AERODYNAMICS AND AEROELASTICITY METHODOLOGIES FOR FUTURE CONCEPTS IN VERTICAL LIFT

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Aerodynamics Tools and Methods in Aircraft Design
The Evolution of Modern Vertical Lift Design

Aeromechanics of a Traditional Helicopter

- Dynamic Stall
  - Loads
  - Performance

- Rotor Fuselage Interactions
  - Vibration

- Rotor-Wake Interactions
  - Vibration
  - Noise
  - Loads
  - Performance

- Transonic Flow
  - $M > 1$
  - $M < 1$

- Tail-rotor Interactions With:
  - Empennage
  - Main Rotor
  - Main-Rotor Wake

- Performance, Handling Qualities

- Fuselage Flow
  - Drag
  - Component Loads
The Evolution of Modern Vertical Lift Design

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Vertical Lift in the 21st Century

- Low Reynolds Numbers
  - Unmanned Vehicles/Drones
- Coaxial/Corotating Rotors
  - FLRAA and FARA
- Shrouded/Ducted Rotors
- Distributed Electric Propulsion
- Vertical Lift in the 21st Century
  - Jaunt Air Mobility
  - Bell Flight

Urban Air Mobility

- Bell Flight

- Jaunt Air Mobility
- Distributed Electric Propulsion
Aeromechanics Prediction Requirements

- Vehicle performance
- Blade loads
- Airframe & drive train loads
- Vibration (rotor and fuselage)
- Aeroelastic stability
- Flight dynamics
- Handling qualities
- Noise

Figures courtesy of US Army
Aerodynamic Tools for 21st Century VL

Conceptual and Preliminary Design
- NDARC
- GTABBB/COMPASS

Detailed Design and Engineering Analysis
- Comprehensive Codes: CAMRAD, RCAS, HOST
- Panel-Based Methods
- Dual Solver Hybrid Methods
- Adjoint Design: FUNtoFEM

Physics and High Fidelity Analysis
- Helios, FUN3D, OVERFLOW
- FLOWer, ELSA, TAU
- Academic Codes: Liverpool/Glasgow, UMD
## 21st Century Aerodynamic Prediction Goals

<table>
<thead>
<tr>
<th>Goal</th>
<th>Engineering Tool</th>
<th>Physics-Based Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight performance</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Hover performance</td>
<td>0.5%</td>
<td>2%</td>
</tr>
<tr>
<td>Airloads (c_n/c_m), without mean</td>
<td>1%</td>
<td>10% / 35%</td>
</tr>
<tr>
<td>Airloads (c_n/c_m), with mean</td>
<td>1%</td>
<td>10% / 35%</td>
</tr>
<tr>
<td>Blade loads (flap / chord / torsion)</td>
<td>3%</td>
<td>20 / 35 / 25%</td>
</tr>
<tr>
<td>Vibration</td>
<td>10%</td>
<td>100%</td>
</tr>
<tr>
<td>Stability (fraction critical damping)</td>
<td>0.002</td>
<td>0.02</td>
</tr>
<tr>
<td>Noise</td>
<td>3 dB</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

What Capabilities are Needed?

Multiple Core/Processor Capabilities
Ability to model or include the effects of
New Technology
New Designs

Multiple Rotors/Propellers

Active Flow Control

Active Surfaces/Dampers
What Capabilities are Needed?

Multiple Core/Processor Capabilities
Ability to model or include the effects of
New Technology
New Designs

Incorporate the effects of
Environment
Urban and Nap of the Earth
Near-ground Operations
In-Flight Operations
What Capabilities are Needed?

Reduce the scope of wind tunnel testing during design and flight testing for certification

- Digital Threads
- Uncertainty Quantification
- Removal of User-generated Errors
Quantitative Data Analysis Techniques

CIFER
• Developed for system identification (USRA)
• Computes difference between frequency response of two datasets

• Coherence: Linearity between response of two data sets, illuminates missed harmonics. Coh < 0.6 → missed harmonic
• Cost Function: Scalar measure of difference between response of two data sets
  J < 100 → Very little difference
  J < 50 → Virtually identical

\[ J = \frac{20}{\pi} \sum_{\omega_n} W_y \left( |\hat{f}_{\omega_n}| - |f_{\omega_n}| \right)^2 + W_p (\angle f_{\omega_n} - \angle f_{\omega_n})^2 \]

where \( W_y, W_g, \) and \( W_p \) are weighting factors for coherence, magnitude, and phase, respectively

Quantitative Data Analysis Techniques

Aerodynamic Tools for Design and Modeling & Simulation
NASA Design and Analysis of Rotorcraft (NDARC)

Capabilities for:
- Off-design mission analysis
- Flight performance
- Vehicle sizing

Flexibility for non-conventional vehicles through
- Synthesis of component modules
- Propulsion system options (electric, turbojet, turbofan, reaction drives, fuel cells, etc.)
- Surrogate models for trade-space analysis

A New Approach for Design and M&S: GTABB and COMPASS

• Development of physics-based reduced order models for aerodynamic and bluff bodies
• Extensible to new configurations: Not an interpolation
• New features:
  - Shadowing orientation effects
  - GUI
  - Rotor and engine effects
  - Multiple body types
• Validated with CFD, wind tunnel, and flight test
• Adopted/in adoption by US Army, US Navy, Drone Racing League, academia
  - Slung loads
  - Control law and autonomous algorithm design
  - Virtual reality-based training (M&S)

GT Aerodynamics of Bluff Bodies (GTABB)

External Control Module
Unsteady Aerodynamics in Real Time

- Unsteady phase lag
- Large vortex shedding fluctuations
- Three-dimensional effects (finite bodies)

Captures Onset of Instability

US Army Blackhawk Flight Test Validation
COMPlEx Aerodynamic Shape Simulation (COMPASS)

- Use canonical shapes with corrections to estimate the characteristics of complex shapes.
- Add corrections for shadowing (feature blockage) and shear layers.
Nondimensional Aerodynamic Characteristics

Predict the $C_p$ distribution about the body.

Integrate to get force and moment coefficients.
Nondimensional Aerodynamic Characteristics

Quasi-Steady Predictions

Typical Control Law Design:
• Flat plate wetted area used for forces
• Moments are neglected
Vehicle Performance

Flat plate aerodynamics overpredicts performance by ~10% and underpredicts rotor trim by ~15%
Split-S Trajectory predicted by GTABB

Height Above Ground (m)
Flight Test Validation

https://www.youtube.com/watch?v=UNoGxq8pQGE, Courtesy Drone Racing League
Hybrid CFD Analyses
CFD + Free Wake Model

- Data is exchanged between the CFD and free wake code at fixed intervals.
- CFD near-body solver calculates the sectional loads along the blades as the solution advances.
- The vortex filaments which model the wake are updated based on the sectional loads.
- The outer boundary conditions of the CFD domain are updated from the wake-induced flow field to reflect the influence of the wake.
Hybrid CFD Methods

• Promise of CFD-level accuracy without the costs, up to 90% savings in some cases
• Many approaches through the decades, but with limitations:
  • Single blade
  • No fuselage (except DLR)
  • Very mixed results with significant errors in pitching moment, structural bending, and hub forces
  • Some have known numerical formulation errors
  • Many are “academic” codes without formal version control

Past (US) engineering experience not positive to adoption in work flow
CDI-GT Hybrid CFD Approach

- CFD/CFD-CSD provide highest accuracy at highest cost
- Hybrid CFD methods mitigate costs by 50%-90% while maintaining accuracy
- Increase CFD-based applications to earlier design and additional analysis

- Carefree: Couple CFD solvers with commercial wake solvers
- Flexible: Takes advantage of near-body capabilities
- Physics: Multiple level of physics
- Cost-effective: Can use same meshes
- Expanded Capabilities: Multiple components, full vehicles
Non-contiguous Methodology

- Remove the inertial background grids
- Allow boundary motion and arbitrary boundary shapes
- Velocity at all unblanked outer boundaries determined by the free wake code

Illustration of tip vortex passing between domains

Blade Vortex Interaction

Conglomeration of vortex filaments modeling the tip vortex

Contiguous vs non-contiguous
S-76 Hover

- $M_{\text{tip}} = 0.65$, trimmed to $C_T/\sigma=0.09$
- 3.9M nodes per blade (15.4M total)
- O-grid topology

Hover is complex computation with significant wake interactions
S-76 Integrated Loads

Figure of Merit

Exp. uncertainty ~0.6 counts
Helios ~ 1 count
OF-Charm ~ 2 counts
OF-alone >2 counts

Comparable or better to all US and International participants

Torque coefficient vs. Thrust coefficient

Vertical Wake

Non-contiguous wake predictions (lines) comparable to those in Contiguous CFD domain (symbols)
## Computational cost

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Number of grid nodes (millions)</th>
<th>Core-hours</th>
<th>Cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERFLOW-Helios (Jain 2015)</td>
<td>448</td>
<td>122,880</td>
<td>57.5</td>
</tr>
<tr>
<td>OVERFLOW (Narducci 2015)</td>
<td>63.4</td>
<td>28,080</td>
<td>13.14</td>
</tr>
<tr>
<td>OVERFLOW-CHARM with background grids</td>
<td>28</td>
<td>14,400</td>
<td>6.74</td>
</tr>
<tr>
<td>OVERFLOW-CHARM non-contiguous grids (5 revs)</td>
<td>15.4</td>
<td>2,140</td>
<td>1</td>
</tr>
</tbody>
</table>

The full grid non-contiguous simulations cost about 7.6% of the number of core-hours as the stand-alone engineering OVERFLOW simulations.

Evaluation in Forward Flight

- Baseline mesh was provided by Boeing-PHL
- Represents a typical near-body mid-size mesh
- 3.7M point mesh on each of four blades
- 32.9 M background Cartesian mesh (orig)
- Menter kw-SST turbulence model with full viscosity in the near-body region and Euler terms in the off-body region
- Sensitivity to mesh sizes, coupling updates, turbulence model
- Aeroelastic coupling
- Examination of different rotor blade structural properties on same rotor (experimental set-up)
- Evaluation of fuselage and wind tunnel floor effects

Min, B.-Y. et al., “Toward Improved UH-60A Blade Structural Loads Correlation,” AHS 74th Annual Forum, Phoenix, AZ, May 14-17, 2018
Dual-Solver Vortex Interactions
Correlation with Industry CFD-alone

Normalized, means removed

- Not a correlation with experiment – correlation with “best industry mesh/practices”
- Reduction in background mesh by 40% nodes – no difference in loads
- Convergence occurs at 75% of full CFD convergence requirements
- None of the poor correlations with structural, hub or pitching moments as observed with other hybrid approaches
Full CFD Analysis
Rotorcraft simulation and adjoint-based derivative evaluation framework

(Graeme Kennedy at Georgia Tech)

- FUNtoFEM: A general interface for aeroelastic simulation and adjoint-based gradient evaluation
- Enables use of either loosely or tightly coupled simulation
- Separation of time integration schemes for CSD/CFD
- Different bodies can employ their own load/displacement transfer methods
- Efficient hand-coded derivative terms enable efficient computation of coupled Jacobian-vector products
Helios Overview

- **Rotary-wing product of CREATE™-AV**
  - Jointly developed by CREATE and Army ADD

- **Multi-mesh/Multi-solver**
  - Strand, unstructured, structured curvilinear
  - Cartesian high-order with AMR
  - Automated domain interpolation

- **Interfaces to rotorcraft comprehensive analysis codes for CSD and trim**

- **Scalable execution on HPC systems**

- **100+ active user licenses**
  - DoD organizations (Army, Navy)
  - Various US rotorcraft companies
  - Various academic institutions
US Army Helios Development

- Helios integrates simulation codes from CREATE, Army, and outside organizations
- Software integrated through an extensible Python infrastructure
Apache INSTALLED ROTOR PERFORMANCE

- High-fidelity, time-accurate rotor and fuselage combinations
- Boeing Mesa

Narducci & Tadghighi, Boeing
AIAA-2016-0564
Helios wake velocities, vortex locations and strength predictions are within experimental errors.
Helios models the interactional aerodynamics between lift-offset coaxial compound rotors, fuselage, and propulsor configuration.

Validation with Bell XV-15 Tiltrotor

<table>
<thead>
<tr>
<th></th>
<th>$C_T/\sigma$</th>
<th>Download/Thrust (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wing</td>
</tr>
<tr>
<td>CFD</td>
<td>0.1195</td>
<td>10.31</td>
</tr>
<tr>
<td>Flight test</td>
<td>0.1271 – 0.1296</td>
<td>-</td>
</tr>
<tr>
<td>(Arrington et al.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Download Validation with JVX

Config 1
FUN3D-OVERFLOW

Config 2
mStrand

Felker et al, '87
JVX DOWNLOAD ANALYSIS

Rotor Thrust CT

- Low thrust
  \( \theta = 6^\circ \)
  - Test
  - FUN3D/OFLOW
  - mStrand

- High thrust
  \( \theta = 12^\circ \)
  - Test
  - FUN3D/OFLOW
  - mStrand

Wing/Flap Download CZ

- Low thrust
  \( \theta = 6^\circ \)
  - Test
  - FUN3D/OFLOW
  - mStrand

- High thrust
  \( \theta = 12^\circ \)
  - Test
  - FUN3D/OFLOW
  - mStrand

Download - CT/CZ

- 0%
- 2%
- 4%
- 6%
- 8%
- 10%
- 12%
- 14%
- 16%
- 18%
- 20%

- 10.8%
- 11.3%
- 11.4%

- 10.1%
- 9.6%
- 10.2%

FUN3D-OVERFLOW
mStrand
Manuver: UH-60A UTAAS Pull-Up

- 40 revs, 9 sec (real-time)
- Flight path angle 3 deg at start to 35 deg at end
UH-60A UTTAS Maneuver
Section Pitching Moment $C_m \, M^2$

86.5 % R
Helios demonstrates big improvement over RCAS for pushrod load prediction.
Joint CFD-Experimental Validation!

- Full-scale UH-60A rotor in Air Force 40- by 80-foot Wind Tunnel under NASA/Army Airloads Wind Tunnel Test Program (2010)
  - Extensive database of performance, hub loads, air loads, structural loads, wake PIV, blade deformation, RBOS on highly instrumented rotor for validating analytical tools

- PIV phase
  - Wake measurements at 90 deg azimuth over 50% of outer blade
  - Vortex characteristics extracted: circulation, size, position
Future Research Directions

• Continuous improvement in speed and efficiency on multi-core processors for all levels of aerodynamic prediction tools
• Integration of reduced-order modeling that is physics-based for earlier design of maneuvering and operational effects
• Advanced design capabilities for rapid, highly-accurate design
• Using high-fidelity methods, exploration of physics to understand complex interactional phenomena and shortcomings of current algorithms
• Improved prediction of acoustics (interior and exterior) from unsteady aerodynamics
• Jointly designed experimental datasets with sufficient information for CFD validation!
  • International collaboration to solve complex problems
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Questions?