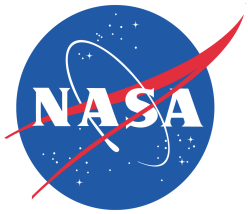

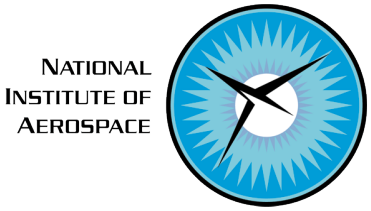

High-Fidelity Multidisciplinary Sensitivity Analysis and Design Optimization for Rotorcraft Applications

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National Institute of Aerospace, Hampton, VA, USA

98th CFD Seminar
National Institute of Aerospace
February 20, 2018

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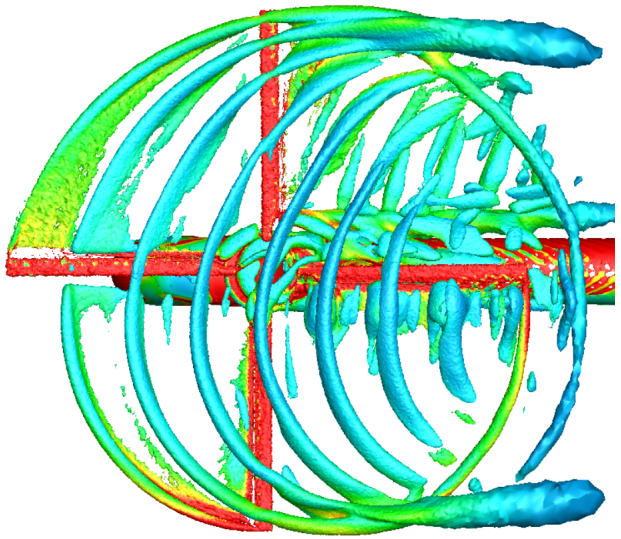
Rotorcraft

- Access remote areas
- Provide fast mobilization
- Transport severely ill patients
- Need small areas for takeoff & landing
- Higher chance of crashes
- Vibration and noise
- Increased performance
- Reduced impact on environment

All images taken from Google

State of the Art

- Rotorcraft Aeromechanics Requires Many Disciplines
  - Aerodynamics, structural dynamics, aeroacoustics, flight dynamics, etc.
  - Capture complex physics and large elastic motions
  - Multidisciplinary rotorcraft comprehensive analysis (CA)
    - Low cost, but relying on low-fidelity aero
- High-Fidelity Rotorcraft Analysis
  - Couple CA with computational fluid dynamics (CFD)
  - FUN3D/DYMORE (F/D) coupling
  - CFD/CA coupled analysis is now somewhat routine
- Extend SOA with Coupled CFD/CA to Optimize Existing or New Designs
  - High cost of CFD rules out genetic algorithms
  - Gradient-based optimization is viable
- Gradient-Based Design/Optimization
  - Require sensitivity derivatives of design function to inputs
  - Indicate how function varies with change in input parameters
  - Multidisciplinary problems require sensitivities from all disciplines

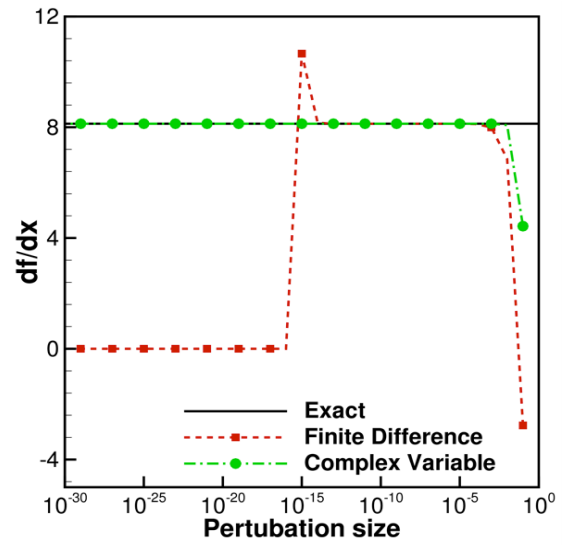


Approaches to Sensitivity Analysis

- Real-Valued Finite-Difference Approach
  - Perturb design parameters one at a time
  - Efficient for optimization requiring a few design parameters
  - Affordable for obtaining CA sensitivities and used in practice
  - Suffer from subtractive cancellation errors
- Complex-Variable Method
  - Operate on complex numbers with imaginary-part perturbations
  - Increased robustness and accuracy
  - Provide true sensitivities for functional derivatives

$$f(x+ih) = f(x) + ih\frac{df}{dx} - \frac{h^2}{2}\frac{d^2f}{dx^2} - i\frac{h^3}{6}\frac{d^3f}{dx^3} + \cdots$$

$$f(x) \approx Re[f(x+ih)] \qquad \boxed{\frac{df}{dx} \approx \frac{Im[f(x+ih)]}{h}}$$



$$f(x) = e^x \Big/ \left(\sin(x^3) + \cos(x^3) + \sin x^3 + \cos x^3\right)$$

- Discretely-Consistent Adjoint Method
  - Cost independent on number of design parameters
  - Suitable for optimization with large number of design parameters but a few design functions

Derivation of Adjoint Model

- General nonlinear equation

$$g(x, D) = 0$$

  - Notation *x* is vector of state variables and *D* is set of design parameters

- Objective function

$$f(x, D)$$

  - Evaluated using *x* solved from the nonlinear equation

- Lagrangian formulation

$$L(x, D, \lambda) = f(x, D) + \lambda^T g(x, D)$$

  - Lagrange multiplier, λ, can be chosen freely

- Total derivative of Lagrangian formulation with respect to *D*

$$\frac{d\,L}{d\,D} \equiv \frac{d\,f}{d\,D} = \frac{\partial f}{\partial x}\frac{\partial x}{\partial D} + \frac{\partial f}{\partial D} + \frac{\partial \lambda^T}{\partial D} g(x, D) + \lambda^T \left(\frac{\partial g}{\partial x}\frac{\partial x}{\partial D} + \frac{\partial g}{\partial D} \right)$$

  - The term $\frac{\partial \lambda^T}{\partial D} g(x, D)$ in the equation vanishes due to $g(x, D) = 0$

Derivation of Adjoint Model

- The total derivative of Lagrangian becomes

$$\frac{d\,L}{d\,D} \equiv \frac{d\,f}{d\,D} = \left(\frac{\partial f}{\partial x} + \lambda^T \frac{\partial g}{\partial x}\right)\frac{\partial x}{\partial D} + \lambda^T \frac{\partial g}{\partial D} + \frac{\partial f}{\partial D}$$

- Setting the coefficient of state variable sensitivity to zero yields the adjoint equation

$$\frac{\partial f}{\partial x} + \lambda^T \frac{\partial g}{\partial x} = 0$$

Or equivalently,

$$\left[\frac{\partial g}{\partial x}\right]^T \lambda = -\left(\frac{\partial f}{\partial x}\right)^T$$

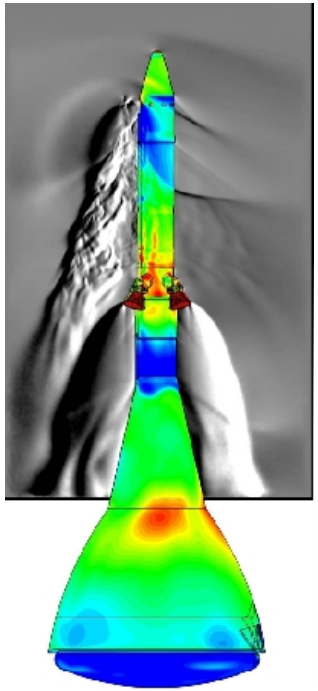
- Adjoint-based sensitivity derivative is evaluated as

$$\frac{d\,L}{d\,D} \equiv \frac{d\,f}{d\,D} = \lambda^T \frac{\partial g}{\partial D} + \frac{\partial f}{\partial D}$$

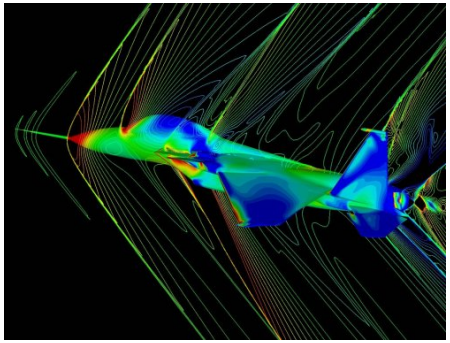
CFD and CA Models

FUN3D Model

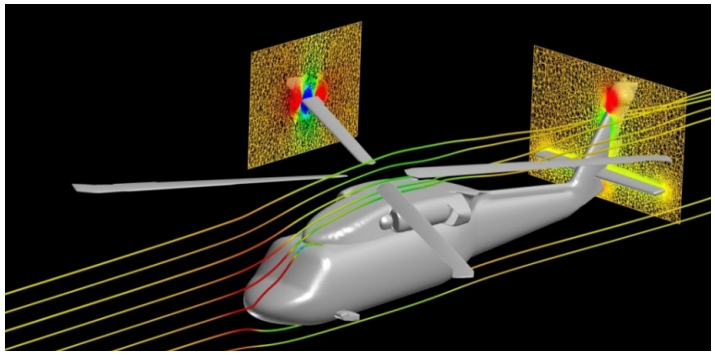
- Fully-unstructured, node-centered, finite-volume CFD solver, developed by NASA Langley
- Sensitivity-enabled including time-dependent flows, CA interfaces for rotorcraft



Launch Abort System



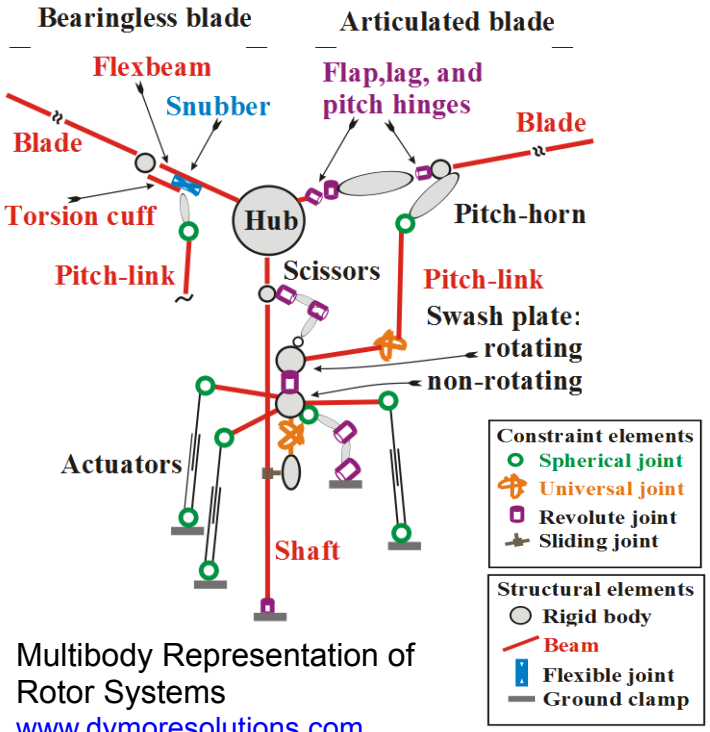
Supersonic Simulation of F-15 Configuration



UH-60 Black Hawk Configuration

DYMORE Model

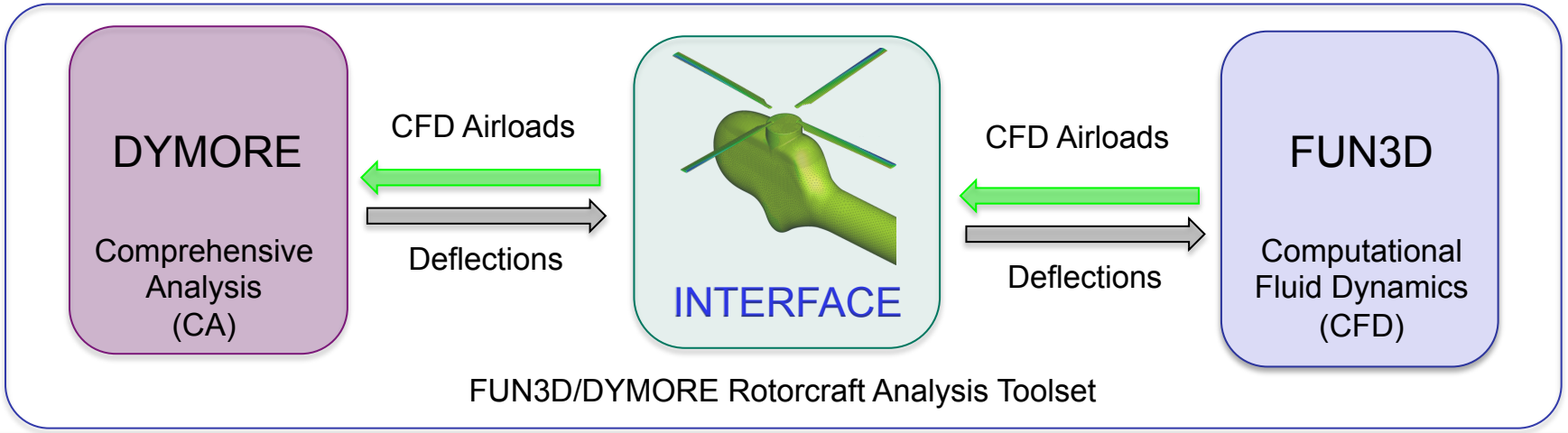
- Nonlinear flexible multibody dynamics comprehensive analysis code
- Production-level, low cost



Multibody Representation of Rotor Systems
www.dymoresolutions.com

Overview

- F/D Coupling Interface
  - Loose and tight coupling
  - Airloads and deflections exchanged in memory
- Multidisciplinary Sensitivity Analysis
  - Execution times of FUN3D and DYMORE differ by several orders of magnitude
  - Integration of adjoint-based FUN3D sensitivities with complex-variable DYMORE sensitivities
  - Previous work involved coupled FUN3D/DYMORE4 system
    - 21.9 hours for optimization cycle: forward – 11.4%; sensitivity – 88.6%
  - Current work of sensitivity analysis emphasizes computational efficiency



Outline

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  - Tight and loose-coupling algorithms
  - Sensitivity analysis
  - Cost and efficiency improvement
  - Design optimization cycle
- Verification of F/D Rotorcraft Analysis
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  - Maximization of Lift constrained with moments
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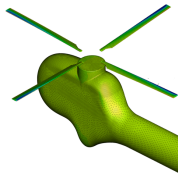
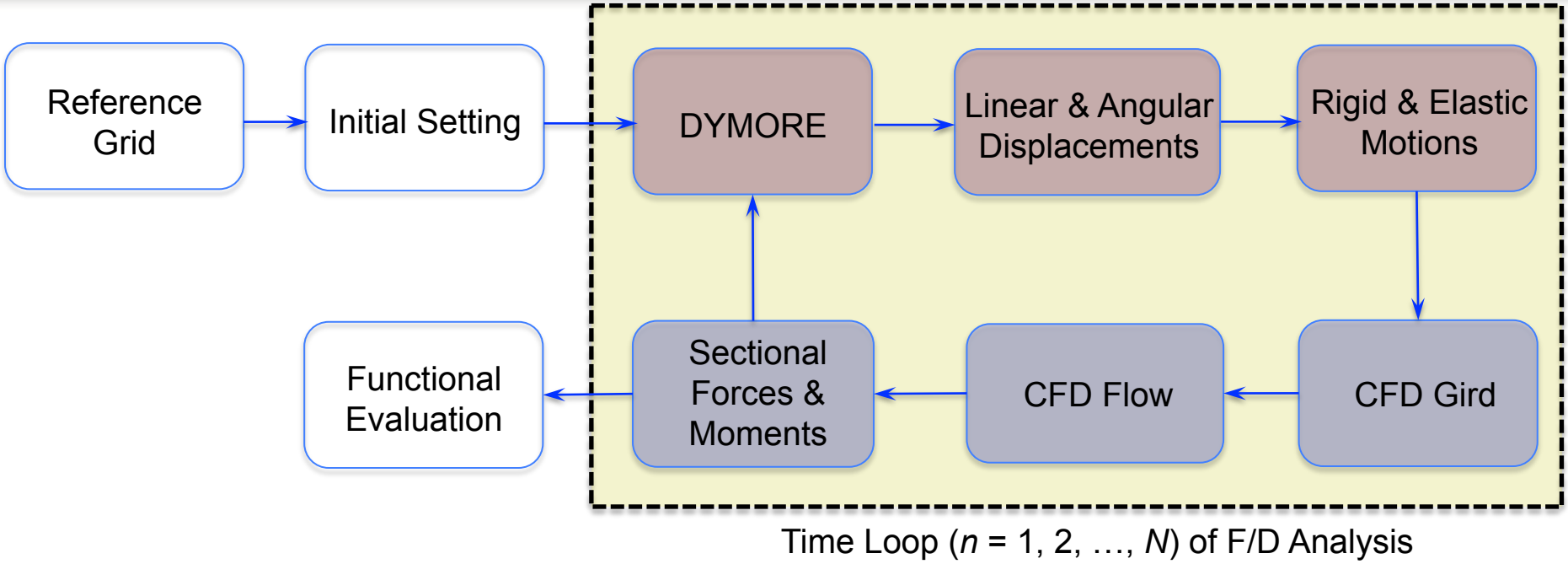
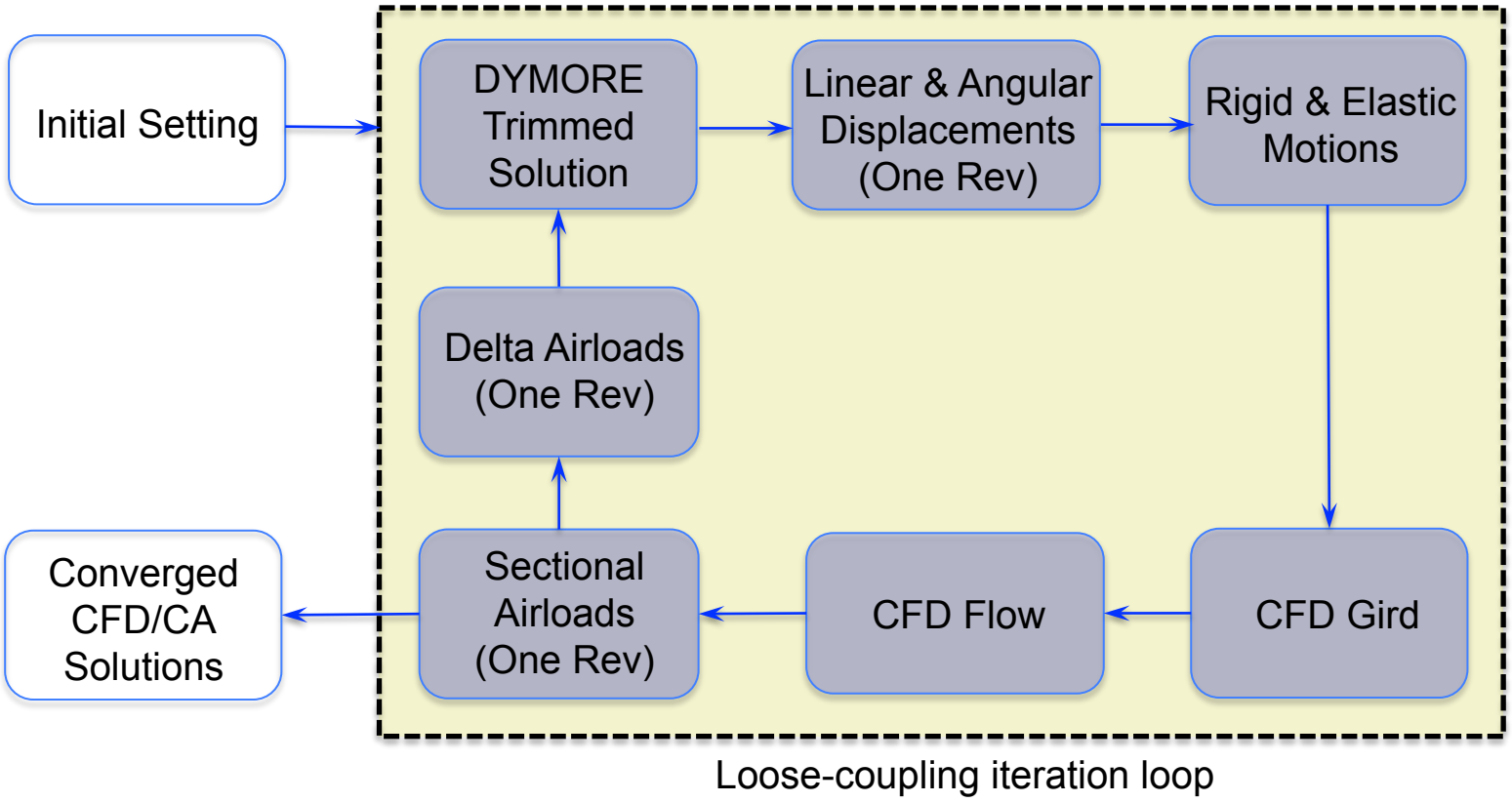


F/D Tight-Coupling Algorithm



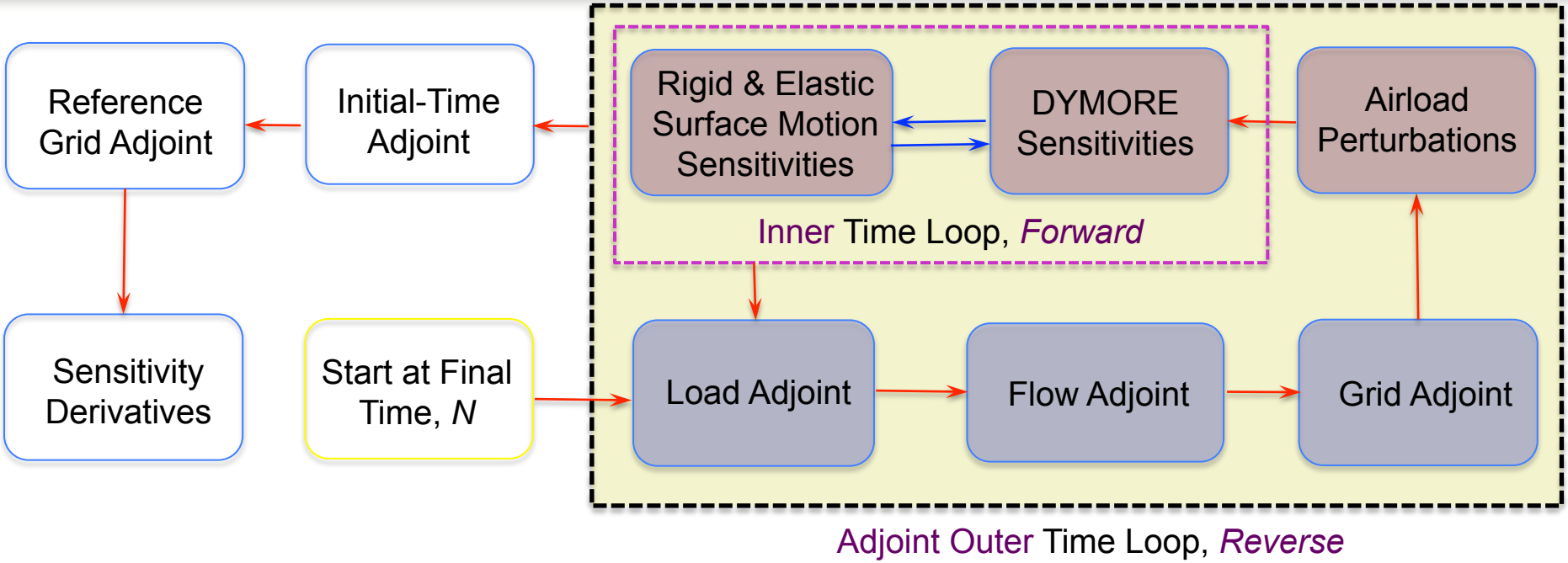
- Data transferred once per time step
- Displacements and airloads have the same degrees of freedom
- Modules in pink denote complex-mode operations

F/D Loose-Coupling Algorithm



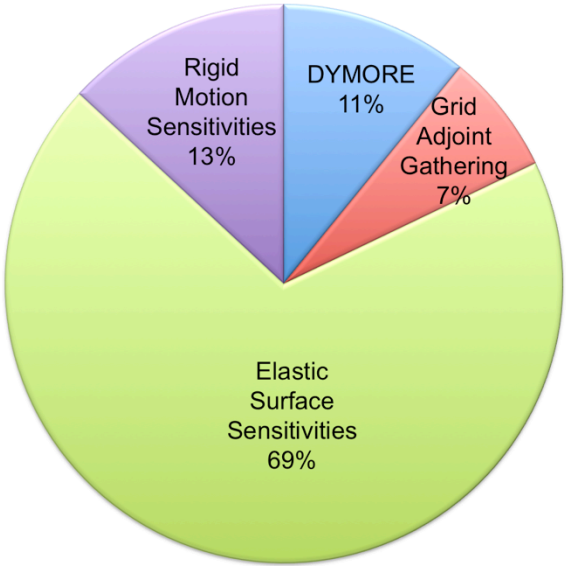
- Rotor trim performed in DYMORE, requiring many revolutions of simulation
- Delta airloads are differences in loads between CFD and CA internal aero
- CFD can be performed with minimum of 1/(no. rotor blades) revolutions at each coupling cycle

F/D Multidisciplinary Sensitivity Analysis

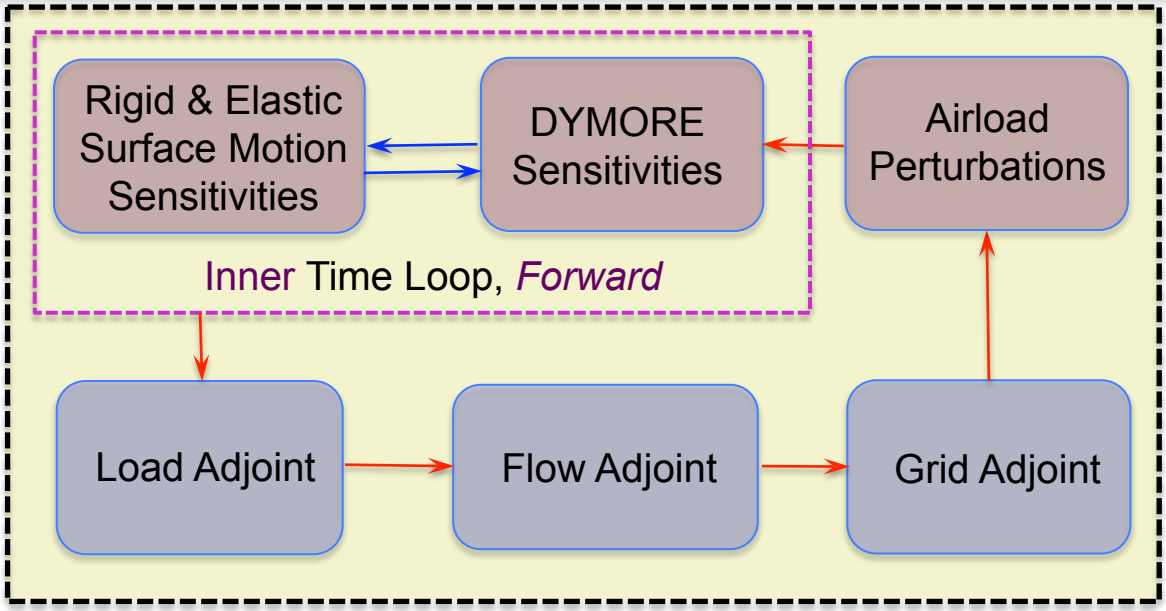


- Multidisciplinary adjoint equations derived by differentiating a Lagrangian functional
- Load, flow, and grid adjoint solutions computed in the reverse order in time (outer time loop)
- Rigid & elastic surface motion sensitivities
  - Compute via complex-variable analysis for time levels from *n+1* to *N* (inner time loop)
  - Lead to quadratic dependence on the number of time steps, *N*
  - Contribute to load adjoint solution

Computational Cost Analysis



Component Cost of Load Adjoint
(Previous Coupled System)



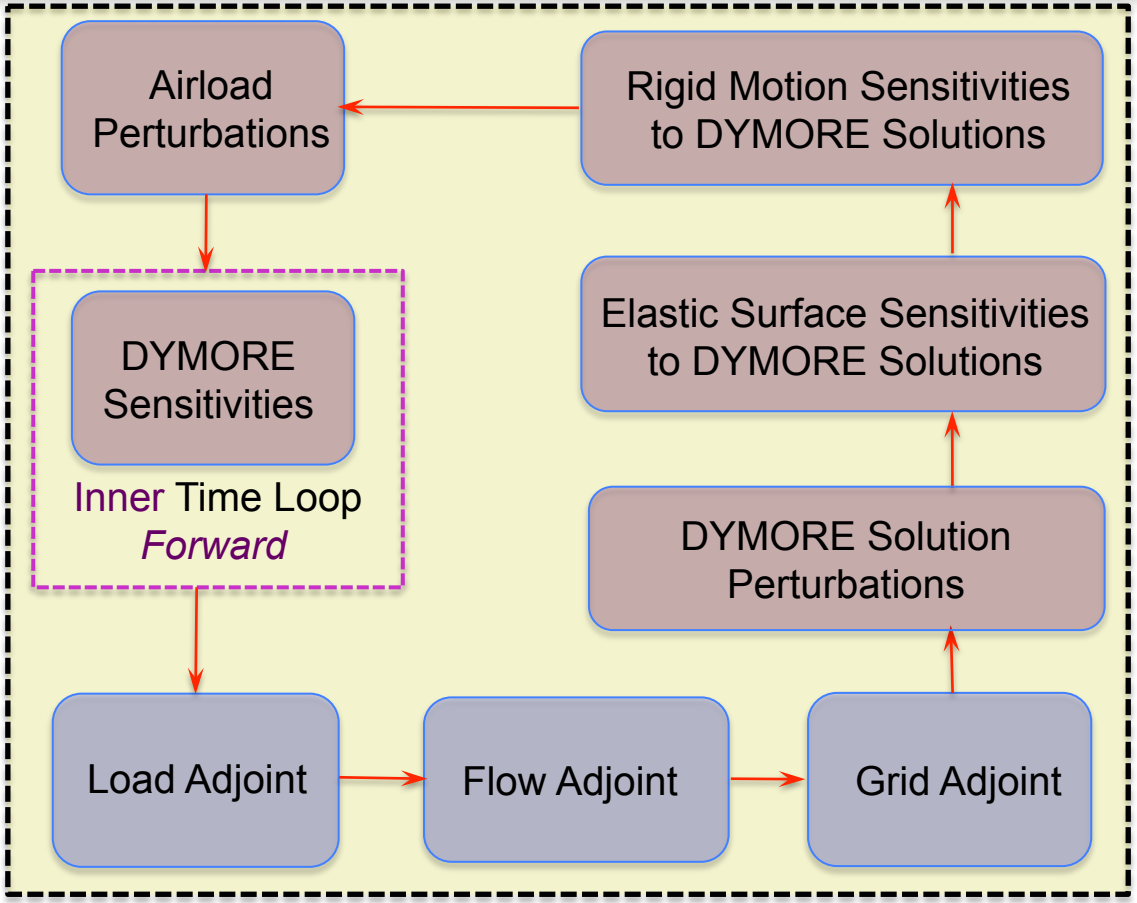
Adjoint Outer Time Loop, *Reverse*

- Linear dependence on number of airload components
  - Eliminated by parallel computation using same number of cores as number of airload components
- Quadratic dependence on number of time steps
- Previous work with FUN3D/DYMORE4 system
  - Load adjoint took 62.5% of optimization cycle cost
  - 69% of load adjoint spent on evaluations of elastic surface sensitivities to airloads

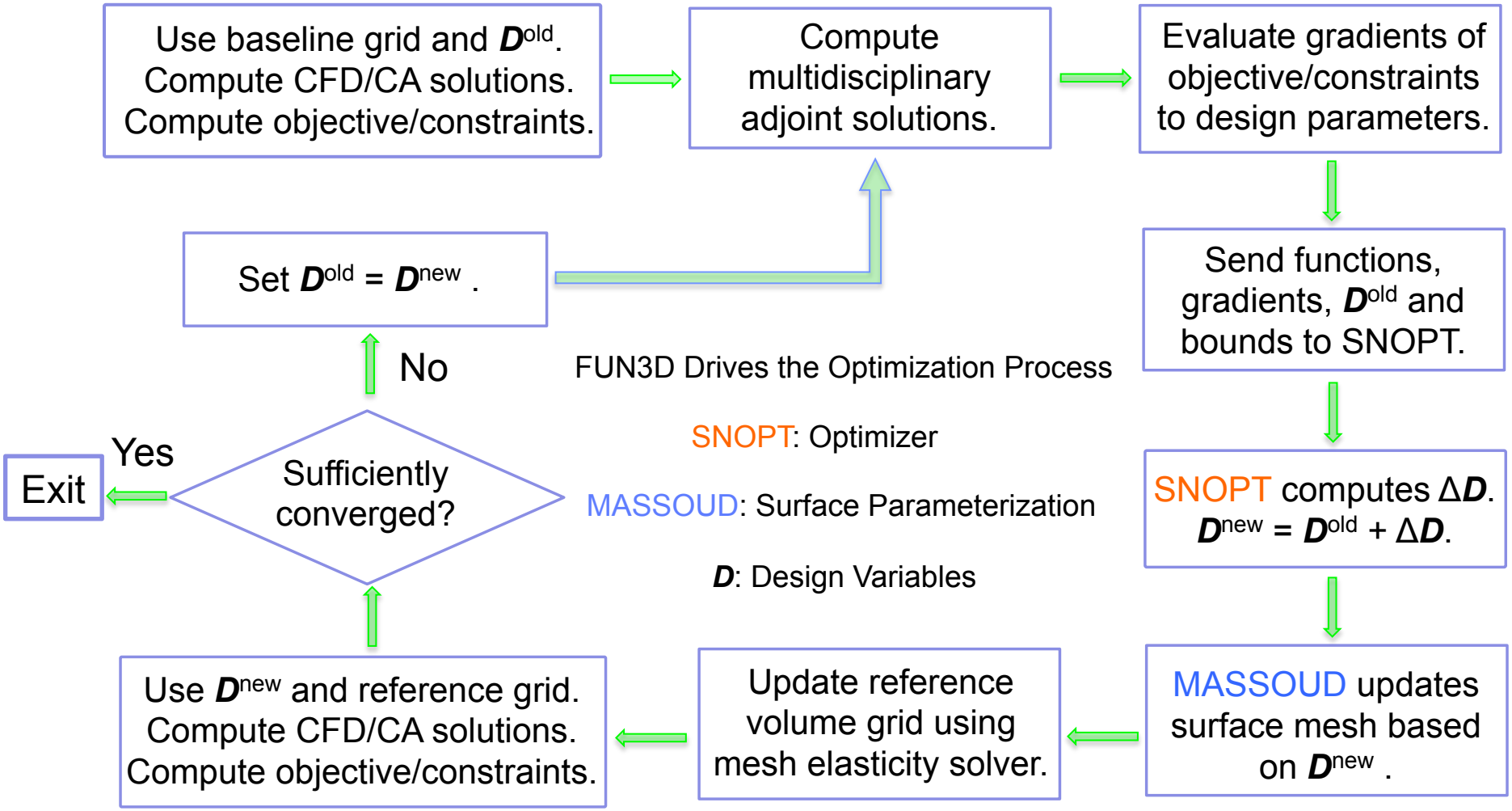
Improvement of Computational Efficiency

- Three key advancements for efficiency improvement

- Elastic surface sensitivities to DYMORE solutions
  - Separated from DYMORE sensitivities to airloads
  - Eliminated quadratic dependence on number of time steps
  - Precomputed using complex-variable analysis
  - Performed in parallel
- Rigid motion sensitivities to DYMORE solutions
  - Separated from DYMORE sensitivities to airloads
- New model, DYMORE5
  - Motion formalism
  - Domain decomposition and parallel computing



Design Optimization Cycle



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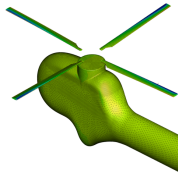
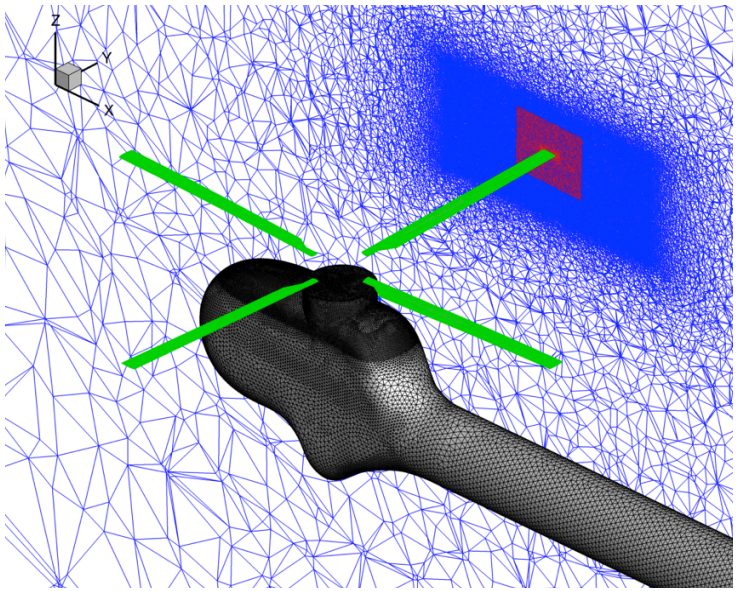
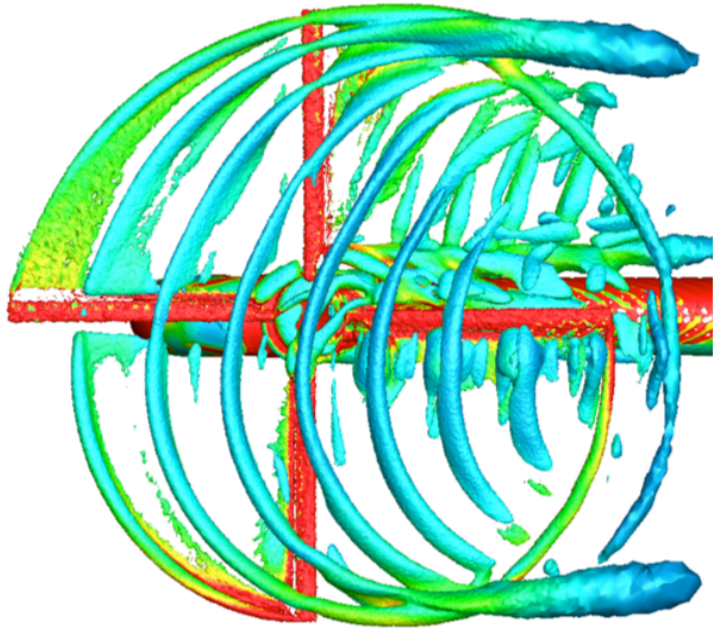


FUN3D/DYMORE5 Loose Coupling Solutions

- HART-II Baseline
  - 4.5° angle of attack, 1042 rpm, 7M node CFD overset mesh
  - BDF2opt temporal scheme, 1° per time step, 87 airstations per blade
  - Fully turbulent with Spalart-Allmaras (SA) turbulence model



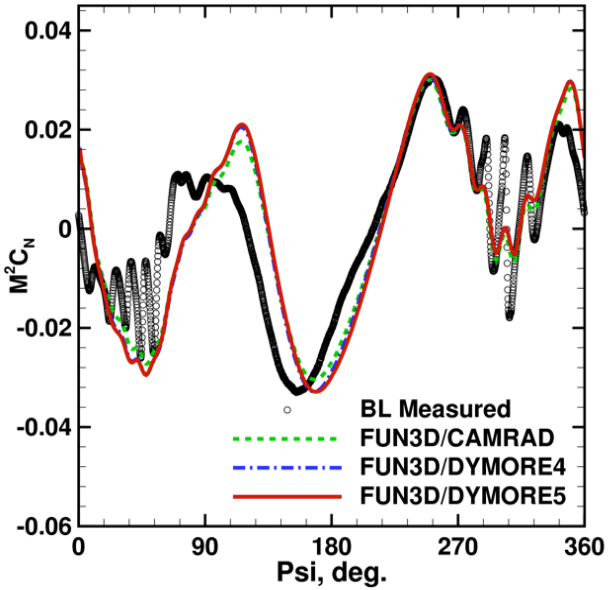
Unstructured overset computational mesh



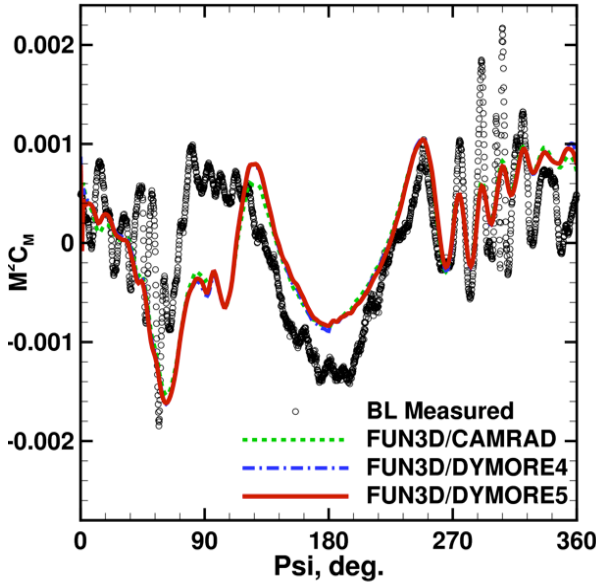
Blade vortex interactions of HART-II baseline rotorcraft simulated by loosely coupled F/D analysis

Loose Coupling Simulation for Baseline HART-II

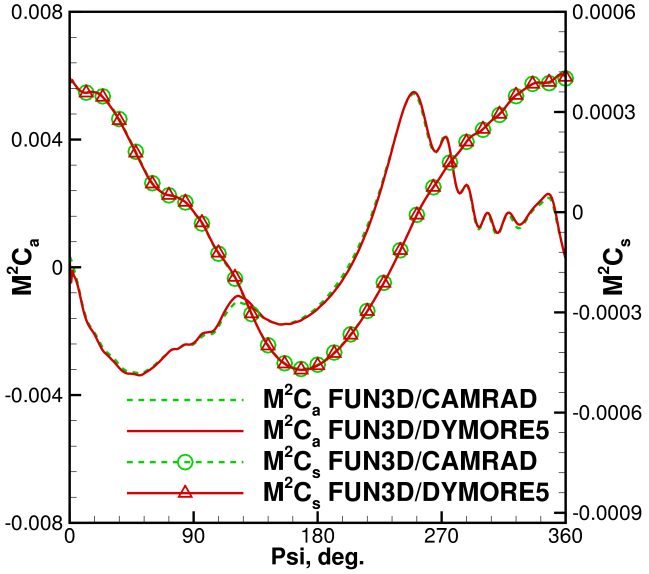
- 12 loose coupling cycles performed
- Predictions of forces and moments at 87% radial station



Normal force, mean removed



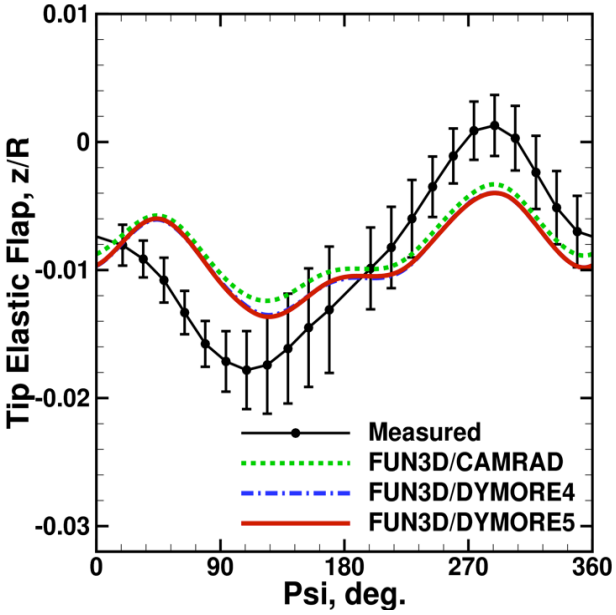
Pitching moment, mean removed



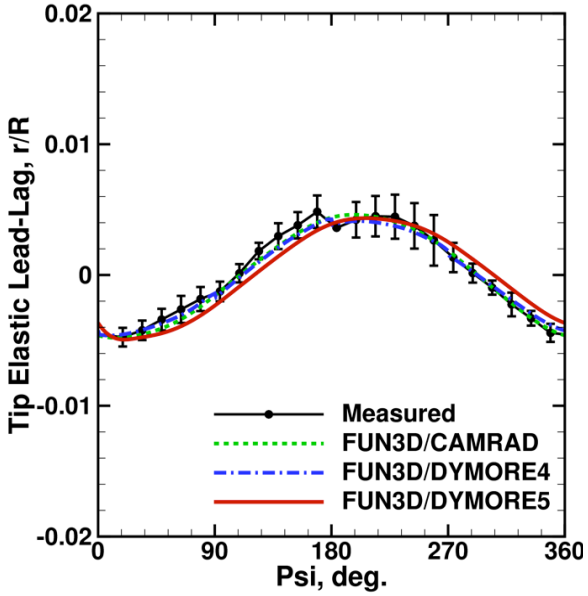
Chord and spanwise forces

Loose Coupling Simulation for Baseline HART-II

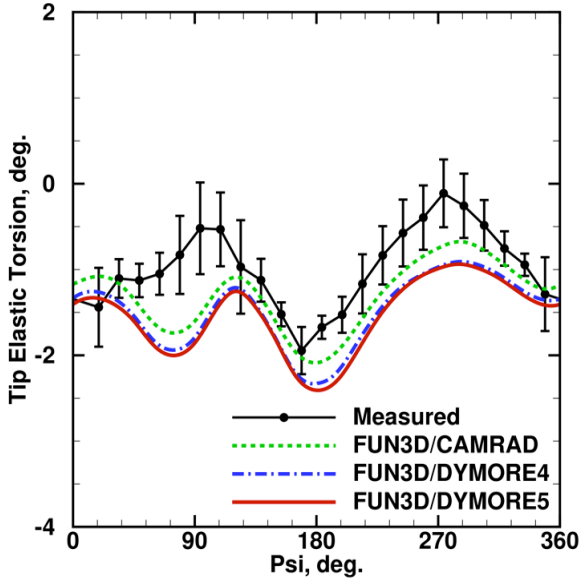
- Predictions of blade tip deflections



Flap relative to precone



Lead-lag, mean removed



Torsion relative to pretwist and control angles

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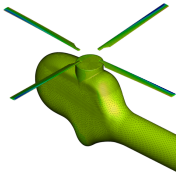
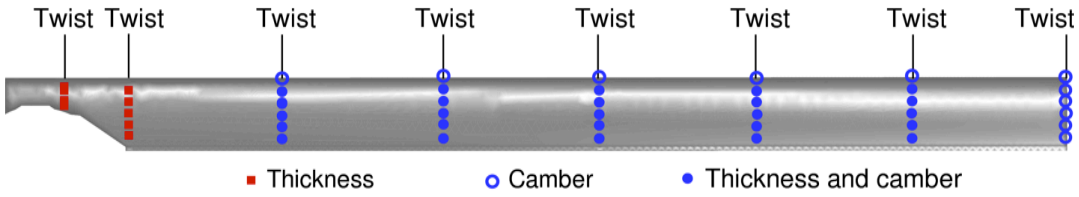


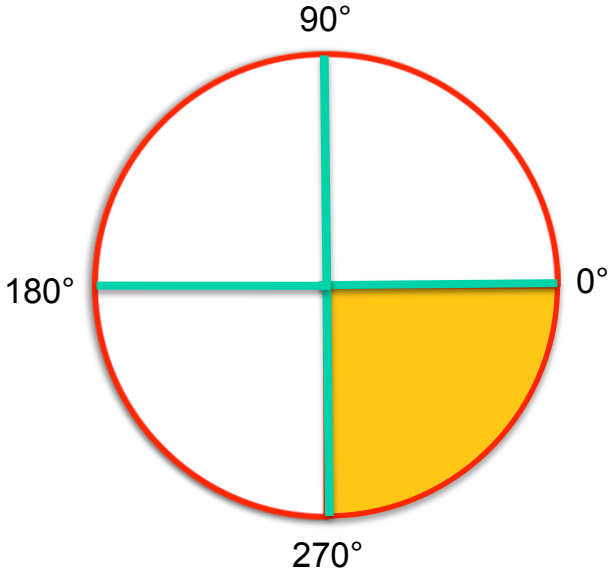
Multidisciplinary Design Optimization for HART-II

- Design Parameters
  - 79 aircraft-centric shape design parameters per blade
    - 8 twist, 35 thickness, and 36 camber
  - 3 trim control design parameters

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



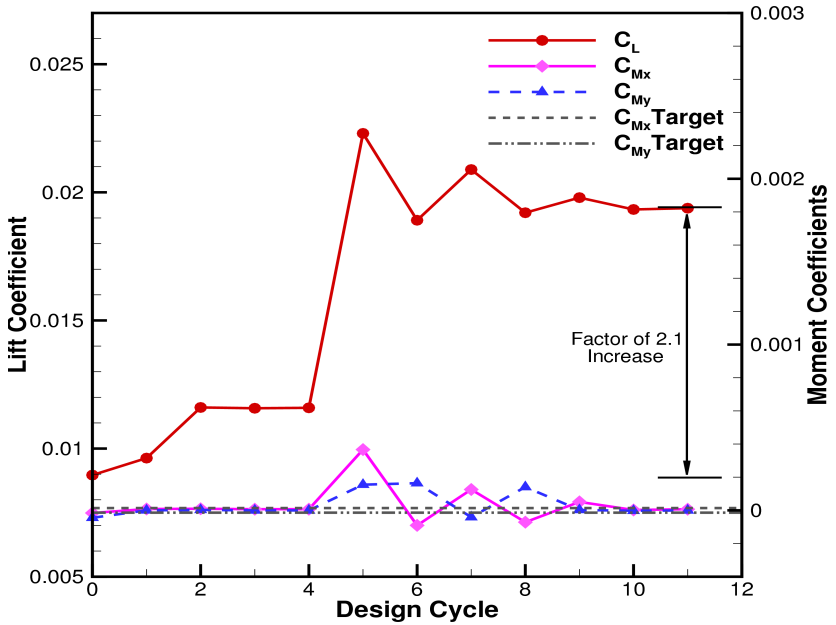
- FUN3D/DYMORE5 Simulations
  - Overset grid with 7M nodes and 29M mixed elements
  - BDF2opt scheme with 1°per time step
  - 87 airstations per blade
  - Start with loose-coupling FUN3D/DYMORE5 solution
- Optimization Time Interval
  - 4th quarter of 1st rotor revolution



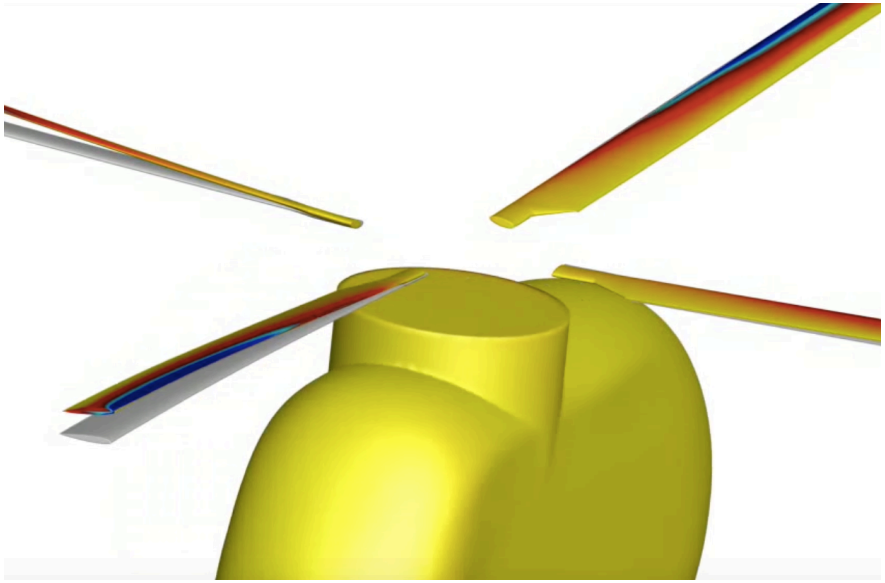
Optimization Results for Lift Maximization

- Objective and Constraints
  - Maximization of lift, subject to rolling and pitching moment constraints
  - 3 multidisciplinary adjoint solutions
  - No structure constraints
  - 2.1 times more lift production
  - Constraints are satisfied

	θ_0	θ_{1c}	θ_{1s}
Experiment	3.80°	1.92°	-1.34°
Baseline	3.99°	1.88°	-1.15°
Optimized	6.59°	2.70°	-6.14°



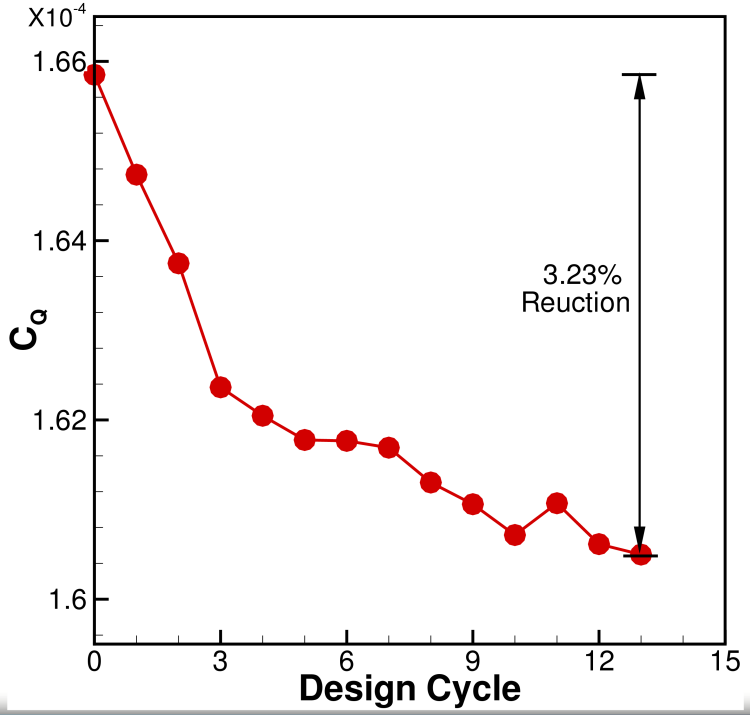
Convergence of lift and moment constraints

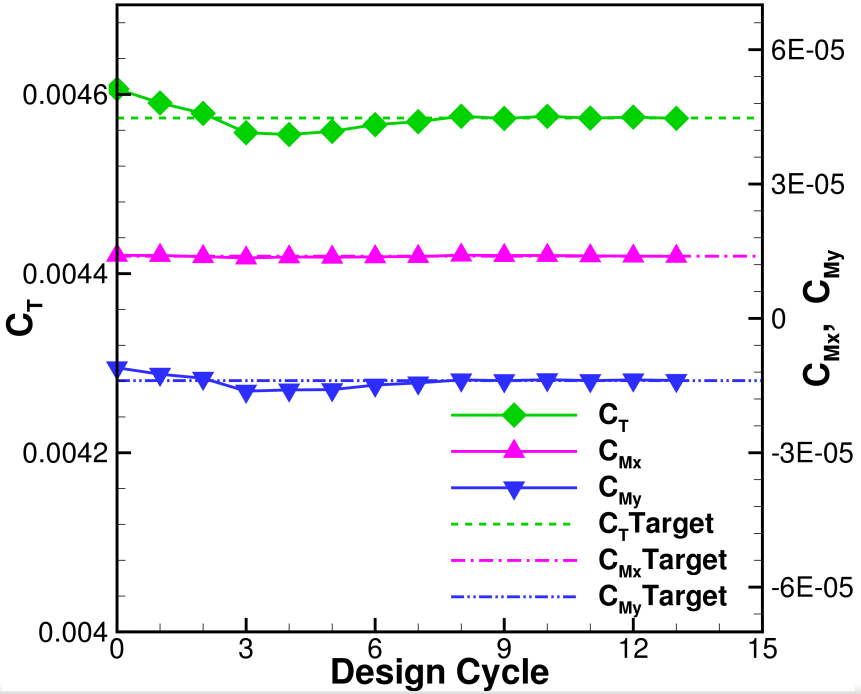


Blade deflections of optimized configuration compared to baseline

Optimization Results for Torque Minimization

- Objective and Constraints
  - Minimization of rotor torque, subject to thrust, rolling and pitching moment constraints
  - 4 multidisciplinary adjoint solutions
  - Objective and constraints defined for rotor blade surfaces; no structure constraints
  - 3.23% reduction in rotor torque in 13 design cycles
  - All constraints meet targets

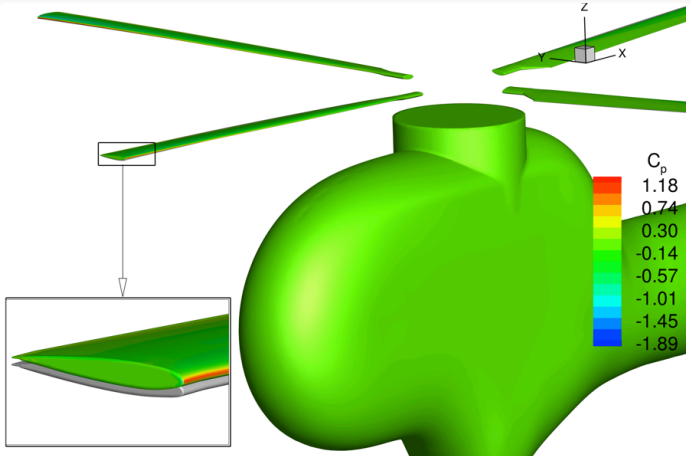


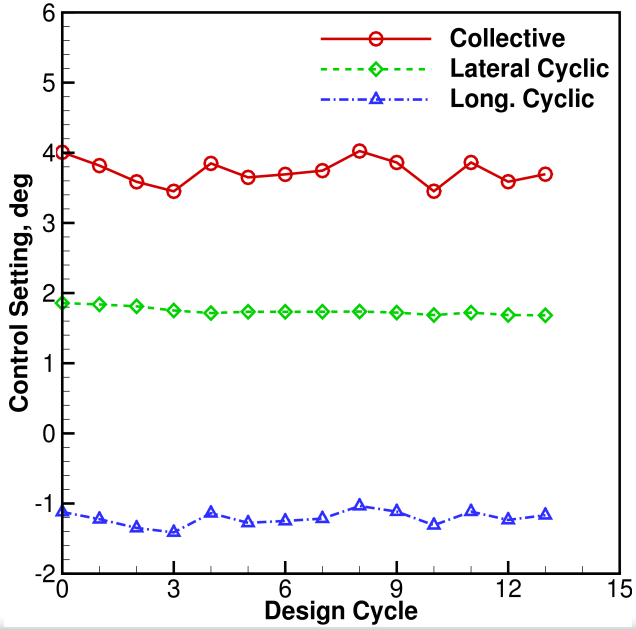


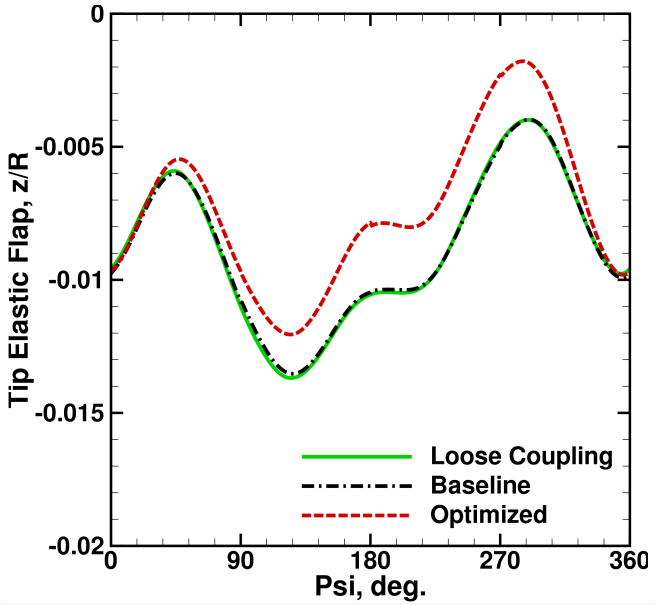
Optimization Results for Torque Minimization

- Variation of Trim Design Variables
- Comparison of Blade Deflections

	θ_0	θ_{1c}	θ_{1s}
Experiment	3.8°	1.92°	-1.34°
Baseline	4.0°	1.86°	-1.12°
Optimized	3.7°	1.68°	-1.17°

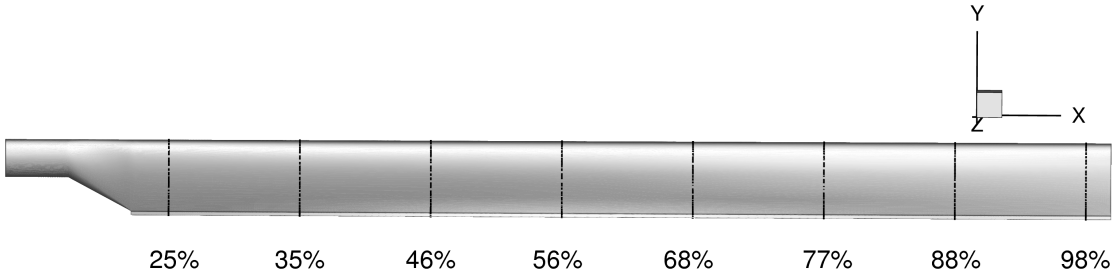


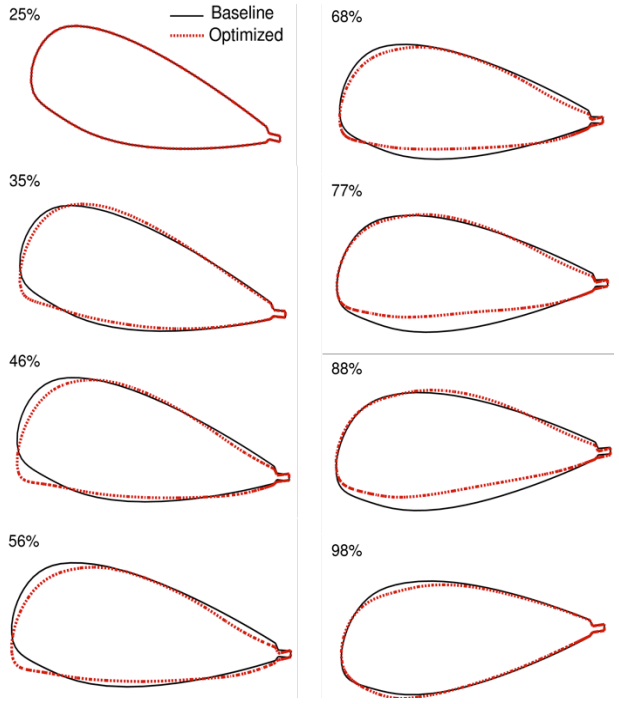




Optimization Results for Torque Minimization

- Comparison of Blade Section Geometries





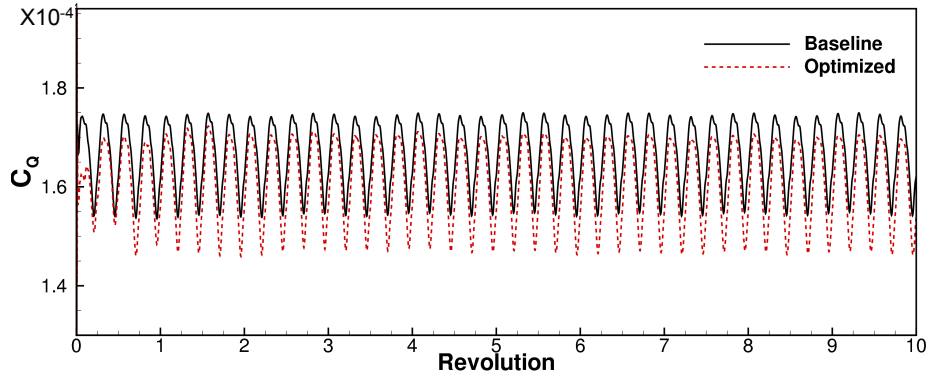
- Smaller twist angles (nose down)
- Thinner airfoil outboard and aft regions
- Increased positive camber front and midchord regions
- Negative camber aft regions close to TE
- More flat lower surface in middle of blade span

- Blade material properties considered invariant

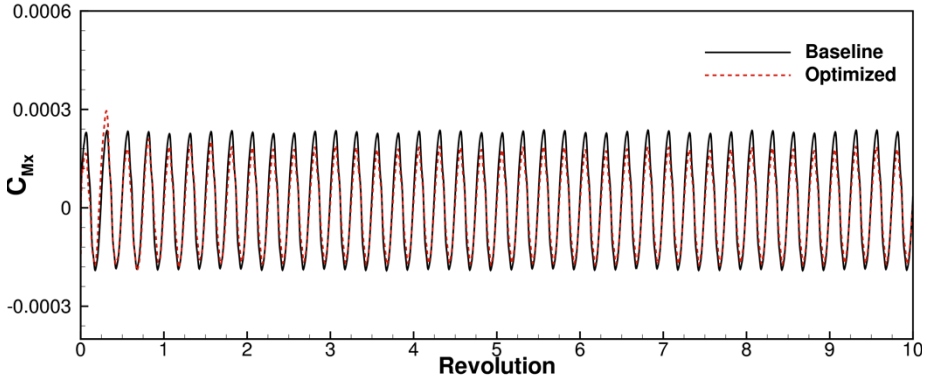
Enlarged vertical scale to view details

Optimization Results for Torque Minimization

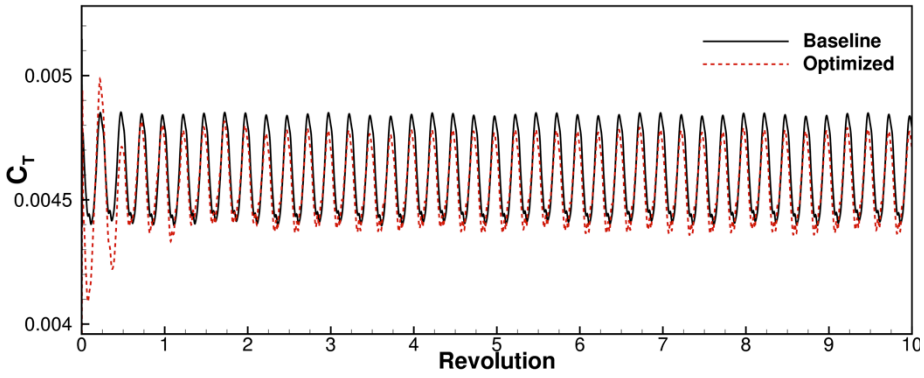
- Long-Term Simulations
  - 10-revolution tight coupling



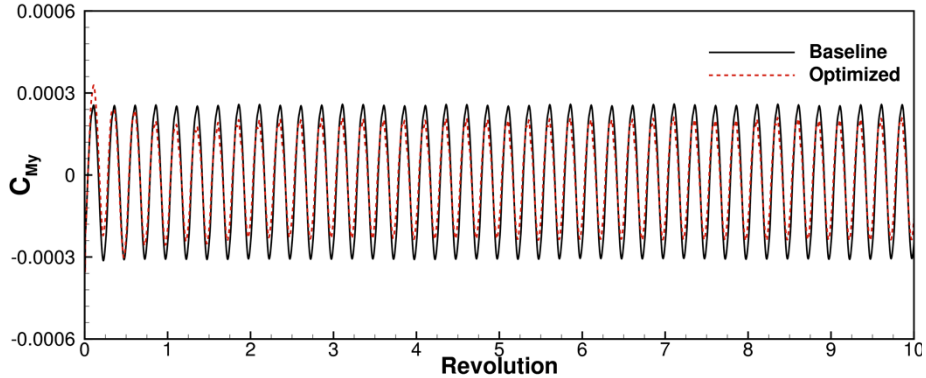
Torque



Rolling moment



Thrust

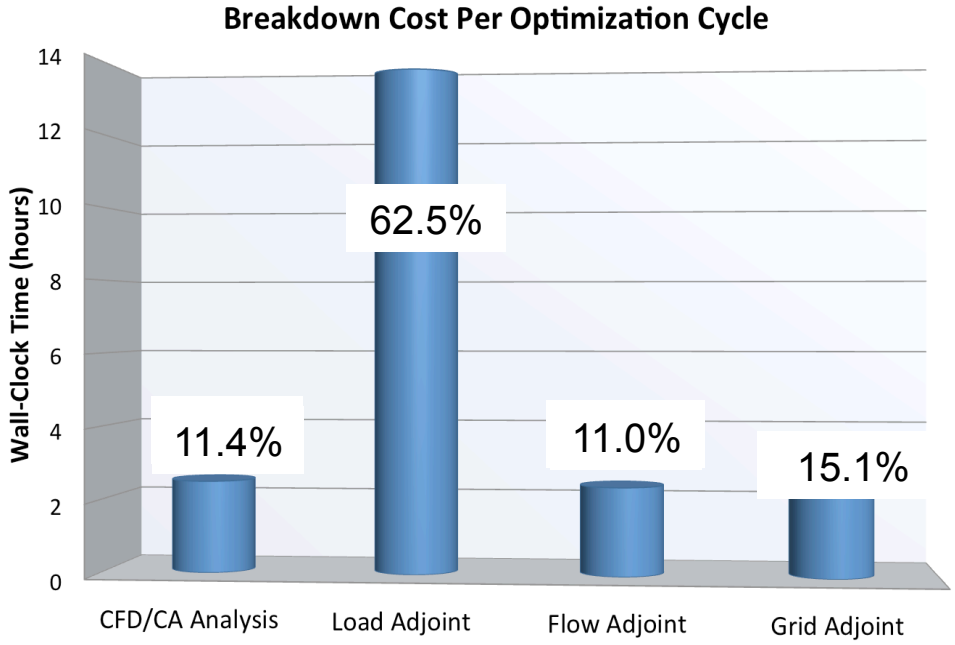


Pitching moment

  - Torque reduction well maintained
  - Thrust, rolling and pitching moments preserved

Improved Optimization Performance

- NAS Pleiades supercomputing facility - 2088 cores
- Comparison of performance between old and new coupled systems

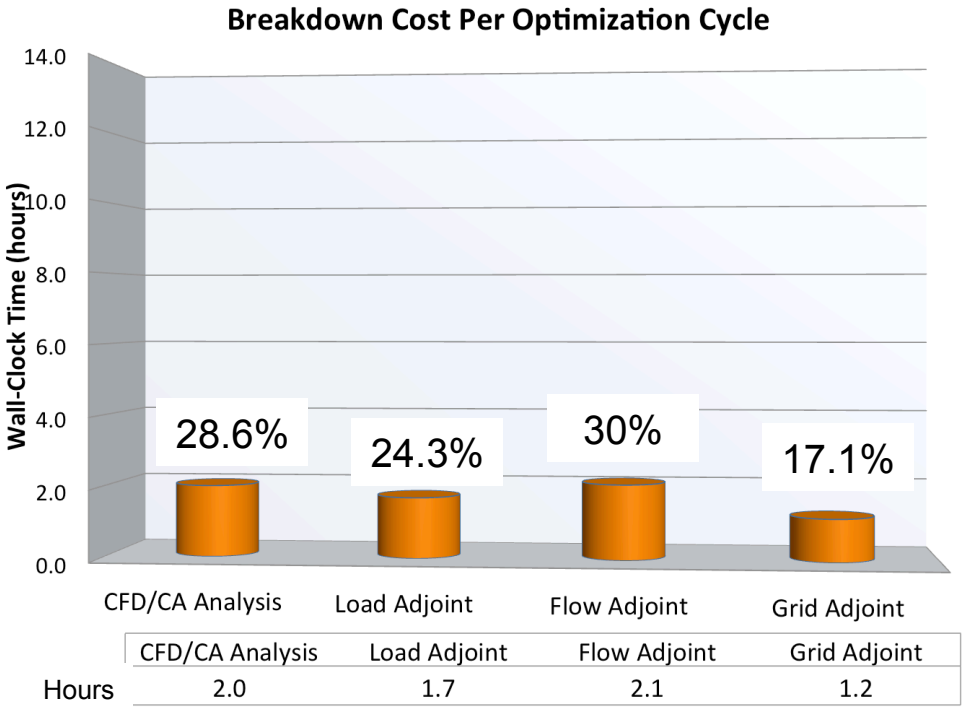


	CFD/CA Analysis	Load Adjoint	Flow Adjoint	Grid Adjoint
Hours	2.5	13.7	2.4	3.3

FUN3D/DYMORE4 System

Improved Optimization Performance

- NAS Pleiades supercomputing facility - 2088 cores
- Comparison of performance between old and new coupled systems
- Cost for computing load adjoint reduced to 1.7 hours in wall-clock time (was 13.7 hours)
  - DYMORE5
    - > 8 acceleration at each time step (fewer iterations, different compilers)
    - 1 hour saving
  - Separated elastic surface sensitivity to DYMORE solution
    - Removed quadratic dependence
    - 9.8 hours saving
  - Separated rigid motion sensitivity to DYMORE solution
    - 1.2 hours saving



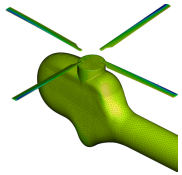
	CFD/CA Analysis	Load Adjoint	Flow Adjoint	Grid Adjoint
Hours	2.0	1.7	2.1	1.2

FUN3D/DYMORE5 System

- Total cost for one optimization cycle reduced to 7 hours, including 2.0 hours of forward analysis

Outline

- Background & Overview
- F/D Forward and Multidisciplinary Sensitivity Analyses
  - Tight and loose-coupling algorithms
  - Sensitivity analysis
  - Cost and efficiency improvement
  - Design optimization cycle
- Verification of F/D Rotorcraft Analysis
  - Simulations of HART-II baseline rotorcraft (loose coupling)
- Gradient-Based Multidisciplinary Design Optimization
  - Maximization of Lift constrained with moments
  - Minimization of rotor torque constrained with thrust and moments
  - Performance analysis
- Summary and Future Work



Summary and Future Work

- Developed high-fidelity multidisciplinary sensitivity analysis framework for tightly coupled FUN3D/DYMORE rotorcraft simulations
- Validated and verified FUN3D/DYMORE rotorcraft analysis by comparison with established high-fidelity simulations and experiments
- Demonstrated feasibility and effectiveness of high-fidelity multidisciplinary gradient-based design optimization applied to rotor blades
  - Reducing rotor torque while maintaining baseline thrust, rolling and pitching moments
  - Reduction of rotor torque and constraint targets well maintained in long-term simulations
- Significantly improved efficiency of multidisciplinary sensitivity analysis
  - Factor of 4 acceleration achieved
- Future work
  - Additional efficiency improvements
    - Manual differentiation for elastic surface and rigid motion sensitivities to DYMORE solutions
    - Real-valued perturbations
  - Loose coupling sensitivity analysis and design
  - Other design cases, UH-60 rotor design
  - Formulation and implementation of adjoint capabilities in DYMORE

Thank You!

National Institute of Aerospace

Any Questions?