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
  o High-fidelity, first-principle approach
  o Major simulation tools for aerodynamics
  o Large-scale simulations performed in supercomputing environment
  o Widely applied to rotorcraft simulations
  o Understanding of complex rotor flows and interactions
  o Insights to optimize design

• Rotorcraft aeromechanics requires multiple disciplines
  o Aerodynamics – airloads, rotor performance
  o Structure/multibody dynamics – blade deflections, trim, stability
  o Aeroacoustics – rotor noise and propagation
  o Flight dynamics, etc.
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
Overview

• High-fidelity rotorcraft analysis – state of the art
  o Couple CA with CFD to replace low-fidelity aerodynamics model
  o 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
Coupled CFD/CA Solvers

**FUN3D Model**
- Unstructured-grid, node-centered, finite-volume, CFD solver developed by NASA Langley
- Dynamically deforming, overset grids
- Interfaces for CFD/CA simulations

**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

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**FUN3D**
solver used for rotorcraft applications

**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

Impact of Parameter Change to Output

Example of Using Sensitivity to Seek Functional Minimum
Approaches to SA

• Finite difference method
  o Perturb input variables one at a time and analyze relative change in output
  o Simplest, minimum source code modifications
  o Computational cost depends on number of inputs
  o Suitable for “black-box” systems with “light” computations – SA can be conducted in parallel
  o Not affordable for high-fidelity CFD

• Adjoint method
  o Linearize system and transpose
  o Cost does not depend on number of inputs, similar to one analysis
  o Efficient for design with large number of input/design variables and few outputs
  o 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

![Diagram showing the flow of data between FUN3D, DYMORE, and CFD/CA Rotorcraft Sensitivity Analysis Toolset]
SA for Multidisciplinary CFD/CA System

• What kind of sensitivities does the coupled system account for?
  o **CFD flow** sensitivities from unsteady, turbulent flow
  o **CFD grid** sensitivities from overset and dynamically deforming meshes reflecting structural deflections
  o **Structure** sensitivities from various structural elements such as beams, mechanical joints, springs, dampers, etc.
  o **Integrated, mathematically rigorous system**

• What types of input variables can be enabled for design optimization?
  o **Geometry** *shape* design variables – blade planform, twist, thickness, camber, etc.
  o **Kinematics** design variables – pitch controls
  o **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

- Coupled system tested for various rotorcraft configurations and flight conditions

<table>
<thead>
<tr>
<th>HART-II</th>
<th>UH-60A Blackhawk</th>
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<tbody>
<tr>
<td><strong>Descending Flight</strong></td>
<td><strong>Forward Flight</strong></td>
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<tr>
<td>BVI</td>
<td>Hover Flight</td>
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<td>HHC for Minimum Noise</td>
<td></td>
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<tr>
<td>HHC for Minimum Vibration</td>
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</tbody>
</table>

- **Normal Force**

- **Figure-of-Merit**

![Diagram showing coupled system tested for various flight conditions](image-url)
Multipoint Design Setup – UH60A Rotor

- Design points - hover flight (C9605) and forward flight (C8534)
- Design outputs - 2 objectives & 6 constraints
  - Objectives - maximize rotorcraft figure of merit \((FM = \frac{C_T^{3/2}}{2\sqrt{C_P}})\) 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

\[
\theta = \theta_0 + \theta_1 c \cos \psi + \theta_1 s \sin \psi
\]

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

- 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
  o Combination of changes in many design variables
  o Pitch control angles excluded
  o 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.)
  - Initial transients pass quickly
  - Periodic solutions established
  - Improved rotor performance preserved
  - Trim conditions maintained

Hover flight (C9605)

Forward flight (C8534)
Concluding Remarks

• 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
  o Maximize rotorcraft figure of merit in hover flight
  o Minimize rotor power in forward flight
  o Constrained rotor thrust and rolling and pitching moments
  o Improved rotor performance preserved and trim conditions maintained

• Future work
  o Extend to coupled aero/structure/acoustics analysis and design optimization framework for low-noise rotorcraft optimization
  o Develop discretely-consistent, adjoint-based, FUN3D/DYMORE sensitivity analysis system and apply to maneuvering rotorcraft optimization
Thank you for your attention!