Review of Rotorcraft Aeromechanics Methodology

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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
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! & CO₂ level
- More autonomy requirements
- Runway saturation & terminal area gridlock
- Asymmetric & urban warfare
Index of Rotor Efficiency

**Figure of Merit**

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

**Power Loading**

\[ \text{PL} = \frac{\text{Thrust Produced}}{\text{Actual Power required}} \]
Power Loading (Thrust/Power)

Momentum Theory
- FM = 1.0
- FM = 0.8
- FM = 0.6
- FM = 0.4

Effective disk loading (lb/ft²)

Power loading (lb/hp)

Hummingbird
Fruit fly
Hawkmoth
Orchid bee
Bumblebee
Bat
Dragonfly
MAVs
Cyclocopter MAV
Helicopters
Tilt-rotors
Vectored thrust

1000
100
10
1
0.1
0.01
0.001
10
100
1000
State-of-Art of Helicopter Technology

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>~150 Knots</td>
<td>Airplane of 1920’s</td>
</tr>
<tr>
<td>Range</td>
<td>&lt;500 nm</td>
<td>low</td>
</tr>
<tr>
<td>Payload</td>
<td>&lt;40,000 lbs</td>
<td>low</td>
</tr>
<tr>
<td>Ceiling</td>
<td>&lt;15,000 ft</td>
<td>low</td>
</tr>
<tr>
<td>Figure of merit</td>
<td>&lt;0.8</td>
<td>Up from 0.6 in 1940</td>
</tr>
<tr>
<td>Lift-to-drag ratio</td>
<td>5-6</td>
<td>Up from 4-5 in 30 years</td>
</tr>
<tr>
<td>Productivity</td>
<td>Low c.f. of airplane</td>
<td>Small increase in 30 years</td>
</tr>
<tr>
<td>Vibration levels</td>
<td>High</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>Noise levels</td>
<td>High</td>
<td>Obtrusive</td>
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</table>

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

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
Aeromechanics involves coupled, multi-, inter-disciplinary
- Dynamics (Aeroelasticity)
- Aerodynamics & Performance
- Acoustics
- Flight Dynamics & Controls
- Structures
Aerodynamics
Aerodynamics: Challenges

- Nonsteady and complex aerodynamics and rotor wakes

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

- Main rotor wake/tail wake structure
- Blade/tip vortex interactions
- Tip vortices
- Rotor wake/airframe interactions
- Main rotor/empennage interactions
- Hub wake
- Active flaps
- Transonic flow on advancing blade tip region

ψ = 270°  Blade stall on retreating blade
ψ = 180°  Blade/tip vortex interactions
ψ = 90°   Main rotor/tail vortex interactions

Active flaps
Rotor Wakes

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

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

Blade/Vortex Interactions: Rotor loads, Performance & Acoustics
### Analysis Methods: Wake Geometry Calculation

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

<table>
<thead>
<tr>
<th></th>
<th>Past</th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blade Aero</strong></td>
<td>Lifting line</td>
<td>Indicial response functions for unsteady and dynamic stall</td>
<td>CFD/CSD coupling</td>
</tr>
<tr>
<td></td>
<td>Table-lookup</td>
<td></td>
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<tr>
<td></td>
<td>Empirical stall</td>
<td></td>
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<tr>
<td><strong>Rotor Wake</strong></td>
<td>Linear inflow</td>
<td>Free wake</td>
<td>CFD-generated wake capture</td>
</tr>
<tr>
<td></td>
<td>Prescribed</td>
<td>Frequency &amp; time-domain</td>
<td></td>
</tr>
<tr>
<td><strong>Airframe</strong></td>
<td>Flat plate area</td>
<td>Table lookup</td>
<td>CFD rotor/body coupled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Panel method</td>
<td></td>
</tr>
<tr>
<td><strong>CFD Modeling</strong></td>
<td>Euler</td>
<td>Navier-Stokes CFD/CSD loose coupling</td>
<td>CFD/CSD tight coupling</td>
</tr>
<tr>
<td></td>
<td>Uncoupled</td>
<td></td>
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Structural Modeling
Structural Modeling: Challenges

• Coupled and nonlinear phenomena involving complex Coriolis/Gyroscopic forces

• Blade modeled as a beam undergoing moderately large deformations involving coupled flap and lag bending, torsion and axial motions

• Airframe 3-D structure with complex joints and cutouts
Nano-composite Erosion Protection Tape
Nomex Honeycomb Core
Graphite Composite Skin
Tungsten Nose Mass
Uni-directional S-glass D-spar
Airframe Assembly

- Tail Rotor Gear Box and Electrical Actuator
- Supercritical Tail Rotor Shaft
- Monocoque Composite Tail Boom
- Seperation Bulkhead for Easy Removability
- Active Vibration Isolation Struts
- Keel Beams
- Transmission and Engine Deck Note: Located Behind Cabin for Improved Noise and Safety

- Energy Absorbing Semi-Monocoque Composite Cockpit
  Note: Shaped for No Earth Flowing
- Crashworthy Landing Gear with Low Drag Fairing
- Lightweight, Crashworthy Al-Li Primary Bulkheads
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

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<th>Past</th>
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<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deflections</strong></td>
<td>Moderate-large Ordering scheme</td>
<td>Moderate-large</td>
<td>Large (no ordering)</td>
</tr>
<tr>
<td><strong>Blade Modeling</strong></td>
<td>FEM/modal</td>
<td>FEM/Multibody</td>
<td>Multibody</td>
</tr>
<tr>
<td><strong>Airframe</strong></td>
<td>Stick model</td>
<td>3-D FEM/modal</td>
<td>Multibody</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Small strain Isotropic</td>
<td>Small strain Anisotropic</td>
<td>Large strain Coupled laminates</td>
</tr>
</tbody>
</table>
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)

Dominant 4/rev hub loads transmitted to fuselage
**Helicopter Vibration: Definition**

- **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, $pN_b/\text{rev}$ are filtered through hub

- $1/\text{rev}$ due to rotor asymmetry
Sources of Vibration

- Asymmetric flow in forward flight
- Complex wake
- Compressibility on advancing side and dynamic stall on retreating side
- Flexible rotor blades
High Vibration: Flight Conditions

• **4 Critical flight regimes:**
  - low speed transition
  - high speed
  - high altitude-high thrust
  - Maneuvering flight

• **Enormous vibration:**
  - High operating cost
  - Reduced crew/system performance
Rotor Definitions

\[ V_\infty \]

\[ 180^0 \]

\[ 90^0 \]

\[ 0^0 \]

\[ y \]

\[ r \]

\[ \psi \]

\[ R \]
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

- 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

Predicted cockpit vibration – 158 knots

AA - 2GCHAS   AR - Flightlab   D - CRFM
M - UMARC (Maryland)   N - CAMRAD1
SR - RDYNE   SU - UMARC (Sikorsky)   W - R150
Vibratory Loads at High Speed: Prediction vs. Flight in 2000

\[ \mu = 0.368 \quad C_w \]

\[ \frac{\mu}{\sigma} = 0.078 \]

2GCHAS/RCAS

CAMRAD/JA

UH-60A Lift at 77.5% R

Flight Test

Lift Phase Error

Phase error in advancing blade lift prediction

Pitch-Link Load

Flight Test

Error in pitch link load prediction
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 $\mu = 0.37$
2. Low speed transition $\mu = 0.15$
3. High altitude dynamic stall $\mu = 0.24$

Maneuver:
4. Severe pull-up Maneuver $\mu = 0.341$
   (load factor = 2.09)

Lift 0-10/rev

Vibratory Lift 3-10/rev

Pitching Moment 1-10/rev

Azimuth, degs.
Pitch Link Load at high speed: CFD/CSD

Pitch Link Load, lbs

Azimuth, deg

CFD-wake capture
CFD-free wake
Flight C8534
Predicted Pitching Moment and Stall Map at High Altitude & High Thrust

Pitching Moment 86.5% R

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

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

**Dynamic stall, vortex loading, transonic effects can occur simultaneously**
Flight Test Measurement

Rev 14
\( \mu = 0.341 \)
Load factor = 2.09

3 Stall Cycles

- High trim angle stall
- Elastic twist and inflow stall
- Fuselage induced flow separation
- Transonic stall
- Wake cuts through rotor disk twice
Pitching Moment C11029: Rev 18

Flight Test

Lifting-line w/prescribed deformations

Advancing blade stall predicted accurately using prescribed deformations

Three stall cycles
Prediction with CFD/CSD shows good correlation for two stall cycles on retreating side -- advancing blade stall not predicted
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
## Dynamics: State-of-Art

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

\[
[A(\psi, y, \dot{y})]\{y\} = \{G(\psi, y, \dot{y})\}
\]
Analysis Methods: Rotor Codes

Specialized Rotor Codes

• Greater details, accuracy and scope to model some physical mechanisms while simplifying most other interactions
• RotorCRAFT to CHARM – detailed free wake, rotor-fuselage aerodynamic interaction
• KTRAN-RDYNE-GENHEL – structural dynamics and flight dynamics
• DYMORE II – multibody rotor-fuselage dynamic model
• R150 and Westland/DERA
• C81 and COPTER
• R85/METAR

Comprehensive Codes

• Includes all basis components to handle multidisciplinary loads, vibration and stability, Can perform trim, transient and flutter
• CAMRAD family
• UMARC family
• 2GCHAS to RCAS
  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
## Analyses: State-of-Art

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<th>Future</th>
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</thead>
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<tr>
<td><strong>Trim/Steady Response</strong></td>
<td>Modal method/Harmonic Balance</td>
<td>Modal/Complete FEM time</td>
</tr>
<tr>
<td><strong>CFD/CSD Coupling</strong></td>
<td>Iteratively</td>
<td>Loose</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Linear Modal/Floquet</td>
<td>Linear Modal/Full Floquet</td>
</tr>
<tr>
<td><strong>Maneuver Analysis</strong></td>
<td>Modal/Time integration</td>
<td>Fully coupled time marching</td>
</tr>
</tbody>
</table>
Rotorcraft Technology Needs
Technology Needs

• **High Performance index**
  - Low airframe drag (exploit CFD and active flow control)
  - 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)

- **Expand Validation of Comprehensive Codes**
  - Carefully planned component and configuration tests under controlled flight environment and systematic validation by team (government, industry & academia)
  - Nurture active participation with existing and new test data
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!!)

• “Nurture active team (industry, labs and academia) validations of methodology (both at component & configuration level)”
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.