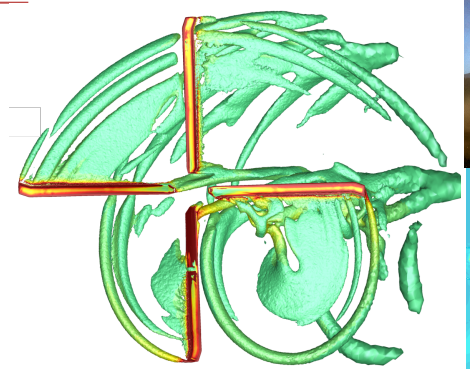
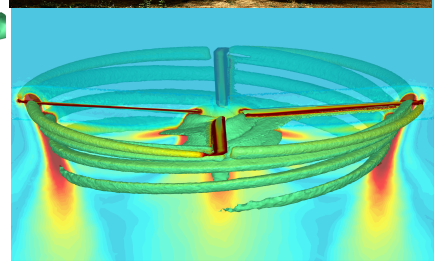
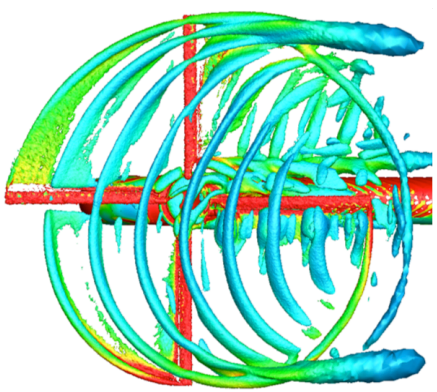
- Coupled system tested for various rotorcraft configurations and flight conditions

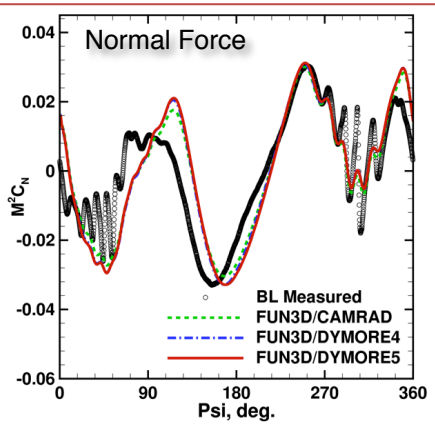
HART-II			UH-60A Blackhawk	
Descending Flight			Forward Flight	Hover Flight
BVI	HHC for Minimum Noise	HHC for Minimum Vibration		

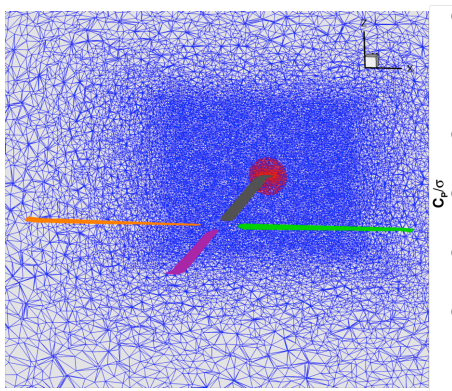


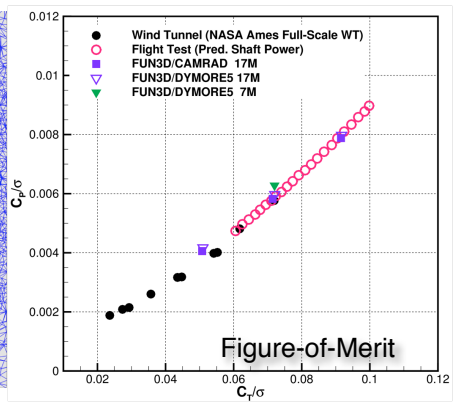












Multipoint Design Setup – UH60A Rotor

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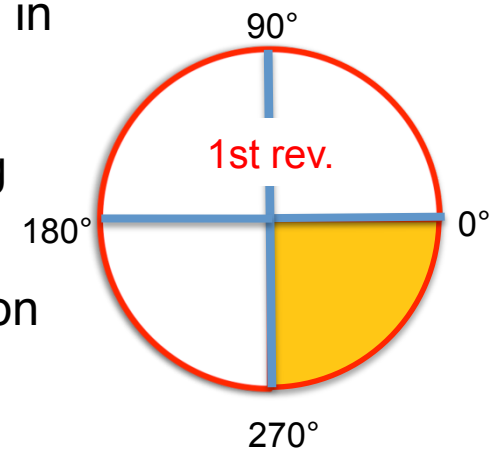
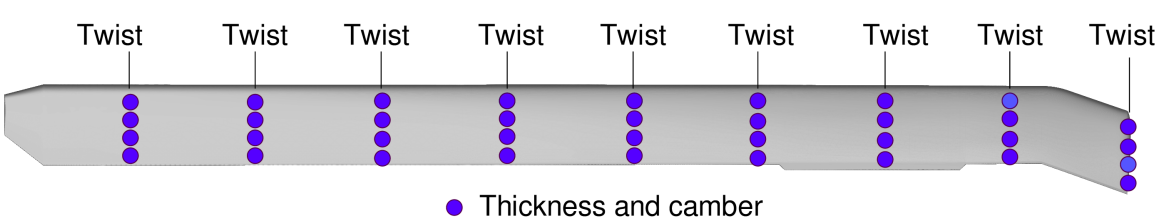
- Design points - hover flight (C9605) and forward flight (C8534)
- Design outputs - 2 objectives & 6 constraints
  - *Objectives* - maximize rotorcraft figure of merit ($\mathrm{FM} = \frac{C_T^{3/2}}{2\sqrt{C_P}}$) in hover flight and minimize rotor power in forward flight
  - *Constraints* - meet specific targets of rotor thrust and rolling and pitching moments at both design points
  - Optimization time interval - 4th quarter of *first* rotor revolution
- Initial conditions - FUN3D/DYMORE5 trimmed (loosely coupled) solutions for baseline configuration





$$\theta = \theta_0 + \theta_{1c}\cos\psi + \theta_{1s}\sin\psi$$

Design variables:

81 *shape* variables (9 twist, 36 thickness, and 36 camber) shared by all design points

3 *trim* variables for each design point, total 6 *trim* variables

Grid: 7M nodes

Optimization Results – UH60A Rotor

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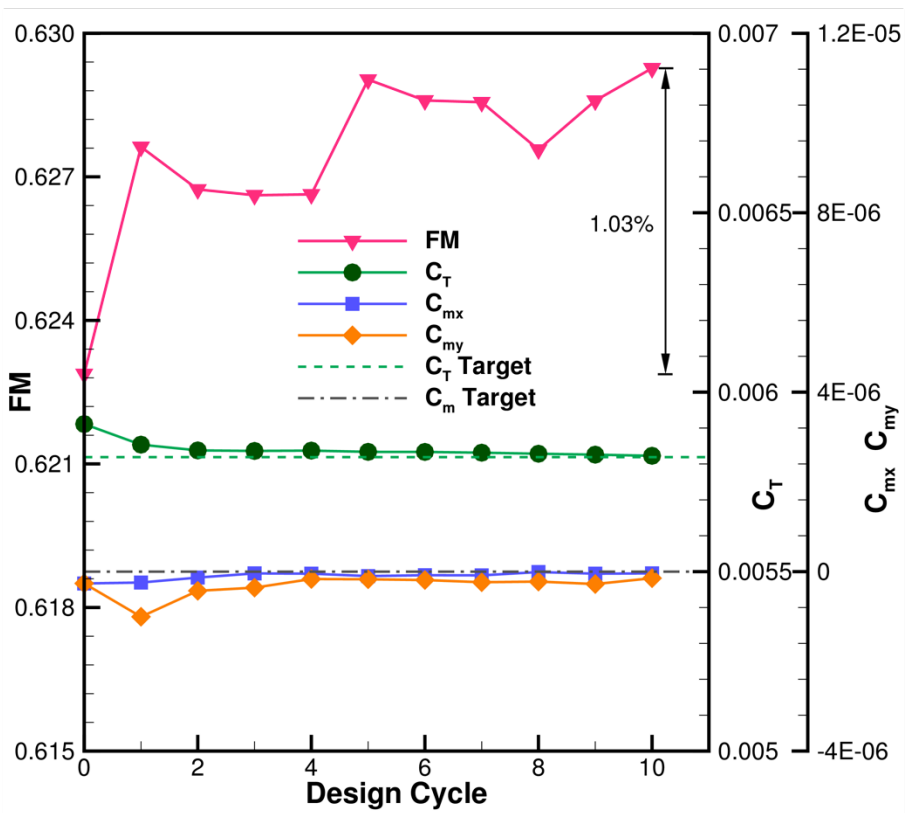
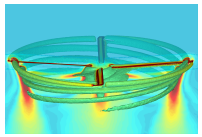
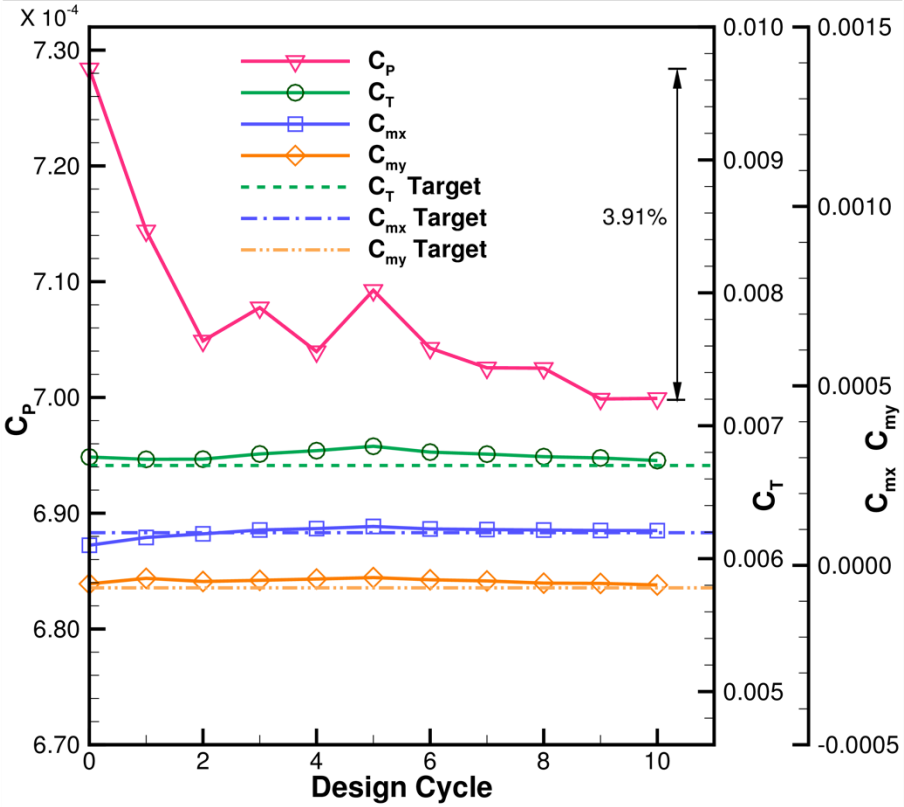
- Convergence of objectives & constraints

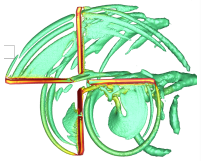




Hover flight (C9605)
1.03% increase in FM

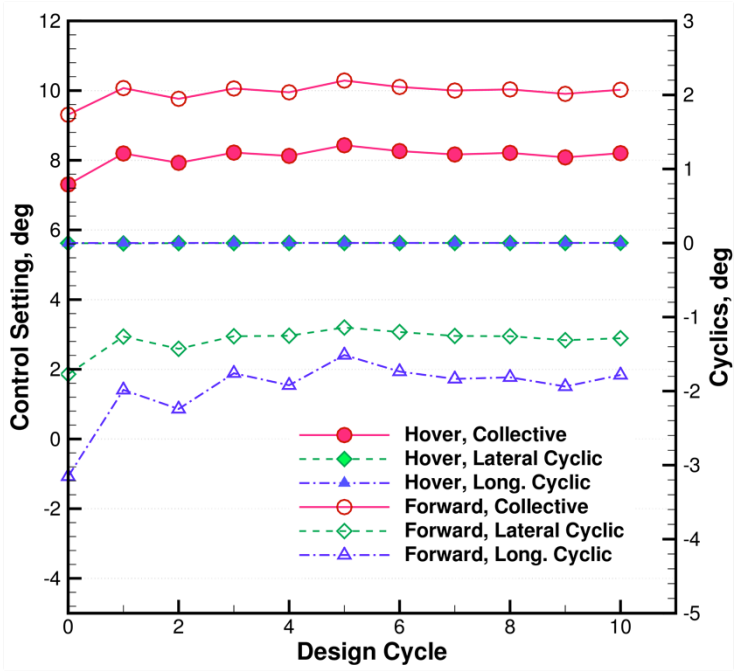


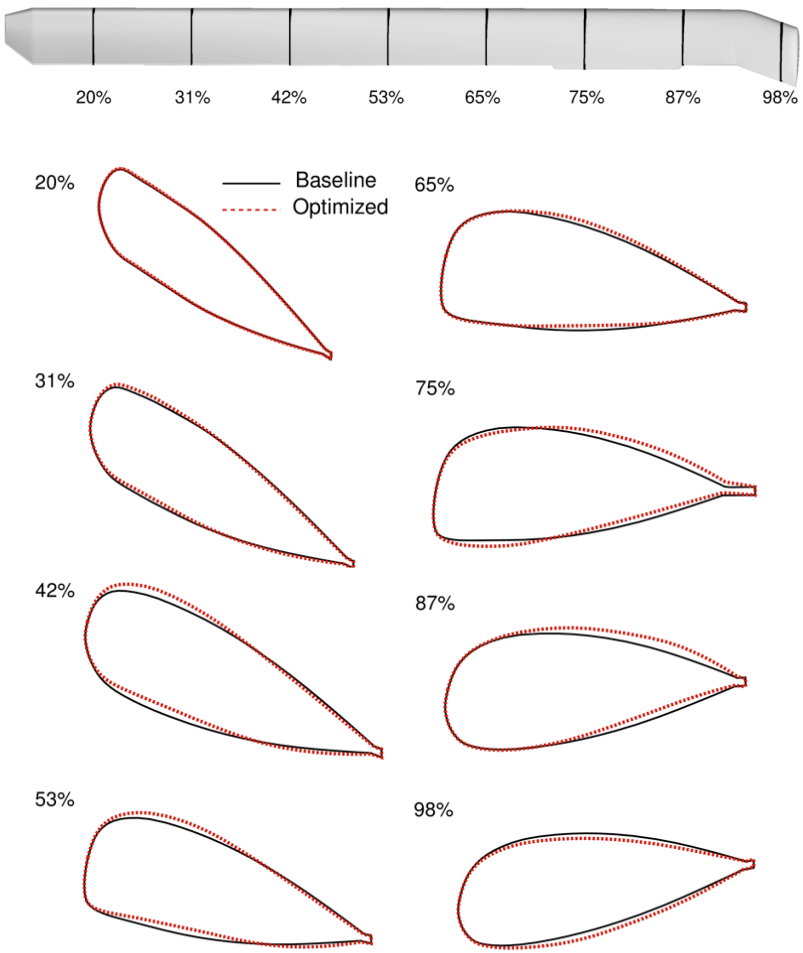
Forward flight (C8534)
3.91% reduction in rotor power



Optimization Results – UH60A Rotor

- Blade shape optimization
  - Combination of changes in many design variables
  - Pitch control angles excluded
  - Larger camber changes
- Trim variables



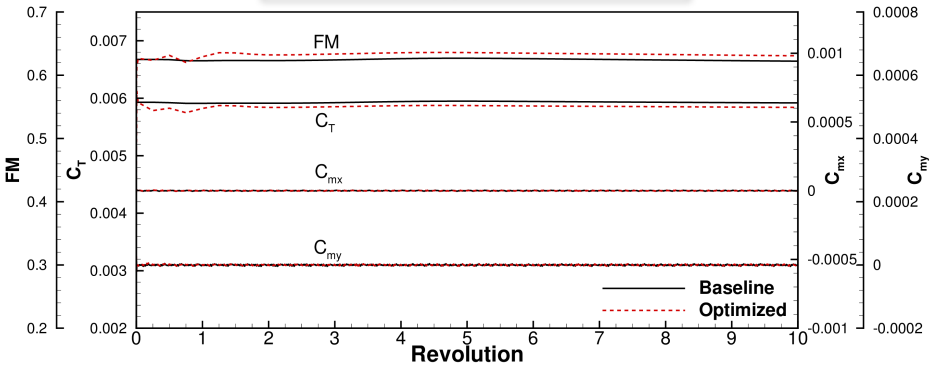


Blade cross-section geometry
Enlarged vertical scale (4:1)

Assessment of Optimization Results

- Long-term FUN3D/DYMORE5 tight-coupling simulations for baseline and optimized configurations (10 rev.)

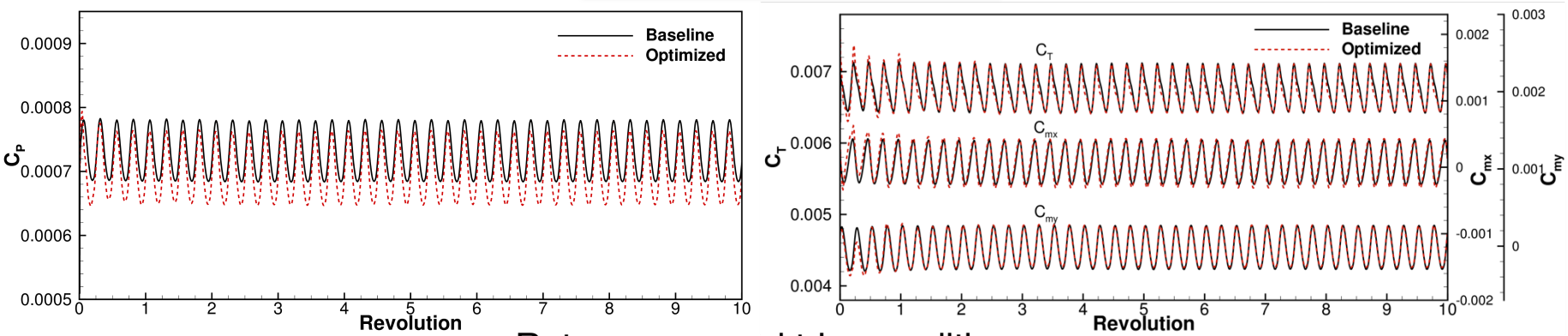
Hover flight (C9605)



FM and trim conditions

- Initial transients pass quickly
- Periodic solutions established
- Improved rotor performance *preserved*
- Trim conditions *maintained*

Forward flight (C8534)



Rotor power and trim conditions

Concluding Remarks

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- High-fidelity FUN3D/DYMORE5 multidisciplinary analysis and design optimization framework developed and assessed for rotorcraft applications
- Verification and validation conducted for FUN3D/DYMORE5 analysis of HART-II and UH-60A Blackhawk rotor in various flight conditions
- Constrained, gradient-based, multipoint design optimization procedure formulated and applied to optimization of UH-60A Blackhawk rotor blades
  - Maximize rotorcraft figure of merit in hover flight
  - Minimize rotor power in forward flight
  - Constrained rotor thrust and rolling and pitching moments
  - Improved rotor performance preserved and trim conditions maintained
- Future work
  - Extend to coupled aero/structure/acoustics analysis and design optimization framework for low-noise rotorcraft optimization
  - Develop discretely-consistent, adjoint-based, FUN3D/DYMORE sensitivity analysis system and apply to maneuvering rotorcraft optimization

Thank you for your attention!