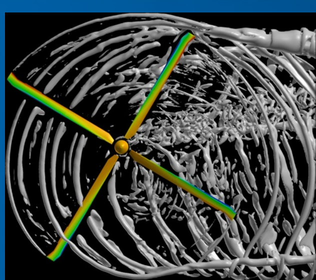
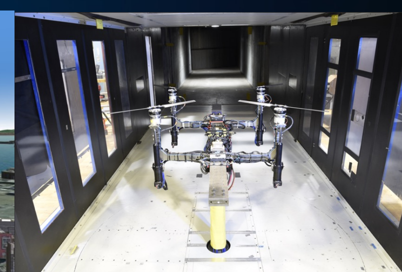
VTOL Aeromechanics from 1974 to 2024 and the Future —Aerodynamics

A Review on the Occasion of the 6th Decennial VFS Aeromechanics Specialists' Conference

Wayne Johnson
and
Members of the VFS Aerodynamics Committee

6th Decennial VFS Aeromechanics Specialists' Conference
Santa Clara, CA, February 2024

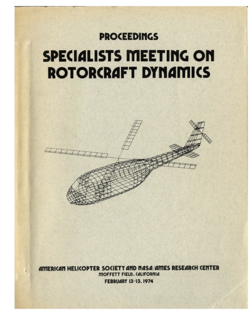


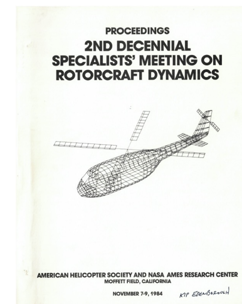



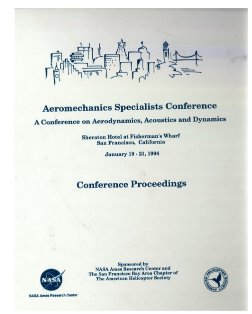

Rotorcraft Aerodynamics from 1974 to 2024 and 2074

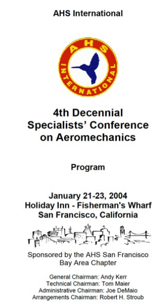
- **Background: Five Decennial Aeromechanics Conferences of American Helicopter Society / Vertical Flight Society**

- **Specialists Meeting on Rotorcraft Dynamics, February 1974**
- **Specialists' Meeting on Rotorcraft Dynamics, November 1984**
- **Aeromechanics Specialists Conference, January 1994**
- **Specialist's Conference on Aeromechanics, January 2004**
- **Aeromechanics Specialists' Conference, January 2014**
- **Aeromechanics Specialists' Conference, February 2024**









5th Decennial AHS Aeromechanics Specialists' Conference 2014

Current Challenges and Future Directions in Rotorcraft Aeromechanics

San Francisco, California, USA
22-24 January 2014

Vertical Flight Society

SAN FRANCISCO BAY AREA CHAPTER OF VFS

CALL FOR PAPERS

VFS Transformative Vertical Flight 2024

6th Decennial VFS Aeromechanics Specialists' Conference

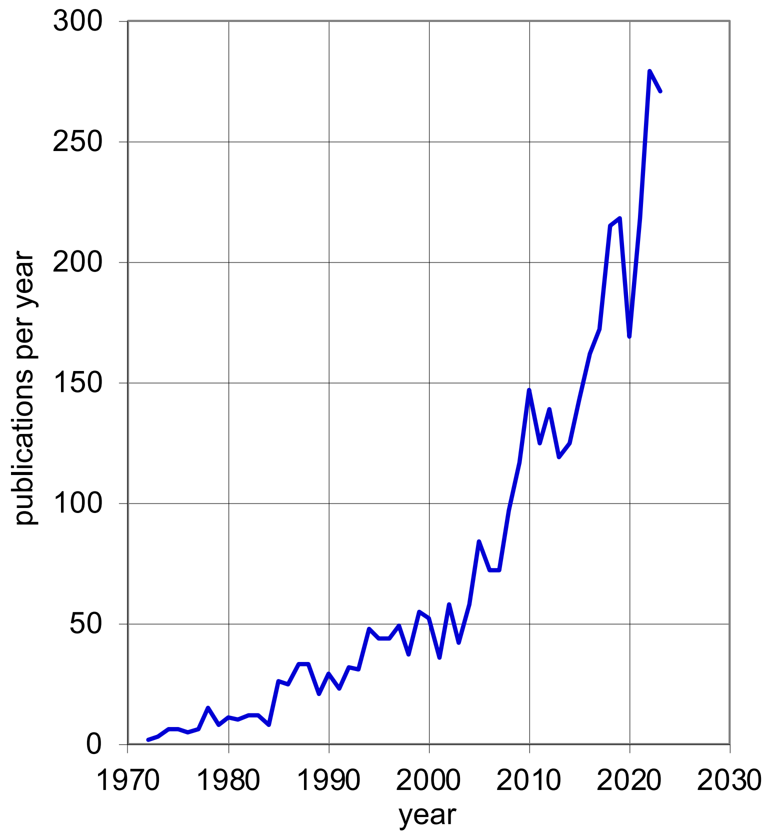
Santa Clara Convention Center, Santa Clara, California
February 6-8, 2024
Hosted by the San Francisco Bay Area Chapter

Topics in Rotary Wing Aerodynamics

- Computational Fluid Dynamics
- Dynamic Stall
- Finite-State Wake Models
- Rotor Airloads Tests

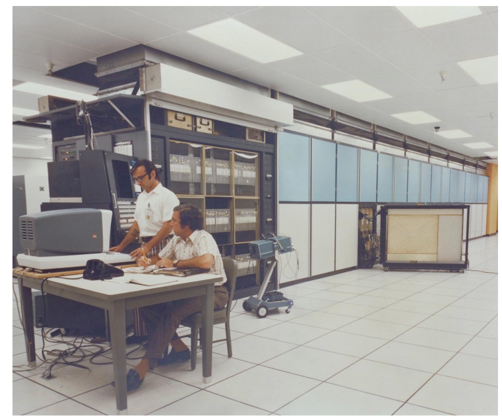
Computational Fluid Dynamics

- **Advanced numerical aerodynamics today means Computational Fluid Dynamics (CFD)**
  - Quest for accurate first-principles solution for flow about helicopter rotor
    - Three-dimensional, unsteady, vortical, compressible, viscous, turbulent
    - Rotation of wing makes everything harder
- **Goal is accurate calculation of performance, airloads, and noise of any rotor that can be built**



Computational Fluid Dynamics — to 1974

- **Before 1970: panel methods, acceleration potential for rotors — not today what CFD means**



- **1972: Illiac IV at NASA Ames (online 1975)**
  - Rotorcraft applications among first for high-performance computing (as for computers of 1960s)

- **1970: Murman and Cole** (transonic airfoil solution)

- **1972: Caradonna and Isom**
  - First application of CFD to rotary wing
  - Transonic small disturbance potential, rotating frame equations, hover (steady), non-lifting

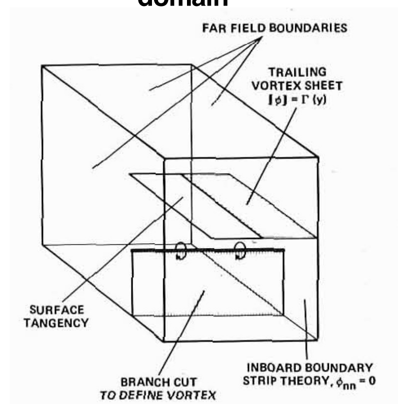
- **1974 Rotorcraft Dynamics Conference**

  Less than 10 papers per year on CFD applied to rotorcraft

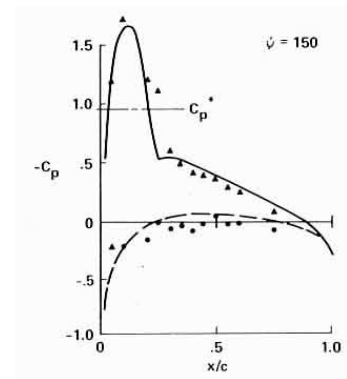
Computational Fluid Dynamics — to 1984

- **1982: Caradonna, Tung, and Desopper**
  - CFD for rotor blade
    - Three-dimensional, unsteady, lifting flow on rotor in forward flight
  - Transonic small disturbance potential
  - Effective angle of attack for influence of wake and blade motion

computational domain



blade section pressures



- **Mid 1980s: solutions for rotor blade flow using full potential equations and Euler equations**

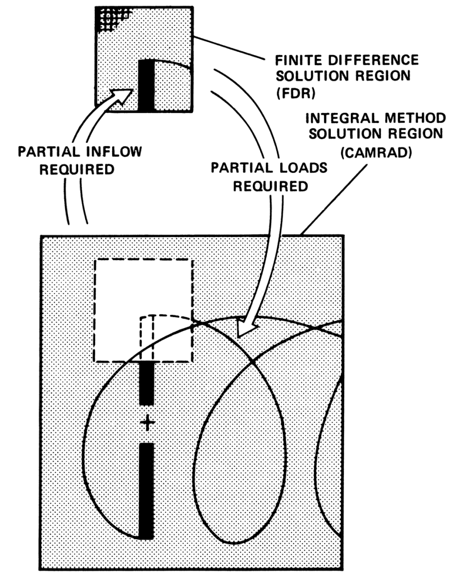
- **Late 1980s: solution of Navier-Stokes equations**

- **1984 Specialists' Meeting on Rotorcraft Dynamics**

  ~20 papers per year on CFD applied to rotorcraft

Computational Fluid Dynamics — 1984

- **1984: CFD/CSD loose coupling developed (Tung, Caradonna, and Johnson)**
  - Combining CFD and CSD codes requires fluid-structure interface, and coupling strategy
    - Tight coupling: information exchanged at every time step
    - Loose coupling: information exchanged for entire revolution of periodic loads or motion
  - Transonic small disturbance, outboard blade, advancing side loading and wake near blade
  - Comprehensive analysis handles trim and blade motion — plus inboard blade and wake away from blade



- **1984: Cray XMP at NASA Ames**

Computational Fluid Dynamics — to 2004

- **1991: first papers on TURNS applied to rotorcraft**
- **1992: first papers on OVERFLOW applied to rotorcraft**

- **1994 Aeromechanics Specialists Conference**

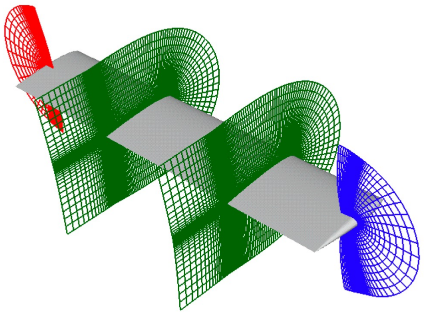
  ~35 papers per year on CFD applied to rotorcraft

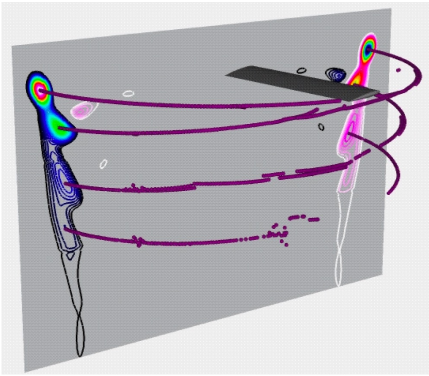
- **1996: first papers on FLOWer applied to rotorcraft**
- **2000: first papers on elsA applied to rotorcraft**
- **2000-2002: first papers on FLUENT applied to rotorcraft**

- **2004 Specialist's Conference on Aeromechanics**

  ~60 papers per year on CFD applied to rotorcraft

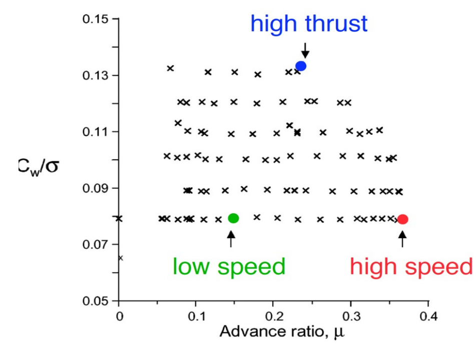
Ahmad and Strawn





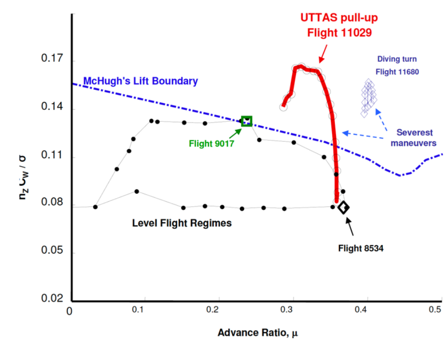
Computational Fluid Dynamics — to 2007

- **2004: CFD/CSD loose coupling applied to flight conditions from UH-60A Airloads Program (Potsdam, Yeo, and Johnson; Sitaraman, Datta, Baeder, and Chopra)**
  - Navier-Stokes equations, aerodynamics full blade and complete wake
    - comprehensive analysis handles trim, blade motion
  - Loose coupling confirmed as sound and efficient method for rotor loading



- **2004: first papers on TAU applied to rotorcraft**
- **2005: first papers on HMB applied to rotorcraft**

- **2007: CFD/CSD tight coupling applied to UTTAS maneuver from UH-60A Airloads Program (Bhagwat, Ormiston, Saberi, Xin)**
  - Airloads and blade loads in pull-up maneuver



Computational Fluid Dynamics — to 2024

- **2008: Pleiades computer at NASA Numerical Aerodynamic Simulator (NAS)**

- **2008: first papers on HELIOS applied to rotorcraft**
- **2009: first papers on rFlow3D applied to rotorcraft**
- **2013: first papers on STAR-CCM+ applied to rotorcraft**

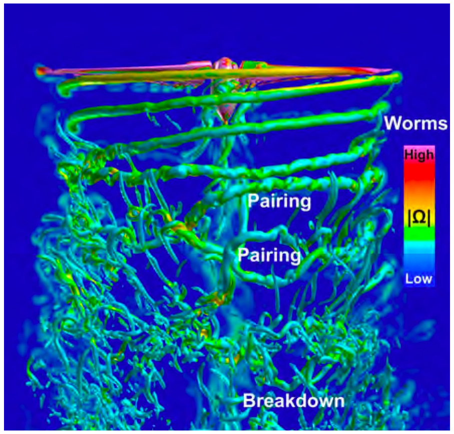
- **2014 Aeromechanics Specialists' Conference**

  ~130 papers per year on CFD applied to rotorcraft

- **2024 Aeromechanics Specialists' Conference**

  More than 250 papers per year on CFD applied to rotorcraft

Chaderjian



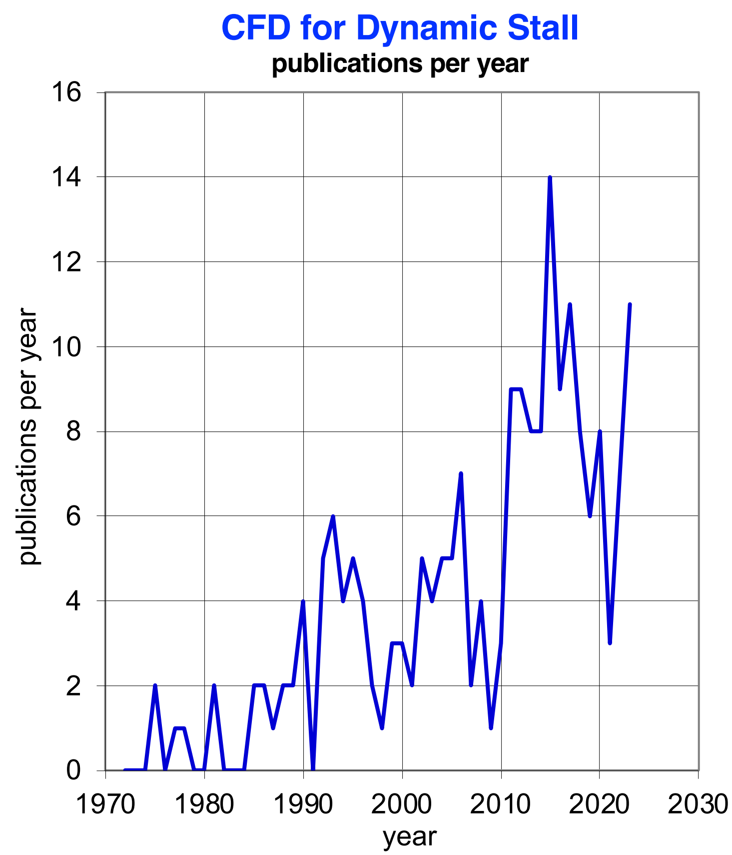
Computational Fluid Dynamics — Now and Future

- **2024**
  - CFD tools in widespread use for rotorcraft design, development, and assessment

- **2074**
  - **GUI-driven, integrated software suites; automated grid generation**
  - **Routine airframe and full aircraft analysis, rotor-rotor interactions**
  - **Tight coupling with consistent structural dynamic models**
  - **Linearized system for stability evaluation, control design**
  - **Advanced treatment of turbulence and transition, separation and dynamic stall, wake capture ??**
  - **Advances in computer hardware and architecture permit calculations for ever-larger aerodynamic problems**
  - **Robust and reliable prediction of rotorcraft performance to 1% accuracy ??**

Dynamic Stall

- **Stall on rotor blades is unsteady aerodynamic phenomenon**
  - Compressible, three-dimensional
- **Rapid increase in angle of attack delays occurrence of stall**
  - Wings capable of higher lift in unsteady conditions
- **When stall does occur, more severe than static, large hysteresis**
  - Transient lift increase and nose-down moment, due to shed of vortex from leading edge
- **Dynamic stall responsible for high blade and control loads in forward flight**



Dynamic Stall — to 1982

- 1969-1973: Boeing empirical stall model
- 1970: UTRC (alpha, A, B) empirical stall model
- 1972: Crimi empirical stall model

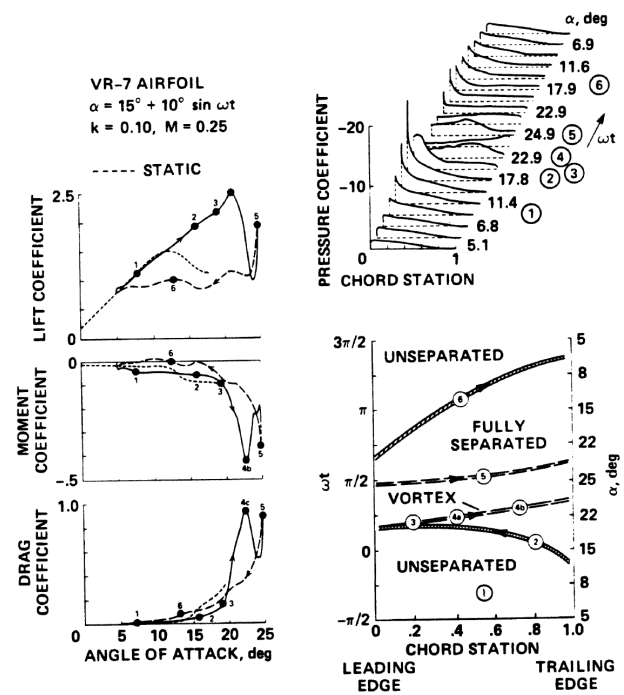
- 1974 Rotorcraft Dynamics Conference

  Paper on dynamic stall modeling and flight test correlation

- 1975: First application Navier-Stokes calculations to airfoil dynamic stall for rotor blades

- 1976-1982: Dynamic stall wind tunnel tests at Ames Army Laboratory (McCroskey, Carr, McAlister)

McCroskey



Dynamic Stall — to 1993

- **1975: Beddoes empirical stall model**
- **1980: ONERA EDLIN empirical stall model**
- **1981: Gangwani empirical stall model**

- **1984 Specialists' Meeting on Rotorcraft Dynamics**

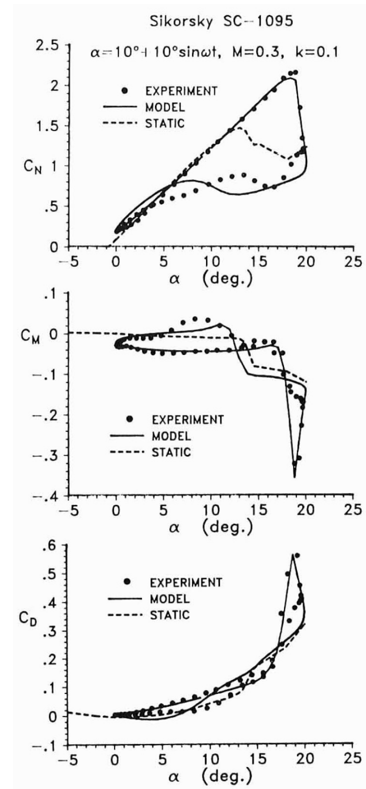
  Paper on dynamic stall modeling

- **1986: Leishman-Beddoes empirical stall model**

- **1988-1993: CFD (Navier-Stokes) calculations of stall on rotors**

- **1993: ONERA BH empirical stall model**

Leishman and Beddoes



Dynamic Stall — to 2004

- **1994 Aeromechanics Specialists Conference**

  Paper on stall delay

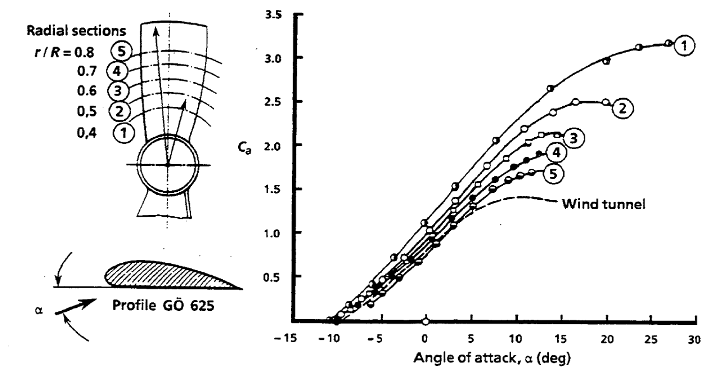
- **1994: stall delay (Corrigan and Schillings)**
- **1994: stall delay (Snel)**
- **1998: stall delay (Selig)**

- **2004 Specialist's Conference on Aeromechanics**

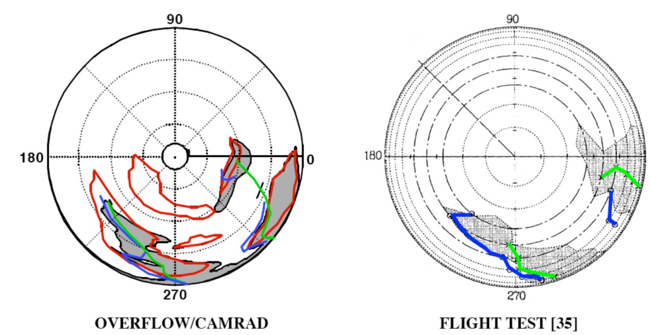
  Papers on rotor stall limits, CFD

- **2004: Navier-Stokes calculations of stall for UH-60A Airloads Program flight test**

Himmelskamp



Bousman



Comparison of dynamic stall rotor maps, μ = 0.24, high C_T

lift stall, moment stall, upper surface x/c = 0.96: pressure coefficient, skin friction

Dynamic Stall — to 2024

- **2008: Sheng, Galbraith, and Cotton empirical stall model**

- **2014 Aeromechanics Specialists' Conference**

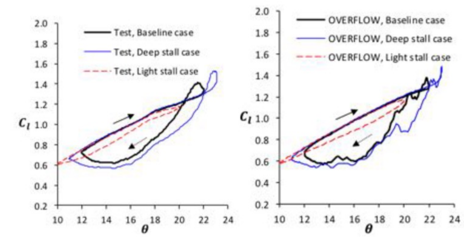
  Paper on CFD applications to dynamic stall

- **2016: Ahaus-Peters, Modarres-Peters empirical stall models**

- **2020: Navier-Stokes calculation of dynamic stall on airfoils and rotor blades (Smith, Gardner, Jain, Peters, Richez)**
  - Established prediction capability for 2D dynamic stall

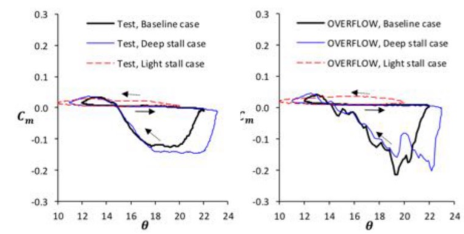
- **2024 Aeromechanics Specialists' Conference**

Smith



(a) Experiment (b) Computation

Figure 14: Blade section lift at an outboard span location ($r/R = 0.8$)



(a) Experiment (b) Computation

Figure 15: Blade section pitching moment at an outboard span location ($r/R = 0.8$)

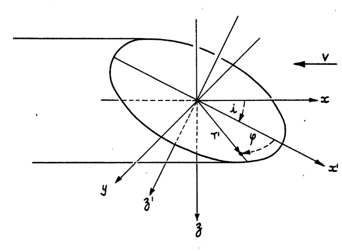
Dynamic Stall — Now and Future

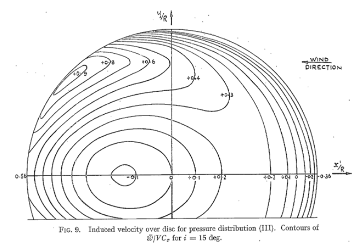
- **2024**
  - Navier-Stokes calculation of dynamic stall on airfoils and rotor blades possible

- **2074**
  - **Navier-Stokes calculation of dynamic stall for all operating conditions and blade designs**
  - **Effective and robust empirical models for use in comprehensive analyses**
    - Methodology to identify models from test and CFD data

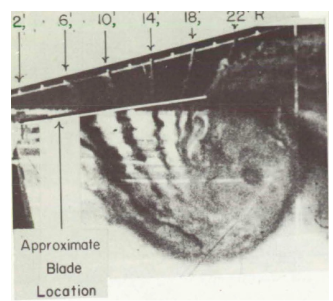
Finite-State Wake Models

- **Rotor wake important for most helicopter problems**
  - For stability analysis and real time simulations, finite-state model of wake needed
- **Dynamic Inflow: 3-state model**
  - Uniform and gradient inflow variables responding to aerodynamic thrust and hub moments
  - Based on vortex theory for actuator disk





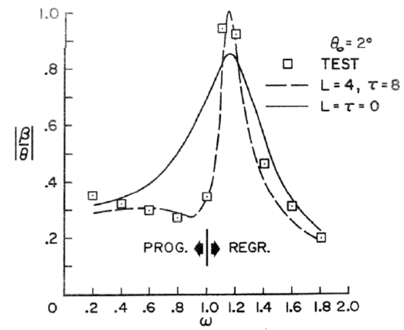
- **1948: Mangler (Kinner, 1937; Joglekar and Loewy, 1970)**
  - Derivatives for inflow (mean and gradient) due to thrust



- **1953: Carpenter and Fridovich; 1958: Rebont**
  - Mean inflow/thrust time lag

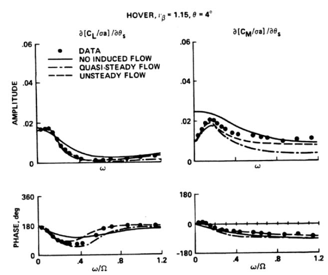
Finite-State Wake Models — to 1981

- **1974: Hohenemser and Crews**
  - Gradient inflow/moment time lag

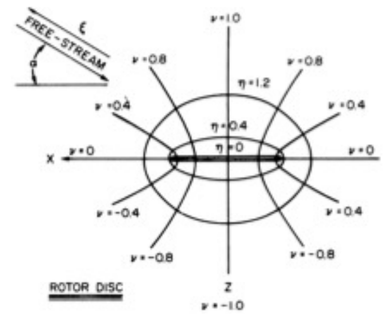


- **1974 Rotorcraft Dynamics Conference**

  Paper on hingeless rotor frequency response with unsteady inflow (Peters)



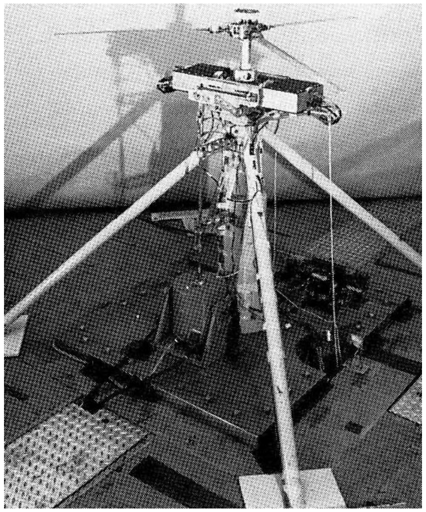
- **1981: Pitt and Peters**
  - Dynamic inflow model for wake in unsteady rotor aerodynamics
  - Full 3x3 derivative matrix and time lag matrix

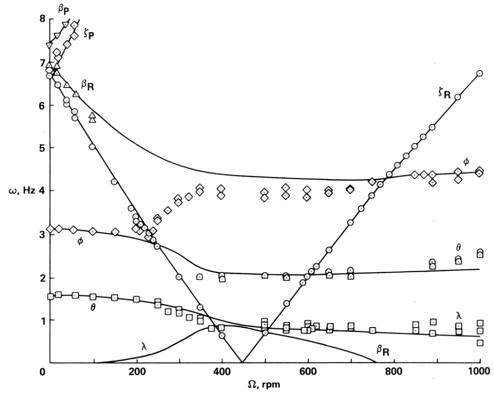


Finite-State Wake Models — to 1981

- **1981: Bousman**
  - Test of ground resonance of model rotor
    - Hingeless rotor, so hub moments that produce inflow gradients
  - Found unexpected state in measured data

- **Analysis identified additional state in measured data as “inflow mode” (Johnson 1982)**
  - Experimental evidence that air about rotor (wake) behaves as characterized by dynamic inflow states

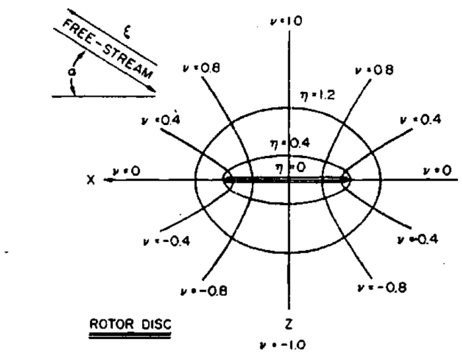


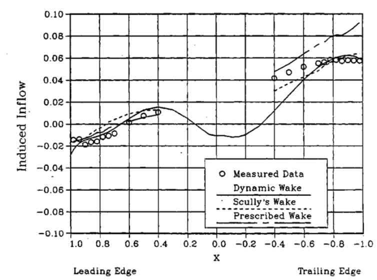


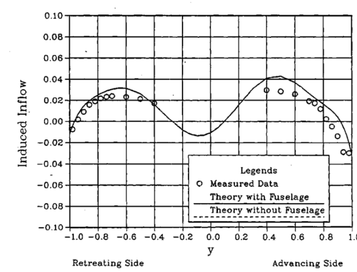
Finite-State Wake Models — to 1994

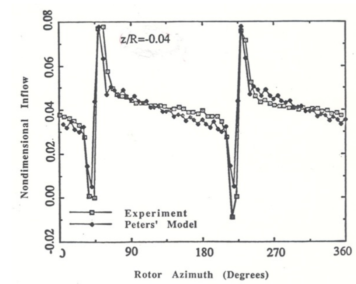
- **1984 Specialists' Meeting on Rotorcraft Dynamics**

- **1989: Peters and He**
  - multi-state (radial polynomial and azimuthal harmonic) representation of inflow





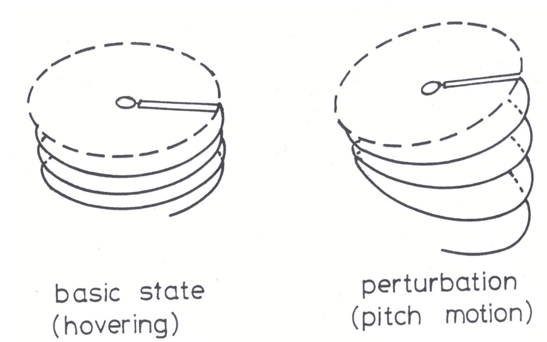


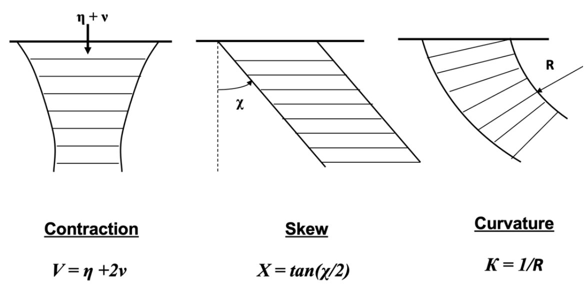


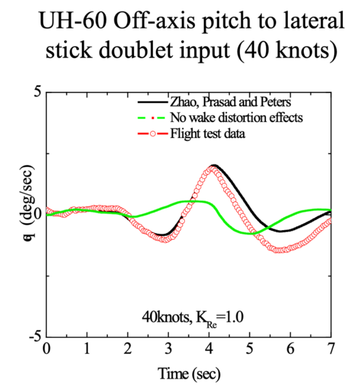
- **1994 Aeromechanics Specialists Conference**

Finite-State Wake Models — to 2004

- **1995-1996: Wake curvature and off-axis response (Rosen and Isser, Keller and Curtiss)**







- **2002: Velocity potential model, all components of flow throughout field (Morillo and Peters)**

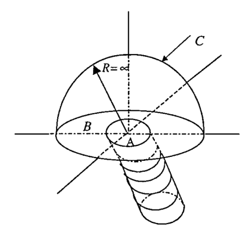


Fig. 2 Volume and area of integration.

- **2004 Specialist's Conference on Aeromechanics**

Finite-State Wake Models — to 2014

- **2008: Peters Nikolsky Lecture: “How Dynamic Inflow Survives in the Competitive World of Rotorcraft Aeromechanics”**

- **2014 Aeromechanics Specialists' Conference**

Finite-State Wake Models — to 2024

- **2015: Flow below rotor disk (Fei and Peters)**

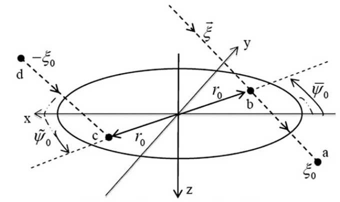
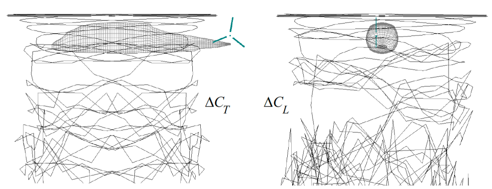


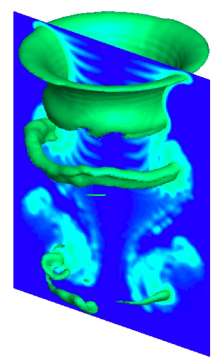
Fig. 2 3-D perspective of costates.

- **2016: Identification of dynamic inflow models from higher-fidelity aerodynamic analyses**
  - Flight dynamics, coaxial rotors, etc.

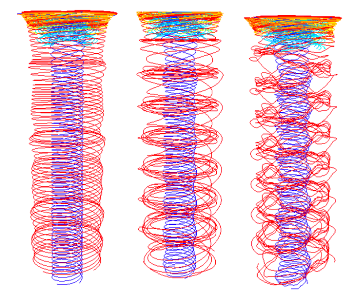
Rand (free wake)



He (VPM)



Keller (CHARM)



- **2024 Aeromechanics Specialists' Conference**

Finite-State Wake Models — Now and Future

- **2024: 70 years since Mangler, Carpenter and Fridovich**
  - Working on inflow off rotor disk, rotor-rotor and multi-rotor interference
  - Parameter identification methods for complex configurations

- **2074**
  - **Definitive finite-state wake models for rotorcraft ??**
    - **Standard parameter identification methods**
  - **Multi-rotor interference, arbitrary rotorcraft configurations**

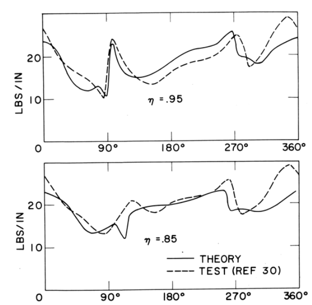
Rotor Airloads Tests

- **The knowledge of the distribution of the airloads on a rotor blade in flight is fundamental to an understanding of how a helicopter works and for the design of new and improved rotorcraft. — William G. Bousman, 1994**

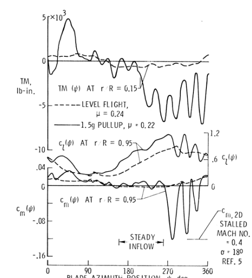
- **1954: 15-Foot Diameter Model Rotor; LaRC Full-Scale Tunnel**

- **1961: CH-34 flight test (LaRC, 1961-1962) and wind tunnel test (ARC 40x80, 1964)**
  - Data used to develop wake models for harmonic airloads (BVI); dynamic stall; high advance ratio airloads

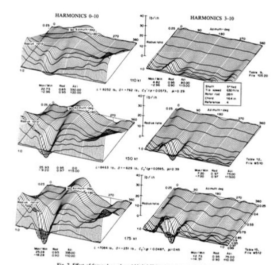
Miller



Ward

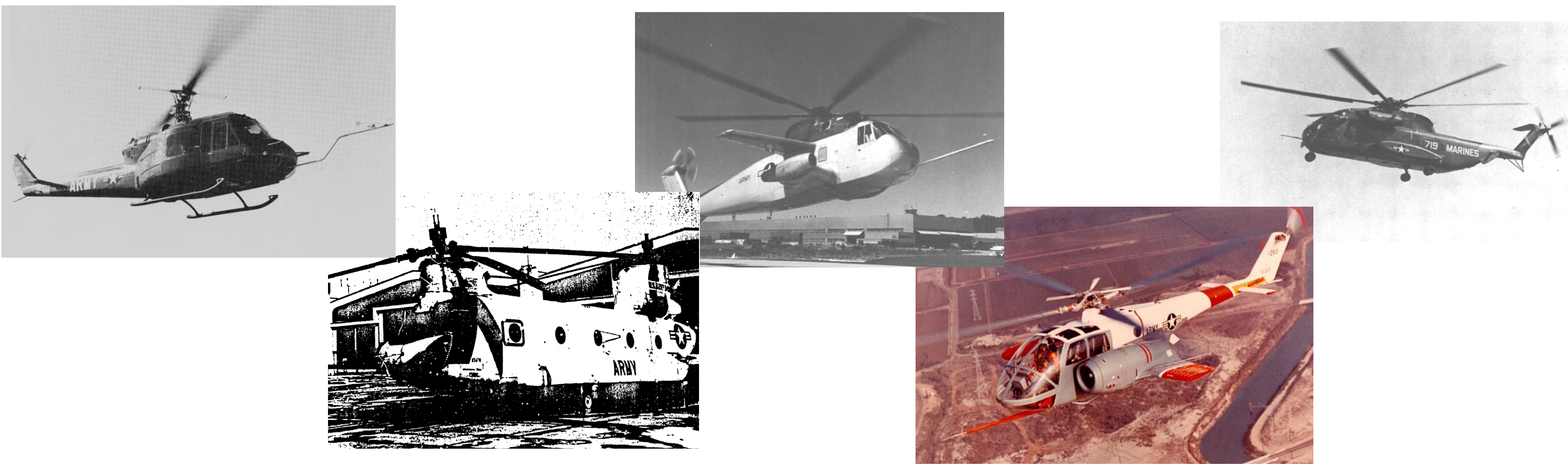


Hooper



Rotor Airloads Tests — to 1974

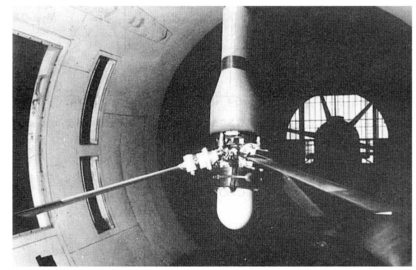
- **1961-1969: 7 flight test programs; few chordwise stations, much of data lost**
  - 5-7 chord stations, 5-9 radial station, 49-166 rotating sensors
  - UH-1A, CH-47A tandem, NH-3A compound, XH-51A compound, CH-53A

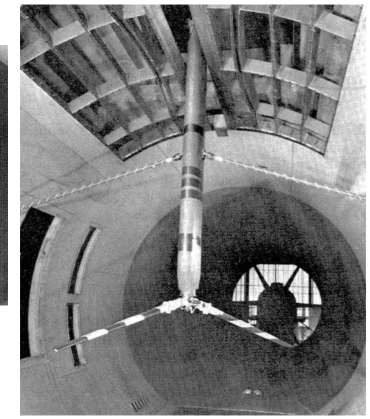


- **1974 Rotorcraft Dynamics Conference**

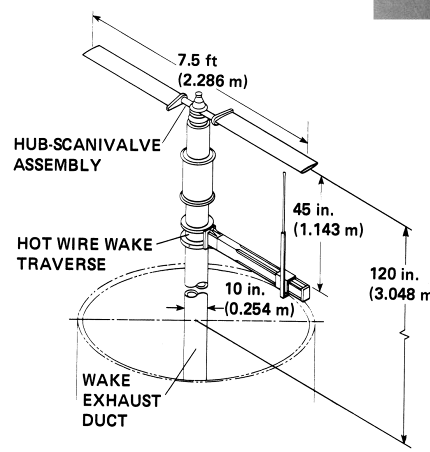
Rotor Airloads Tests — to 1984

- **1975: ONERA test of non-lifting tail rotor, lifting rotor with rectangular and swept tips**
  - Development of first CFD applications to rotor blades





- **1981: Caradonna and Tung**
  - Hover airloads and wake geometry, high tip Mach number (transonic flow)
  - Benchmark test to aid the development of various rotor performance codes utilizing advanced aerodynamic models



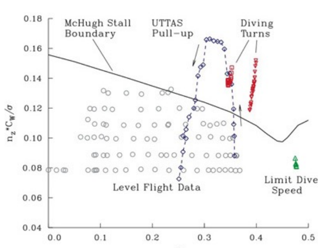
- **1984 Specialists' Meeting on Rotorcraft Dynamics**

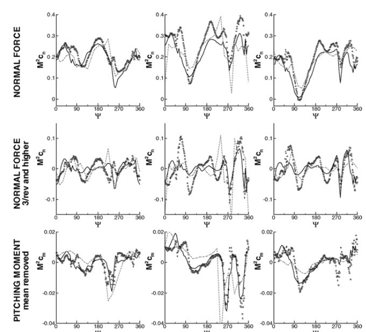
Rotor Airloads Tests — to 1994

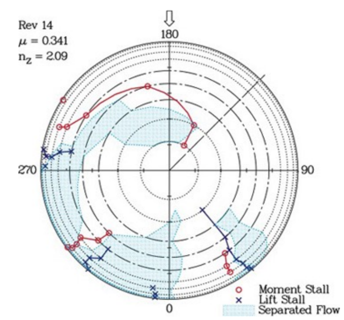
- **1984: Puma airloads flight test; blade tip**
- **1986: SA349/2 Gazelle airloads flight test**

- **1994 Aeromechanics Specialists Conference**

- **1994, 2010: UH-60A Airloads Program flight test (1993-1994) and wind tunnel test (40x80, 2010)**
  - Data used to develop CFD calculations for rotor aerodynamics
  - UH-60A Airloads Workshop (2001-2018)

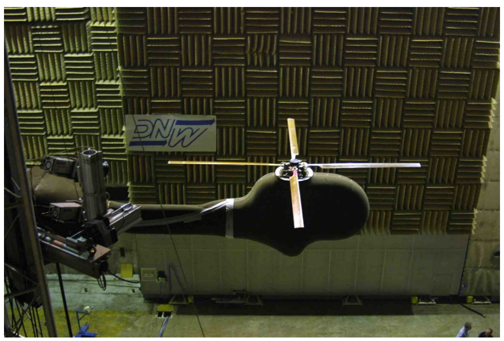


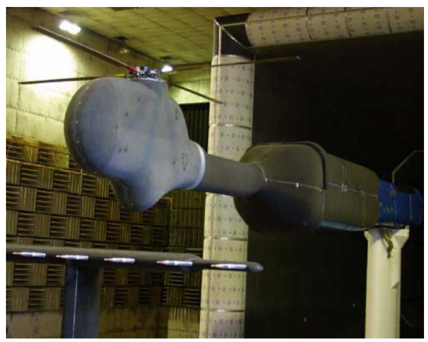


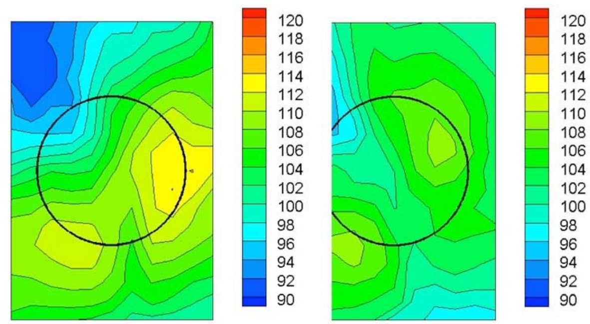


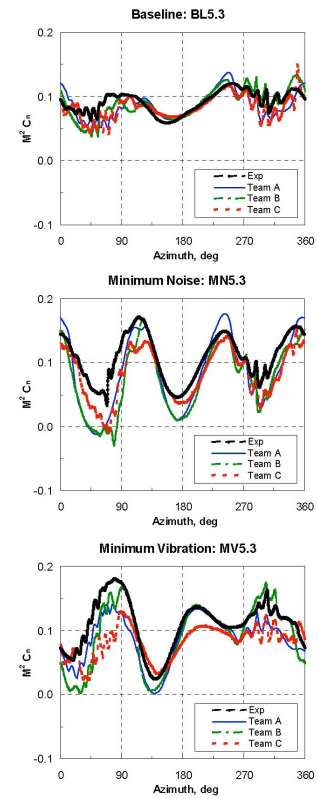
Rotor Airloads Tests — to 2001

- **1994, 2001: Higher-harmonic-control Aeroacoustics Rotor Test**
  - Extensive acoustic and wake flow field measurements
  - HART I (DNW wind tunnel, 1994)
  - HART II (DNW wind tunnel 2001)



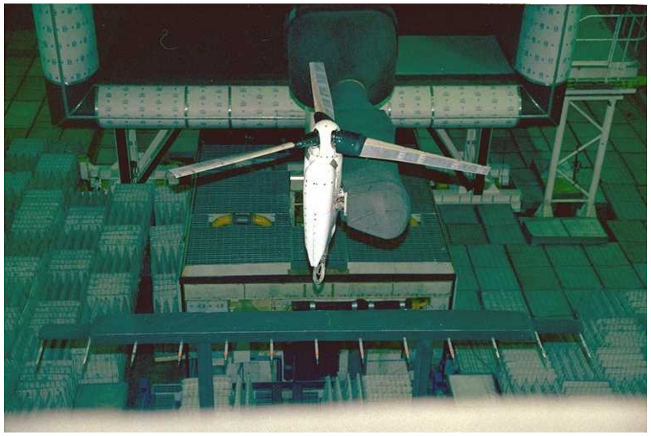






Rotor Airloads Tests — to 2004

- **1998: Tilt Rotor Aeroacoustic Model (TRAM) in DNW**
  - Performance, airloads, structural loads, acoustics
  - Single ¼-scale tiltrotor in hover, helicopter flight, and low speed axial flight



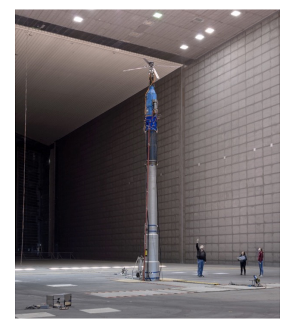
- **2004 Specialist's Conference on Aeromechanics**

Rotor Airloads Tests — to 2024

- **2008: GOAHEAD test of helicopter model (main rotor, tail rotor, fuselage) in DNW-LLF wind tunnel**
  - Measurements of airframe, hub, interference

- **2014 Aeromechanics Specialists' Conference**

- **2023: Hover Validation and Acoustic Baseline (HVAB) test**
  - ARC 80x120, hover
  - Performance, blade airloads, blade motion, boundary layer, transition, wake geometry



- **2024 Aeromechanics Specialists' Conference**

Rotor Airloads Tests — Future

- **2074**
  - **Extensive measurements**
    - Performance, pressures, boundary layer, wake, acoustics
  - **Tiltrotor blades — high twist (hover/cruise compromise), low aspect ratio blades**
    - Full-scale, conversion, high speed axial flight
  - **Propeller (UAM) — stiff, hingeless rotor**
    - Edgewise flight, high advance ratio (low tip speed), large lift offset
  - **Planetary rotors**
    - Low Reynolds number, high Mach number

Concluding Remarks — Rotorcraft Aerodynamics in the Future

- **Computational Fluid Dynamics**
  - Advanced treatment of turbulence and transition, separation and dynamic stall, wake capture
  - Robust and reliable prediction of rotorcraft performance to 1% accuracy

- **Dynamic Stall**
  - Effective and robust empirical models for use in comprehensive analyses

- **Finite-State Wake Models**
  - Definitive finite-state wake models for rotorcraft

- **Rotor Airloads Tests**
  - Tiltrotor blades, propellers (UAM), planetary rotors

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