Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

Alfred Gessow Rotorcraft Center: Past, Present and Future

Inderjit Chopra

Director Alfred Gessow Rotorcraft Center &
Alfred Gessow Professor of Aerospace Engineering

Presentation At: Korea Aerospace Research Institute (KARI), Daejeon
June 27-30, 2011

Agenda

1. Monday June 27
   - Introduction: Alfred Gessow Rotorcraft Center
   - Dynamics: Introduction to Hover & Forward Flight, Flap Dynamics
2. Tuesday June 28
   - Dynamics: Flap-Lag-Torsion, Unsteady Aerodynamics
   - MAV Challenges & Opportunities
3. Wednesday June 29
   - Dynamics: Aeroelastic Stability in Hover, Ground/Air Resonance
   - CFD Applications
4. Thursday June 30
   - Dynamics: Bearingless Rotor, Vibration
   - Review Aeromechanics
5. Friday July 1: Visit to SNU & Review Cyclocopter Work

Department of Aerospace Engineering
in
A. James Clark School of Engineering
University of Maryland

Undergraduate Program

- 19 Faculty members
- 337 undergraduates
- Average SAT score 1316
- 16% female
- 92 BS degrees in 2009
- Ranked 6th by US News and World Report

Graduate Program

- Graduate students 170
- MS Students 78
- PhD Students 92
- Female Grad students 29
- Minority Grad students 13
- Non-US Citizens 54
- 69 MS awarded in 2009
- 19 PhD awarded in 2009
- Ranked 9th by US News and World Report

Department of Aerospace Engineering

Vital Statistics 2009-10

- *8 Major Research Program (Lead)*
  - *VLRCOE: Army/Navy/NASA (2011-16) Vertical Lift Research Center of Excellence*
  - *MURI: ONR (2006-11): Galfenol Smart Material Actuators*
  - *MURI: AFOSR (2008-13): Helicopter Brownout*
  - *CTA-MAST: ARL (2008-18): Micromechanics Center*
  - *NAVAIR: Rotorcraft & Propulsion + Education: (2009-14)*
  - *CUIP: Constellation University Institute Program; (2002-cont)*
  - *Space: Institute for Dextrous Space Robotics*
  - *Neuro-Bio Program: AFOSR (2009-14): Flying insect Performance*
- *Major Research Programs (Support Role)*
  - *MURI: AFOSR (2007-12) Flapping MAV*
  - *MURI: ONR (2010-15) Micro Biological Systems*
- *Research Grants FY09:*
  - *Total number of grants 84*
  - *Total research expenses $17.3M*

Alfred Gessow Rotorcraft Center

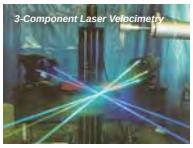
Mission of Rotorcraft Center

To advance rotorcraft technology through:

- Provide an exciting and effective educational environment to train the next generation rotorcraft engineers
- Carry out inter-disciplinary, multi-disciplinary basic research in rotorcraft
  - Timely solution of technical barrier problems
  - Introduce innovative and disruptive technologies
- Speedily transfer technology to industry and government laboratories

Alfred Gessow Rotorcraft Center
Vital Statistics 2010

• Faculty: Rotorcraft	9
Faculty: Non-Rotorcraft	5
• Research Scientists/ Visiting Prof.	4
• Graduate Students	50
• M.S. Degrees awarded	10
• Ph. D. Degrees awarded	5
• Presentations at Conferences	80
AHS (28), SDM (10), SPIE(12), Other (30)	
2008 AHS Forum	16
• Journal Publications: Published	40
Accepted	49
• 2011 Vertical Flight Scholarships	10

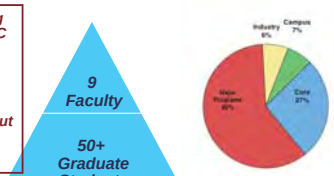


Rotorcraft Tech Base

Core Rotorcraft funding from Navy, NASA, NRTC $2M/year

Other Major Programs:
Army-MURI: MAV
Army-CTA: MAST
Airforce-MURI: Brownout
$4.5M/year

Industry: $0.4M/year



9 Faculty

50+ Graduate Students

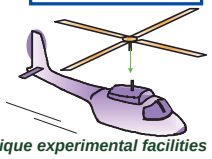
40 Undergraduate Students (AHS Student Chapter, Elective Research projects)

Signifcian Support fron Campus: Fellowshipa, Travel budget, Fabrication, etc $0.5M/ year

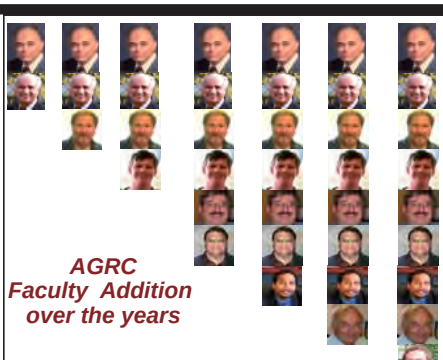
Alfred Gessow Rotorcraft Center
Overall Accomplishments

• M.S. Degrees awarded	200+
• Ph.D. Degrees awarded	100+
• Presentations at Conferences (All)	800+
AHS Forum	200+
• Journal Publications (All)	500+
AHS Journal	130
• VFF Scholarships (last 5 years)	45

Established in 1982 by Army as one of three Rotorcraft Centers of Excellence; Competitive renewal every 5 years; Program ended in June 2006



- Significant technology transfer
- Developed specialized graduate courses & unique experimental facilities
- Graduates employed by Army Labs, Industry, NASA, Navy, FAA, Academia and Army-Uniform



AGRC Faculty Addition over the years

1982 1985 1987 1993 1995 1999 2005 2007 2008

Aerodynamics: Prof. Leishman
• CFD: Assoc. Prof. Baeder
• Acoustics: Visiting Prof. Schmitz
• Dynamics: Prof. Chopra
• Flight Mechanics: Prof. Celi
• Smart Structures Prof. Wereley
• Transmissions and Health Monitoring Prof. Pines
• Design: Dr. Nagaraj
• Navigation and Control Systems Asst. Prof. Humbert

Rotorcraft Courses

Graduate:

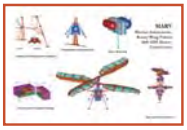
- Rotorcraft Aerodynamics 1 & 2 (Leishman)
- Rotorcraft Dynamics (Chopra)
- Rotorcraft Stability and Control (Celi)
- Rotorcraft Design (Chopra, Nagaraj, Tishchenko)
- CFD 1 & 2 (Baeder)
- Composite Structures (Wereley)
- Engineering Optimization (Celi)
- Smart Structures (Chopra)
- Rotorcraft Aeroacoustics (Schmitz)
- Advanced Structural Dynamics (Pines, Hubbard)
- Multi-Body Dynamics (Celi)

Undergraduate:

- Rotorcraft Analysis (Baeder)

UM Winning Designs (98-02)

1998



2000

1999

2001

2002

UM Winning Designs (03-07)

2003

2005

2004

2006

2007

UM Winning Designs (08-09)

2008

2009

Rotorcraft Experimental Facilities

Rotor Rig & Glenn L. Martin Wind Tunnel

Hover Tower

Vacuum Chamber

Autoclave for Composites

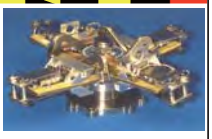
Laser Doppler Velocimetry

Bearingless Rotor Rig

Rotorcraft Experimental Facilities

Aeroacoustic Facility

6 ft Mach Scaled Rotor



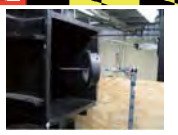
Model Rotor Hub

Vacuum Hot Press

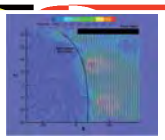
MTS Testing Machine

Mechanical Shock Rig

Rotorcraft Experimental Facilities



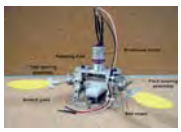
Open-Jet Wind Tunnel



PIV System for flow studies

MAV System

Autonomous Lab



Insect-Motion-Based Flapping-Wing Apparatus

MAV Hover Test Rig

Alfred Gessow Rotorcraft Center
Research Programs

I. Core Aeromechanics (RCOE: 1982- 2006,VLRCOE 2011-16)
- *Aerodynamics*
- *Dynamics*
- *Flight Dynamics and Control*
- *CFD*
- *Acoustics*
- *Transmission and Drive Trains*
- *Smart and Composite Structures*
- *Advanced Designs including Heavy Lift Rotorcraft*

II. Army: MURI: Micro Hovering Air Vehicles (2004-10)

III. MAST CTA: Center for Microsystem Mechanics(2008-18)

IV. Airforce: MURI: Brownout of Rotorcraft (2008-13)

V. Smart Structures Programs (URI, 2 MURI, DARPA)
- *Army: URI(92-97), MURI (96-01) Smart Structures Applications*
- *DARPA Galfenol Compact Actuator Development (2003-05)*
- *Navy-MURI on Galfenol actuators (06-11)*

VI. ONR: Heavy Lift Rotorcraft Aeromechanics (2010-12)

VII. NASA: 5 NRAs (2007-11): Rotorcraft Aeromechanics

VIII. NAVAIR: (2008-13): Rotorcraft Aeromechanics

IX. Other Programs (NRTC, Sikorsky, Boeing, etc):
- *Boeing: Active Rotor, Morphing Rotor*
- *NRTC: CFD Applications, High Performance actuators, Crashworthy seat*
- *Sikorsky/UTRC: Composite Rotor, Swashplateless rotor, etc.*

10-Ft Diameter Vacuum Chamber

Notable Technical Capabilities

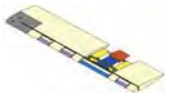
1. *State-of-Art Experimental facilities:*
   Glenn L. Martin wind tunnel (8.5-ftx11-ft), 2 rotor rigs, 10-ft diameter vacuum chamber, hover tower, State-of-art PIV system, anechoic hover chamber, model fabrication facility, modern composite lab, extensive smart structures labs and growing MAV facilities
2. *Extensive set of specialized up-to-date rotorcraft courses*
3. *Breadth and depth of core rotorcraft programs:*
   Expanded activities in MAV, brownout and CFD
4. *Extensive micro air vehicles research program (MAST-CTA & MURI)*
5. *Opportunity-driven faculty and team-work*
6. *High caliber graduate students (Largest number of Vertiflite scholarships, 40% of total awards during past 10 years)*
7. *Alfred Gessow Rotorcraft Chair & Scholarships*
8. *Significant campus support:*
   - *Extensive labs*
   - *Co-location of grad students*

Alfred Gessow Rotorcraft Center:
Major Accomplishments & Technology Transfer

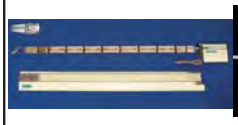
- *Provided trained talented graduate students to industry and government laboratories*
- *Provided comprehensive aeromechanics analysis and design tools to industry and laboratories*
  UMARC, Free-wake and unsteady models, TURNS CFD
- *Provided strategic leadership in rotorcraft technologies:*
  - *Bearingless rotor aeromechanics*
  - *Composite rotor technology*
  - *Advanced CFD methodology*
  - *Smart Structures technology*
  - *UAV and MAV technologies*
  - *Rotor wakes and unsteady aerodynamics*
  - *Vibration prediction & active control methodologies*

Smart Structures Activities at Maryland

6-ft dia Froude scale rotor model in Glenn Martin Wind tunnel: active twist with embedded piezoelectric elements



6-ft dia Mach scale rotor model in Glenn Martin Wind tunnel: trailing edge flaps actuated with multi-layered piezobimorphs

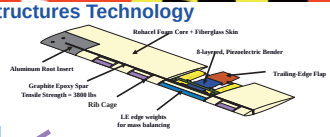


6-ft dia Mach scale rotor model on hover tower: tip actuated with embedded piezos in conjunctions with bending-torsion composite couplings

Example: Technology Transfer

Smart Structures Technology

Smart Actuator Development: Piezostacks with L-L Amplification



Smart Rotor Development: Mach-Scale with Piezo Acutated Flap

Boeing: Full-Scale Smart Rotor Development: MD-900 Rotor with Smart Flaps, Successfully tested in 40x80-ft wind tunnel in April 2008, Demonstrated 90% reduction in vibration and acoustic signatures

Smart Rotor Test in Glenn Martin Tunnel Mach-Scale with Smart Flaps

Technology Transfer

- Upgraded comprehensive rotorcraft code UMARC provided to industry, federal laboratories and academia.
- Boeing-Mesa: Helped them in their development of full-scale smart rotor system with flap actuated with piezostacks (Friedrich Straub).
- Unsteady aerodynamic analysis codes (Leishman) provided to industry and federal labs, inserted in many comprehensive codes.
- Free wake codes provided to industry, federal labs and academia, inserted in many comprehensive codes.
- Army-Ames: Assessment of active vibration control from perspective of flight mechanics (Mark Tischler)
- NREL: Helped them in identification of aerodynamic issue focused to windmills (Bir).
- Lord Corp.: Development & characterization of MR dampers (Mark Jolly).
- Sikorsky: Helped them in the assessment of composite couplings to control vibratory load and improve performance (Andy Bernhard)
- Army Science Board: Heavy Lift Cargo Rotorcraft design studies
- DARPA: Technology assessment of heavy lift systems (Don Woodbury)
- Progeny/Army: Helped them in the development of RotorChute (Murphy)

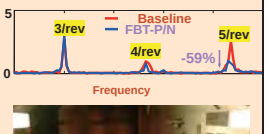
Technology Transfer

- Bell: Quadrotor peformance and download studies (Bob Moullins)
- CSA: Helped them in the development of compact hybrid actuator (Eric Anderson)
- Baldwin: Helped in the design and aeromechanics issues related to mono-tiltrotor (Baldwin)
- FAA: Wire strike assessment of civil helicopters (Dy Le)
- Kaman: Helped them in the development of tab actuated flaps for primary controls (Mike Bielefield)
- Army Picatinny Arsenal: Development of MR recoil dampers (Mike Mattice)
- Army-ARDEC: Helped them in the development of active/passive hybrid APPN smart actuator gun-fuselage vibration isolation and precision control
- Navy David Taylor Carderock: Helping them in their initiative on "Rotor Head Fault Detection" called JAHUM (David Haas).
- NASA-Ames: provided assessment for an all electric helicopter (Bill Warmbrodt)
- Army Science Board: Carried out heavy lift corgo rotorcraft design studies

Composite Rotor Technology

Pretwisted Mach Scale Composite Tailored Blade

Black-Hawk Composite Tailored Rotor:
Vibration Reduction 30%, Power Reduction 8%
May Save Vibration Absorbers Penalty: 240 lbs

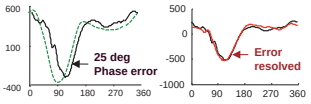


Mach Scale Composite Tailored Rotor in Wind Tunnel

Black Hawk Loads Prediction:
Technology Barrier Problem

Black Hawk Airloads at High Speed

Lift 92% R lbs/ft

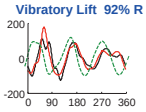


UMARC lifting-line — UMARC/TURNS coupling — Flight 8534

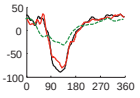
Comprehensive analysis + CFD
- Lift Phase error resolved
- Vibratory air loads resolved
- Transonic pitching moments captured

Unresolved Issues:
- High thrust condition (stall)
- Maneuvering flights

Vibratory Lift 92% R



Pitching Mom. 96.5% R



Accomplishments:
Technology Barrier Problems (00-11)

- Rotor loads prediction: Resolving phase issue for predicted vs measured loads (Collaboration with NASA, Army & Industry)
- Composite rotor blade modeling: adequate coupled beam modeling, comprehensive aeromechanics analysis and unique vacuum chamber and wind tunnel test data
- Active vibration control (HHC & IBC) coupling with flight control stability (issue with hingeless and bearingless rotors)
- Power minimization with 2/rev active pitch input: expect nominal gain less than 5%
- Smart rotor development: smart actuator stroke limitation and innovative amplification
- Rotor wakes: resolving vortex core issue and its interaction, precise model under steady flight condition
- Rotor wakes in maneuvering flight: Time domain non-steady model and resolving off-axes response issues
- Unsteady aerodynamics of flapping rotor
- CFD couplings with comprehensive aeroelastic analyses: issue of moment coupling
- HUMS for transmissions & drive-trains: Robust ID schemes to overcome false alarms
- Comprehensive aeromechanics analyses for advanced rotor systems: bearingless (multiple load paths), tiltrotor, circulation-control, trailing-flap and smart rotor
- Flight stability and acoustics analysis in maneuvering flight

RCOEs Accomplishments:
Technology Barrier Problems

Damperless Rotor

Past: Hydraulic Dampers Articulated Rotors, Heavy

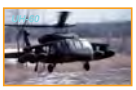
Present: Elastomeric Dampers Hingeless & Bearingless, Expensive

Future: ER/MR Fluid Dampers Composite Couplings and IBC Flaps active damping, Cheap and reliable

Swashplateless Rotor

Past: Swashplate with pitchlinks, Drag penalty plus maintenance cost

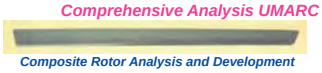
Present: Servo-Flap Rotor, SH-2, Mach-Scale Black-Hawk Model test in wind tunnel



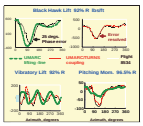
Future: Smart flaps using hybrid actuators for primary controls.

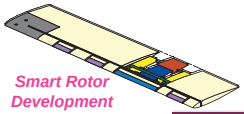
Major Accomplishments over past 28 years
Research

Comprehensive Analysis UMARC

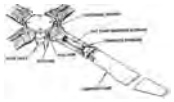


Composite Rotor Analysis and Development





Smart Rotor Development



Bearingless Rotor Analysis

Free Wake Modeling

CFD/CSD Blackhawk Loads Prediction

Free Wake Models
Bagai-Leishman (Relaxation)
Bhagwat-Leishman (Time-marching
Shreyas-Leishman (Vortex filament)

Alfred Gessow Rotorcraft Center
National & International Impact

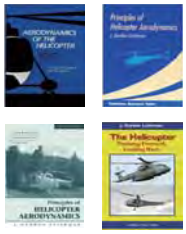
- Publications in Archival Journals and Presentation at Helicopter Conferences: Especially AHS
- Graduates: Extremely successful in academia, industry and federal laboratories, For example at recent American Helicopter Society Annual Forum, every fourth paper was from or had roots in Maryland.
- Significant technology transfer to industry and government via publications and presentations, trained graduates and comprehensive codes and cooperative arrangements.

AHS INTERNATIONAL
THE VERTICAL FLIGHT SOCIETY

AIAA
American Institute of Aeronautics and Astronautics

Major Accomplishments over past 28 years
Education

Comprehensive Graduate Curriculum



Quality of graduate students
- Placement & success
- Largest number of Vertiflite Scholars
- 7 received AHS Bagnoud Awards
- 4 became Technical Fellows of AHS
- 800+ Conference papers
- 200+ AHS Forum papers
- 500+ Journal papers
- 130 AHS Journal papers
- 19 took academic appointments
- Many now in high level positions

Balanced research: between theory and experiment

AGRC: Graduates in Rotorcraft Industry

Sikorsky

1. David Matuska (MS, 83)
2. John Bate (MS 86)
3. Chris Van Buten (BS 86)
4. Mark Scott (MS 88)
5. Mike Torok (PhD 89)
6. James Wang (PhD 91)
7. Ashish Bagai (PhD 95)
8. Vinit Suhasrabudhe (PhD 97)
9. Alan Coyne (MS 97)
10. Cliff Smith (PhD 99)
11. Andy Bernhard (PhD 00)
12. Dan Griffin (MS 01)
13. Mat Tarascio (MS 01)
14. Jinsong Bao (PhD 04)
15. Robin Preator (MS 04)
16. Ben Hein (MS 05)
17. Eric Parsons (MS 05)
18. Michael Brigley (MS 06)
19. Jayant Sirohi (PhD 01)
20. Lin Leo (PhD 03)

Boeing

1. Brahamananda Panda (PhD 85)
2. Hieu Ngo (MS 87)
3. Alan Stemple (PhD 89)
4. Antonio Llanos (MS 89)
5. Dan Newman (MS 89)
6. Steven Ingle (MS 90)
7. Curtis Walz (MS 94)
8. M. Daghir (MS 94)
9. Joseph Orso (MS 94)
10. Josh Ellison (MS 04)
11. Justin Kearns (MS 05)
12. Dan Clingman (MS 06)
13. Lynn Gravatt (MS 06)
14. Patrick Downey (PhD 08)

Bell

1. Brian Schweissow (MS 85)
2. Bob idol (BS 85)
3. D. K. Samak (MS 87)
4. David Platz (MS 94)
5. Melanie Hurt (MS 96)
6. J. S. Park (MS 03)
7. Chehab Mustafa (MS 03)
8. Taeoh Lee (PhD 99)
9. Marc Gervais (PhD 04)

AGRC: Graduates in NASA/Army/Navy

Ames: NASA/Army

1. Bimal Aponso (MS 83)
2. Joon Lim (PhD 88)
3. Hyensoo Yeo (PhD 99)
4. Theodore Colin (PhD 00)
5. Mahindra Bhagwat (PhD 01)
6. Preston Martin (PhD 01)
7. Randy Cheng (PhD 01)
8. Anubhav Datta (PhD 04)
9. Mani Ramasami (PhD 05)
10. Carlo Malpica (PhD 08)

Langley: Army

1. Mark Nixon (PhD 93)
2. Kevin Noonan (MS 85)
3. Jinwei Shen (PhD 03)
4. Jayana Sitaraman (PhD 03)
5. Beatrice Roget (PhD 04)
6. Ugrina Sandra (PhD 06)
7. Terry Ghee (MS 90)
8. Eric Greenwood (MS 08)
9. Rajneesh Singh (PhD 98)

Navy: David Taylor/Pax River

1. David Haas (PhD 89)
2. Neipei Bi (PhD 91)
3. Judah Milgram (Ph 97)
4. Mark Kammeyer (MS 86)
5. John Vorwald (MS 86)
6. Randy Barber (MS 86)
7. Steve Wunder (MS 88)
8. William Pogue (MS 89)
9. Chris Bruner (MS 89)
10. Joe Leifner (MS 89)
11. Darryl Lenhardt (MS 89)
12. Nancy Mueller (MS 89)
13. Steve Dirlik (MS 90)
14. Jody Smith (MS 92)
15. Andy Baker (MS 95)
16. Divyang Shukla (MS 00)
17. William Facey (MS 03)
18. Youngjoon Kim (MS 04)
19. Danial Everson (MS 05)
20. Eric Silberg (MS 06)
21. Kristi Kleinhesselink (MS 07)
22. Sean Roark (MS 07)

UM Graduates in Academics: Faculty

1. Ed Smith (PhD 92) Professor Penn State
2. Farhan Gandhi (PhD 95) Professor, Penn State
3. Nikhil Koratkar (PhD 00) Professor, RPI
4. Chang-Ho Hong (PhD 85) Professor Choong-Nam University
5. James Milke (PhD 91) Professor, University of Maryland
6. Yong Hyup Kim (PhD 89) Professor, Seoul National University
7. Gil Crouse (PhD 92) Associate Professor, Auburn University
8. Ranjan Ganguli (PhD 94) Professor, IISc Bangalore
9. Anne Spence (PhD 94) Assistant Professor, UMBC
10. David Flemming (PhD 95) Professor, Florida Institute of Tech
11. Yang Mao (PhD 02) Associate Professor, Northwest University, China
12. Z. Xie (PhD 03) Associate Professor, Northwest University, China
13. Karthik Duraisamy (PhD 05) Lecturer, Glasgow University
14. Jayant Sirohi (PhD 01) Asst. Professor, University of Texas at Austin
15. Beatrice Roget (PhD 03) Asst. Professor, Wyoming University
16. Jaina Sitaraman (PhD 02)) Asst. Professor, Wyoming University
17. Atul Atulsimha (PhD 06) Asst. Professor, Virginia Commonwealth University
18. Gang Wang (PhD, 02) Asst. Professor, University of Huntsville

Alfred Gessow Rotorcraft Center
Important Honors & Awards

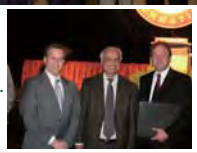
- Chaired Professorships: Alfred Gessow Professor (Chopra), Minta-Martin Professor (Leishman), Farvardin Professor (Pines), Techno-Sciences Professor (Wereley)
- AHS Hon Fellow: Gessow (81), Chopra(08); AHS Fellows: Schmitz(93), Chopra (96), Leishman (07)
- AHS Alexander Nikolsky Honorary Lectureship: Gessow (85), Schmitz (08)
- AIAA Fellows: Gessow (82), Chopra (91), Schmitz (04), Pines (10)
- Royal Aero Soc Fellow: Leishman (05); ASME Fellow: Chopra (03), Wereley (08), Flatau (07), Pines (09)
- AIAA SDM Award: Chopra(02)
- AHS Alexander Klemin Award: Life-time Achievement Award in rotorcraft: Gessow(96), Chopra (09)
- ASME Adaptive Structure and Material Systems Prize: Chopra (01)
- SPIE Life-Time Achievement Award: Chopra (04), Flatau (10)
- Francois Xavier Bagnoud Vertical Flight Award: In recognition of outstanding contributions to rotorcraft by a young engineer: Smith (94), Torok (96), Gandhi (98), Bernhard (99), Koratkar (04), Sohasrabudhe (05), Datta (06)
- Grover E. Bell Award: Given for outstanding research contributions to AGRC: 1992, 2002
- ARO Young Investigator Awards (Smith, Wereley, Koratkar)
- NSF Young Investigator Awards (Pines, Wereley, Etkins, Koratkar)
- Other Important Lectureships: Pilcher Memorial Lectureship & Medal (02), von Karman Lectureship (04), Cierva Memorial Lectureship (05), AGARD Lectureship (91), Bisplinghoff-Mar-Pian (93), Paul Hamke Lectureship (04), Henry Kelley Lecture (03), Roy Aero Aus(01), AIAA SDM Lecture (03), ASME Adaptive Structures Lecture (2001)
- Editor-in-Chief: AHS Journal, Leishman (2004-07)
- Editor: Journal Intelligent Materials Systems & Structures (JIMSS): Wereley
- Associate Editors: JIMSS (Chopra, Pines, Flatau), Smart Mat & Struc (Chopra, Pines, Wereley), J. of Aircraft (Chopra), AHS Journal (Chopra, Vizzini, Celi, Nagaraj)
- AHS Lichten Award: Bernhard (96), Gervais (01)
- AHS Student Design Competition: Graduate Category First Place for 9 years (1998-2005, 08), 2nd Place (2006-07, 09)
- AJ Clark School of Engineering Faculty Outstanding Research Award: Chopra (2002)

Some RCOE Graduates in Key Positions:
Industry, Government and Academia

- COL Keith Robinson, PM, Armed Scout Helicopter
- Dr. Mike Torok, Vice President & Chief Engineer CH-53K, Sikorsky
- Dr. James Wang, Vice President Research & Development, Agusta-Westland
- COL(Ret) Andy Dull, Manager Lockheed Martin
- Dr. Mark Nixon, Director U.S. Army Research Laboratory Vehicle Technology Directorate
- Dr. Ed Smith, Professor, and Director Rotorcraft Center of Excellence at Penn State
- Dr. Jeanette Epps, NASA Astronaut
- Dr. & Col (Ret) Shmuel Fledel, Senior Vice President Maintenance & Engineering, El Al Israel Airline
- Dr. Jinseok Jang, Principal Researcher & Head of Rotorcraft Program, Agency for Defense Development, Korea
- Ms Kelly McCool, Chief Engineer VH-71 (Presidential Helicopter) Program
- Col (Ret) Lazar Alon President & CEO Elbit Systems
- Mr. Chris Van Buiten, Technical Fellow & Director of Technology & Innovation, Sikorsky
- Mr. Bimal Aponso, Chief NASA Aerospace Simulation Operations Branch
- Mr. Philippe Benquet, Program & Key Account Director, Thales Avionics, France
- Mr. David Matuska, Manager Engineering System Safety, Sikorsky
- Mr. Mark Scott, Chief Design Group, Sikorsky
- Dr. Andy Bernhard, Chief Engineer SAS, Sikorsky
- Ms. Megan McCluer, Program Manager Wind & Hydropower Technology, DOE
- Dr. David Haas, Head Surface Aviation Group, David Taylor, Navy
- Mr. Dan Newman, Program Manager DARPA, Formerly Head Design Office, Boeing
- Dr. Farhan Gandhi, Professor Penn State
- Dr. Berend G. van der Wall, Head Simulation in Wind tunnel, DLR
- Mr. Carl Ockier, Head of Civil Flight Test, Eurocopter, Germany
- Mr. Mat Tarascio, Specialist Business Development/Strategic Planning, Sikorksy
- Dr. Chang-Ho Hong, Professor and Department Head Aerospace Engineering, Choong-Nam National University
- Dr. Nikhil Koratkar, Professor Aerospace Engineering, RPI
- Dr. Stephen Turnour, Manager Flight Mechanics, Robinson Helicopters

Notable Graduates

2007 Academy of Distinguished Alumni



2008 AHS Hon. & Technical Fellows

1982 1985 1987 1993 1995 1999 2005 2007

Graduate Students of Alfred Gessow Center
National & International Impact

Director of Penn State Rotorcraft Center of Excellence: Ed Smith

Director Vehicle Technology Army/ARL Aberdeen: Mark Nixon

Vice President Sikorksky Aircraft Co. Mike Torok

Program Director, Thales Avionics: Philippe Benquet

Senior VP Engineering El Al Col. Ret Fledel Shamuel

Head of Korea Rotorcraft Program: Jinseok Jang

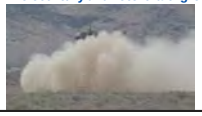
Vice President S&T James Wang

PM Armed Scout, AMCOM Col. Keith Robinson

NASA Astronaut Jeanette Epps

Rotorcraft Aeromechanics: Future Directions

- Expand & nurture core multidisciplinary aeromechanics programs:
  - Maintain balance between theory & experiment
  - Tackle barrier problems systematically such as maneuvering flight aeromechanics, variable speed rotors, robust HUMS, swashplateless rotors, etc.
- High efficiency mission-adaptive morphing rotor
- Expand micro air vehicle program
  - Revolutionary concepts in gusty environment
- Brownout/whiteout: Understanding and mitigation
- Exploit advanced CFD methodology to develop next-generation rotorcraft
- All electric/hybrid rotorcraft: green aviation



Alfred Gessow Rotorcraft Center
University of Maryland at College Park

Emerging CFD as a Viable Tool to Predict Vibratory Loads in a Helicopter

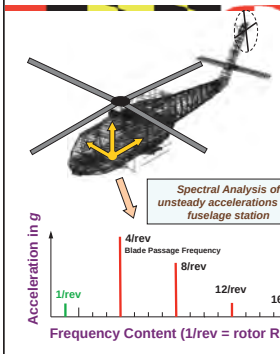
Inderjit Chopra
Alfred Gessow Professor and Director
chopra@umd.edu

Presentation At: Korea Aerospace Research Institute (KARI), Daejeon
June 27-30, 2011

Outline

- **Introduction: Vibration**
  - Barrier Issues
- **Identification Critical Flight Conditions**
  - High speed
  - Low speed transition
  - High altitude dynamic stall
  - Severe pull-up maneuver
- **Systematic Vibration Solution using CFD**
- **Other CFD Activities and Future Work**

Helicopter Vibration: Definition

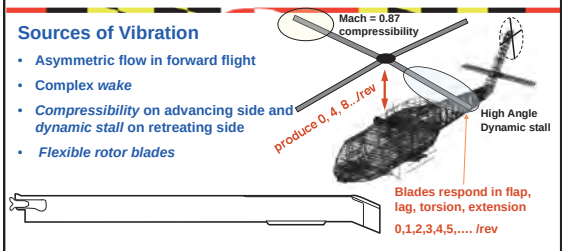


- Unsteady accelerations at a station in airframe
- Intrusion Index: weighted mean of *4 largest frequencies* in vertical, lateral and longitudinal directions up to 60 Hz
- Source of vibration: Rotor Blades are excited at all harmonics, only harmonics consisting integer multiples of blade number, pN_b/rev are filtered through hub
- 1/rev due to rotor asymmetry

Rotor Dynamics in Forward Flight

Sources of Vibration

- Asymmetric flow in forward flight
- Complex *wake*
- *Compressibility* on advancing side and *dynamic stall* on retreating side
- *Flexible rotor blades*

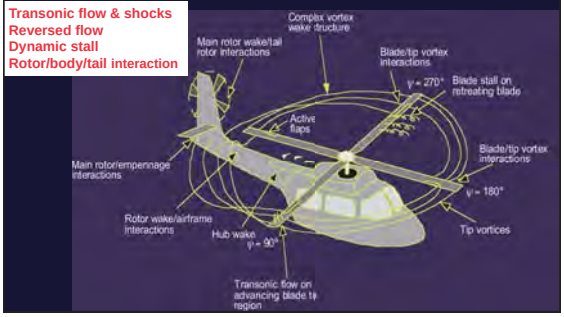


- Blade undergoing moderately large deformations involving coupled flap, Lag, torsion and axial motion, nonlinear inertial couplings
- Airframe 3-D structure with complex joints and cutouts, Gyroscopic nonlinear couplings in vehicle dynamics

Aerodynamics: Challenges

- Nonsteady and complex aerodynamics and rotor wakes

Transonic flow & shocks
Reversed flow
Dynamic stall
Rotor/body/tail interaction



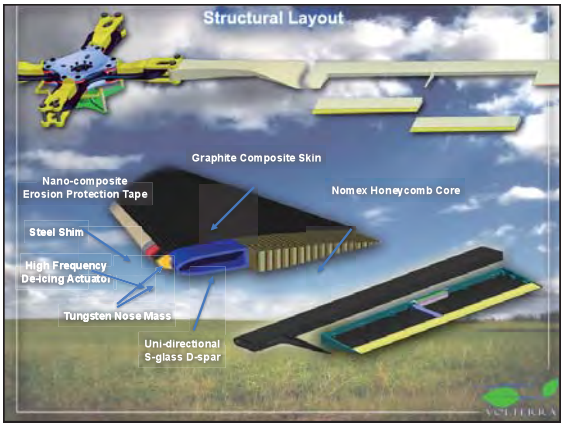
Rotor Wakes: Challenges

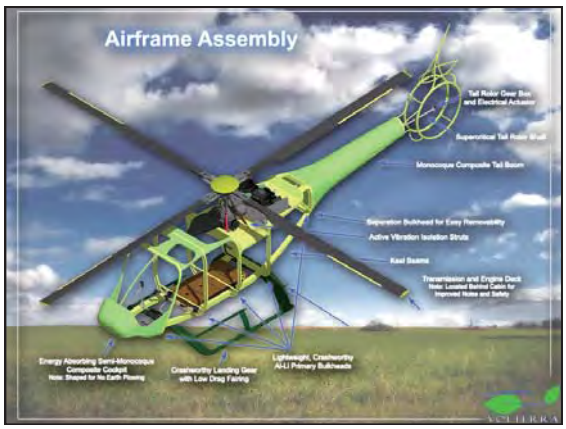
Main rotor wake interactions with fuselage, empennage, tail-rotor

Blade Tip Vortices: High induced velocities

Blade/Vortex Interactions: Rotor loads, Performance & Acoustics

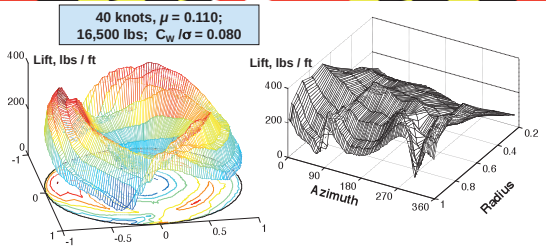
Vortex/Vortex Interactions: Highly three-dimensional induced flow-field



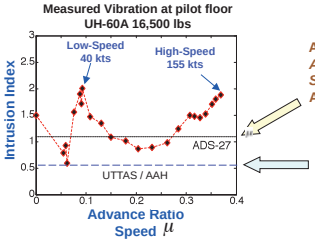


Lift Variation in Low Speed Transition Flight UH-60A

40 knots, $\mu = 0.110$; 16,500 lbs; $C_W/\sigma = 0.080$



Helicopter Vibration vs. Forward Speed



ADS-27 : Revised *Aeronautical Design Standard* set by the U.S. Army, 1986

UTTAS/AAH : Original design standard of *0.05g* which none of the helicopters could meet

- *Excessive vibration: Discomfort,* reduced life (cost), degraded performance
- *90% of vibration at low speed and high speed from main rotor loads*
- Non-rotor sources : transmission, tail rotor, engine, external systems

Analysis Methods : Blade Structural Model

Blade Modeled as elastic 1-D beam undergoing flap bending, lag bending, elastic twist and axial deformation

Blade Model

- *Linear* flap-lag-torsion dynamics for small deformations (*Houbolt and Brooks 1958, Ormiston 1972*)
- *Nonlinear* equations for moderate deformations (*Hodges/Dowell 1974, Hodges/ Ormiston/Peters 1980, Friedmann/Rosen 1978, Johnson 1977, Kvaternik 1976*)
- Anisotropic, *composite* rotor with cross-sectional warping and transverse shear (*Hodges 1990, Smith/Chopra 1993, Bauchau 1998*)
- *Advanced geometry* rotors with sweep and droop (*Celi/Friedmann 1992, Benquet/Chopra 1989, Ganguli/Chopra, 1992*)

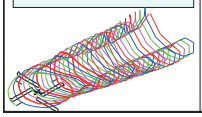
Spatial discretization

- Lumped parameter methods, transfer matrix, *Myklestad* (*Murthy 1986, Sangha 1990*)
- *Finite element* approach (*Straub/Friedmann 1980, Chopra/Sivaneri 1982*)
- Modal reduction vs. full finite element
- Topology independent *multi-body formulations* (*Johnson 1998, Saberi 2004, Bauchau 1993, Ghiringhelli/Masarati 1999*) large deformations

Analysis Methods : Unsteady Aerodynamic Modeling

- **Classical inviscid, incompressible, thin airfoil theories (Theodorsen, Wagner)**
- **Semi-empirical indicial models**
  - attached flow *(Beddoes 1984, Leishman 1988)*
  - separated flow *(Beddoes 1983)*
  - dynamic stall *(Leishman/Beddoes 1989)*
  - effect of sweep on dynamic stall *(Leishman 1989)*
  - Boeing dynamic stall model *(Gormont 1970)*
  - Johnson dynamic stall model *(Johnson 1970)*
  - ONERA EDLIN dynamic stall model *(Petot 1990)*
  - ONERA BH dynamic stall model *(Truong 1998)*
- **Detailed CFD models (Euler, Full Potential, Navier-Stokes)**

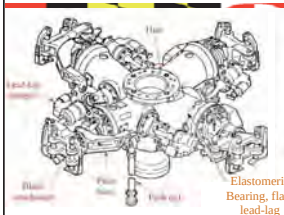
Analysis Methods: Wake Geometry Calculation

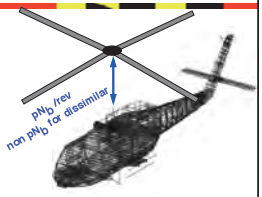
Prescribed geometry	Free Geometry	Free, time accurate
• Prescribed wake (Piziali/ DuWaldt 1962)	• Relaxation model (Scully 1975)	• Hover (Crimi 1965, Scully 1967) instability
• Refined by experimental induced velocities (Landgrebe 1969) to improve hover performance	• General free wake method (Johnson 1995)	• Clark/Leiper 1970 (enforced periodicity), forward flight (Landgrebe 1969, Sadler 1971)
• Kocurek/Berkovitz 1982	• Pseudo-implicit predictor-corrector (Bagai/Leishman 1995)	• Vortex lattice model (Egolf 1988), Baron/ Baffadossi 1993
• *Refined for forward flight, (Landgrebe/Egolf 1983, Beddoes 1985)*	• Multiple trailer method (Johnson 2002)	• Jain 1998, Chung 2000 studied hover instability
	• Constant vorticity contour method (Wachspress 2003)	• *Bhagwat/Leishman 2003 for hover, steady and maneuvering flight*, explained hover instabilities
	• *Multiple rotors, multiple trailers, dual peak, dissimilar blades (Bagai/ Leishman 1996*, Johnson 1988	

Analysis Methods: Trim, Response and Loads

- **Trim models**
  Free flight propulsive trim - solve for 3 rotor controls, 2 fuselage attitudes, tail rotor collective with 3 force/3 moment equations
- **Rotor Response Calculation (periodic in level flight)**
  - Harmonic balance (Johnson 1980) : CAMRAD, RCAS
  - Floquet theory (Dugundji/Wendell 1983)
  - Finite element in time (Panda/Chopra 1987) : UMARC
  - Numerical integration : Lockheed REXOR, Bell C81, Sikorsky DYMORE
- **Blade Loads Calculation**
  - Deflection or curvature or modal method
  - Force summation method
    superior in case of spatial discontinuity, rigid members, concentrated loads
  - Mixed formulation

Analysis Methods : Coupled Rotor-Fuselage Vibration





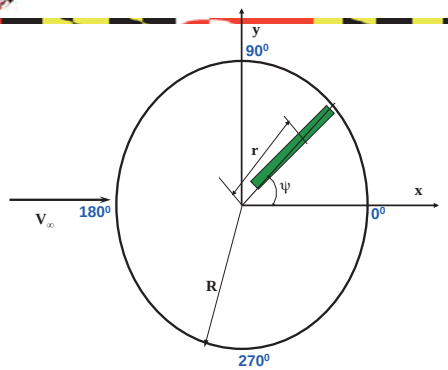
- **Rotor vibratory hub harmonics (4/rev, 8/rev, etc) transmitted to elastic airframe**
- **Say 1P = 300 RPM or 6 Hz, 4P=24 Hz**
- **Airframe 20 modes less than 25 Hz, requires detailed modeling of airframe including joints, cutouts and secondary structures**

Analysis Methods : Rotor Codes vs. Comprehensive Analyses

Specialized Rotor Codes	Comprehensive Codes
• *Greater details, accuracy and scope to model some physical mechanisms while simplifying most other interactions*	• *Includes all basis components to handle multidisciplinary loads, vibration and stability, Can perform trim, transient and flutter*
• RotorCRAFT to CHARM – detailed free wake, rotor-fuselage aerodynamic interaction	• CAMRAD family
• KTRAN-RDYNE-GENHEL – structural dynamics and flight dynamics	• UMARC family
• DYMORE II – multibody rotor-fuselage dynamic model	• 2GCHAS to RCAS
• R150 and Westland/DERA	*free wake model* *unsteady aero, stall model* *flexible blade dynamics* *free flight trim* *airframe dynamics* *advanced geometry blades* *composite, modern rotors* *3D CFD loose coupling*
• C81 and COPTER	
• R85/METAR	

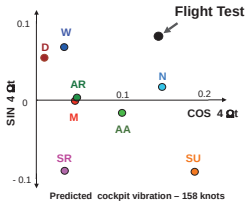
Vibration Prediction: Barriers

Rotor Definitions



Vibratory Loads at High Speed: Prediction vs. Flight Data in 1998

Predicted 4/rev vibratory hub load at high speed from 8 different rotor codes for LYNX



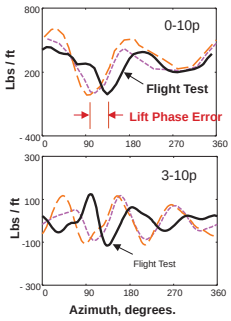
AA - 2GCHAS AR - Flightlab D - CRFM
M - UMARC (Maryland) N - CAMRAD1
SR - RDYNE SU - UMARC (Sikorsky)
W - R150

- None of predictions agreed with flight test data
- No two predictions agreed with each other
- LYNX Blades were not pressure instrumented, hence systematic correlation study with air loads and blade loads could not be possible

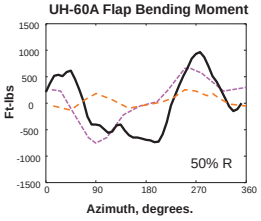
Vibratory Loads at High Speed: Prediction vs. Flight in 2000

UH-60A Lift at 77.5% R

$\mu = 0.368$
$C_w/\sigma = 0.078$
2GCHAS/RCAS
CAMRAD/JA



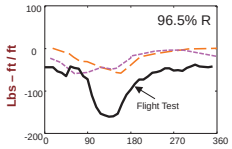
UH-60A Flap Bending Moment



- Phase error in advancing blade lift, and flap bending moment

Vibratory Loads at High Speed: Prediction vs Flight

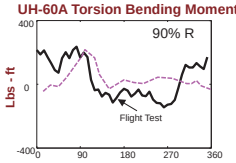
UH-60A Aero Pitching Moment



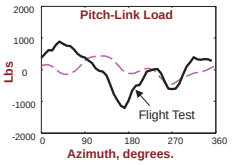
2GCHAS/RCAS
CAMRAD/JA

- Error in aero pitching moment, torsion bending and pitch link load

UH-60A Torsion Bending Moment



Pitch-Link Load



"… we have not made any significant progress in the last 30 years in the accuracy of our prediction methods."
Bousman, 8th ARO Workshop 1999

" …we do not understand the basics : is this discrepancy from the structural or aerodynamic modeling (especially wake) or both ?"
Lim, 1st UH-60A Airloads Workshop 2001

Prediction of Vibration

Vibration Validation Study

Major undertaking in 2001: Team involving industry, academia, NASA/ Army to resolve vibration barrier issues. Loads Workshop: Meet every 6 months since 2001

Vehicle: UH-60A Black Hawk, extensive flight test data with pressure instrumented blades

Identified 4 critical flight conditions:

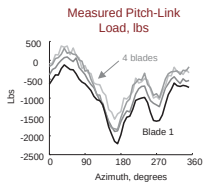
Level Flight:

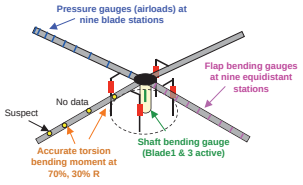
1. High speed	$\mu = 0.37$	UH-60A flight 8534
2. Low speed transition	$\mu = 0.15$	UH-60A flight 8513
3. High altitude dynamic stall	$\mu = 0.24$	UH-60A flight 9017

Maneuver:

4. Severe pull-up Maneuver (load factor = 2.09)	$\mu = 0.341$	UH-60A flight 11029

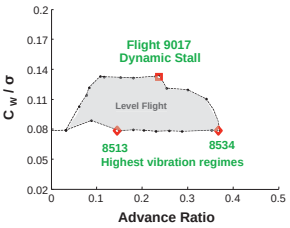
UH-60A Flight Test Data Repeatable and Reliable





- **31 test flights: 7 level, 3 maneuver, 9 ground acoustics, 6 inflight acoustics, 6 flight dynamics**
- **Pressure at 9 blade stations, Flap bending 9 stations, Chord bending 8 stations, Torsion 4 stations (around 460 transducers in total)**
- **Oscillatory waveform variations repeatable over blades**

3 Critical Flight Conditions: Level Flight



CFD challenges :

- **Low Speed :** *Grid for wake capture*
- **High speed :** *3D transonic effects on pitching moment*
- **High altitude:** *turbulence modeling for dynamic stall*

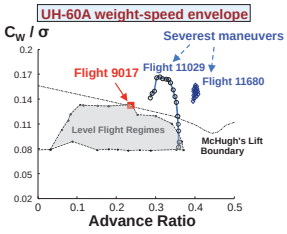
CSD challenges :

- **Low Speed :** *3/rev flap bending*
- **High speed :** *Elastic twist low frequency*
- **High altitude :** *Elastic twist high frequency*

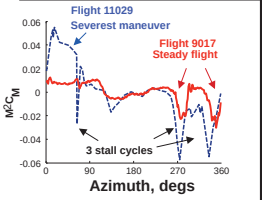
Separate mechanisms: wake, transonic effect, and dynamic stall

4th Critical Flight: Pull-Up Maneuvering Flight

UH-60A weight-speed envelope



Sectional Pitching Moment 86.5% R



- **Design loads set by severe maneuvers under stall**
- **C11029 : 2.12 g pull up at 139 kts, highest flap bending, and Pitch-Link (PL) load, severest maneuver**

- **C9017 stall similar to severest maneuver**
- **Compressibility, dynamic stall and wake all occur simultaneously in maneuvering flight**

Vibration Prediction Approach

I. Uncoupled Solution

Separate structural dynamics from aerodynamics

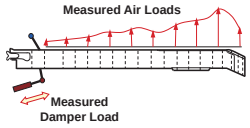
II. Coupled Solution

Structural dynamics coupled with aerodynamics

Focus on rotor, effect of airframe neglected

Separate structural dynamics from aerodynamics

Phase-1: Use measured air loads



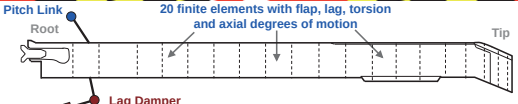
Calculate rotor response using comprehensive code (UMARC) and validate blade bending with measured data

Calculate blade deformation

Phase-2: Use calculated blade deformations

Calculate blade loads using lifting-line analysis (UMARC) and CFD analysis (TURNS) and compare with test data

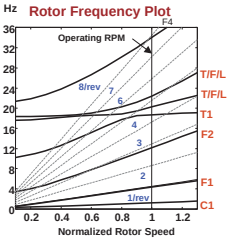
Structural Dynamics with Measured airloads using *UMARC*



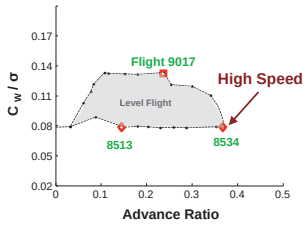
- *2nd order nonlinear beam theory*
- *FEM in space (10 modes) and time*
- *Measured damper force and kinematics*
- *Flexible pitch link, elastomeric bearing*

Baseline Rotor Frequencies: Stiff PL

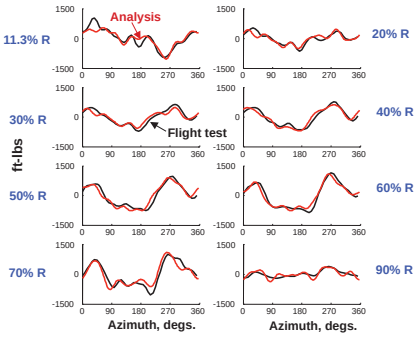
1 Lag	0.27p	3 Flap	5.20p
1 Flap	1.04p	4 Flap	7.89p
2 Flap	2.83p	5 Flap	11.41p
1 Torsion	*4.38p*	3 Lag	12.38p
2 Lag	4.69p	2 Torsion	12.44p



High Speed Flight

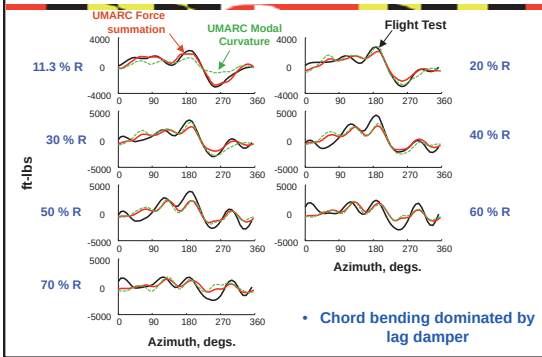


Phase-1: Using Measured Air Loads: Flap Bending Moment



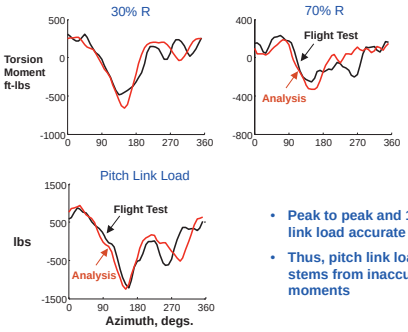
Predictions satisfactory

Phase-1: Using Measured Air Loads: Chord Bending Moment



- Chord bending dominated by lag damper

Phase-1: Using Measured Air Loads: Torsion Moment

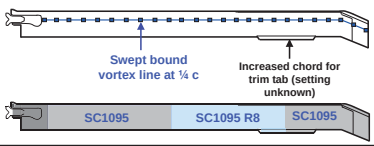


- Peak to peak and 1-3/rev pitch link load accurate
- Thus, pitch link load problem stems from inaccurate pitching moments

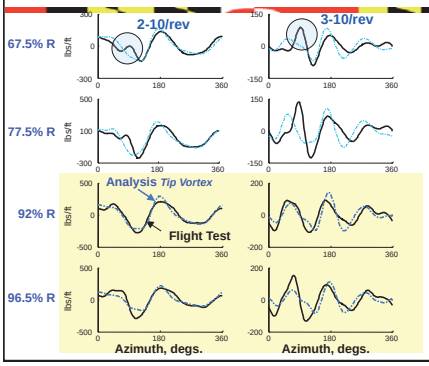
Phase-2: Using calculated deformations: Blade aero loads

UMARC (University of Maryland Advanced Rotorcraft Code)

- Lifting line model
- Bagai-Leishman free wake
  fully rolled up, 5 degs., 4 turns
  single, moving, dual, full-span, root vortex, inboard trailers, vortex lattice
- Leishman-Beddoes unsteady model
  attached, separated, dynamic stall extracted for SC1095, SC1095 R8
- 2D test airfoil tables
- Weissinger-L based nonlinear near wake

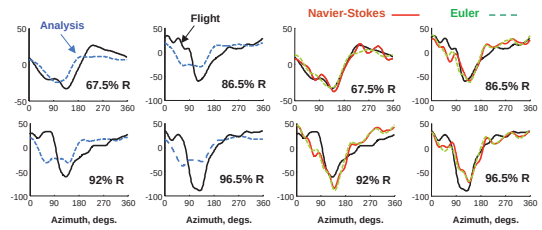


Phase-2: Using calculated blade deformations: Lift using lifting-line



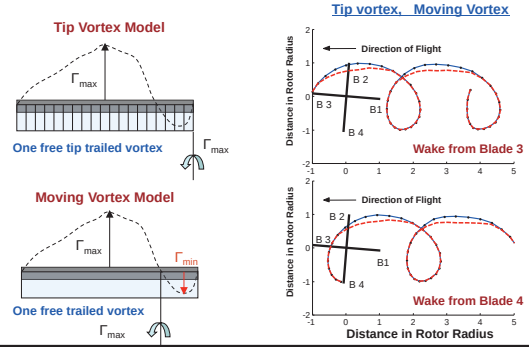
- Phase and vibratory lift accurate outboard
- Accurate twist not enough inboard
- Refined wake roll-up required in addition to twist

Phase-2: Using calculated blade deformations: Pitching moment using lifting-line & CFD



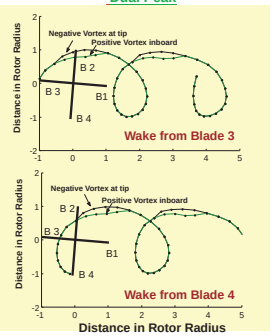
- Lifting-line does not capture 3D unsteady transonic pitching moment
- Both Navier-Stokes / Euler captures 3D unsteady transonic pitching moment

Lifting-line: Effect of roll up model Tip vortex, Moving vortex, Dual Peak

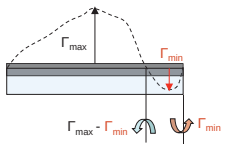


Lifting-line: Effect of roll up model Tip vortex, Moving vortex, Dual Peak

Dual Peak



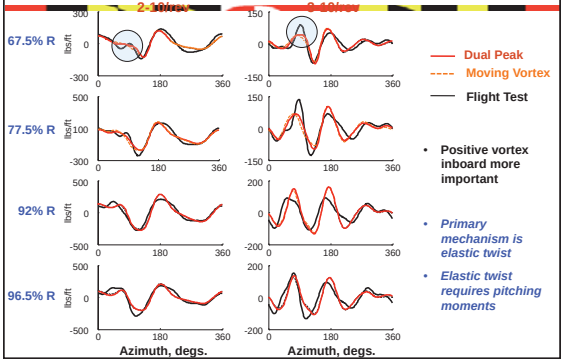
Roll Up Model



***Dual Peak*:**

- *Two free vortices, negative vortex at tip*
- *Positive vortex rolled up at zero bound circulation cross over point*

Lifting-line: Effect of roll up model Tip vortex, Moving vortex, Dual Peak

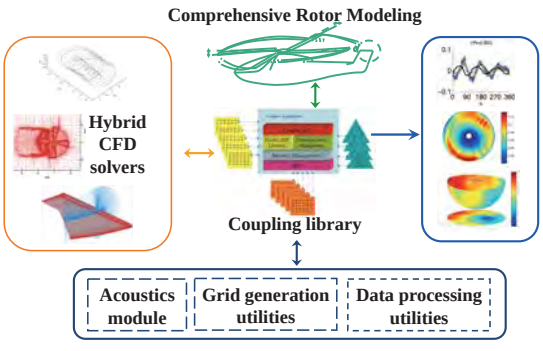


- Positive vortex inboard more important
- *Primary mechanism is elastic twist*
- *Elastic twist requires pitching moments*

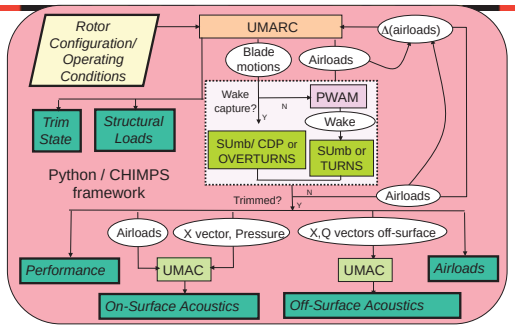
II. Coupled Solution

CFD Methodology

Computational Framework – Schematic

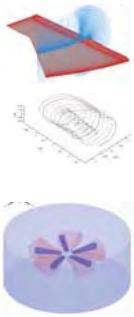


Coupling Procedure *"HUSH"*



Wake-coupling vs. Wake-capturing

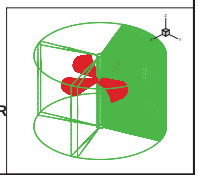
- **Two strategies for predicting rotor far wake geometry and induced velocities**
- **Wake Coupling**
  - **Stand-alone Lagrangian free-wake model (PWAM) coupled to CFD using field velocity approach**
  - **CFD solves only the near-body flow-field Captures near wake evolution**
  - **Single blade sufficient for steady flight**
- **Wake capturing**
  - **Wake calculated using CFD. Solve both near-body and off-body flow-field**
  - **Captures wake sheet evolution and roll-up from first principle**
  - **Grid resolution critical in preserving vorticity**
  - **Computational intensive**



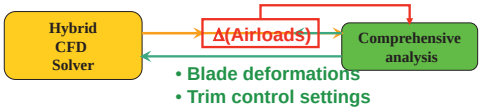
UMTURNS & OVERTURNS

- **UMTURNS (wake coupling)**
  - ***Near-body solution using a C-O mesh Single blade only***
  - ***Wake effects included using field-velocity approach***
  - **Roe's flux differencing with MUSCL-type limiter**
  - **Second-order stencil for viscous terms**
  - **Baldwin-Lomax and Spalart-Allmaras turbulence models**

- **OVERTURNS (wake capture)**
  - ***C-O mesh used for near-body solution Models all blades***
  - ***Wake-capturing using overset meshes Cylindrical background meshes***
  - **Essentially an overset version of UMTUR**



CFD-CSD Coupling



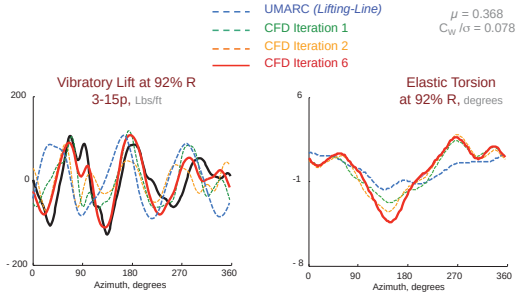
- Tight coupling
  - Exchange data at every timestep/sub-iteration
  - Computationally intensive
- Loose coupling ✓
  - Exchange data every rotor revolution
  - Delta airloads methodology
  - Determine trim solution within comprehensive analysis
  - Iterate until trim convergence

Details of CFD analysis

Grid spacing:

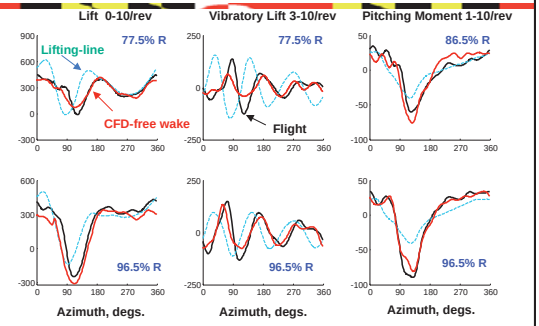
- **Partial CFD: 133-43-43 (total 0.25M) coarse grid**
- **Full CFD: 133-125-48 (0.8 M) + background grid 2.2 M (total 3M)**
- **high speed airloads – grid independent**
- **low speed – Practically independent; refinement necessary to see grid dependency is beyond today's capability (BVI)**
- **Stall airloads – sensitive to grid spacing**
- **Power predictions – profile power (airfoil drag) sensitive to grid**

Evolution of vibratory lift and elastic torsion with CFD iterations

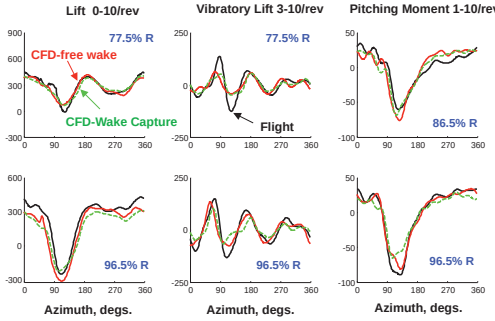


- *Improved vibratory lift driven by improved elastic torsion*

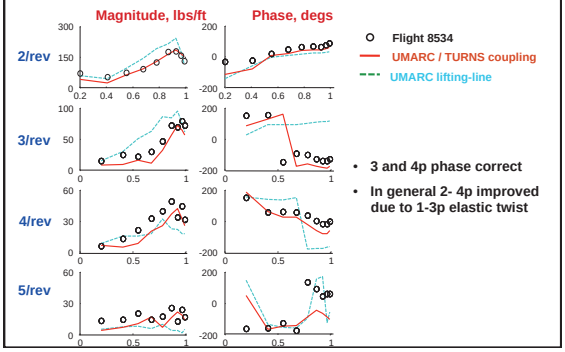
High Speed: CFD/CSD coupled Solution: First barrier problem resolved



High Speed: CFD/CSD coupled Solution: First barrier problem resolved

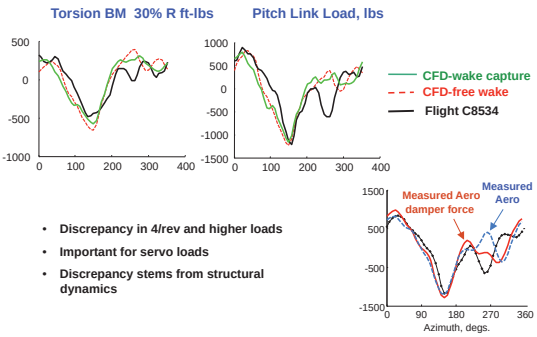


Lift: Contribution of CFD/CSD Coupling



- 3 and 4p phase correct
- In general 2- 4p improved due to 1-3p elastic twist

Pitch Link Load at high speed: CFD/CSD Second barrier problem resolved

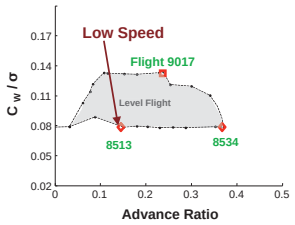


- Discrepancy in 4/rev and higher loads
- Important for servo loads
- Discrepancy stems from structural dynamics

Loads in High Speed Flight: Conclusions

- Key barrier problems resolved
  - Physics of vibratory lift in place: phase problem resolved
  - Peak-to-peak pitch link load captured
- Outstanding Issues
  - 4p and higher pitch link load less satisfactory: *structure*
  - Phase error of 7-10 degree in flap bending: *aerodynamic*

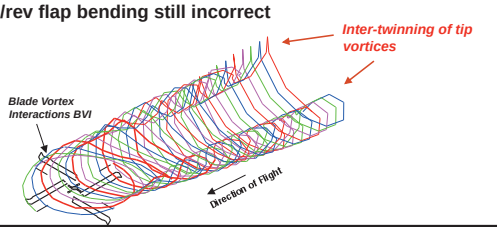
Low Speed Flight



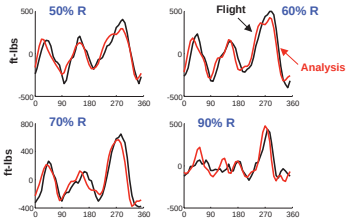
Prediction of vibratory loads at low speed

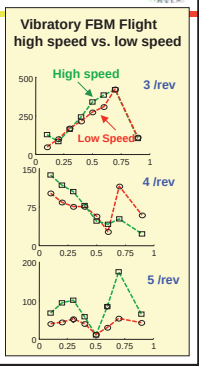
UH-60A Flight C8513 : $\mu = 0.153$ $C_T/\sigma = 0.076$

- Key mechanisms :
  - *Free wake inter-twinning*
  - *Inboard lift important ?*
- Key challenge : *CFD wake capture*
- 3/rev flap bending still incorrect



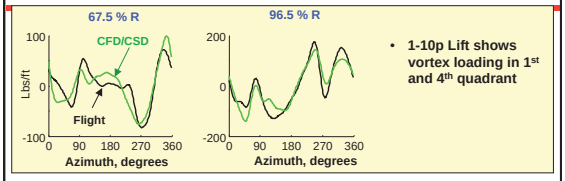
Flap Bending Moments using Measured Air loads C8515





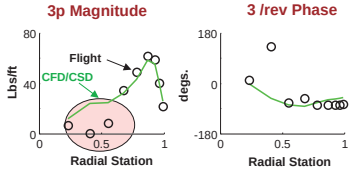
- Flap bending is pre-dominantly 3/rev
- Comparable to high speed
- Other loads benign

Predicted Lift from CFD/CSD using CFD wake capture: Low Speed

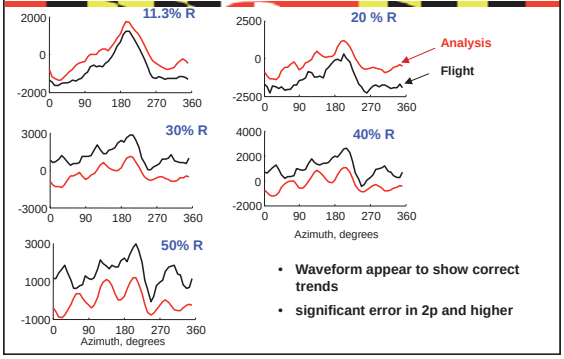


- 1-10p Lift shows vortex loading in 1st and 4th quadrant

- 3p lift accurate 77.5% R outboard



Chord Bending Moment using Measured airloads: Low speed

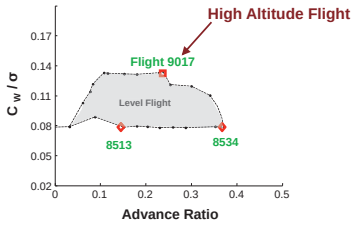


- Waveform appear to show correct trends
- significant error in 2p and higher

Loads in Low Speed Transition : Summary

- Vibratory air-loads can be captured by CFD, but only slightly changed from lifting line results
  - 0.05c background grid adequate
  - artificial dissipation of tip vortices does not prevent capturing 3-5/rev air loads
- Key Technical Barrier :
  - 3/rev flap bending moment still wrong

High Altitude Dynamic Stall Flight

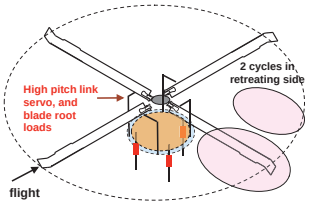


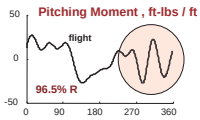
Fundamental Understanding and Prediction of Dynamic Stall Loads

UH-60A Flight C9017 : $\mu = 0.237$ $C_T/\sigma = 0.129$

- Key barriers :
  - 2 retreating blade stall cycles
  - 3-5/rev pitch link load
- Key mechanisms : Trim stall and Twist stall
- Key challenge : CFD turbulence model

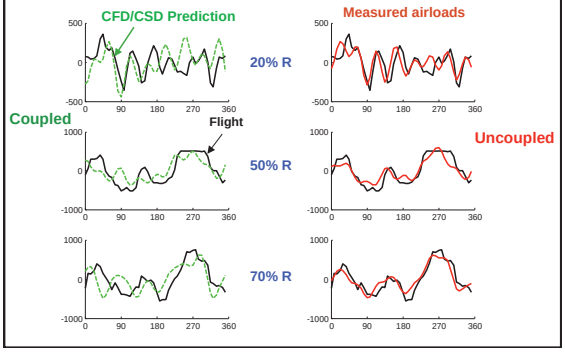
Dynamic Stall Flight 9017



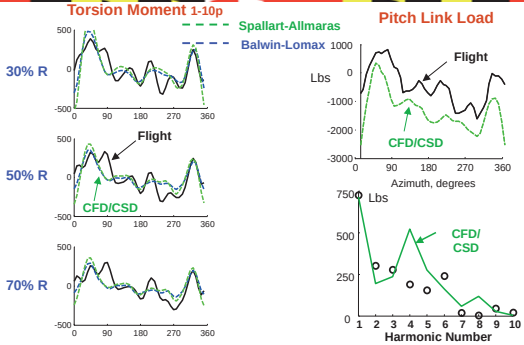


- 3 - 5/rev torsion loads excite swashplate servo
- Peak flap bending and pitch link load important for design
- Trim, torsion response, and turbulence important for prediction

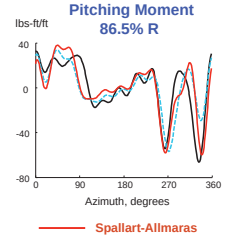
Flap Bending Moments: CFD/CSD vs. Measured airloads

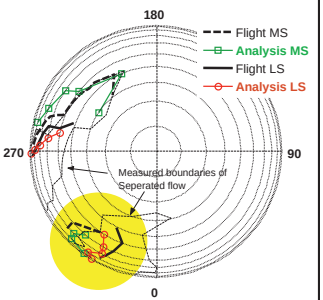


Torsion Moments and Pitch Link Load: CFD/CSD



Predicted Pitching Moment and Stall Map: CFD/CSD

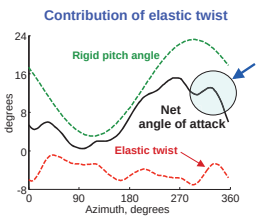


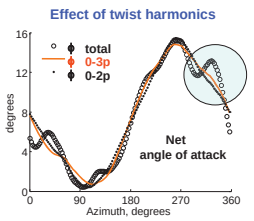


- 2nd stall cycle mostly 2D
- 1st cycle is 3D; stall vortex moving across span

Physical Mechanism of the two Stall Cycles: Trim and Twist

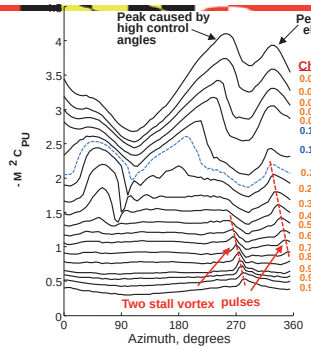
Angle of Attack study at 86.5% R





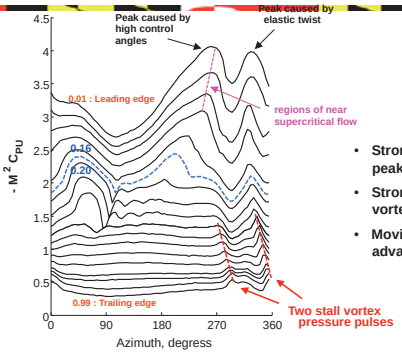
- Rise in 3rd quadrant due to high trim angles: 1st cycle is a trim stall
- 4th quadrant excitation due to 4 and 5p twist: 2nd cycle triggered by twist

Predicted chord-wise pressure on upper surface : 86.5% R



- pressure near LE follows control angle variation
- twist peak in 4th quadrant
- Pressure near TE shows stall vortex pulse

Predicted chord-wise pressure on upper surface : 92% R



- Stronger twist peak
- Stronger 2nd stall vortex pulse
- Moving shock in advancing side

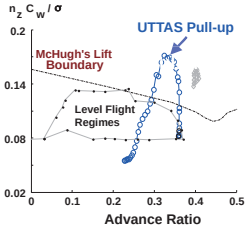
Loads in Dynamic Stall Flight : Summary

- Mechanism of retreating blade stall understood
  - 1st cycle due to high trim angles
  - 1st cycle excites 4 and 5p twist (torsion freq 4.38p)
  - 4 and 5p twist sets location of 2nd stall cycle
  - Inflow important
  - CFD turbulence model important
  - Stall near tip 96.5% R not captured
- Peak to peak blade loads satisfactory
  - 4p and higher pitch link load unsatisfactory : *struct problem*
  - Important for servo loads

Level Flight: Key Conclusions: CFD/CSD Coupling

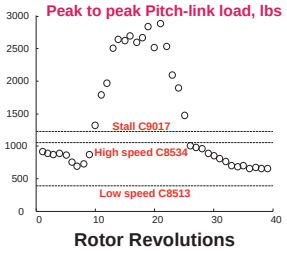
- CFD provides fundamental capability at high speed
  – 3D unsteady transonic pitching moments
- CFD provides improved capability at low speed and stall
  - no semi-empirical wake roll up or stall models
  - key for *calculating* loads on new rotor designs
- Structural loads not significantly improved as air loads
- 4p and higher torsion unsatisfactory – struct. Problem
- 4p and higher chord bending unsatisfactory – struct. Problem

Unsteady Maneuvering Flight



UTTAS Pull-up Maneuver

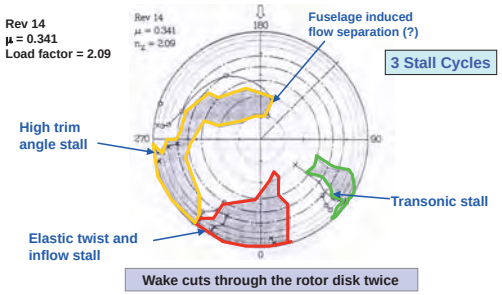
- Flight 11029
  – Based on Utility Tactical Transport Aerial System (UTTAS)
  – Third highest pitch link load (2.5 times steady flight)
  – Highest root flap bending moment



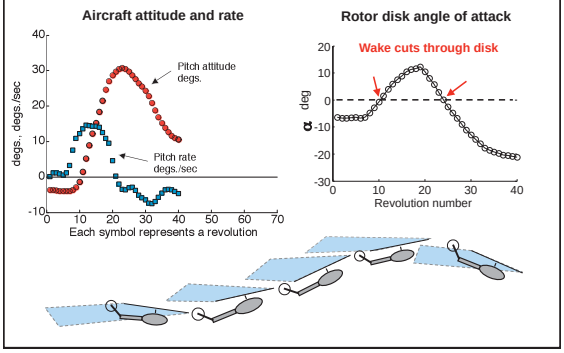
All aerodynamic mechanisms can occur simultaneously during maneuver

Flight 11029: Severest UH-60A Maneuver: Stall Map

Flight Test Measurement from Bousman & Kufeld 1997

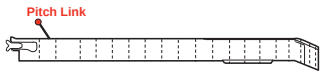


Flight 11029 Severest UH-60A Maneuver: UTTAS pull-up



Multibody Analysis

- **Structural dynamics model**
  - Full finite element large frame (multibody) analysis capable of modeling large deformations



- **Aerodynamics model: N_b bladed transient model**
  - Unsteady lifting surface including roll and pitch rates
  - Weissinger-L type lifting surface model iteratively coupled to 2D airfoil tables
  - Dynamic Stall (Leishman-Beddoes)
  - Transient Freewake (Ananthan-Leishman)

Large Deformation Analysis

Large deformations can be modeled:

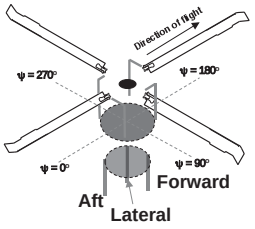
Approach 1: Geometrically exact beam theory

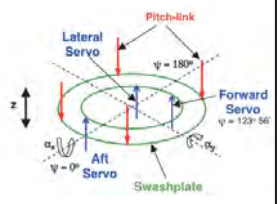
Approach 2: Second order non-linear beam theory coupled to multibody formulation

Approach 2: (Followed)

- Additional frame attached to individual elements
- Elements undergo only moderate deformation
- Rigid body motions accommodated by finite rotation of frames

Swashplate Model





- 4-bladed full FEM multibody model, 20 finite elements for each blade
- Pitch link stiffness (1090 ft-lbs)
- Elastomeric bearing: flap/lag damper : 100 ft-lb/rad/s

- 3 dof Swashplate model
  - Heave (z), pitch (α_y), and roll (α_x)
  - Swashplate idealized as rigid disk
  - Servos modeled as linear spring-damper system

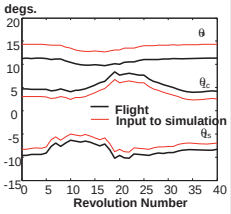
Fluid Structure Coupling

- **Inputs to aerodynamic model**
  - Blade deformations for all blades
  - Instantaneous advance ratio, shaft tilt angle, rotor pitch and roll angles, angular rates and the control angles
- **Output: instantaneous air-loads and inflow velocities**

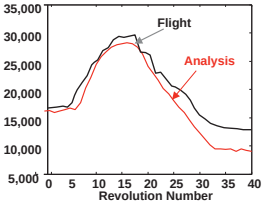
- **Tight coupling: structure, aerodynamic, and free wake model exchange information at every time step**
  - Similar to CFD/CSD serial staggered tight coupling without sub iterations
  - Transfer of information via subroutine calls

Maneuvering Flight Simulation

- Flight 11029 simulated using control angles, vehicle attitude and rates obtained from flight test
  - Maneuver initiated from trimmed high speed flight 8534
  - Control angles applied as increments to the trimmed control angles
- Time step of 5 degrees for time integration as well as wake
- Runtime: 4.5 hrs approx on a 1.87 GHz Intel Core Duo based PC

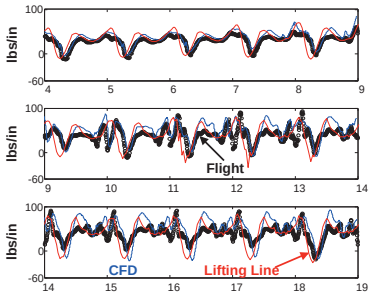


Thrust Prediction



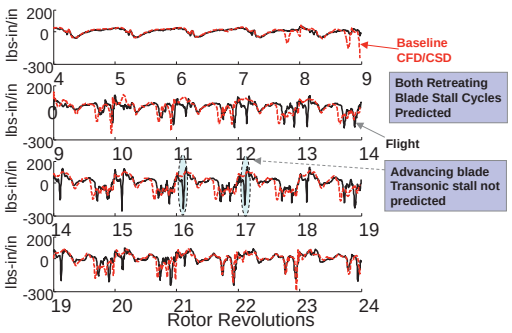
- Flight test thrust obtained by integrating measured normal force across span
- Inaccuracies in prescribed control motion, resulting in accumulated differences

Normal Force At 86.5%R



Improved Higher Harmonics (3-5/rev) and Stall Loads Prediction with CFD

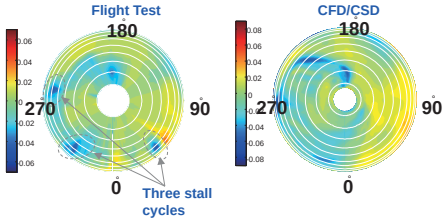
Pitching Moment: 86.5%R



Both Retreating Blade Stall Cycles Predicted

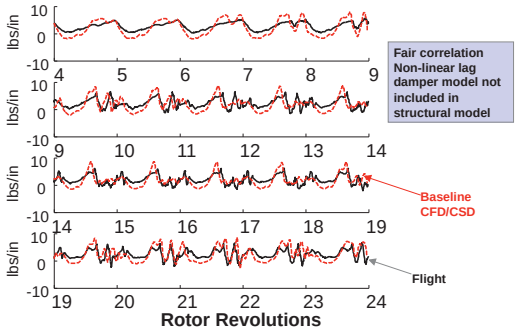
Advancing blade Transonic stall not predicted

Pitching Moment: Maneuver Rev 14



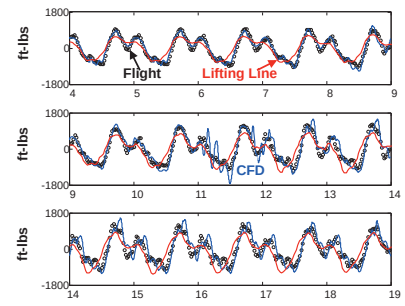
- Pitching moment variation during maneuver shows steep gradients
- Prediction show good correlation for two stall cycles on retreating side -- advancing blade stall not predicted

Chord Force: 86.5%R



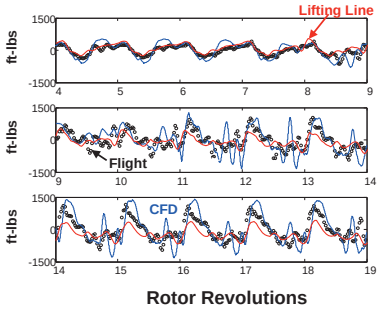
Fair correlation Non-linear lag damper model not included in structural model

Flap Bending Moment: 50%R



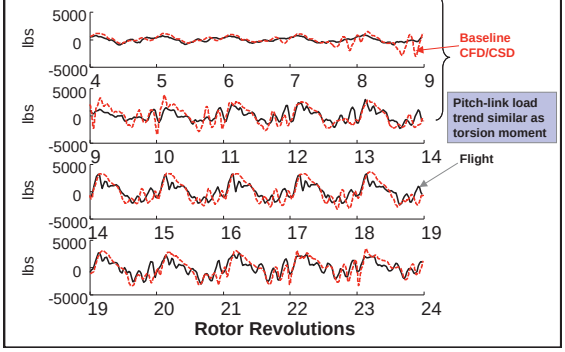
CFD Predictions Show Excellent Correlation with Flight Test

Torsion Moment: 30%R

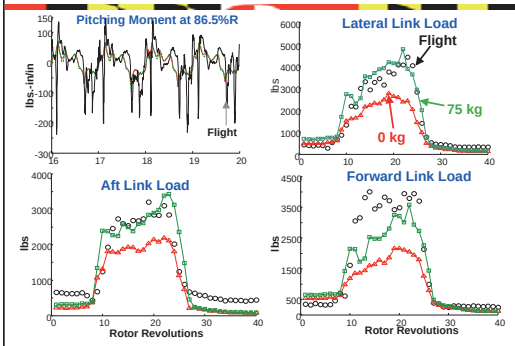


Peak-to-peak Moment Significantly Improved

Pitch-link Load



Effect of Swashplate Dynamics



Conclusions

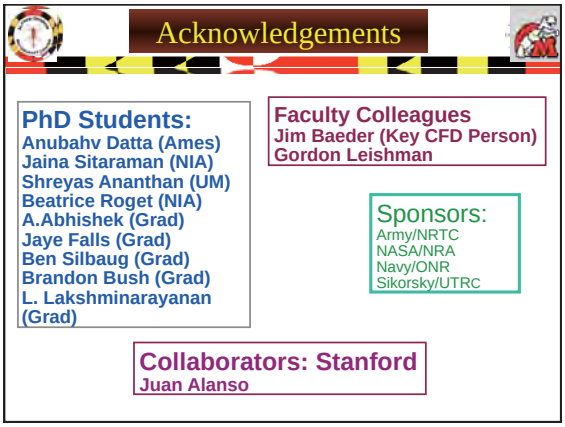
- Pull-up maneuver studied is a stall dominated flight.
  - Two distinct stall cycles predicted on retreating side
- Predicted peak-to-peak torsion moment and pitch-link load show trend similar to test data.
  - Peak-to-peak magnitude under-predicted
- Servo loads predicted satisfactorily
- Average thrust prediction showed trend similar to test data.

Other CFD Applications in Rotorcraft

- Generation of 2-D airfoil data tables (c_L, c_D, c_M) for current and future airfoils
- Performance evaluation of new rotor configurations:
  - Coaxial rotors
  - Swashplateless system with trailing-flaps

- Stall Alleviation with leading-edge slats
- Micro air vehicle systems (low Reynolds aerodynamics)
  - rotor based system
  - Avian-based flapping
  - Insect-based flapping

- Mission adaptive morphing rotor
- Parallelization of CFD methodology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Ben Silbaug (Grad)
Brandon Bush (Grad)
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Juan Alanso

Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

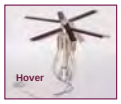
Hovering Micro Air Vehicles: Challenges & Opportunities

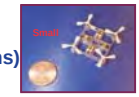
Inderjit Chopra
Alfred Gessow Professor &
Dirctor Alfred Gessow Rotorcraft Center
(chopra@eng.umd.edu)

Presentation At: Korea Aerospace Research Institute (KARI), Daejeon
June 27-30, 2011

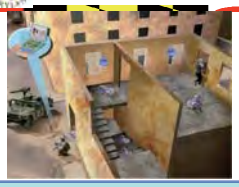
Micro Air Vehicles: Definition

- **Design Requirements**
  - No dimension exceeds 15 cm (6 inch)
  - Gross takeoff weight 100 grams
  - Loiter time of 60 minutes
  - Payload capacity of at least 20 grams
- **Additional considerations**
  - Fully autonomous (out of sight operations)
  - All weather operations
  - Low production cost
  - Rapid deployment
  - Low detection





Future Vision of Microsystems



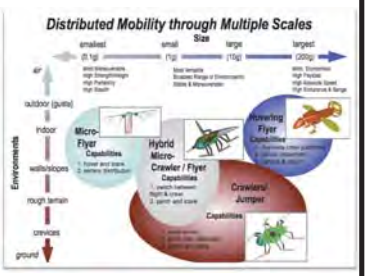
Scenario 1: Small unit building search
Challenges: hover and low speed, medium endurance, quiescent airflow

Scenario 2: Small unit cave / demolished building search
Challenges: Hover and low speed, high endurance, mediocre gust

Scenario 3: Autonomous small unit perimeter defense
Challenges: High speed, range and endurance, strong wind gusts

Microsystem Platforms

Range of platforms at:
- Macroscale (50-100 cm)
  To verify modeling tools, performance, functionality and mobility
- Mesoscale (1-10 cm)
  Final design goal
- Aerial: Rotary and flapping wings
- Hybrid: Thrust augmented entomopter, hybrid crawler/flyer



Size Scaling for MAV platforms

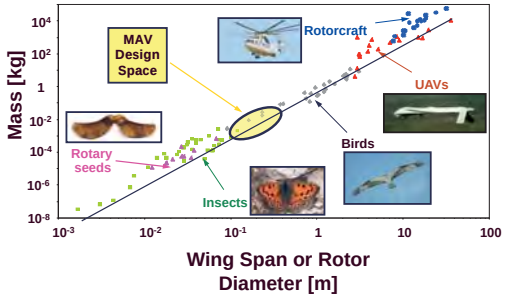
(Mobility)(Intelligence)(Multiplicity) = Capability

	Larger	Smaller	N*small=large
Mobility	↓	↑	↑
Gust Sensitivity	↑	↓	No change
Frequency	↓	↑	No change
CPU MIPS	↑	↓	no change
Multiplicity	↓	↑	N/A
Sensing	no change	no change*	$O(N^2)$ ↑
Communication	↑	↓	$O(N^2)$ ↑

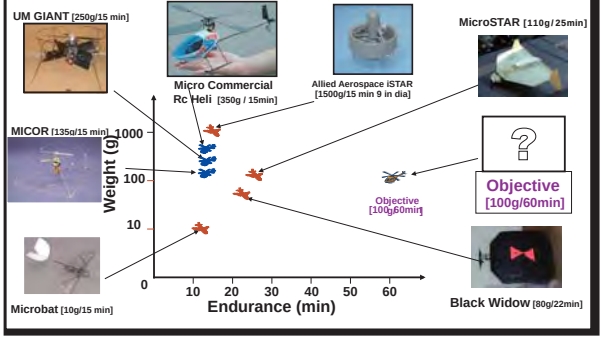
Micro Air Vehicles: Key Drivers!!

- Asymmetric warfare environment: urban warfare
- Micro-electronics: Miniaturized sensors availability
- Micro-processing: IT and transmission power growing
- Low cost systems: (can be organic with a soldier)
- Increasing focus on biologically-inspired flight systems

Perspective on Scale



Existing MAVs



Micro Air Vehicles: Key Challenges!!

- **Lack of knowledge how scaling affects micro-vehicle performance and limitation of existing aeromechanics tools.**
  - Low efficiency of existing air vehicles
  - Extreme vulnerability to gust
  - Low mobility, maneuverability and autonomy of existing vehicles
- **Requires fundamental understanding in key areas:**
  - Efficient aerodynamic performance in highly unsteady vortex dominated flows at low Reynolds number
  - Bio-inspired actuation and articulation air vehicles
  - Lightweight and adaptive structures
  - Insect-like navigation and control for autonomous operations in uncertain environment (such as gusty environment)
  - Efficient bio-inspired propulsion and efficient power distribution

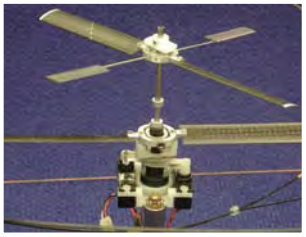
MICRO HOVERING AIR VEHICLES

- **Non-Hovering Vehicles: Fixed-wing based**
- **Hovering Vehicles: Rotor Based**
  - Single main rotor (with & without tail rotor)
  - Ducted fan rotor
  - Co-axial rotor
  - Tiltrotor, tiltwing, quadrotor, hybrid systems
  - Revolutionary designs
- **Hovering Vehicles: Flapping-Wing Based**
  - Bird-flight based
  - Insect-flight based (Efficiency at small scale?)
- **Hovering Vehicles: Reaction Based (power intensive)**

Micro Hovering Air Vehicles: Rotor-Based

Coaxial Rotor MAV

- MICOR (University of Maryland)
- 15 cm (6") dia coaxial 2-bladed rotors

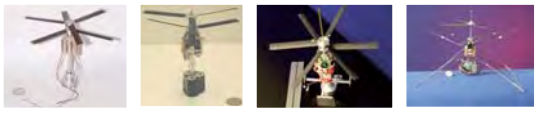


Swashplate controls only lower rotor

Weight~100 g, Payload ~10g
8% camber circular arc airfoils
$Re_{.75R}$ ~20,000
Endurance ~ 10 minutes
Fixed pitch, variable speed rotors (feedback on lower)

Coaxial Rotor MAV Development at UM

Evolution of the MICOR MAV



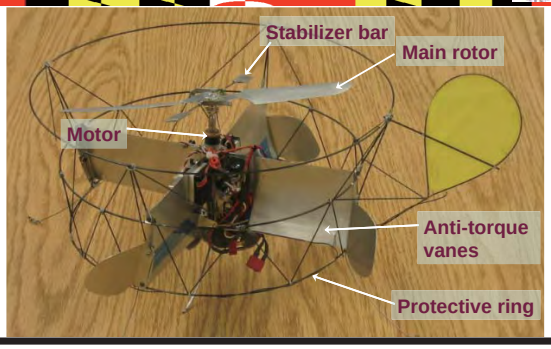
1st Gen. 2nd Gen. 3nd Gen. 4nd Gen.

1999 2008

1st Generation
- 100 g Weight
- Maximum Single Rotor FM ~ 0.4
- No Payload Capacity
- No Lateral Control - Unstable
- 3 Minute Hover Endurance

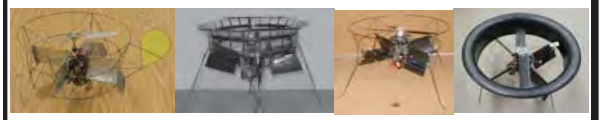
4th Generation
- Two bladed teetering rotors
- 135 gr. Single rotor max FM ~ 0.65
- Swashplate for cyclic control
- 20 minute hover endurance
- 25 g payload

MAV: Single Rotor & Anti-Torque Vanes



MAV: Single Rotor & Anti-Torque Vanes

Evolution of the Giant MAV



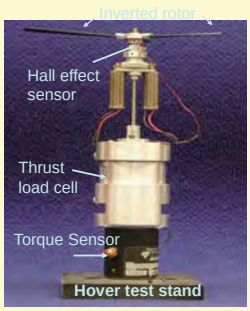
1st Gen. 2nd Gen. 3nd Gen. 4nd Gen.

1999 2008

1st Generation
- 27 cm diameter
- 310 gm gross weight
- Aluminum construction
- Basic RC Components

4th Generation
- 20 cm rotor diameter
- 200 gm gross weight
- Carbon fiber construction
- Refined spider-type swashplate
- On-board stability augmentation

Rotor Hover Test



Measurement of Hover Performance:

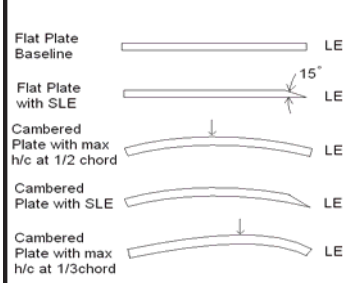
- Thrust
- Torque
- Rotational speed

} FM, C_T, C_P

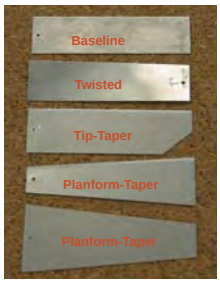
Figure of Merit

$$FM = \frac{\text{Ideal Power required to hover}}{\text{Actual Power required to hover}}$$

Blade Airfoil Variations



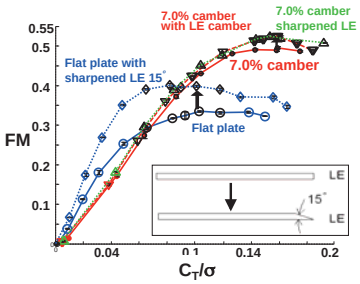
Camber Distribution



Planform Distribution

Sharpened Leading-Edge Airfoils

- Sharp leading-edge increases FM
- Smaller rise in FM for cambered airfoil

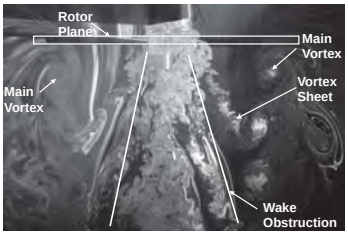


Sharpened LE can improve airfoil performance

Flow Visualization

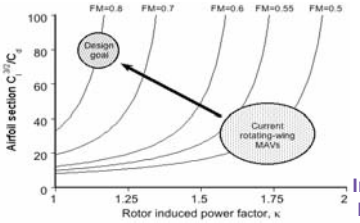
- Strong tip vortices
- High induced velocities in tip region
- Vortical shed wake obstruction increases DL and lowers FM

7% camber, 2.75% thickness with sharpened LE
D=6" 2-bladed rotor, 3600 RPM, Re=36.8*10^3



Rotating-Wing MAV Performance

Profile Effects



Induced Effects

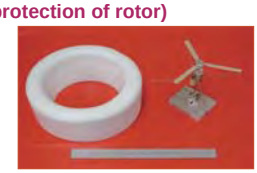
Better designs may come through careful aerodynamic optimization that minimizes both induced power and profile power

Shrouded Rotor System

Rotor Hover Efficiency

Figure of Merit M: Hover Efficiency is defined in terms thrust production per unit input power
For present designs: M is less than 0.6
Goal:Increase M over 0.8

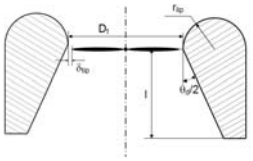
Improvement of hover efficiency using duct around the rotor (plus safety protection of rotor)



Shrouded-Rotor Concept

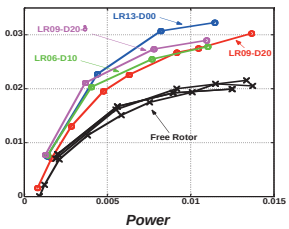
Key Design Parameters

- **Expansion ratio/Diffuser angle**
  - *Want this to be as large as possible for best performance*
- **Inlet lip radius**
  - *Incoming flow forms a suction peak on the inlet lip; cause of thrust augmentation*
- **Blade tip clearance**
  - *Proximity of shroud wall reduces strength of blade tip vortices; reduces blade tip losses*



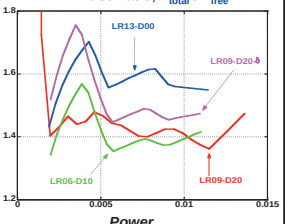
Experiment: Thrust Ratio vs. Total Power

Thrust Coefficient, C_T



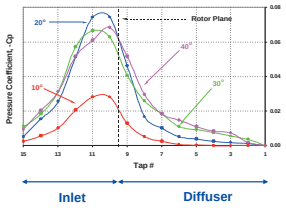
Increase lip radius: Increase thrust
Decrease tip clearance: Increase thrust

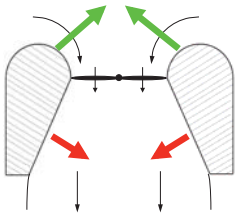
Thrust Ratio, T_{total} / T_{free}



Diffuser angle: Thrust increases with small angle <10^0

Shrouded-Rotor



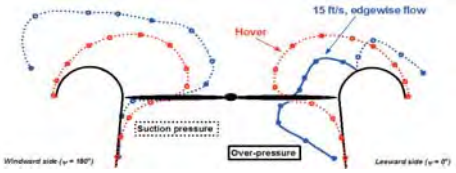


Optimized Configuration: 13% lip radius, 10^0 diffuser angle and 72% diffuser length results in 95% increase in thrust for same power

Challenge: Structural weight of shroud must be less than lift augmentation plus possible performance degradation in forward flight

Pressure Distribution – Edgewise Flow

- Pressure distributions asymmetric
- Increased suction on windward side, decreased suction on leeward side
  => Nose-up pitch moment
- Over-pressures on lateral surfaces facing into flow
  => Drag
- Net increase in suction in axial direction
  => Increase in thrust



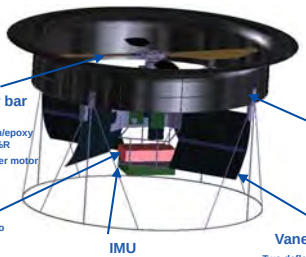
Shrouded rotor vehicles

Cypher	GTSpy	ISTAR	TiShrov

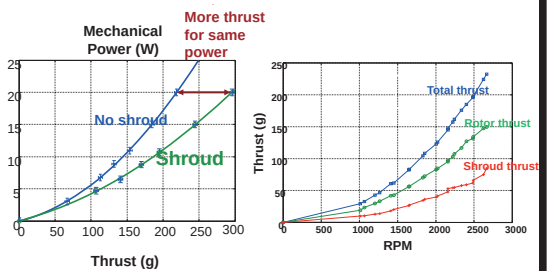
115 Kg → 2 Kg → 1.8 Kg → 0.28 Kg
Weight

2.2 m → 0.25 m
Rotor diameter

Shrouded Rotor TiShrov



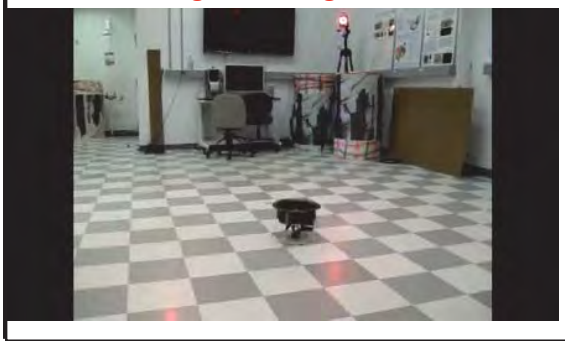
Shrouded Rotor Performance



Stability of Shrouded Rotor

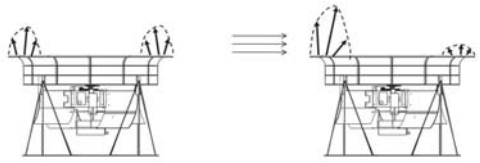
- Shrouded rotor inherently unstable system
- Instability due to asymmetric tip path plane movement more pronounced
- Shroud should be incorporated only with a hingeless rotor
- A feedback control system is required to stabilize shrouded vehicle in hover

Hover flight testing in VICON



Edgewise gust disturbance response

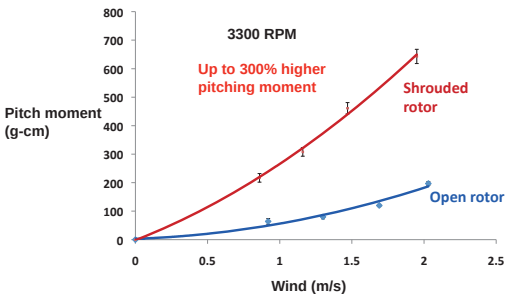
Nose-up pitching moment



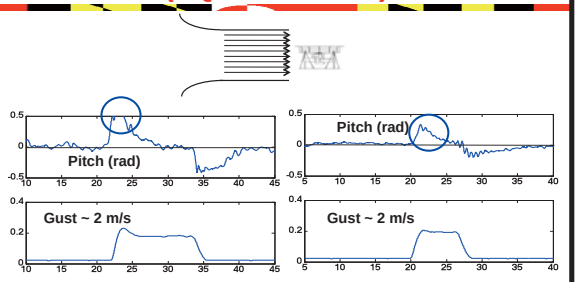
Hover, no gusts

Hover, edgewise gust

Pitching Moment Comparison



Gust Disturbance Rejection (LQR controller)



Shrouded rotor

Unshrouded rotor

Gust Disturbance Rejection (Free Flight)

Conclusions

- MAV shroud should be designed for high hover performance and low adverse pitching moment simultaneously
- Shrouded rotor
  - 30% higher power loading
  - 80% higher control authority (hingeless rotor,swashplate)
  - can accept higher cyclic pitch range (stall delay)
  - 300% higher adverse pitching moment
- Adverse pitching moment of shrouded rotor not a function of operating RPM or rotor collective

Conclusions (2)

- Control authority varies quadratically with RPM, (linearly with operating thrust)
- Improve control authority
  - Increase cyclic pitch range
  - High operating RPM, high rotor solidity and low collective
- Gust tolerance increased from 2 m/s to 3 m/s with suggested changes (increased pitch and rectangular planform)

Shrouded rotor MAV viable platform for low gust environments

Micro Quad Rotor

185-g quadrotor with 10-cm rotor with off-the-shelf electronics

35-g quadrotor with 3-cm rotor with Berkeley's GINA

Quad-Rotor: 6-DOF Terrain Following + Centering Response using Optic Flow Sensor

Rotary Wing Micro Air Vehicles: Unconventional Configurations

Cyclocopter

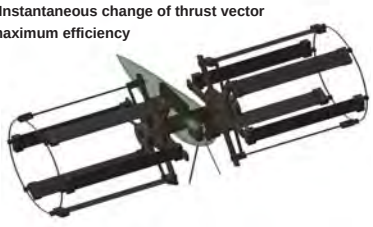
A set of blades rotate around an axis of rotation parallel to blades; pitch varies periodically once per revolution to produce thrust in desired direction

Advantages:

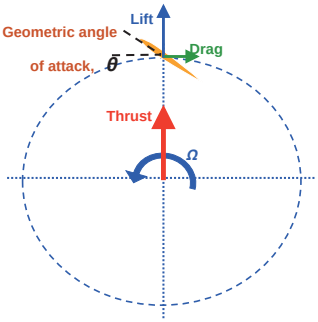
- High maneuverability: Instantaneous change of thrust vector
- All airfoils operate at maximum efficiency

Major Concerns:

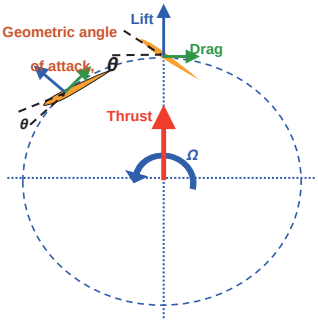
- Complex wake interaction
- Complexity of pitch change mechanism



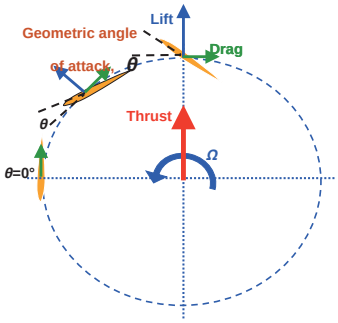
Blade Pitching



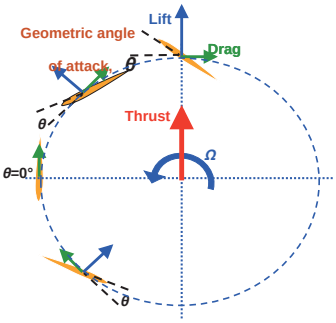
Blade Pitching



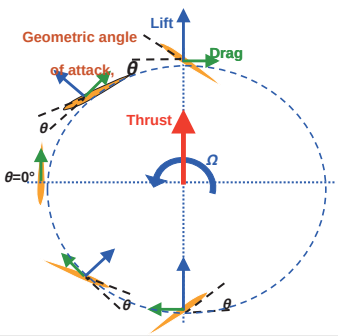
Blade Pitching



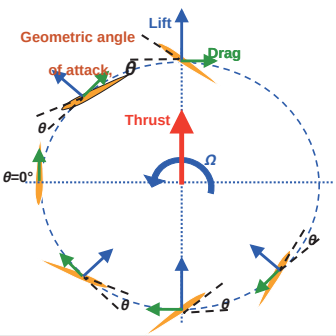
Blade Pitching



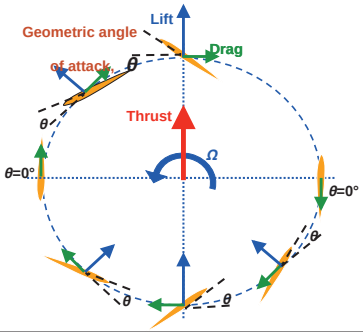
Blade Pitching



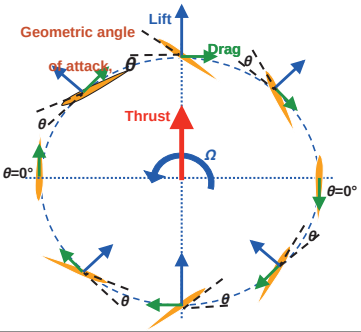
Blade Pitching



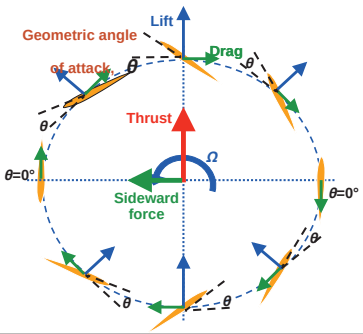
Blade Pitching



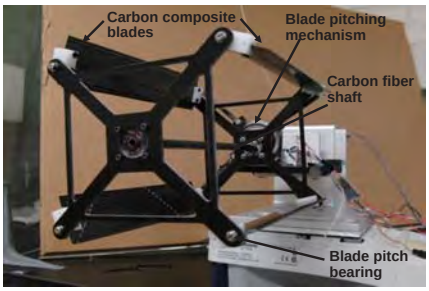
Blade Pitching



Blade Pitching



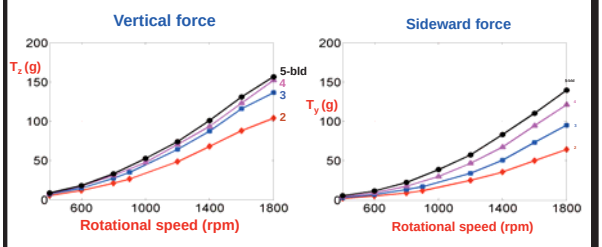
Cycloidal MAV Rotor



Rotor Size
Span = 6”
Diameter = 6”

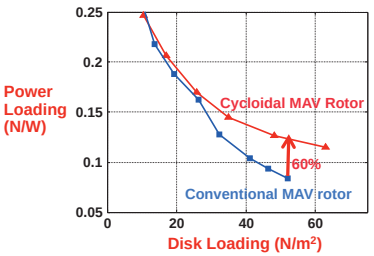
95 gram MAV rotor

Vertical and Sideward Forces



- T_z and T_y vary as square of rotational speed
- Sideward force comparable to vertical force

Comparison with Conventional Rotor

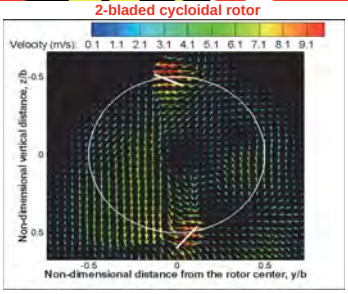


Parameters Varied

- Rotational speed
- Blade airfoil profile
- Blade flexibility
- Blade pitching kinematics
- Pitching axis location
- Number of blades

Flow Inside Cycloidal Rotor

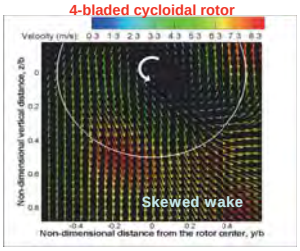
2-bladed cycloidal rotor



- Studies performed at wake ages = 0°, 30°, 120°and 150°
- Key flow features:
  - Large region of rotation flow
  - Non-uniform inflow
  - Interference effects
- Sources of aerodynamic losses

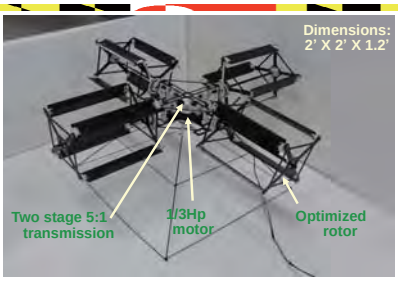
Sideward force

4-bladed cycloidal rotor



- Skewed wake structure – consistent with sideward force

Quad-Cyclocopter

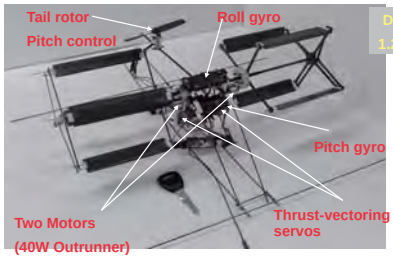


Weight = 750 grams
Operating RPM = 1800

Rotor diameter = 6"
Span = 6.25" Chord = 1.3"

Quad-Cyclocopter: Tethered Hover

Twin-Cyclocopter



Weight = 215 grams
Operating RPM = 2100

Rotor diameter = 5"
Span = 4" Chord = 0.95"

Free Hover

Conclusions

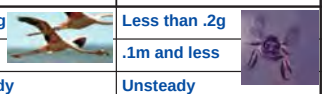
- Power loading better than a conventional rotor
- Optimum cycloidal rotor based on parametric studies
  - 4-bladed, pitch amplitude = 40°, blade chord = 1.3”
- PIV measurements showed presence of a skewed wake – explaining side-force
- Absence of blade stall at high pitching amplitudes (45^0) – high induced velocities in wake

Micro Hovering Air Vehicles: Flapping-Wing Based

Mechanism of Flapping-Wing Flight
Insects vs Birds

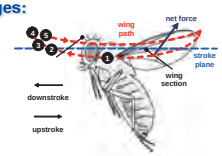
Birds vs Insects

Function	Bird	Insect
Weight	20g to 15 kg	Less than .2g
Size	0.15 to 3m	.1m and less
Aerodynamics	Quasi-steady Drag-reduction	Unsteady Lift enhancement
Morphing	Active wing morphing	Rigid wing, base motion
Wing frequency	Modest <10 Hz	High >50Hz
Hovering	Very rare	Quite common
Speed	High, wing morphing	Modest, tilting body and stroke plane
Reynolds No.	>10,000	<10,000



Insect Flight Fundamentals

- The wing stroke of a hovering insect is divided into four kinematic stages:



1. Upstroke
2. Downstroke

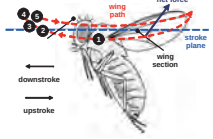
→ *TRANSLATIONAL phase* – when the wings sweep through the air with a high pitch angle

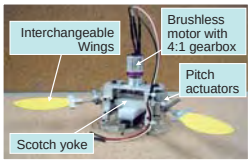
3. Pronation
4. Supination

→ *ROTATIONAL phase* – when the wings rapidly rotate and reverse direction

Flapping-Wing MAV

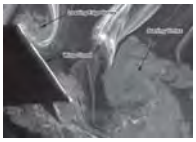
Background: Insect-Based MAV





- Examined insect-based flapping bio-mimetics.
- Hover-capable insect-based flapping causes delayed dynamic stall, rotational circulation and wake capture.
- A folded wake with the presence of multiple vortices on top and bottom surfaces.

- Key Parameters are: wing frequency, flap amplitude, pitch angle, aeroelastic couplings (flexibility)



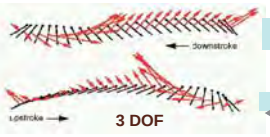
Objective of Flapping-wing MAV

- Develop simplified flapping wing flight worthy system that can emulate insect kinematics
  - Simple and lightweight
- Exploit wing kinematics for control

CHALLENGE

- Heaviest hovering bird = 20 grams
- Flapping MAV with payload = 20 grams
  Gross Weight ~ 50 – 100 grams

Flapping Mechanism



Translation Rotation

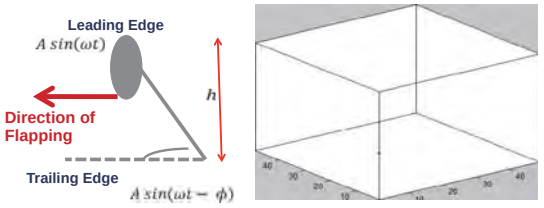
Stroke plane deviation

Translation Rotation

Insect Kinematics

Simplified Kinematics

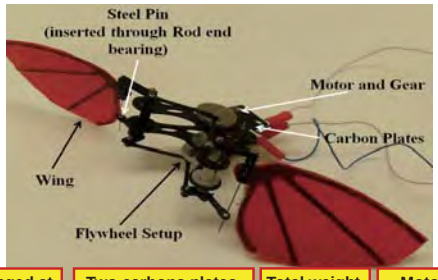
Flapping Mechanism Principle



$$\theta = tan^{-1}\left(\frac{A\,sin(\omega t) - A\,sin(\omega t - \phi)}{h}\right)$$

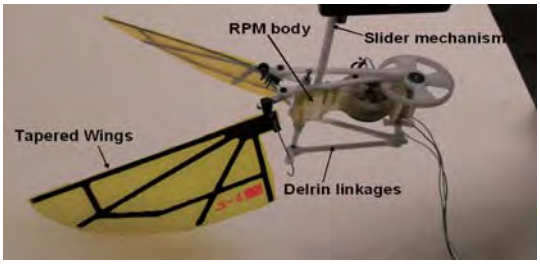
Flapping Mechanism

Second Generation Flapping MAV



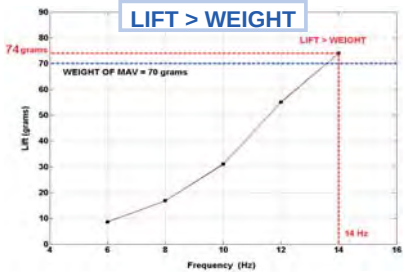
Wings hinged at different locations	Two carbons plates for increased stiffness	Total weight 130 grams	Motor power 140 W

Third Generation Flapping MAV



Weight : 70 grams

Third Generation Flapping MAV

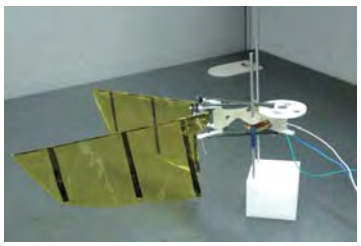


Excessive vibration of slider mechanism

Need lift = weight at lower frequency

Lighter wings

Fourth Generation Flapping MAV



Weight : 56 grams

Wing Design

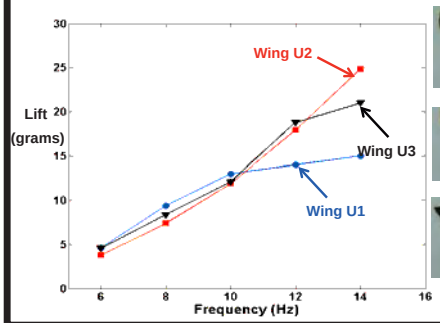
Wing U1
Weight : 1.44g
Span : 5.5 in

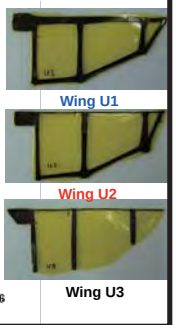
Wing U3
Weight : 1.23g
Span : 5.5 in

Wing U2
Weight : 1.44g
Span : 5.5 in

Wing U3-L
Weight : 1.67g
Span : 7.5 in

Wing Testing





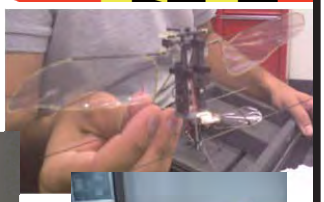
Flapping-Wing

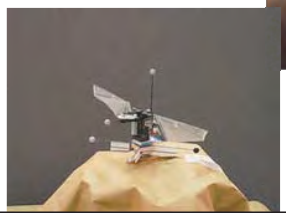
Summary and Conclusions

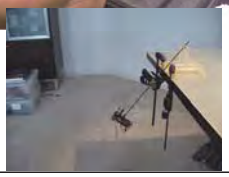
- Demonstrated tethered hover capability of a 60 gram flapping MAV using insect kinematics
- Active pitching improved MAV performance
- Figure of merit 0.1 – 0.2
- Wing design
  - Light – reduce power and inertial loads
  - Maintain bending stiffness and reduce torsional stiffness

Micro Flapper

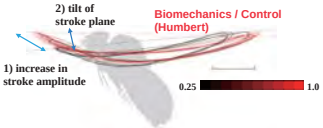
Developed 10-g flapper and demonstrated yaw control in VICON and carried out detailed DPIV studies



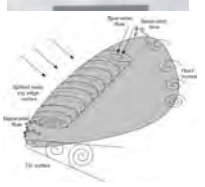


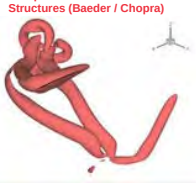


Physics and Actuation of Flapping Flight



Biomechanics / Control (Humbert)





Computational Fluids / Structures (Baeder / Chopra)

Particle Image Velocimetry (Leishman)

Conclusions

MAV is a multidisciplinary system and requires synthesis of:
- Aeromechanics (low Re)
- Micropropulsion
- Microelectronics
- Microprocessing
- Microfabrication

Many Challenges:
- Modeling and simulation
- Adaptive feedback controllers
- Communication and guidance
- Building and flight testing

Flight Inspired by Nature at Low Re

Propulsion and Power
- efficient batteries
- micro engines
- energy Storage/ distribution

Sensing and Navigation
- miniature electronics
- Insect based guidance

Low Reynolds Number
- delayed Stall
- flow separation control
- wake capture

Lightweight Wing Structures
- active shape deformation
- wing morphing

Biomimetic Kinematics
- actuation (thorax)
- efficiency
- frictionless

Maneuvering Capability
- distributed control surfaces
- gust prone

Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

Review of Rotorcraft Aeromechanics and Advanced Designs

Inderjit Chopra

Director Alfred Gessow Rotorcraft Center &
Alfred Gessow Professor of Aerospace Engineering

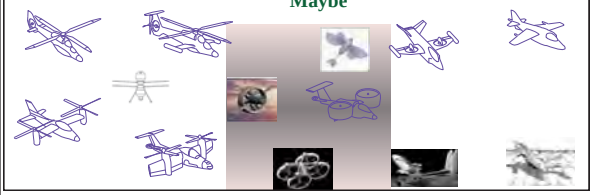
Presentation At: Korea Aerospace Research Institute (KARI), Daejeon
June 27-30, 2011

Definition of Rotorcraft

An air vehicle whose primary means of vertical lift is a rotating airfoil

Is This Air Vehicle a Rotorcraft?

Yes | Maybe | No



Rotorcraft Aeromechanics Research

Today's Technology Drivers

- All round desire to increase performance & efficiency
  SFC, Figure of merit, power loading, L/D etc
- Explosion of IT & wireless technology
- Maturation of composite technology & upcoming smart structures technology
- Availability of sophisticated prediction tools
- Availability of miniaturized sensors & reliable measurement techniques

Rotorcraft Aeromechanics Research

Today's Non-Technology Drivers

- All-round desire to reduce Cost! & Cost!!
  (Acquisition, maintenance and Operating: life cycle)
- More Safety & ease of flying
- Green legislations!!! Noise! & CO_2 level
- More autonomy requirements
- Runway saturation & terminal area gridlock
- Asymmetric & urban warfare

Index of Efficiency

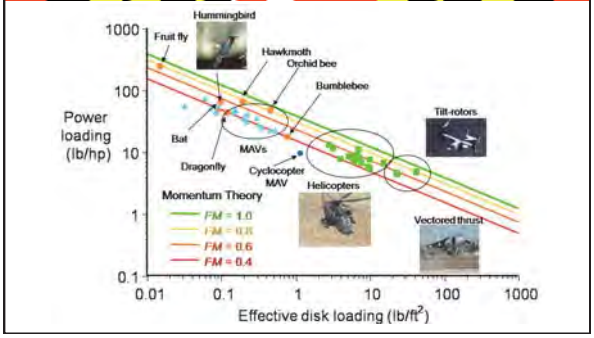
Figure of Merit

$$FM = \frac{\text{Ideal Power required to hover}}{\text{Actual Power required to hover}}$$

Power Loading

$$PL = \frac{\text{Thrust Produced}}{\text{Actual Power required}}$$

Power Loading (Thrust/Power)



State-of-Art of Helicopter Technology

Speed	~150 Knots	Airplane of 1920's
Range	<500 nm	low
Payload	<40,000 lbs	low
Ceiling	<15,000 ft	low
Figure of merit	<0.8	Up from o.6 in 1940
Lift-to-drag ratio	5-6	Up from 4-5 in 30 years
Productivity	Low c.f. of airplane	Small increase in 30 years
Vibration levels	High "	Uncomfortable
Noise levels	High "	Obtrusive

Despite all of the understanding of aeromechanics, why has the helicopter apparently reached a peak in its capabilities?
By our estimate, it HASN'T!!
But, we need to get better at implementing solutions to the problems!

Assessment of Expertise

Integrated methods of analysis & design

Better instrumentation & measurements

Better computational tools CFD, CFD/CSD

- ***Our assessment:***
  - ***We had reached a plateau and a "dip"***
  - ***This plateau is a transition phase toward something better***
  - ***There is "perception" helicopters do what they do and no more***

Postdictive Versus Predictive Capabilities

- ***POSTDICTIVE modeling capability:***
  - ***Significant simplification of physics***
  - ***Too many empirical "constants"***
  - ***Usually operate on the "top" level***
  - ***Calibrated to specific or "favorite" data sets)***
  - ***Cannot "predict" outside bounds of validation***
- ***PREDICTIVE modeling capability:***
  - ***Requires in-depth understanding***
  - ***Need very detailed experiments for proper validation***
  - ***Built from upward from governing equations (first principle)***
  - ***Appropriate predictive capability (especially for new configurations)***
  - ***More expensive but needed for getting over the dip***

Why Does the "Dip" Happen?

- ***We reach our "comfort zone"***
- ***Rooted in "postdictive" capabilities***
- ***As methods are brought to bear on new problems, limitations realized***
- ***Priorities change or low (or no) funding for apparently "well-studied" problems***
- ***"Cultural barriers"***
- ***We close our wind tunnels!***
- ***Helicopter has "reached its peak"!***
- ***Expertise also slowly lost in time:***
  - ***People move on, retire, etc.***
  - ***We forget the fundamentals!***
  - ***Fewer people with "sense of physics"***
  - ***Experience not passed on effectively***
  - ***Information hard to find (rediscovery!)***
  - ***Work not written down in archival literature***

Continuation of "Dip"?

- ***R&D Funds***
  - ***Erratic flow of funds***
  - ***Following of milestones (creativity secondary)***
  - ***Too much bureaucracy***
- ***Future Rotorcraft***
  - ***Overindulgence in upgrades***
  - ***Pursuing infeasible projects***
  - ***Industry: too short sighted***
- ***Government Laboratories (Buyers)***
  - ***Becoming weak in talent and facilities***

Rotorcraft Aeromechanics

Coverage

Aeromechanics involves coupled, multi-, inter-disciplinary

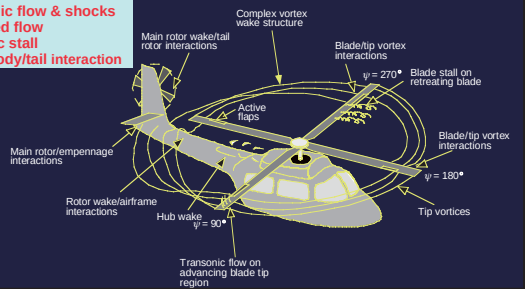
- Dynamics (Aeroelasticity)
- Aerodynamics & Performance
- CFD
- Acoustics
- Flight Dynamics & Controls
- Composite Structures
- Transmission & Power-Trains
- Smart & Adaptive Structures

Aerodynamics

Aerodynamics: Challenges

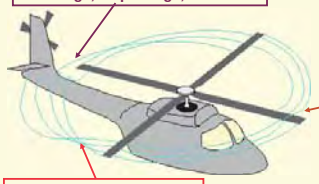
- Nonsteady and complex aerodynamics and rotor wakes

Transonic flow & shocks
Reversed flow
Dynamic stall
Rotor/body/tail interaction



Rotor Wakes

Main rotor wake interactions with fuselage, empennage, tail-rotor

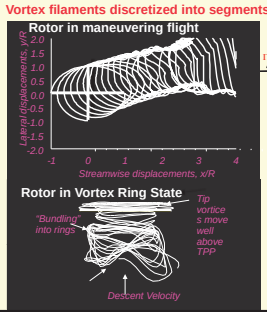


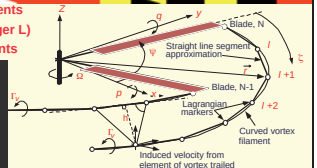
Blade/Vortex Interactions: Rotor loads, Performance & Acoustics

Vortex/Vortex Interactions: Highly three-dimensional induced flow-field

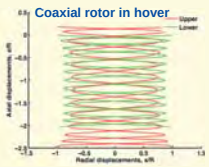
Free Vortex Wake Model

- Rotor wake modeled using vortex filaments
- Blade modeled by lifting lines (Weissinger L)
- Vortex filaments discretized into segments



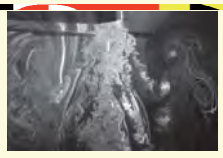


Coaxial rotor in hover



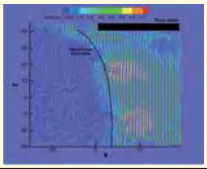
Rotor Wakes: Measurement

Wide-Field Shadowgraphy



Laser Doppler Velocimetry

Schlieren System



Particle Image Velocimetry

Future: DPS-DPIV (Dual-Plane Stereoscopic Digital Particle Image Velocimetry) can measure 3 velocity and 9 velocity gradients using 3 pair of lasers and 3 synchronized cameras.

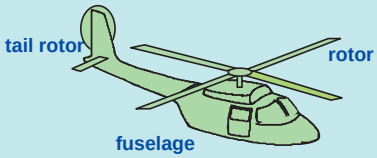
Aerodynamic Modeling: State-of-Art

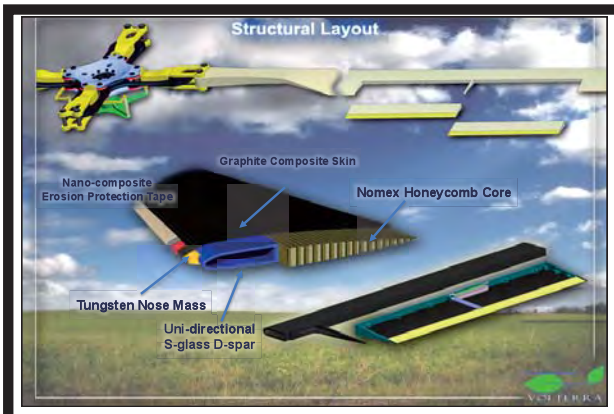
	Past	Present	Future
Blade Aero	Lifting line Table-lookup Empirical stall	Indicial response functions for unsteady and dynamic stall	CFD/CSD tight coupling
Rotor Wake	Linear inflow Prescribed	Free wake Frequency & time-domain	CFD-generated wake capture
Airframe	Flat plate area	Table lookup Panel method	CFD rotor/ body coupled
CFD Modeling	Euler Uncoupled	Navier-Stokes CFD/CSD loose coupling	CFD/CSD tight coupling

Structural Modeling

Structural Modeling: Challenges

- Coupled and nonlinear phenomena involving complex Coriolis/Gyroscopic forces
- Blade undergoing moderately large deformation involving coupled flap and lag bending, torsion and axial deformation
- Airframe 3-D structure with complex joints and nonuniformities





Composite Structures

Rotor and airframe are now increasingly being built out of composites

Key Issues:

- Modeling of composite blades and airframe (coupled, nonlinear, non-classical structural effects important)
- Structural integrity including ply delamination (flexbeam undergoing large dynamic twisting)
- Energy absorption due to landing and ballistic impact (off-axis landing, damaged blades)
- Repair of composites (field, depot and factory)

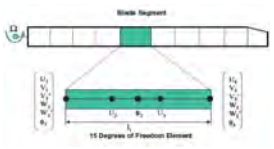
FEM vs Multibody

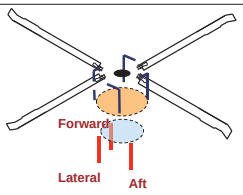
Classical FEM

- Typically uses single body coordinate frame
  - Deformations and loads in body coordinates
  - Topology dependent

Multibody

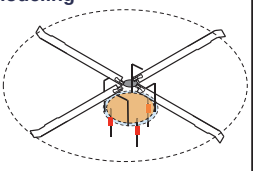
- Body and element coordinates
  - Deformation and loads in element coordinates
  - Increased scope of modeling





Multibody Analysis

- Increased scope of structural modeling
- Detailed modeling of control system and hub assembly
  - Exact pitch link, damper kinematics
  - Swashplate servo dynamics
- Large blade deformations
  - Moderate deformation within element frame
  - Large deformations accommodated by finite rotation of frames (important for maneuvering flight)



Structural Modeling: State-of-Art

	Past	Present	Future
Deflections	Moderate large Ordering scheme	Moderate/large	Large (no ordering)
Blade Modeling	FEM/modal	FEM/Multibody	Multibody
Airframe	Stick model	3-D FEM/modal	Multibody
Materials	Small strain Isotropic	Small strain Anisotropic	Large strain Coupled laminates

Rotorcraft Analysis

Rotorcraft Analysis: Challenges

- **Governing Equations:** Coupled and nonlinear equations with periodic coefficients
- **Solutions:** Trim and rotor response, aeroelastic stability, flight stability, transient response
- **Steady Level Flight Analysis:** Periodic response analysis
- **Non-Steady Maneuvering Analysis:** Time marching analysis

$$[A(\psi, y, \dot{y})]\{y\} = \{G(\psi, y, \dot{y})\}$$

Comprehensive rotorcraft codes: CAMRAD, RCAS, UMARC

Analyses: State-of-Art

	Past	Present	Future
Trim/Steady Response	Modal method/ Harmonic Balance	Modal/ CompleteFEM time	Time integration coupled equations
CFD/CSD Coupling	Iteratively	Loose	Tight
Stability	Linear Modal/ Floquet	Linear Modal/ Full Floquet	Time marching Prony method
Maneuver Analysis	Modal/Time integration	Modal/Time integration	Fully coupled time marching

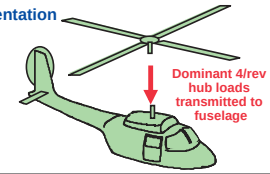
Dynamics

Dynamics

Interaction of structural, aerodynamics and inertial forces (aeroelasticity)

Issues:

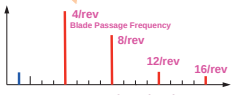
- **Vibration & Loads:** prediction, measurement & suppression (level flight, maneuvering flight and gusty environment)
- **Aeromechanical Stability:** augmentation (flap-lag flutter, pitch-flap flutter, ground/air resonance)



Helicopter Vibration: Definition

Vibration : Accelerations in fuselage

Spectral Analysis of unsteady accelerations

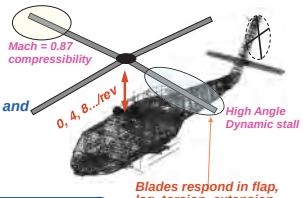


- *Intrusion Index: weighted mean of 4 largest frequencies in vertical, lateral and longitudinal directions up to 60 Hz*
- *Vibratory Forces: Rotor blades are excited at all harmonics, only harmonics consisting integer multiples of blade number, pN_b/rev are filtered through hub*
- *1/rev due to rotor asymmetry*

Rotor Dynamics in Forward Flight

Sources of Vibration

- *Asymmetric flow in forward flight*
- *Complex wake*
- *Compressibility on advancing side and dynamic stall on retreating side*
- *Flexible rotor blades*



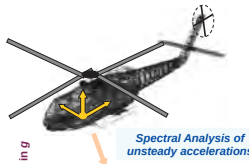
Blades respond in flap, lag, torsion, extension

1,2,3,4,5,.... /rev

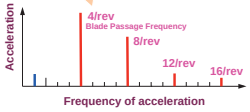
- *Blades undergo moderately large deformations involving coupled flap, Lag, torsion and axial motion, nonlinear inertial couplings*
- *Airframe 3-D structure with complex joints and cutouts, Gyroscopic nonlinear couplings in vehicle dynamics*

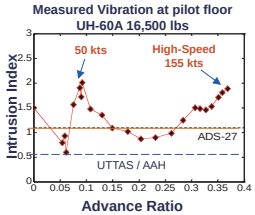
High Vibration: Flight Conditions

Vibration : Accelerations in fuselage



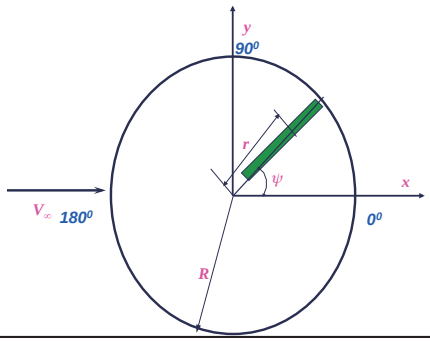
Spectral Analysis of unsteady accelerations





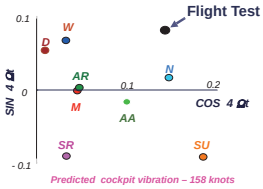
- **3 Critical regimes : low speed transition, high speed, and high altitude-high thrust**
- **Enormous vibration:**
  High operating cost
  Reduced crew / system performance

Rotor Definitions



Vibratory Loads at High Speed: Prediction vs. Flight Data in 1998

Predicted 4/rev vibratory hub load at high speed from 8 different rotor codes for LYNX



Predicted cockpit vibration – 158 knots

AA - 2GCHAS AR - Flightlab D - CRFM
M - UMARC (Maryland) N - CAMRAD1
SR - RDYNE SU - UMARC (Sikorsky)
W - R150

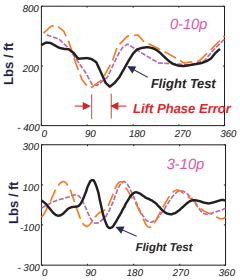
- None of predictions agreed with flight test data
- No two predictions agreed with each other
- LYNX Blades were not pressure instrumented, hence systematic correlation study with air loads and blade loads could not be possible

Vibratory Loads at High Speed: Prediction vs. Flight in 2000

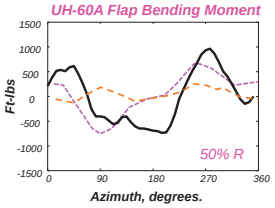
UH-60A Lift at 77.5% R

$\mu = 0.368$
$C_W/\sigma = 0.078$

2GCHAS/RCAS
CAMRAD/JA



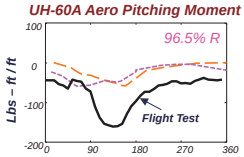
UH-60A Flap Bending Moment



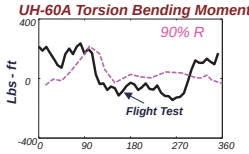
- Phase error in advancing blade lift, and flap bending moment

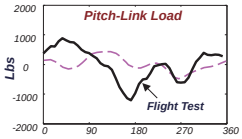
Vibratory Loads at High Speed: Prediction vs Flight in 2000

UH-60A Aero Pitching Moment



UH-60A Torsion Bending Moment





2GCHAS/RCAS
CAMRAD/JA

- Error in aero pitching moment, torsion bending and pitch link load

Vibration Validation Study

Major undertaking in 2001: Team involving industry, academia, NASA/ Army to resolve vibration barrier issues. Loads Workshop: Meet every 6 months since 2001

Vehicle: UH-60A Black Hawk, extensive flight test data with pressure instrumented blades

Identified 4 critical flight conditions:

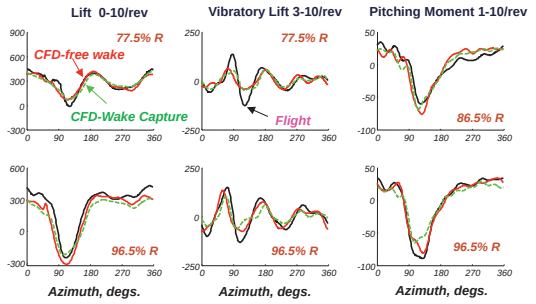
Level Flight:

1. High speed $\mu = 0.37$ UH-60A flight 8534
2. Low speed transition $\mu = 0.15$ UH-60A flight 8513
3. High altitude dynamic stall $\mu = 0.24$ UH-60A flight 9017

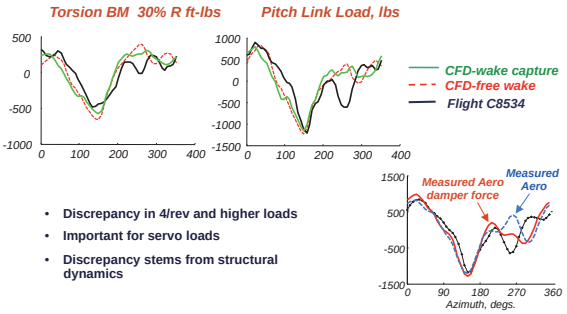
Maneuver:

4. Severe UTTAS pull-up Maneuver $\mu = 0.341$ UH-60A flight 11029 (load factor = 2.09)

High Speed: CFD/CSD coupled Solution: First barrier problem resolved

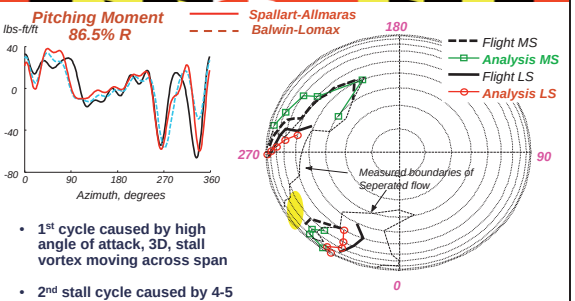


Pitch Link Load at high speed: CFD/CSD Second barrier problem resolved



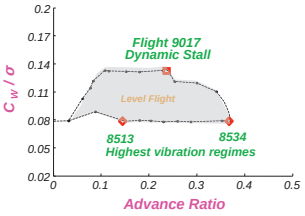
- Discrepancy in 4/rev and higher loads
- Important for servo loads
- Discrepancy stems from structural dynamics

Predicted Pitching Moment and Stall Map at High Altitude & High Thrust



- 1st cycle caused by high angle of attack, 3D, stall vortex moving across span
- 2nd stall cycle caused by 4-5 elastic twist, mostly 2D

3 Critical Flight Conditions: Level Flight



CFD challenges:

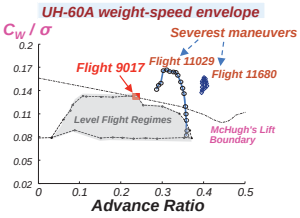
- Low Speed : Grid for wake capture
- High speed : 3D transonic effects on pitching moment
- High altitude: turbulence modeling for dynamic stall

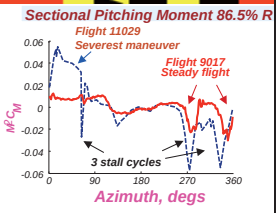
CSD challenges:

- Low Speed : 3/rev flap bending
- High speed : Elastic twist low frequency
- High altitude : Elastic twist high frequency

Separate mechanisms: wake, transonic effect, and dynamic stall

4th Critical Flight: Pull-Up Maneuvering Flight

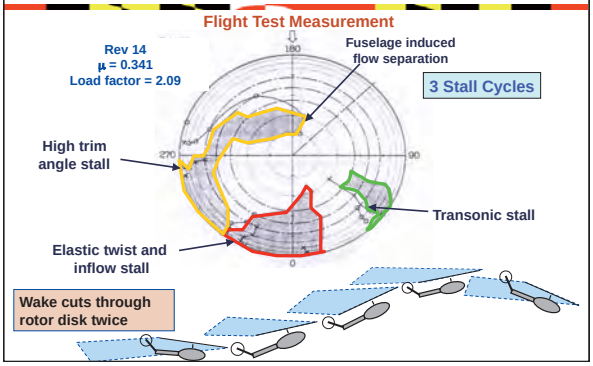




- Design loads set by severe maneuvers under stall
- C11029 : 2.12 g pull up at 139 kts, highest flap bending, and Pitch-Link (PL) load, severest maneuver

- C9017 stall similar to severest maneuver
- Compressibility, dynamic stall and wake all occur simultaneously in maneuvering flight

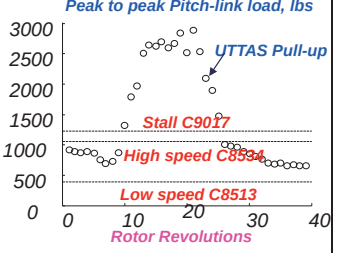
Flight 11029, Severest UH-60A Maneuver: Stall Map



UTTAS Pull-up Maneuver

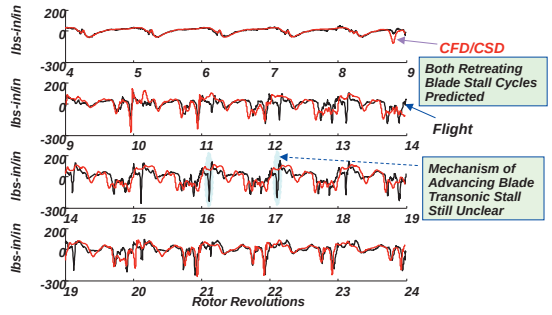
Flight 11029

- Based on Utility Tactical Transport Aerial System (UTTAS)
- Third highest pitch link load (2.5 times steady flight)
- Highest root flap bending moment

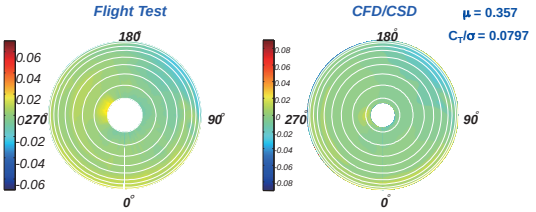


High Loads: Dynamic stall, vortex loading, transonic effects can occur simultaneously

Pitching Moment: 86.5%R

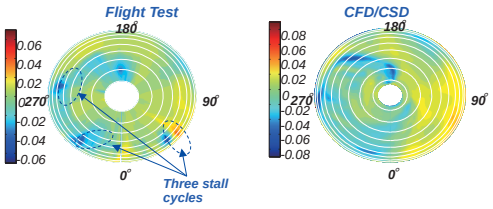


Pitching Moment: Level Flight Rev 1



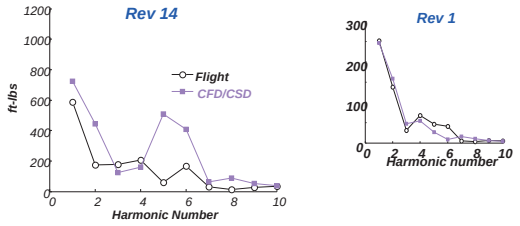
- Pitching moment variation during steady flight regime benign
  - shows no steady gradients across the rotor disk
- Prediction show good correlation with flight test

Pitching Moment: Maneuver Rev 14



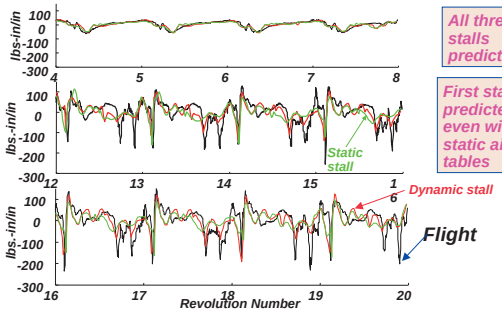
- *Pitching moment variation during maneuver shows steep gradients*
  - *Three stall cycles*
- *Prediction show good correlation for two stall cycles on retreating side -- advancing blade stall not predicted*

Torsion Moment Harmonics: 30%R

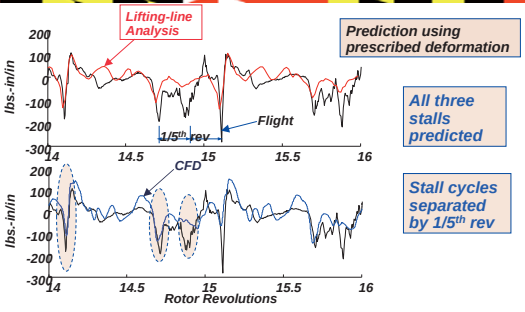


- Over-prediction of 40%–60% in the peak-to-peak magnitude
  - over-prediction of 5 and 6/rev torsional moment stemming from over-prediction of pitching moment stall peaks

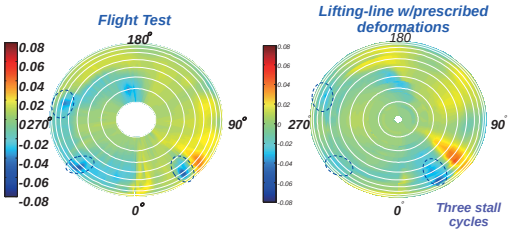
Pitching Moment Using Prescribed Deformation (From Measured Airloads): 86.5%R



Pitching Moment Using Prescribed Deformation: 86.5%R



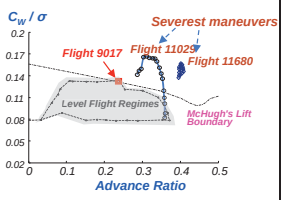
Pitching Moment C11029: Rev 18



Advancing blade stall predicted accurately

Prediction of Vibratory Loads

Critical Flight Conditions:
- High speed forward flight: vibration
- Low speed transition flight: vibration
- High altitude dynamic stall: loads
- Severe maneuvers: pitch link loads



Key Conclusions:
CFD provides fundamental capability
- *At high speed: 3D unsteady transonic pitching moment*
- *At low speed: capturing of inter-twinning of wakes*
- *For dynamic stall flight: capturing of second cycle due to 4 and 5P twist, placement depends upon wake and turbulence model*

Pull-Up Maneuver:
3 dynamic stall cycles, Advancing-side stall triggered by 5/rev twist, Two dynamic stall cycles on retreating side separated by 1/5th cycle excites 5/rev twist deformation

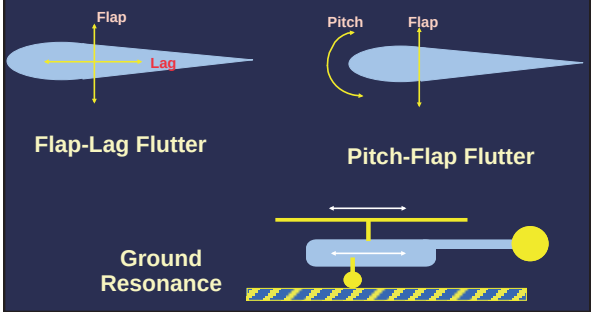
Vibration and Loads Suppression

Currently: passive devices such as absorbers and isolators routinely used, also avoid rotor harmonics coupling with airframe modes
- mostly ad-hoc approaches
- extensive weight penalty (up to 3% of gross weight)

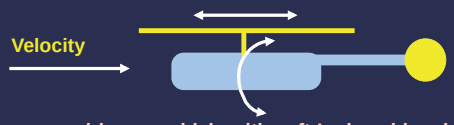
Future: towards active vibration control and structural optimization of rotor and airframe using robust prediction methodology

Goal: Reduction in vibratory loads by one-third from current values, weight penalty less than 1% of gross weight

Aeromechanical Stability



Air Resonance



- Occurs on airborne vehicle with soft-Inplane hingeless and bearingless rotors
- Caused by coupling of low frequency flap & lag modes and body airframe modes (aerodynamics very important)
- Soft Instability: To stabilize, needs mechanical damping in lag mode or negative pitch-lag coupling

Aeromechanical Stability

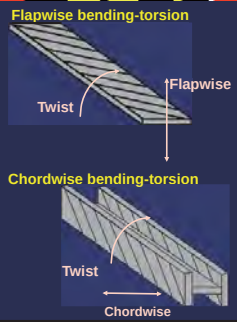
Prediction: For hover & foward flight with normal loading, current analyses predict satisfactorily for hingeless & bearingless rotors
- Needs robust aerodynamic modeling (dynamic stall) for highly loaded rotors (maneuvers)
- Needs refined structural model for complex hubs (bearingless rotors)

Measurement: Challenging to measure high damping modes

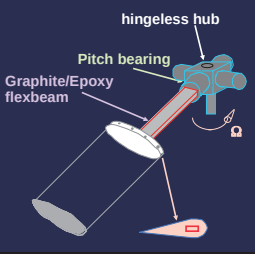
Stability Augmentation: Mechanical dampers routinely used
Possibility of using composite couplings to increase stability

Goal: Build a damperless rotor

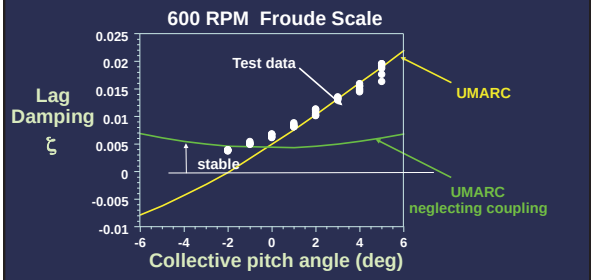
Stability Augmentation:Tailored Composite Rotor



Stability Testing



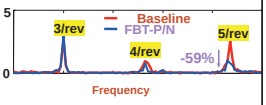
Stability Results for Negative Pitch-lag Coupled Composite Rotor



-ve pitch-lag coupling with symmetric ply lay-up stabilizing at +ve collective pitch

Composite Rotor Technology

Pretwisted Mach Scale Composite Tailored Blade



Black-Hawk Composite Tailored Rotor:
Vibration Reduction 30%, Power Reduction 8%
May Save Vibration Absorbers Penalty: 240 lbs

Mach Scale Composite Tailored Rotor in Wind Tunnel

Dynamics: State-of-Art

	Past	Present	Future
Vibration Prediction (normal flight) Prediction (Maneuvering) Suppression	>50% error Not reliable Passive Penalty 3% GW	~ 20% error Inadequate tools Passive/active (few) 1-3% penalty	<10% desirable ~10% desirable Active/passive/Optimized <1% penalty
Composites Couplings	Tools development	Showed potential to improve vibration and stability, but no implementation	Composite tailoring Full-scale implementation for performance and stability
Aeromechanical Stability Prediction (Normal flight) Prediction (Maneuvering) Suppression	Adequate for conventional rotors Inadequate Hydraulic/Elastomeric	Adequate for advanced rotors Tools development Elastomeric	Exploit couplings Reliable tools needed Damperless

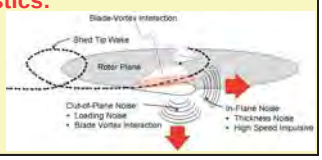
Acoustics

External/Internal Acoustics

Rotorcraft suffer from too much noise

External Aeroacoustics:
- Blade Vortex Interaction (BVI) low speed noise
- High speed impulsive (HSI) noise (transonic waves)
- Low frequency noise (thickness and loading)

Internal Airframe Acoustics:
Rotors, transmission and gear boxes



Rotor Aeroacoustics

Predictive capability
CFD/CSD coupled analysis to predict noise source (unsteady pressure) and apply in acoustic propagation scheme (Fflowcs-Williams-Hawkin) Prediction less than satisfactory.

Noise Control

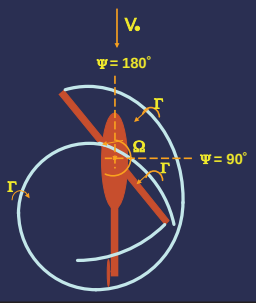
Passive Blade Design: Tip shape, aspect ratio, number of blades and tip speed using CFD tools, uneven blade spacing in fenestron (tail rotor).

Flight Path Management: Optic-based tip-path-plane tracking system to direct flight trajectory for minimum noise.

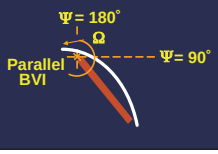
Active noise control: Using trailing-edge and leading-edge slats, actively control phasing and miss distance of vortices, and low frequency detection noise.

Goal: 5-10 db reduction of noise

Blade-Vortex Interaction Noise



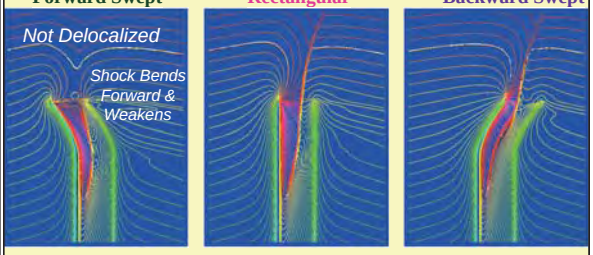
When a trailing tip vortex intersects another blade, dramatic aerodynamic changes occur which generate noise



Results - Sweep Effect

Hover Tip Mach No. = 0.90; In-Plane Mach Contours

Forward Swept | Rectangular | Backward Swept

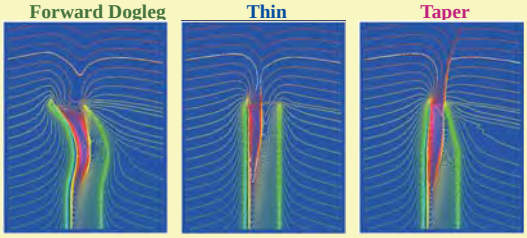


Large noise reduction for *forward* swept rotor
Strong phasing effects with sweep

Results - Individual Parameter

Hover Tip Mach No. = **0.90**; In-Plane Mach Contours

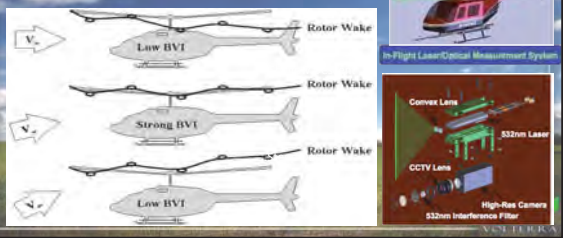
Forward Dogleg | Thin | Taper



Greater noise reduction for *thin and swept* rotors
Shock bends *forward* for swept blade

Flight Path Management for Noise Control

Technology Goal:
Control External Noise by Control of Main Rotor Tip-Path-Plane (TPP) Angle using high-resolution camera. Successfully flight tested on Bell 206 & 407.



Rotorcraft Internal Acoustics

Motivation: Undesirable interior noise levels
Main/tail rotors & gas turbines (40-500 Hz), gears (500-6000Hz)

Passive means for noise reduction: Constrained layer damping and piezo shunting for high frequency suppression

Active noise control: Using piezo patches on fuselage frame and trim panels and with adaptive control strategies for low frequency suppression, active transmission mounts and constrained layer damping for high frequencey noise

Goal: 20 db reduction of noise

Acoustics: State-of-Art

	Past	Present	Future
Exterior Noise Prediction	Lifting-line & Fflowcs-Williams-Hawkins (FWH) Not satisfacotry	CFD & FWH loose coupling Not satisfacotry	CFD/CSD & FWH tight coupling Validations
Exterior Noise Suppression	Passive	Passive	Passive/Active/ Flight path management
Interior Noise Suppression	Passive	Passive	Pasive/Active

Flight Mechanics and Controls

Key Issues:

- System identification for coupled rotor-fuselage system for a wide frequency band
- Flight control systems for mission tailored handling qualities
- High quality simulations, real and non-real time

Barriers:

- Free wake modeling for manuevering flight
- Robust system ID tools
- Modeling of multidisciplinary phenomena

Advanced Rotor Systems

Swashplateless Rotor

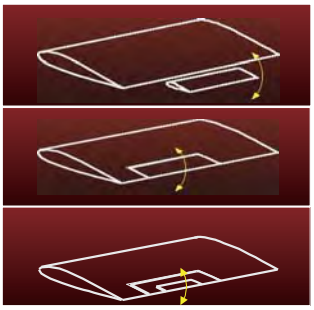
Conventional Helicopter Primary Flight Control

- Conventional helicopter flight control system via swashplate mechanism
  - Main rotor collective system (controls thrust)
  - Main rotor cyclic system (controls direction of thrust)
- Swashplate system involves pitch links, pushrods, and fixed frame hydraulic actuators
  - Weight & drag penalty
  - Mechanical complexity

Swashplate System

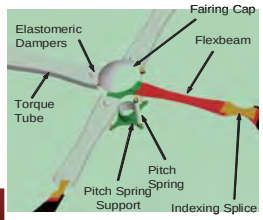
Flap Configurations

- Servo Flap
  - Large pitch moments
  - Exposed linkages, large drag
  - Hinge gaps reduce effectiveness
- Integrated flap
  - Modify lift & pitching moment
  - Internally mounted actuator and linkages (smart actuation)
- Tab-actuated flap
  - Tab moves flap
  - Modify lift & pitching moment
  - Least actuation power



Swashplateless Rotor System

- Swashplateless flight control via smart trailing-edge flaps
  - Flap deflections: collective and cyclic: in turn induce collective and cyclic blade pitch motion
  - Requires torsionally soft blade with blade pitch indexing
  - Potential of low drag and lightweight primary control
  - Hydraulicless system



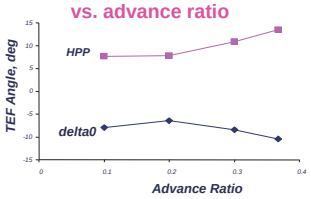
Swashplateless System

Primary Flight Control Requirements

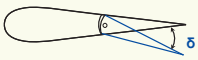
- Black Hawk
- $C_W/\sigma = 0.0783$ (16500 lb)
- $\nu_\theta = 2.0$ /rev
- $\theta_{idx} = 15^\circ$

Primary control requires greater flap angles and hinge moments

Flap Control Angles vs. advance ratio



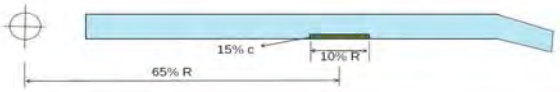
Trailing Edge Flaps Rotor



Trailing Edge Flaps

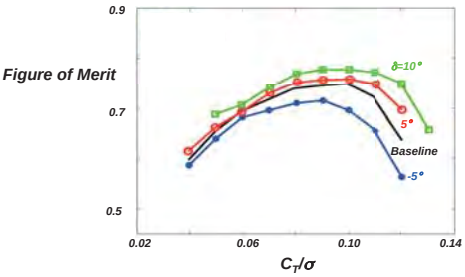
- Primary Control
  - Flap size 30%R
  - Flap amplitude 10^0
  - Flap frequency 1/rev
  - Torsion frequency <2/rev
- Vibration Control
  - Flap size 10%R
  - Flap amplitude 5^0
  - Flap frequency 3-5/rev
  - Torsion freq.~5/rev
- Performance
  - Flap size 10-15%R
  - Flap amplitude 5^0
  - Flap frequency 2/rev
  - Leading-edge slat more important for stall

- TEF geometry
  - 10% span, 15% chord, midspan at 65%R
- TEF operation
  - Primarily moment flap
  - Alters section pitching moment and induces blade twist
  - Effect of reducing blade torsional stiffness on TE flap effectiveness



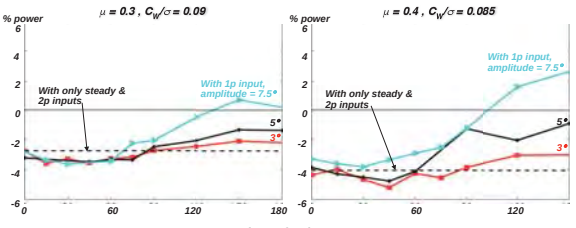
Hover Performance

Effect of steady TEF deflections



TEF geometry : 10%R, 15%c, mid-span at 65%R

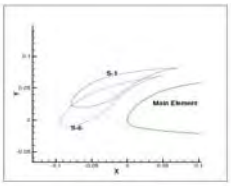
Rotor Performance with Trailing-Edge Flaps



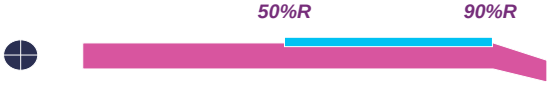
Over 5% power reduction possible:

- *Using a combination of steady, 1/rev and 2/rev flap inputs*
- *Flap geometry : 10% span, 15% chord, midspan at 65% blade span*

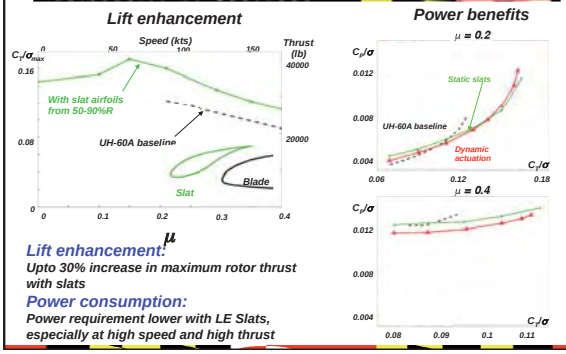
Leading Edge Slat Geometry



- S1 – Baseline position
- S6 – High Lift position
- Slat is ~15% of baseline chord



Rotor Performance with Leading-Edge Slats



Lift enhancement:
Upto 30% increase in maximum rotor thrust with slats

Power consumption:
Power requirement lower with LE Slats, especially at high speed and high thrust

Trailing Edge Flaps Rotor

Past: Kaman SH-2 servo-flap rotor operational since 60s, servo-flaps for primary controls (collective & cyclic)

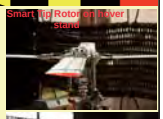
Present: Feasibility studies of integrated flaps to minimize vibration and noise using IBC (individual blade control)
Flight test: Eurocopter-Germany: BK117
Full-scale tunnel tests: Boeing-Mesa: MD900

Future: Development of full-scale integrated smart flap rotors for primary control (Eurocopter, Sikorsky, Boeing)

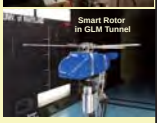
Smart Rotor

Smart Rotor

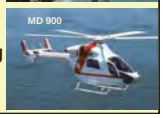
Application of smart structures technology to actively control vibration, noise, stability and performance
Concepts: Flaps, blade twist, active tips



Present: Feasibility studies: Smart flaps
UM: successfully tested Mach-scaled models
Boeing: full-scale tests in 40x80 tunnel(April 08)
Eurocopter: successfully flight tested Sept 2006



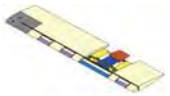
Future: Full-scale smart rotor for primary and noise control and performance enhancement: Sikorsky, Eurocopter & Boeing



Challenges: actuators stroke, integrity

Smart Structures Activities at Maryland

6-ft dia Froude scale rotor model in Glenn Martin Wind tunnel: active twist with embedded piezoelectric elements



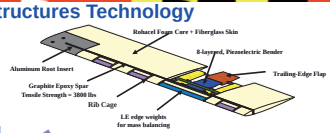
6-ft dia Mach scale rotor model in Glenn Martin Wind tunnel: trailing edge flaps actuated with multi-layered piezobimorphs

6-ft dia Mach scale rotor model on hover tower: tip actuated with embedded piezos in conjunctions with bending-torsion composite couplings

Example: Technology Transfer

Smart Structures Technology

Smart Actuator Development:
Piezostacks with L-L Amplification



Boeing: Full-Scale Smart Rotor Development:
MD-900 Rotor with Smart Flaps, Ready for Flight Testing for Active Vibration Control (expects >80%)

Smart Structures: Enormous Potential to Minimize Vibration & Noise and improve performance

Smart Rotor Development:
Mach-Scale with Piezo Acutated Flap

Smart Rotor Test in Glenn Martin Tunnel
Mach-Scale with Smart Flaps

Eurocopter: Trailing Edge Flaps

- *BK 117 rotor blade with piezoactuated trailing edge flaps*
- *Successfully flight tested September 2006*

Flaps sized for vibration control

Must be scaled up for primary flight control

Boeing: Trailing Edge Flaps

MD900 rotor blade with piezoactuated trailing edge flaps

Successfully hover tested in May 2004

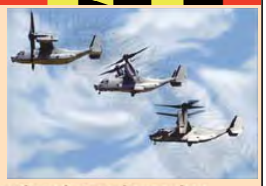
Successfully tested in 40x80 wind tunnel in April 2008

Flaps sized for vibration control

Must be scaled up for primary flight control

Tiltrotor Aircraft

Tiltrotor Dynamics Issues



- Aeroelastic instabilities
  - Rotor instabilities
  - Fixed-wing instabilities
  - Tiltrotor whirl flutter
- Loads & Vibration
  - Rotor-wing-body-tail interactional aerodynamics
  - Fountain effect
  - Gust loading
  - Tail buffeting
  - Conversion flight mode

Tiltrotor Aircraft

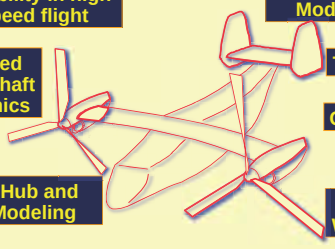
Past: Bell XV-15 flight tested successfully Whirl flutter stability and tail buffeting were major issues; Bell-Boeing V-22 fully operational and large descent speed a major concern (flight stability).

Present: Bell-Agusta 609 Civil tiltrotor under development, dynamics problems and performance.

Future: High speed heavy-lift tiltrotor with variable speed morphing rotor; and Quad-rotor

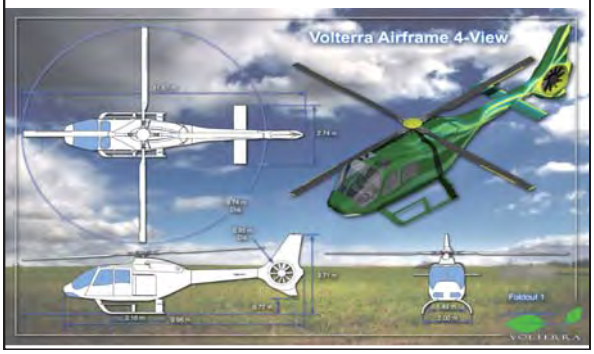
Challenges: Complexity and cost, variable speed engine, high speed dynamic instability

Challenges



- Whirl Flutter instability in high speed flight
- Interactional Aerodynamics Modeling
- Detailed Drive-shaft Dynamics
- Tail Buffeting
- Gust Response
- Detailed Hub and Gimbal Modeling
- Multi-rotor Wake Geometry

UM Winning Designs (2008): Green Helicopter



Volterra: Rotor Hub Assembly

Volterra Performance Summary

	Volterra	EC-120B	Bell 206B3
Standard Accommodation	1 + 4	2 + 3	1 + 4
Design Gross Weight	1750 kg (3858 lb)	1715 kg (3780 lb)	1451 kg (3198 lb)
Useful load	500 kg (1102 lb)	404 kg (891 lb)	393 kg (866 lb)
Fuel Capacity	150 kg (43.5 gal)	321 kg (107 gal)	281 kg (91 gal)
Speed for best range	198 km/hr (107 knots)	204 km/hr (110 knots)	213 km/hr (115 knots)
Speed for best endurance	124 km/hr (67 knots)	120 km/hr (65 knots)	96 km/hr (52 knots)
Fast cruise speed	222 km/hr (120 knots)	222 km/hr (120 knots)	223 km/hr (121 knots)
HOGE Ceiling (ISA+20 deg C)	2238 m (7343 ft)	518 m (1700 ft)	914 m (2998 ft)
Maximum range	708 km (382 n.m.)	710 km (383 n.m.)	693 km (374 n.m.)
Maximum endurance	3 hr 34 min	4 hr 19 min	4 hr 30 min
Specific fuel consumption (SFC)	0.206 kg/kw-hr	0.26 kg/kw-hr	0.33 kg/kw-hr
Acquisition price	$0.9 million	$1.45 million	$1.3 million
Direct operating costs (DOC)	$ 104 / FH	$ 231 / FH	$ 235 / FH

Powerplant - OPOC Engine

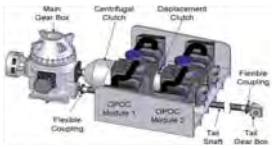
Opposed-Piston/Opposed-Cylinder

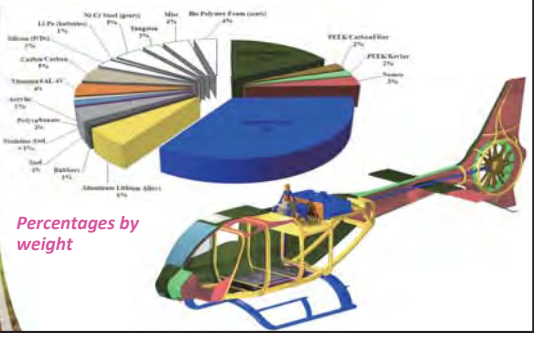
Powerplant - OPOC Engine

Engine	Type	Specific Power (kW/kg)	SFC (lb/hp-hr)	SFC (kg/kW-hr)
Teledyne Brown Engine	Piston	1.2	0.550	0.335
Rolls-Royce 250-C30P	Turbine	2.5	0.592	0.36
Turbomeca TM-333	Turbine	2.8	0.513	0.312
OPOC Engine	Piston	1.96	0.339	0.206

In summary the OPOC is:

- *Cost effective*
- *Highly efficient*
- *Cleaner burning*
- *Multi-module versatile*
- *Multi-fuel versatile*

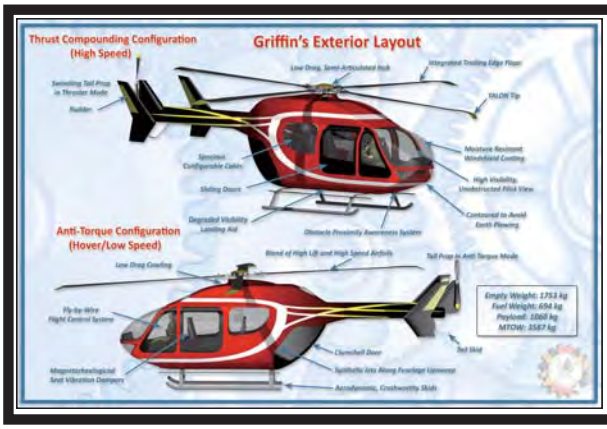




Percentages by weight

AHS Design 2009 - The *Griffin*

- 2009 AHS Student Design Competition: Design of a non-conventional rotor/drive system with improved speed, range, payload and noise signature over a baseline in-service design
- University of Maryland designed the Griffin and its VERITAS: Variable Energy Rotor and Innovative Transmission ArchitectureS, improving on the EC-145

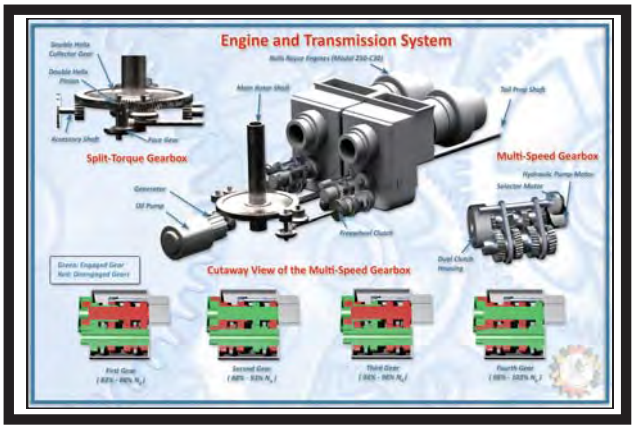


Core Features

- **Main Rotor**
  - ✓ Innovative TALON blade tip: incorporates sweep, taper, anhedral and leading edge notch: reduced compressibility and blade stall penalties and increased figure of merit
  - ✓ Integrated trailing edge flaps: near 100% vibration suppression. Driven by lightweight electric DC motors rather than expensive smart actuators
- **Swiveling Tail-Prop**
  - ✓ Dual-functional tail prop: anti-torque in hover and propulsion in forward flight
  - ✓ Conversion from anti-torque to thrust compounding mode performed automatically
  - ✓ Vertical stabilizers: sufficient anti-torque in the propeller configuration

VERITAS - Engine and Drivetrain

- ✓ Baseline Turbomeca Arriel 1E2 engines replaced with Rolls Royce 250-C30 engines: Lower specific fuel consumption (SFC), greener than the baseline
- ✓ Multi-speed main rotor gearbox: continuous and efficient rotor speed modulation over a 20% range of rotational speed
- ✓ Innovative dual-clutch mechanism: smooth and uninterrupted power delivery at all flight and rotor speeds
- ✓ Superior corrosion resistance and significant weight reduction
- ✓ Drivetrain Safety Features: automatic start-up, engine relight, surge detection and recovery
- ✓ Extensive Health and Usage Monitoring System (HUMS)



Conclusions

- ✓ 77% increase in payload delivery efficiency
- ✓ 22% increase in productivity
- ✓ Total cost of ownership over an assumed 20 year service life: $18.6 million for *Griffin* - nearly a 5% savings over EC-145
- ✓ *Griffin*'s performance meets, and in some cases exceeds, the requirements of the DARPA Mission Adaptive Rotor (MAR) Program

Aerodynamics and Dynamics of High Speed Coaxial Rotor Systems

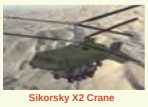
Objective: Develop comprehensive aeromechanics analysis of coaxial rotor system.

Advantages: Compact size (lower foot print), no tail rotor, lower aerodynamic asymmetry in forward flight

Disadvantages: Aerodynamic interference between rotors, complex hub and swashplate (more drag), poor yaw control

Challenges: Limited aeromechanics analysis, aerodynamic interference, trim complexity, variable speed impact (power train, performance and rotor separation)

Futue: Sikorksky has built X2 high speed coaxial rotor with proprotor to achieve 250 knots, Sikorsky is also building X2 crane as a heavy lifter. Coaxial UAVs possible.


Sikorsky X2 Crane

Sikorsky X2 High Speed

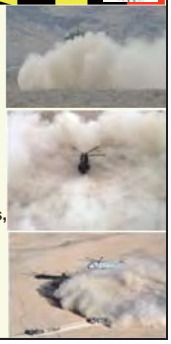
UM Micro Air Vehicle

Rotorcraft Brownout

Brownout: Loose dust, sand, snow, etc. blown up by rotor flow in ground effect (IGE) Cloud of visually restrictive material causes pilot to lose outside visual references and situational awareness. Significant number of accidents caused by brownout.

Objective: Develop comprehensive understanding and mitigation of "brownout" of rotorcraft

Challenges: Interdisciplinary phenomenon involving rotor wake near ground effect and sediment (dust) particle dynamics (particles mass, size and shape, and uplift process)
- highly unsteady 3-D "jet-like" flow
- Embedded vortices near the ground
- 2-Phase fluids with fluid particle and particle/particle collisions



Airforce-MURI: Rotorcraft Brownout: Advlanced Understanding, Control, and Mitigation

Objective: *Develop a design methodology that will capture physical mechanisms of potential mitigation solutions of rotorcraft brownouts*

Team: *UM (lead), Arizona State University, Iowa State, Dartmouth College*

5 years program (2008-13)

Task-1	Fundamental of Rotor and Airframe Aerodynamics in Ground Effect Operations
Task-2	Fundamentals of Particle Suspension
Task-3	Brownout Synthesis Mitigation and Validation

Flight Dynamics and Stabilization with Suspended Loads in High-Speed Flight

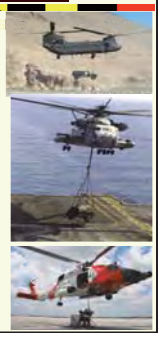
Objective: Study aerodynamics, dynamics and flight stability of a suspended load in hover and forward flight, examine role of unsteady aerodynamics and nonlinearities.

Background & Challenges: In high speed, possibility of dynamic instabilities of suspended loads, but would increase radius of action and productivity index, predictions poor; unsteady aero of sling load important, aero nonlinear, stabilizing challenging, lock-in phenomenon of large amplitude motion

Technical Approach:

1. CFD based model of containers and bluff body
2. Develop transfer function type aerodynamic models
3. Develop dynamic model of rotorcraft with suspended load
4. Investigate trim, aeromechanical stability, handling qualities and dynamic loads
5. Suspended load model tests in GLM Tunnel and validations
6. Stabilization of suspended loads using static and active controls

Major Outcome: Increase speed of rotorcraft with suspended load, improve handling qualities and reduce pilot work load, increase load carrying productivity index



Rotorcraft Technology Needs

Technology Needs

- *High Performance index*
  - *Low airframe drag (exploit CFD)*
  - *Modular engine, high SFC*
  - *Variable speed transmission (exploit automotive technology)*
- *Ultralight Structures*
  - *Next generation composites*
  - *Multidisciplinary optimization*
- *Mission Adaptive Rotors*
  - *Active morphing for "quantum jump" in performance*
  - *Composite couplings for performance and loads*
- *HUMS*
  - *Beyond transmission & drivetrains (rotor head, servo failures, etc)*

Technology Needs

- *Increased level of autonomy*
  - *Collision avoidance*
  - *Embedded miniaturized sensors and transmitters*
- *Green rotorcraft*
  - *High SFC*
  - *Hybrid Engines*
  - *Re-cycling composite materials*
  - *All electric rotorcraft (swashplateless, hydraulicless)*
- *Rapid Prototyping*
  - *Numerical miling and rapid prototyping*
- *Jet Smooth Rotorcraft*
  - *Active controls using smart materials*

Recommendations

- *For competitiveness of rotorcraft industry, seek new state-of-art production rotorcraft (not upgrades!!!).*
- *Nurture rotorcraft centers of excellence (not fragmentations!!!!)*
- *Reward creativity and depth in research (let us not create a culture of milestones!!!!)*
- *Experimental facilities are key to methodology robustness, product refinements and revolutionary designs (let us not close wind tunnels!!!)*
- *Use creativity to reduce life cycle cost (real not fake!!)*
- *Discourage infeasible designs (too many paper studies!!!)*

Crossing the Dip?

- *Advances in aeromechanics appear poised for enormous potential in rotorcraft, especially towards the development of a mission adaptive rotor with a quantum leap in performance*

Wonderful World of Rotorcraft Aeromechanics

Research frontiers are expanding and moving up rapidly

- Rotor designs are tending towards low vibration and low noise rotors (jet-smooth goal)
- Performance (speed, endurance, range) improving
  - Variable rotational speed morphing rotor in future
- Increasing pay-load/gross weight fraction
- Cost: Manufacturing and maintenance costs going down
- Product reliability and survivability increasing
- Autonomy is increasing by leaps and bounds
- **Future vehicles tending towards "Green"**
  - **Fuel efficiency, CO_2 emission and recycling material**
- ***How about all electric or hybrid helicopter?***