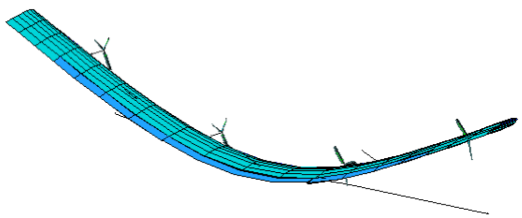
ROTORCRAFT TECHNOLOGY FOR HALE AEROELASTIC ANALYSIS



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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

	Helicopter	Tiltrotor	μUAV	HALE	
Altitude	SLS	20k	SLS	SLS	100k
Density	1.	.53	1.	1.	.014
Speed of sound	1.	.93	1.	1.	.89
Kinematic viscosity	1.	1/.53	1.	1.	1/.017
Flight speed	180 kt	250 kt	10 kt	20 kt	170 kt
Mach number	.27	.41	.02	.03	.29
Dynamic pressure	110	113	.3	1.4	1.4
Re (/ft)	1,935,000	1,610,000	108,000	215,000	30,000
Prop/Rotor V_{tip}	700	600	50	75	640
V/V_{tip}	.43	.70	.34	.45	.45
Max M	.90	.71	.04	.07	.71
Re (/ft)	4,450,000	2,290,000	318,000	477,000	68,000

rotorcraft aerodynamic environment —

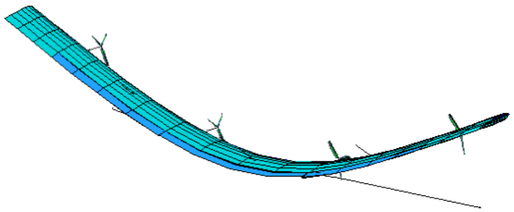
high subsonic to transonic rotor speed

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
    - Johnson (1994), Bauchau (1995), Saberi (2004)

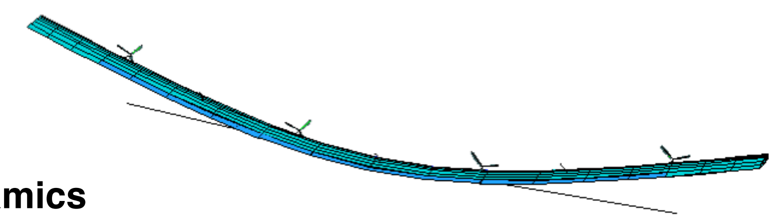


  - Beams
    - Model slender structures
    - Exact kinematics (small strain)
    - Isotropic and composite, closed and open sections
    - Hodges (1990), Bauchau and Hong (1988), Smith and Chopra (1993), Yuan, Friedmann, and Venkatesan (1992), Johnson (1998)

  - 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
    - Johnson (1986, 1990, 1998)
  - Free wake geometry
    - Self-induced distortion of wake
    - Wing and propeller in cruise, static propeller thrust, wing/prop interaction
    - Scully (1975), Bliss, Quackenbush, and Bilanin (1983), Bagai and Leishman (1994), Johnson (1995), Bhagwhat and Leishman (2000)
  - 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