ROTORCRAFT TECHNOLOGY FOR HALE AEROELASTIC ANALYSIS

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Objective of Presentation

• Describe state-of-the-art of rotorcraft technology applicable to aeroelastic analysis of a class of high-altitude long-endurance aircraft

• Analysis requirements —
  • Stability, structural loads, aerodynamic loads, performance, flight dynamics, controls
  • Design conditions, maneuvers, atmospheric turbulence
HALE Configuration Considered

- High aspect-ratio wing
  - Light, flexible structure
  - Low dynamic pressure, low Reynolds number

- Propellers
  - Light structure
  - Flexible mounting to wing

- Aerodynamic surfaces attached to wing

- Nacelles and pods
  - Significant fraction of wing weight
## Operational Environment

<table>
<thead>
<tr>
<th></th>
<th>Helicopter</th>
<th>Tiltrotor</th>
<th>µUAV</th>
<th>HALE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Altitude</strong></td>
<td>SLS</td>
<td>20k</td>
<td>SLS</td>
<td>SLS</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1.</td>
<td>.53</td>
<td>1.</td>
<td>1.</td>
</tr>
<tr>
<td><strong>Speed of sound</strong></td>
<td>1.</td>
<td>.93</td>
<td>1.</td>
<td>1.</td>
</tr>
<tr>
<td><strong>Kinematic viscosity</strong></td>
<td>1.</td>
<td>1/.53</td>
<td>1.</td>
<td>1.</td>
</tr>
<tr>
<td><strong>Flight speed</strong></td>
<td>180 kt</td>
<td>250 kt</td>
<td>10 kt</td>
<td>20 kt</td>
</tr>
<tr>
<td><strong>Mach number</strong></td>
<td>.27</td>
<td>.41</td>
<td>.02</td>
<td>.03</td>
</tr>
<tr>
<td><strong>Dynamic pressure</strong></td>
<td>110</td>
<td>113</td>
<td>.3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Re (/ft)</strong></td>
<td>1,935,000</td>
<td>1,610,000</td>
<td>108,000</td>
<td>215,000</td>
</tr>
<tr>
<td><strong>Prop/Rotor $V_{tip}$</strong></td>
<td>700</td>
<td>600</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td><strong>$V/V_{tip}$</strong></td>
<td>.43</td>
<td>.70</td>
<td>.34</td>
<td>.45</td>
</tr>
<tr>
<td><strong>Max M</strong></td>
<td>.90</td>
<td>.71</td>
<td>.04</td>
<td>.07</td>
</tr>
<tr>
<td><strong>Re (/ft)</strong></td>
<td>4,450,000</td>
<td>2,290,000</td>
<td>318,000</td>
<td>477,000</td>
</tr>
</tbody>
</table>

**rotorcraft aerodynamic environment —**

- high subsonic to transonic rotor speed
- low to moderate Reynolds number

**these are HALE operating conditions for which rotorcraft technology and tools may be applicable**
Available Rotorcraft Technology

• Structures
  • Multibody dynamics + nonlinear finite elements
    • Model wings, propellers, control mechanisms

• Beams
  • Model slender structures
  • Exact kinematics (small strain)
  • Isotropic and composite, closed and open sections
  • Hodges (1990), Bauchau and Hong (1988), Smith and Chopra (1993),

• Can handle large, arbitrary deflections
• Coupled propeller and wing/airframe dynamics
• Geometric, structural, and inertial nonlinearities
Available Rotorcraft Technology

• Aerodynamics
  • Lifting-line theory
    • Model high aspect-ratio wings and propeller blades
    • Two-dimensional airfoil tables (steady, compressible, viscous)
      + vortex wake model

• Free wake geometry
  • Self-induced distortion of wake
  • Wing and propeller in cruise, static propeller thrust, wing/prop interaction

• Wake formation and rollup
  • Models of rollup and vortex core

• Can handle arbitrary planform
• Coupled propeller and wing/airframe aerodynamics
• Nonlinear geometry, dynamic stall
Available Rotorcraft Technology

• Aerodynamics (continued)
  • Unsteady aerodynamics — compressible thin airfoil theory
    • Classical; Johnson (1980)
    • With trailing edge flap; Kussner and Schwartz (1941), Theodorsen and Garrick (1942)
    • ONERA EDLIN; Petot (1990)
    • Leishman and Beddoes; Leishman (1988), Hariharan and Leishman (1996)

• Unsteady aerodynamics — dynamic stall
  • ONERA EDLIN; Petot (1990), Peters (1985)
  • Leishman and Beddoes (1989, 1986)

• Computational Fluid Dynamics
  • Coupled CFD/CSD — RANS, time integration
    • For aeroelastic problems involving transonic/supersonic flows
  • Actuator disk model for propeller
  • 2D airfoil design and analysis
    • Euler + boundary layer
    • RANS
Available Rotorcraft Technology

- Solution procedures
  - Steady state flight
    - Periodic, nonlinear aerodynamics and structure
  - Response to turbulence and maneuvers
    - Time-integration solution

- Linear state-space models
  - For stability, control design, aeroservoelasticity, flight dynamics
    - Including whirl flutter
  - Linearized about steady state flight
  - Coupled airframe and propeller dynamics (multi-blade coordinates)
    - Floquet theory for 2-bladed propellers (state equations periodic, not time-invariant)

- Tools for handling qualities assessment and control law design
  - CIFER, CONDUIT, RIPTIDE — identification, optimization, simulation
Rotorcraft Technology Embodied in Tools

- Verification and validation has been for rotorcraft — little application of tools to HALE configurations
  - Test data required for HALE configurations of interest
  - Followed by correlation — and perhaps further development of tools
- Then will have confidence in application of tools to design
  - Or at least know what additional testing needed

- Limited number of practitioners in community
  - Significant investment required to learn technology, and learn how to use rotorcraft tools

- Comprehensive analysis level of technology (beam + lifting line) can be used in iterative design process
  - CFD applications to complete configuration require major resources, hence limited role in iterative design
Edge of State-of-the-Art in Rotorcraft Technology

• Still developing theory, methods, applications for
  • Maneuver loads
  • Transonic aeroelastic stability
  • Dynamic stall
  • Unsteady aero of wing/prop interaction in linearized models
  • RANS CFD for performance, structural loads, stability

• Not in typical rotorcraft problems
  • Thermal effects
  • Membrane buckling
Rotorcraft Experience Regarding Testing

• Based on rotorcraft experience, what testing can do and should do

• Scale: Helicopter community accepts 20% scale (or larger) model testing of rotors, for performance and loads data in support of design and development
  • At 20–25% scale, this experience shows there will be scaling compromises that limit modeling fidelity sufficient to affect measurements
    • Geometric: Typically compromises in hub and blade root geometry
    • Reynolds: 30-50% more profile power, similar magnitude reduction in maximum lift coefficient
    • Dynamics: Typically hub weight, root stiffness, control system stiffness not matched
    • Mechanical: Typically lag damping not correct, structural shapes not same, often compromises of load path
  • Experience has provided industry the knowledge needed to extrapolate the data to full scale, including allowance for scaling deficiencies — for conventional rotors in conventional operating regimes

• Wind tunnel tests recommended from rotorcraft experience
  • For performance: propeller only
  • For stability and control: propeller(s) on elastic wing (cantilever)
  • For aerodynamic loads and interference and aero: propeller(s) on rigid wing

• Scaled model flight tests seldom used in rotorcraft development
Summary

• Much of technology needed for analysis of HALE nonlinear aeroelastic problems is available from rotorcraft methodologies
  • Consequence of similarities in operating environment and aerodynamic surface configuration

• Technology available — theory developed, validated by comparison with test data, incorporated into rotorcraft codes
  • High subsonic to transonic rotor speed, low to moderate Reynolds number
  • Structural and aerodynamic models for high aspect-ratio wings and propeller blades
  • Dynamic and aerodynamic interaction of wing/airframe and propellers
  • Large deflections, arbitrary planform
  • Steady state flight, maneuvers and response to turbulence
  • Linearized state space models

• This technology has not been extensively applied to HALE configurations
  • Correlation with measured HALE performance and behavior required before can rely on tools