Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

Review of Rotorcraft Aeromechanics Methodology

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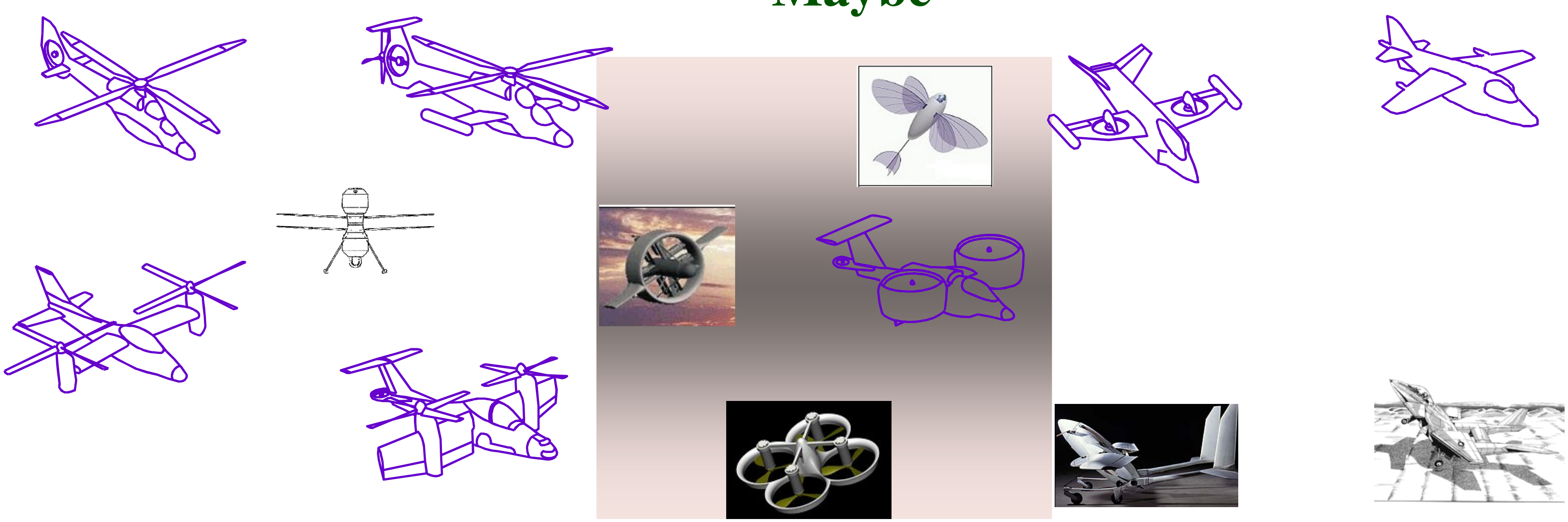
Definition of Rotorcraft

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

Is This Air Vehicle a Rotorcraft?

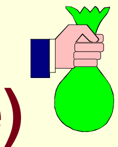
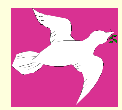
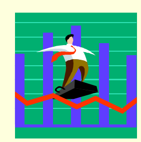
Yes **Maybe** **No**



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**

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 Rotor Efficiency

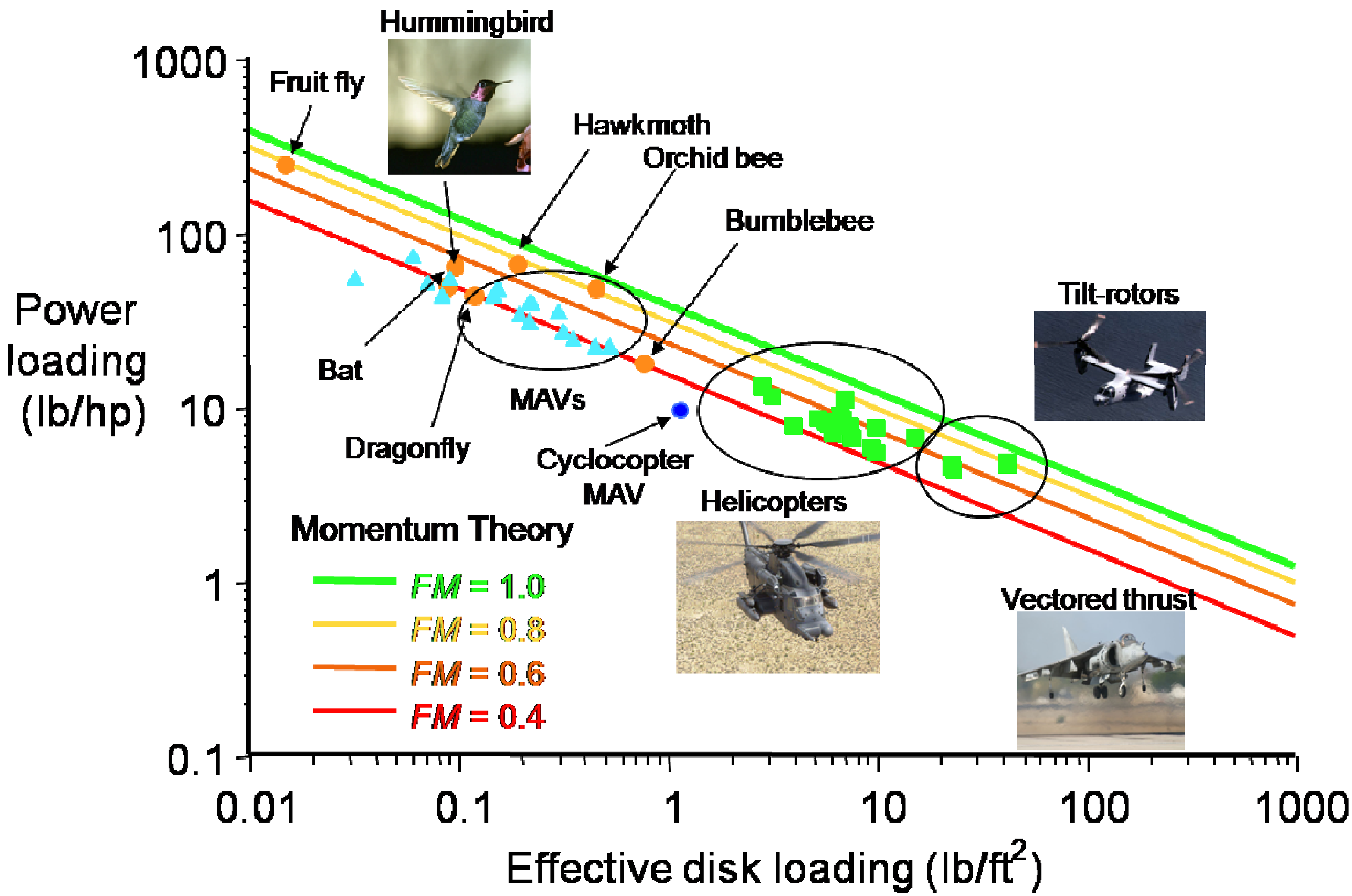
Figure of Merit

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

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 <u>transition</u> phase toward something better***
  - ***There is "perception" helicopters do what they do and no more***

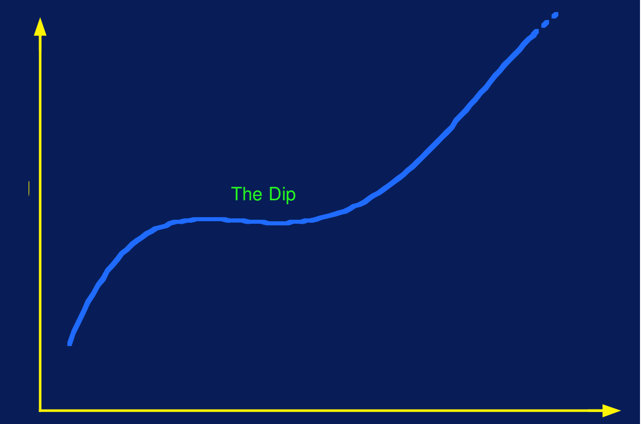
Postdictive Versus Predictive Capabilities

- ***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*

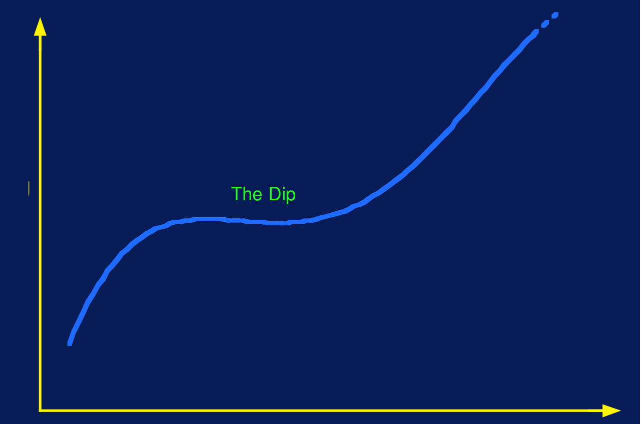
Why Does the "Dip" Happen?

- *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

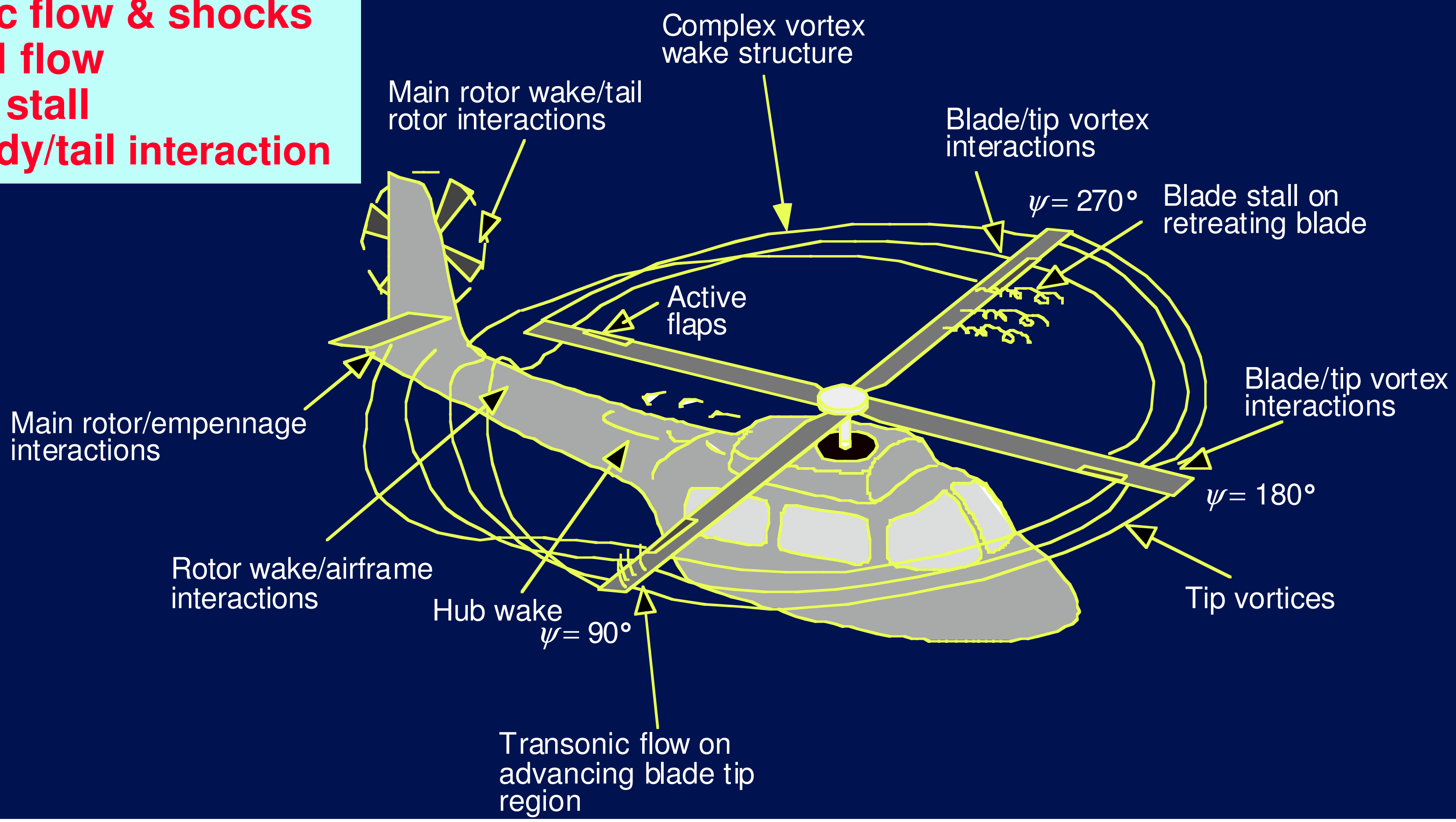
- Dynamics (Aeroelasticity)
- Aerodynamics & Performance
- Acoustics
- Flight Dynamics & Controls
- Structures

Aerodynamics

Aerodynamics: Challenges

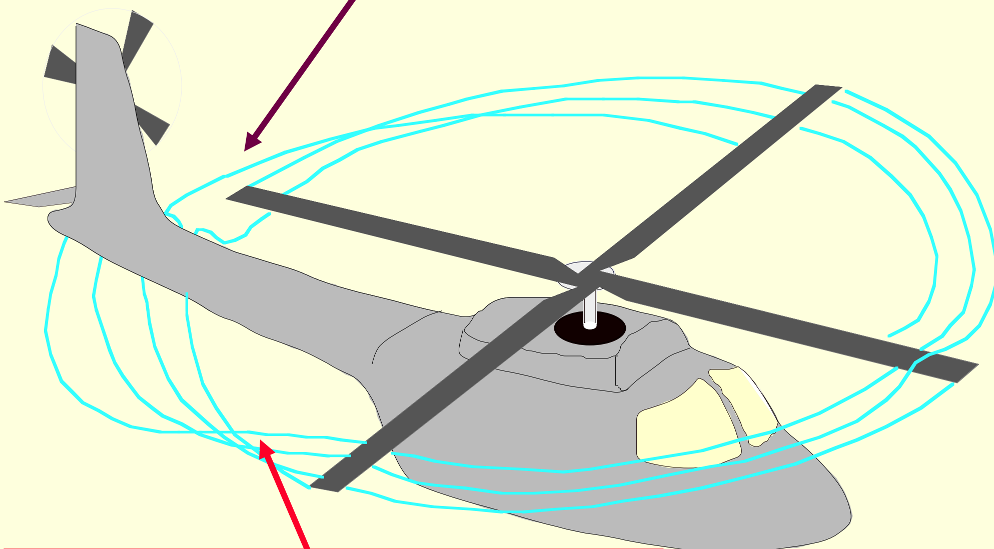
- **Nonsteady and complex aerodynamics and rotor wakes**

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



Rotor Wakes

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



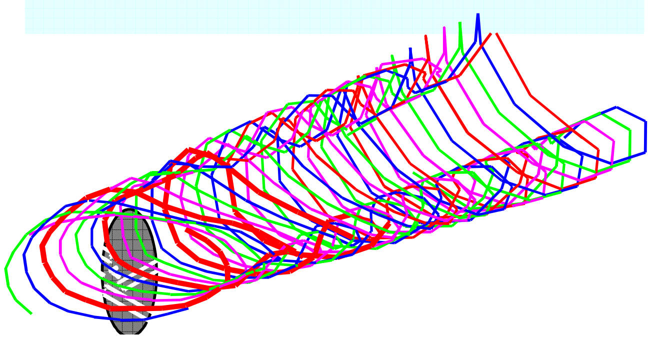
Blade/Vortex Interactions: Rotor loads, Performance & Acoustics

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

Analysis Methods: Wake Geometry Calculation

Prescribed geometry

- Prescribed wake (Piziali/DuWaldt 1962)
- Refined by experimental induced velocities (Landgrebe 1969) to improve hover performance
- Kocurek/Berkovitz 1982
- Refined for forward flight, (Landgrebe/Egolf 1983, Beddoes 1985)



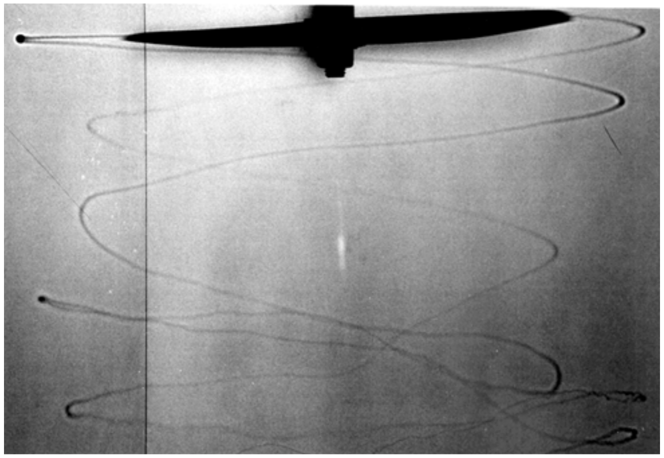
Free Geometry

- Relaxation model (Scully 1975)
- General free wake method (Johnson 1995)
- Pseudo-implicit predictor-corrector (Bagai/Leishman 1995)
- Multiple trailer method (Johnson 2002)
- Constant vorticity contour method (Wachspress 2003)
- Multiple rotors, multiple trailers, dual peak, dissimilar blades (Bagai/Leishman 1996, Johnson 1988

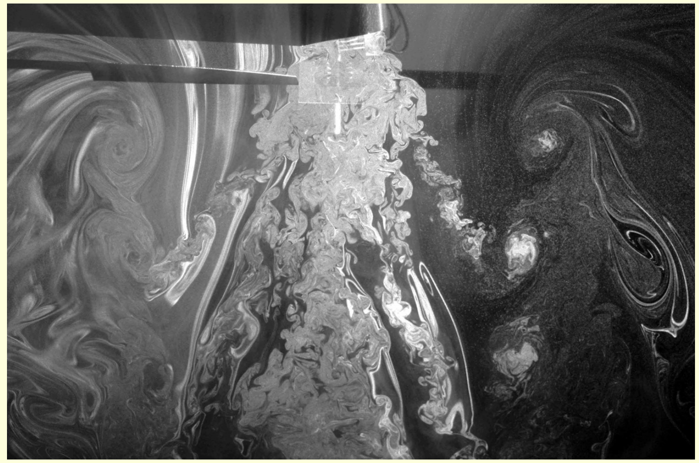
Free, time accurate

- Hover (Crimi 1965, Scully 1967) instability
- Clark/Leiper 1970 (enforced periodicity), forward flight (Landgrebe 1969, Sadler 1971)
- Vortex lattice model (Egolf 1988), Baron/Baffadossi 1993
- Jain 1998, Chung 2000 studied hover instability
- Bhagwat/Leishman 2003 for hover, steady and maneuvering flight, explained hover instabilities

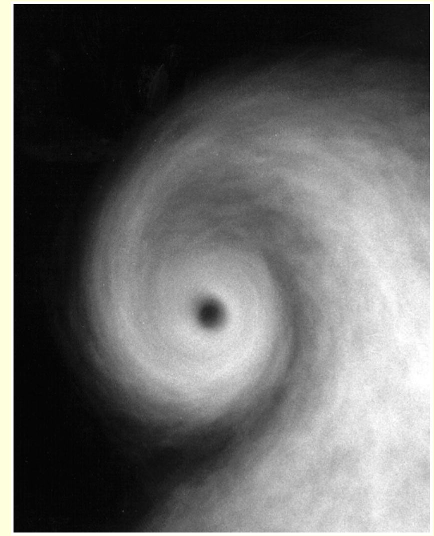
Rotor Wakes: Measurement



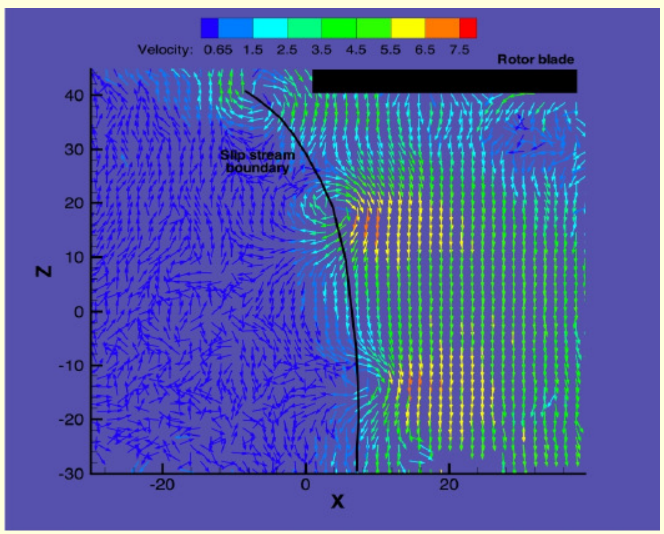
Wide-Field Shadowgraphy



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 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

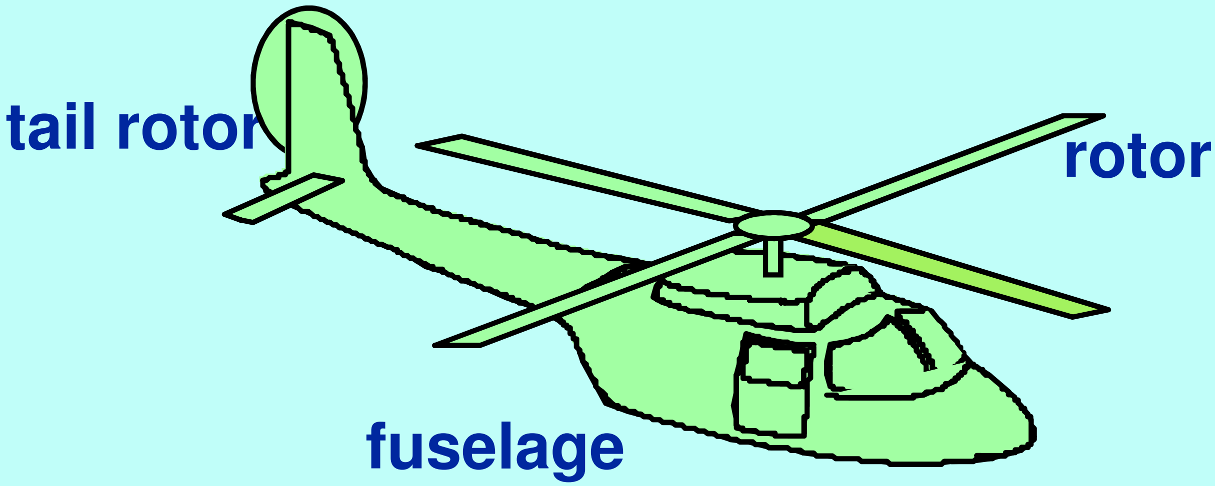
Structural Modeling

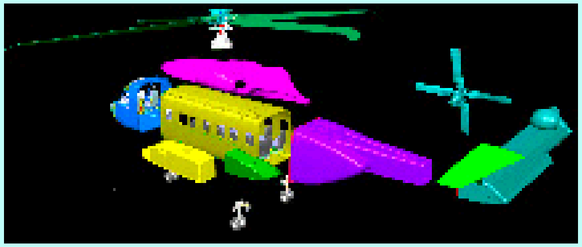
Structural Modeling: Challenges

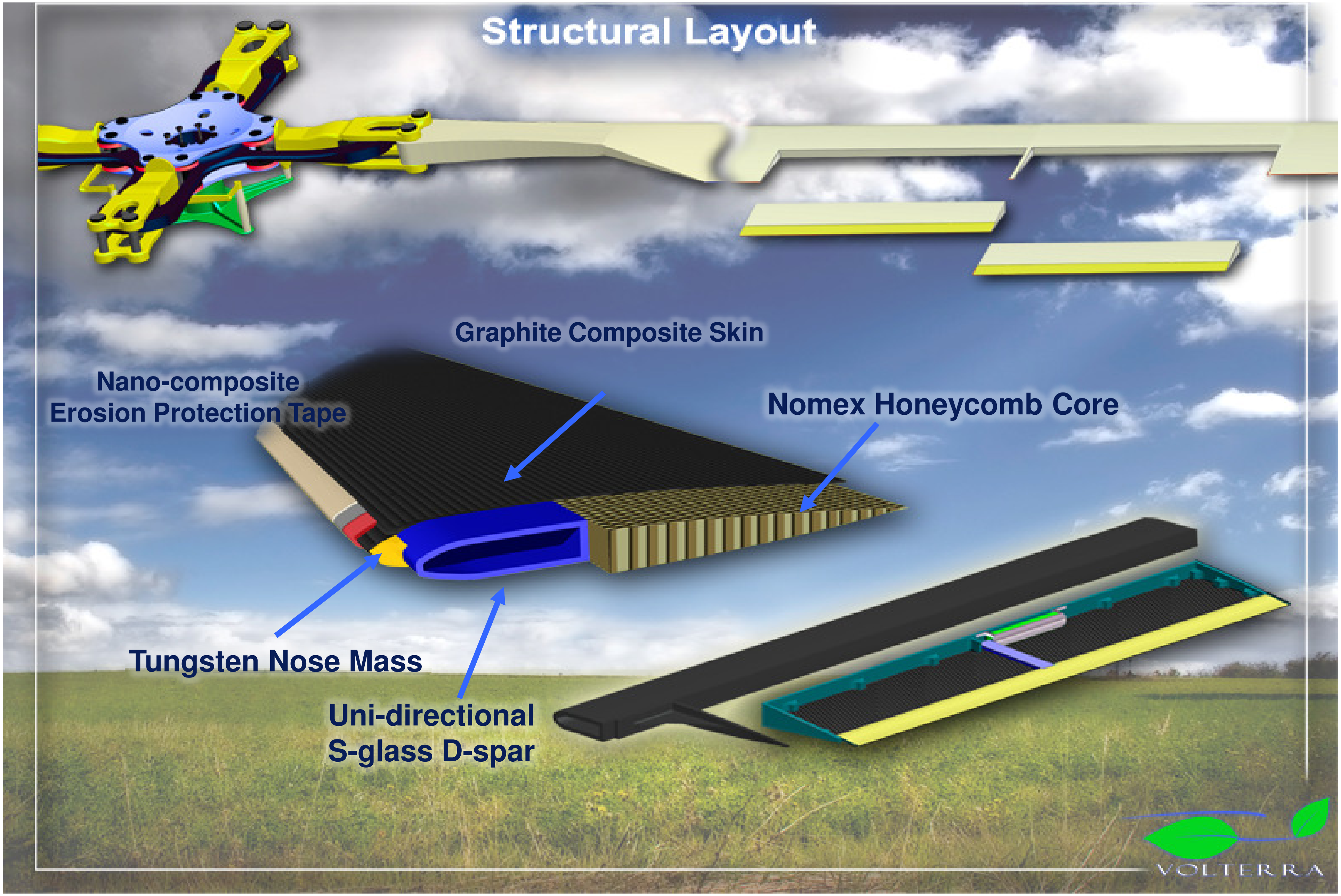
- Coupled and nonlinear phenomena involving complex Coriolis/Gyroscopic forces

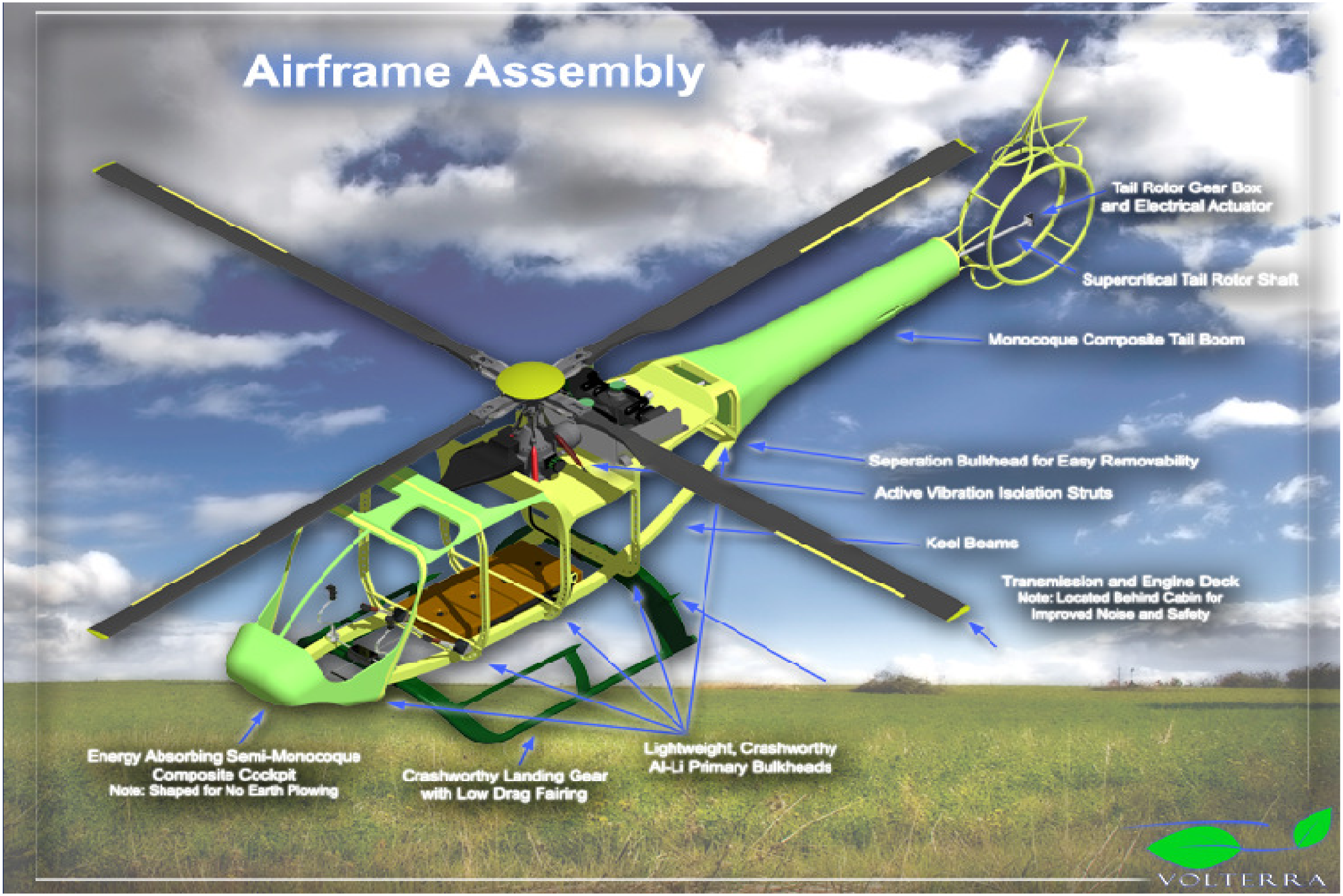
- Blade modeled as a beam undergoing moderately large deformations involving coupled flap and lag bending, torsion and axial motions

- Airframe 3-D structure with complex joints and cutouts






Structural Layout
Graphite Composite Skin
Nano-composite
Erosion Protection Tape
Nomex Honeycomb Core
Tungsten Nose Mass
Uni-directional
S-glass D-spar
VOLTERRA


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 Plowing
Crashworthy Landing Gear
with Low Drag Fairing
Lightweight, Crashworthy
Al-Li Primary Bulkheads
VOLTERRA

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)

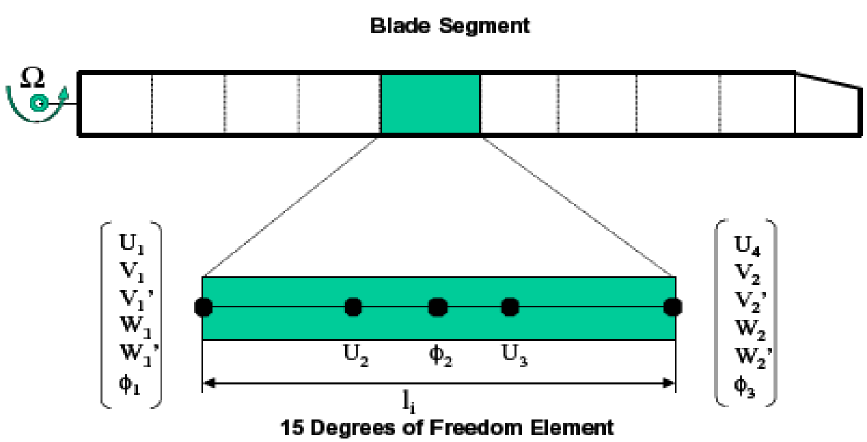
FEM vs Multibody

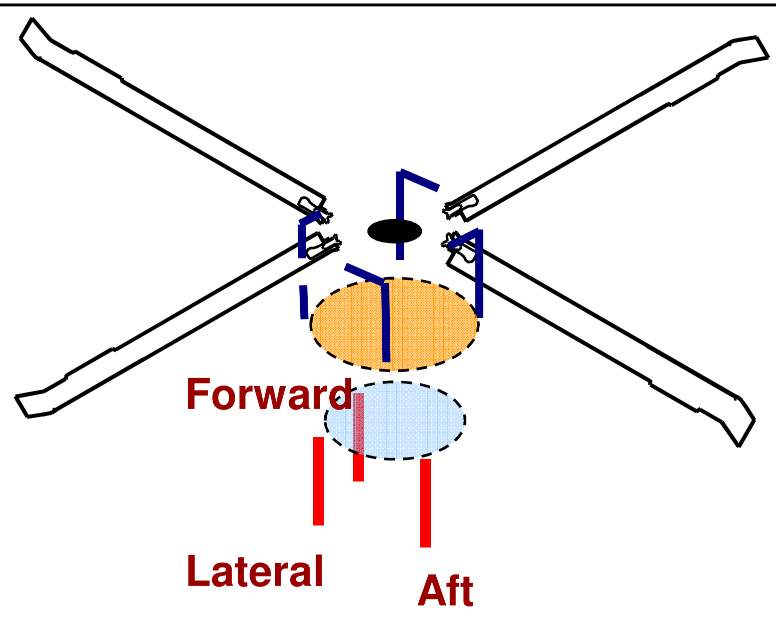
Classical FEM

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

Multibody

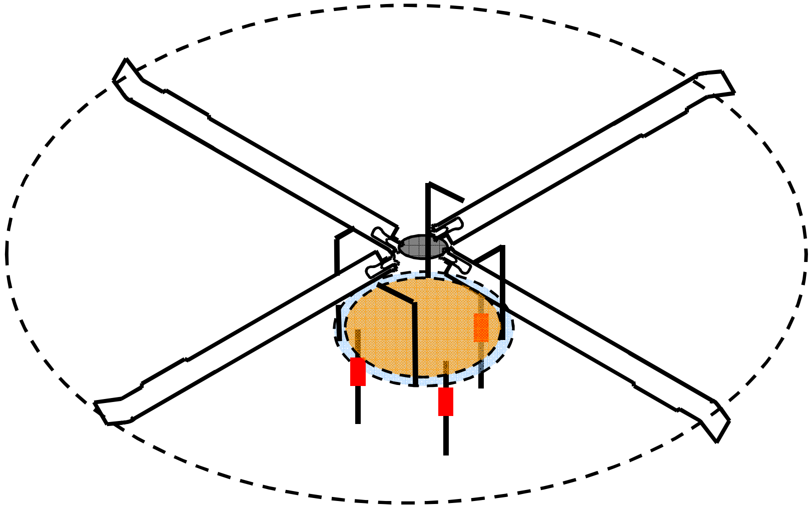
- Body and element coordinates
  - Deformation and loads in element coordinates
  - Increased scope of modeling





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

Dynamics

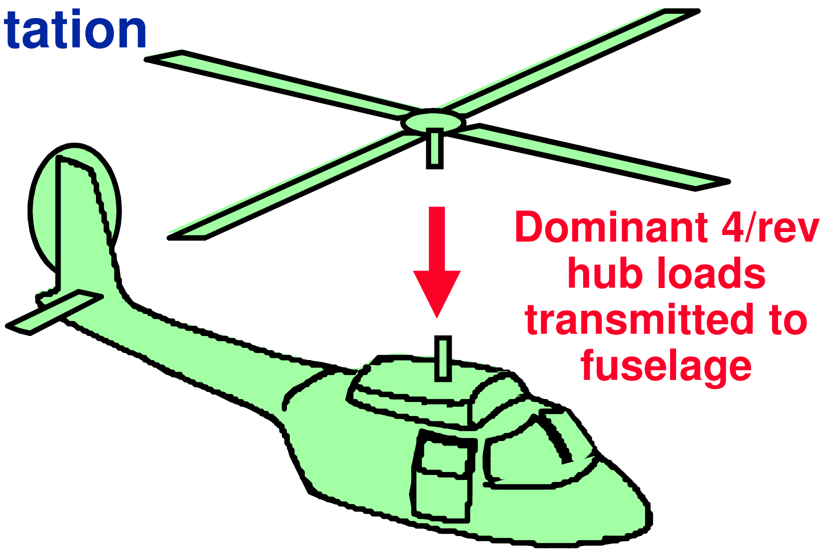
Dynamics

Interaction of structural, aerodynamics and inertial forces (aeroelasticity)

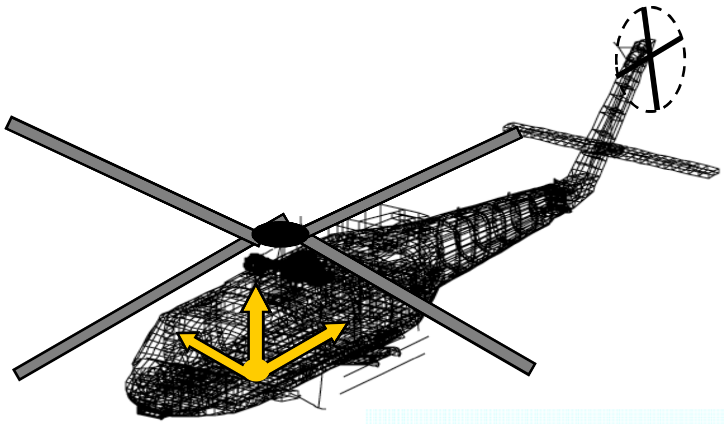
Issues:

- **Vibration & Loads:** prediction, measurement & suppression (level flight, maneuvering flight and gusty environment)

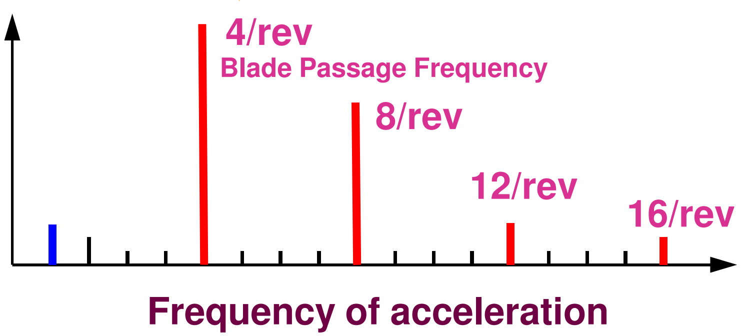
- **Aeromechanical Stability:** augmentation (flap-lag flutter, pitch-flap flutter, ground/air resonance)



Helicopter Vibration: Definition



Spectral Analysis of unsteady accelerations



Vibration : Accelerations in fuselage

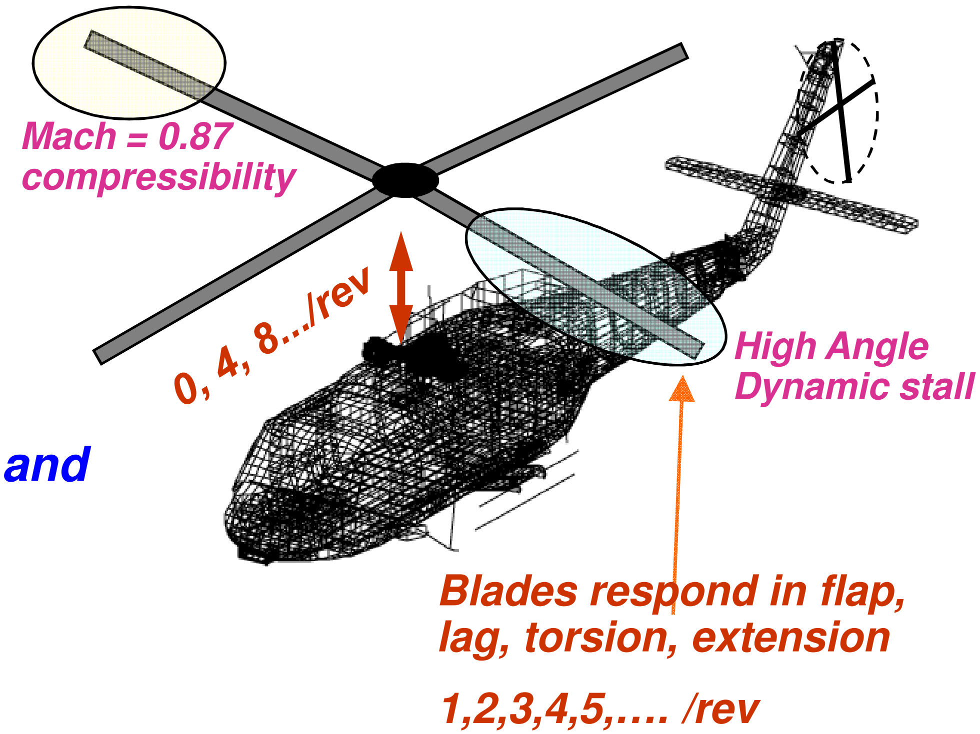
- ***Intrusion Index: weighted mean of 4 largest frequencies in vertical, lateral and longitudinal directions up to 60 Hz***

- ***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

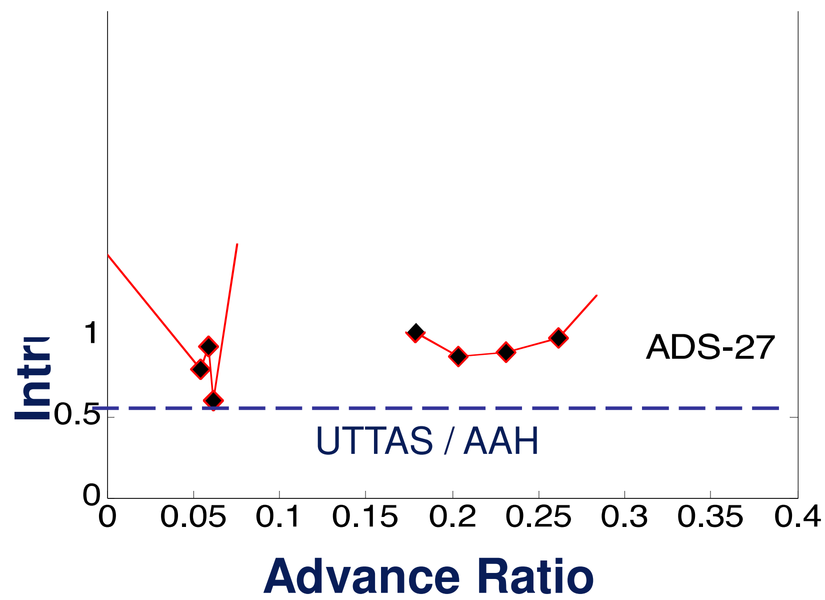
- Asymmetric flow in forward flight
- Complex wake
- Compressibility on advancing side and dynamic stall on retreating side
- Flexible rotor blades



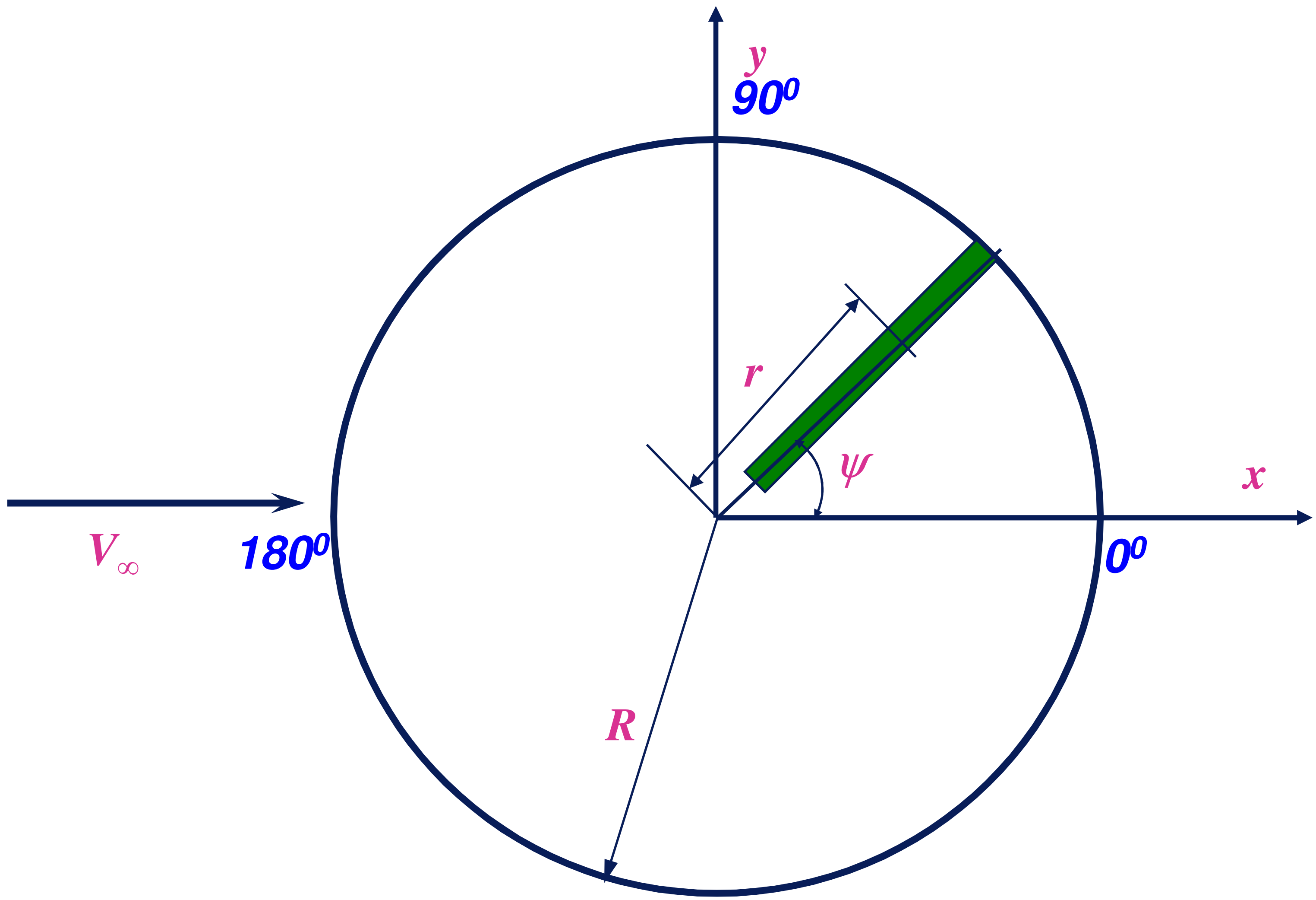
High Vibration: Flight Conditions

- **4 Critical flight regimes:**
  - low speed transition
  - high speed
  - high altitude-high thrust
  - Maneuvering flight
- **Enormous vibration:**
  - *High operating cost*
  - *Reduced crew/system performance*

Measured Vibration at pilot floor

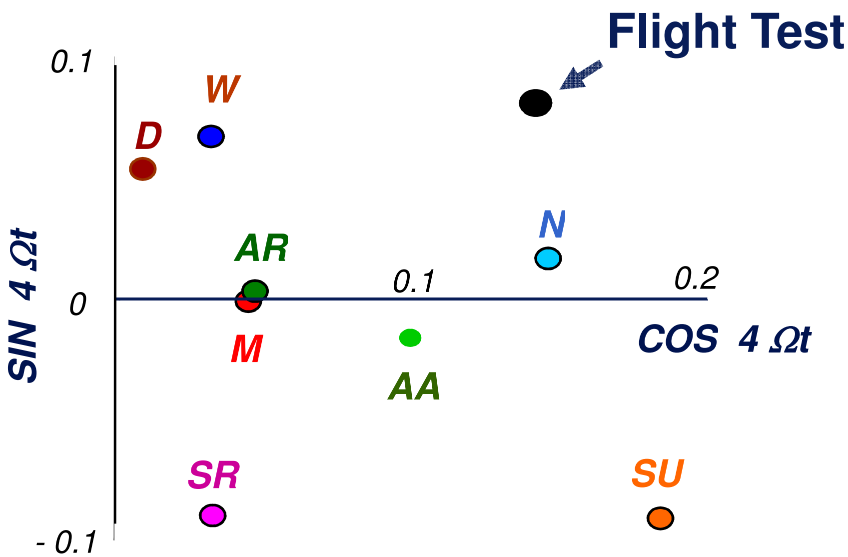


Rotor Definitions



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

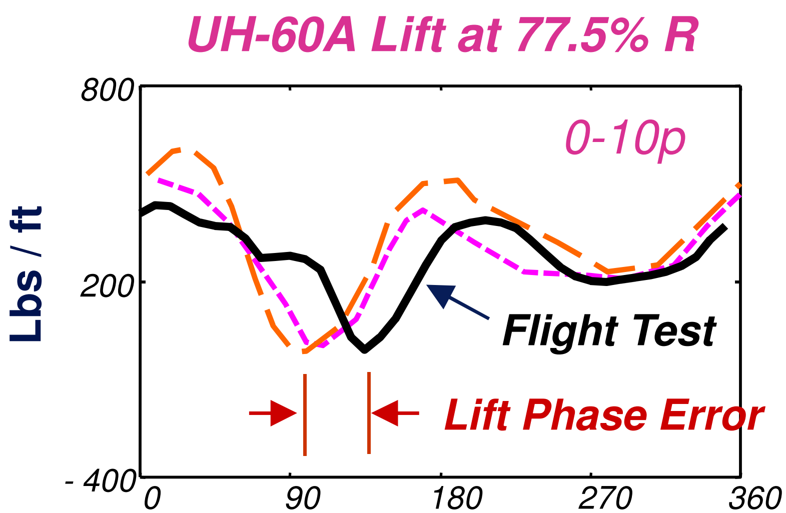
- ***None of predictions agreed with flight test data***
- ***No two predictions agreed with each other***
- ***LYNX Blades were not pressure instrumented, hence systematic correlation study with air loads and blade loads could not be possible***

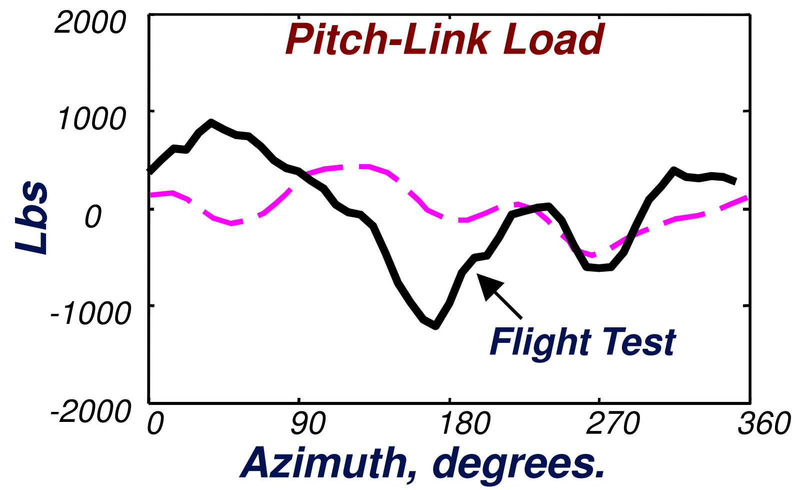
Vibratory Loads at High Speed: Prediction vs. Flight in 2000

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

2GCHAS/RCAS

CAMRAD/JA





Phase error in advancing blade lift prediction

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:

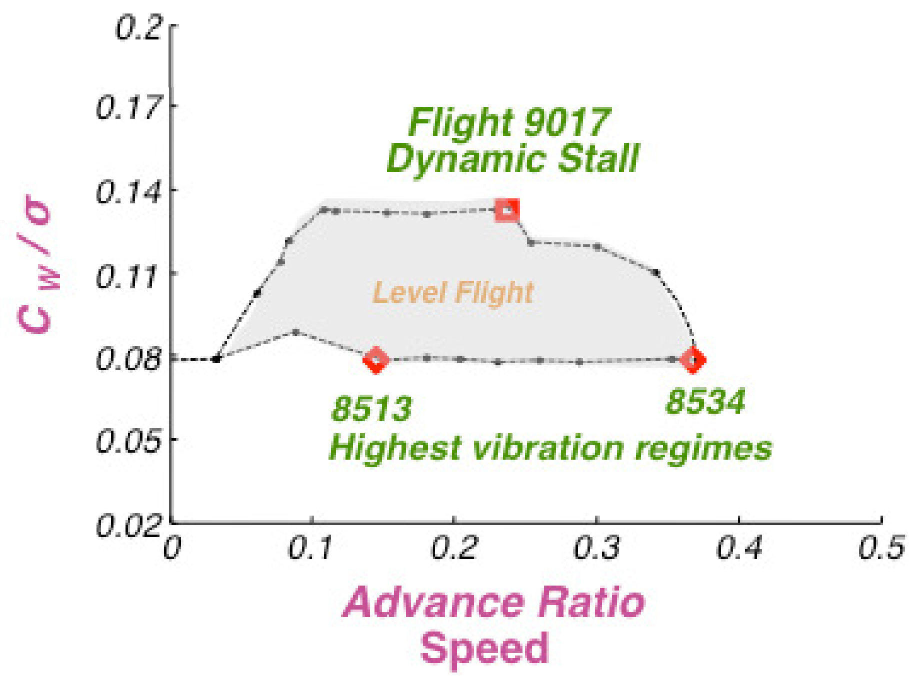
1. High speed $\mu = 0.37$

2. Low speed transition $\mu = 0.15$

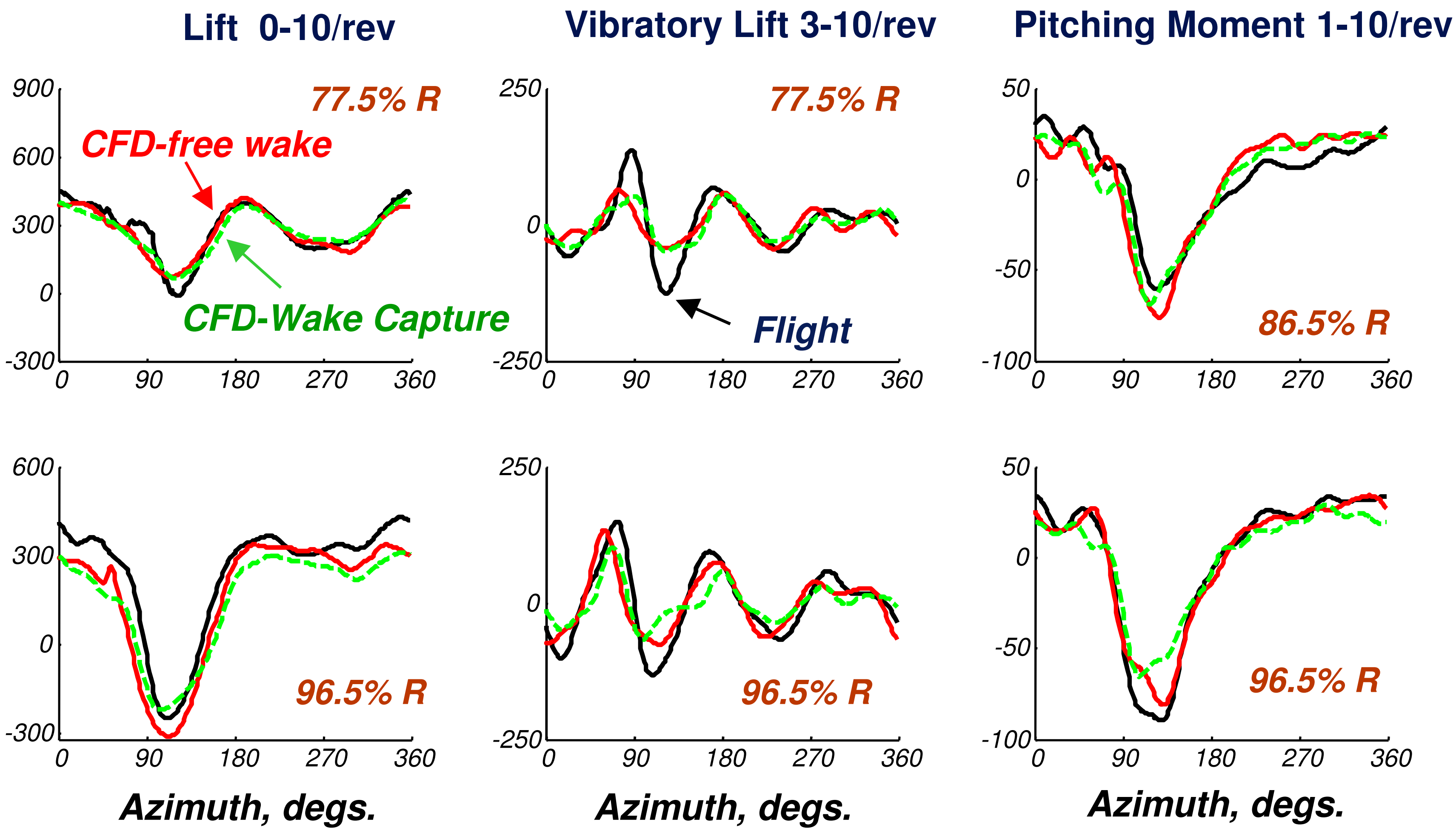
3. High altitude dynamic stall $\mu = 0.24$

Maneuver:

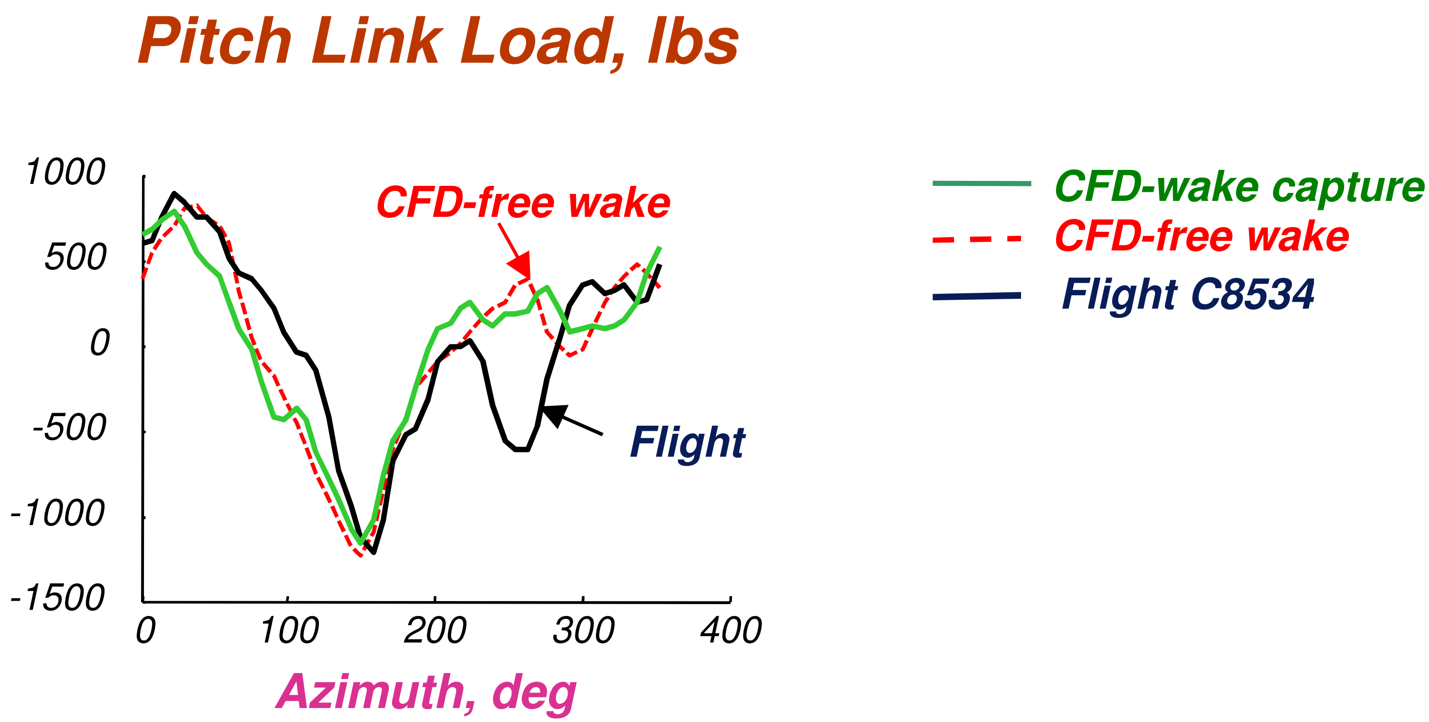
4. Severe pull-up Maneuver $\mu = 0.341$
(load factor = 2.09)



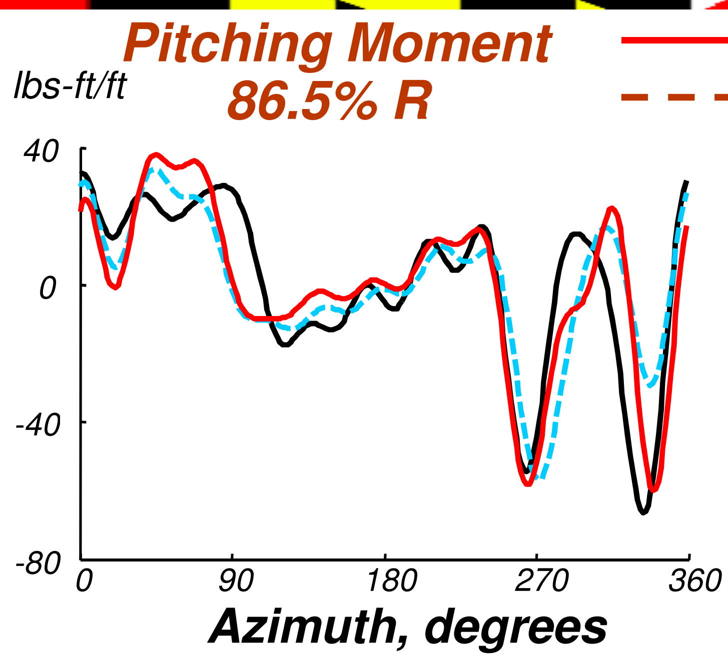
High Speed: CFD/CSD coupled Solution: First barrier problem resolved (2002)

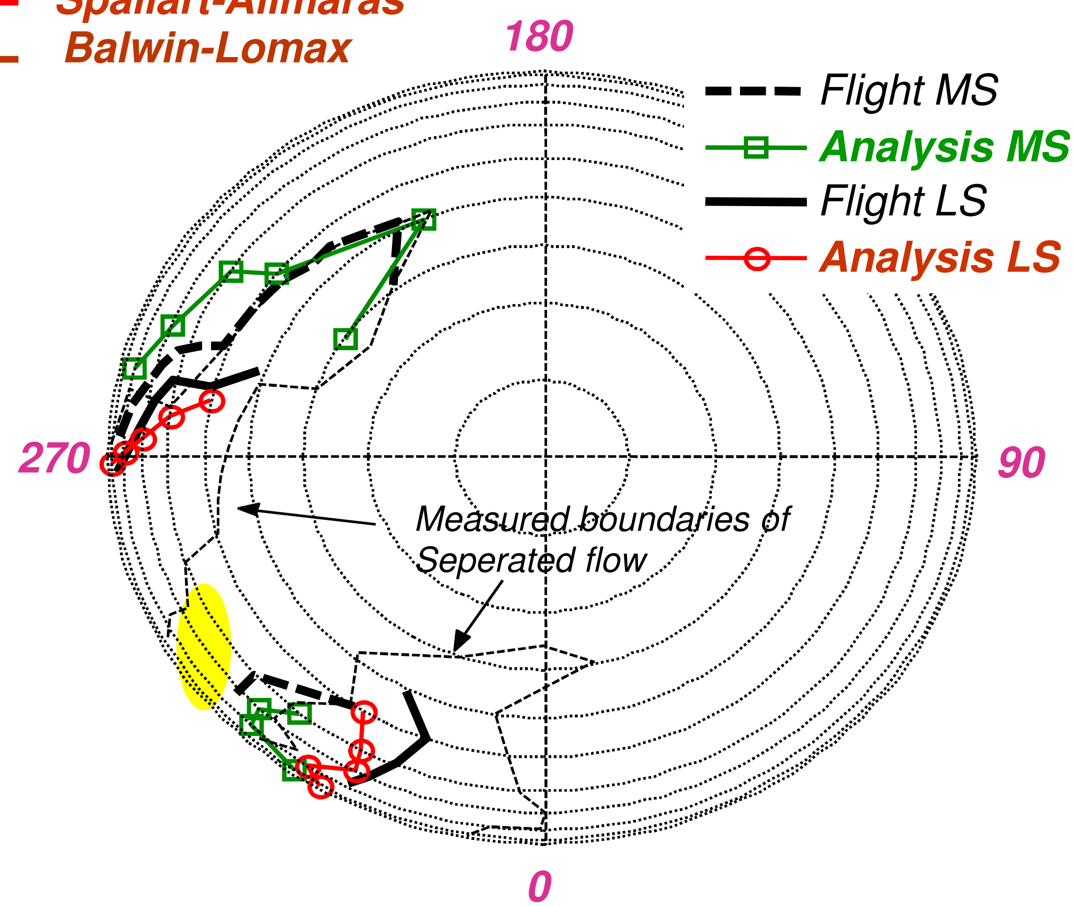


Pitch Link Load at high speed: CFD/CSD Second barrier problem resolved (2003)



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

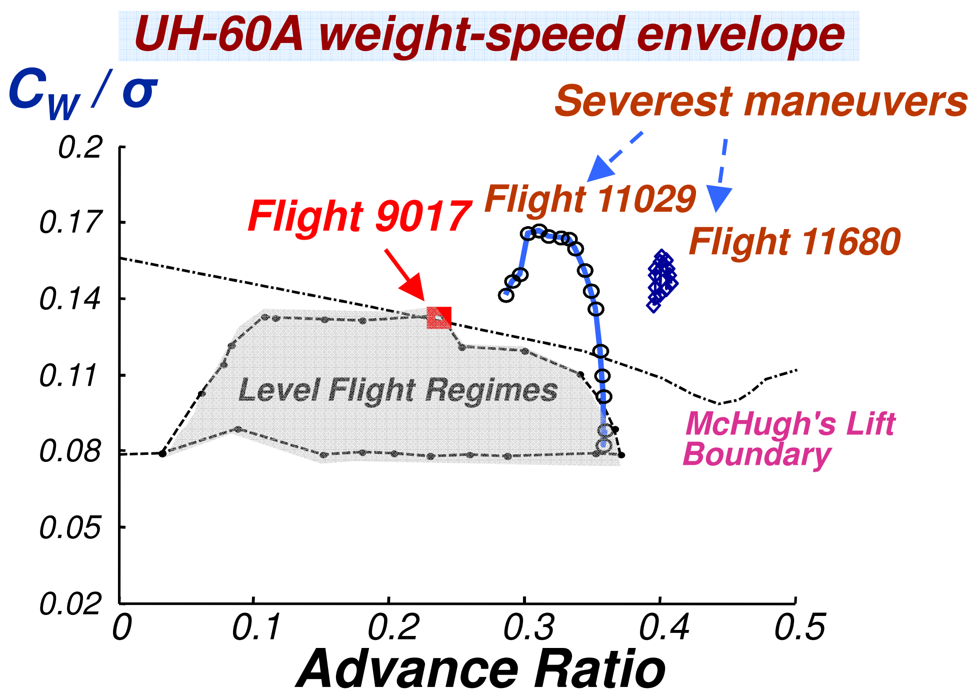


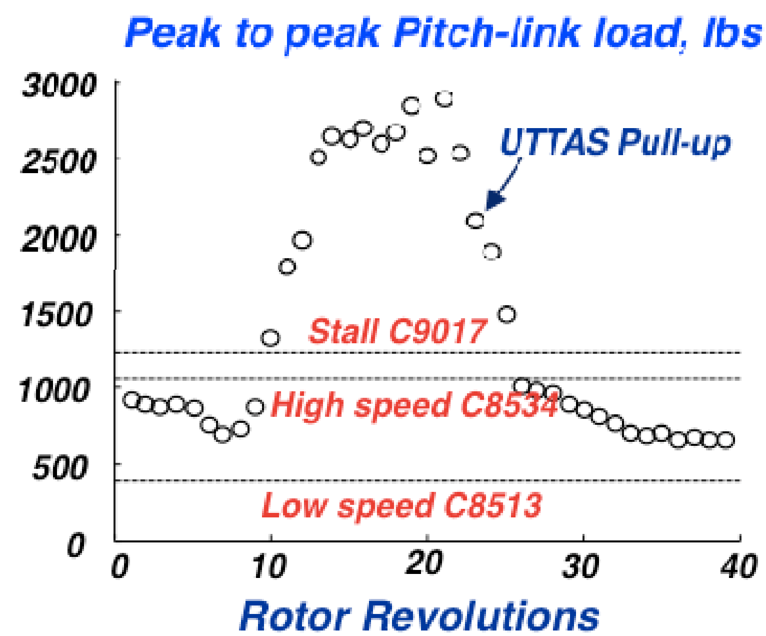


- 1st cycle caused by high angle of attack, 3D, stall vortex moving across span
- 2nd stall cycle caused by 4-5 elastic twist, mostly 2D

Third barrier problem resolved (2004)

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*

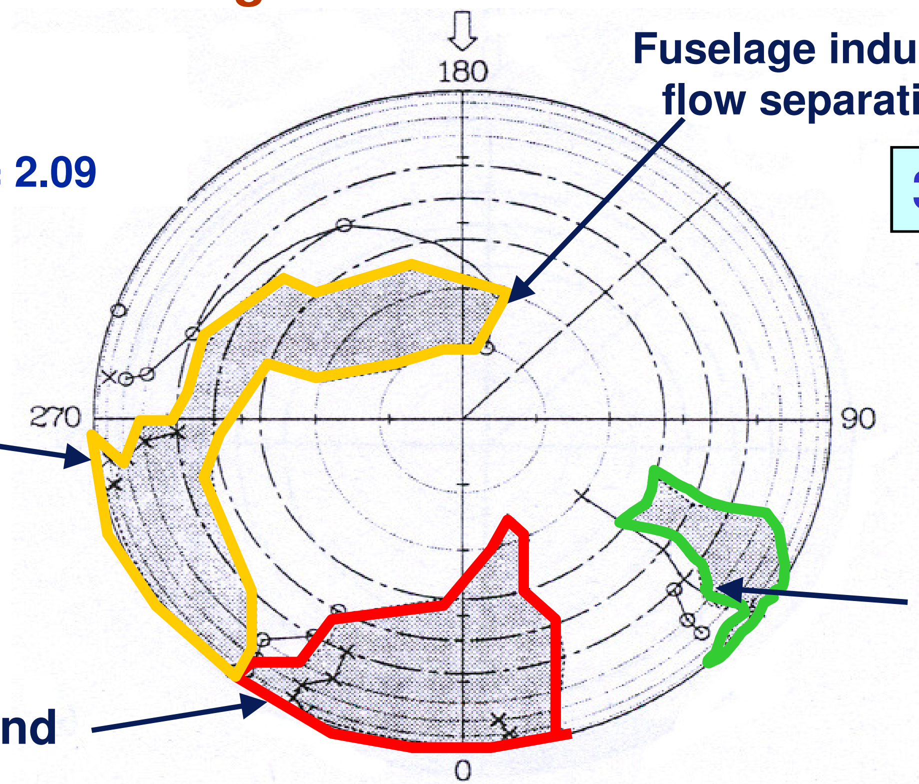
Dynamic stall, vortex loading, transonic effects can occur simultaneously

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

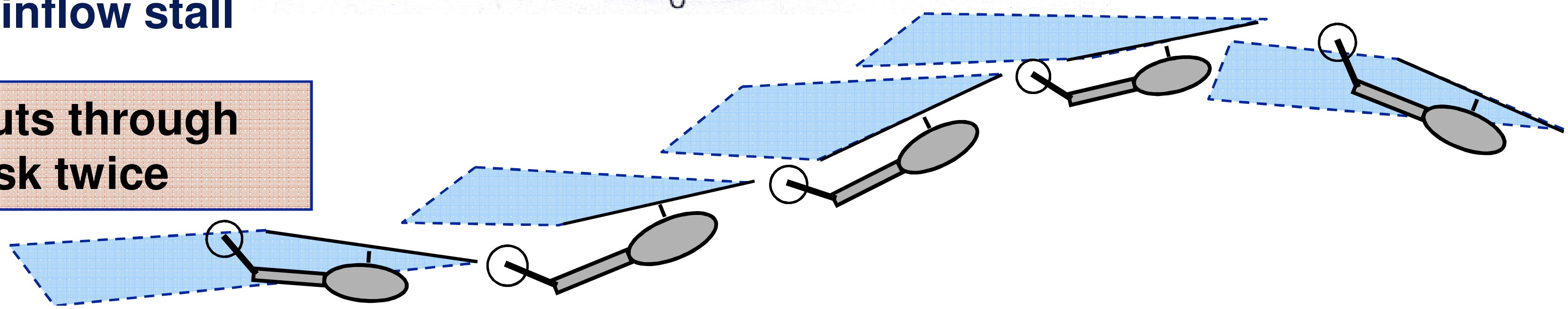
Flight Test Measurement

Rev 14
μ = 0.341
Load factor = 2.09

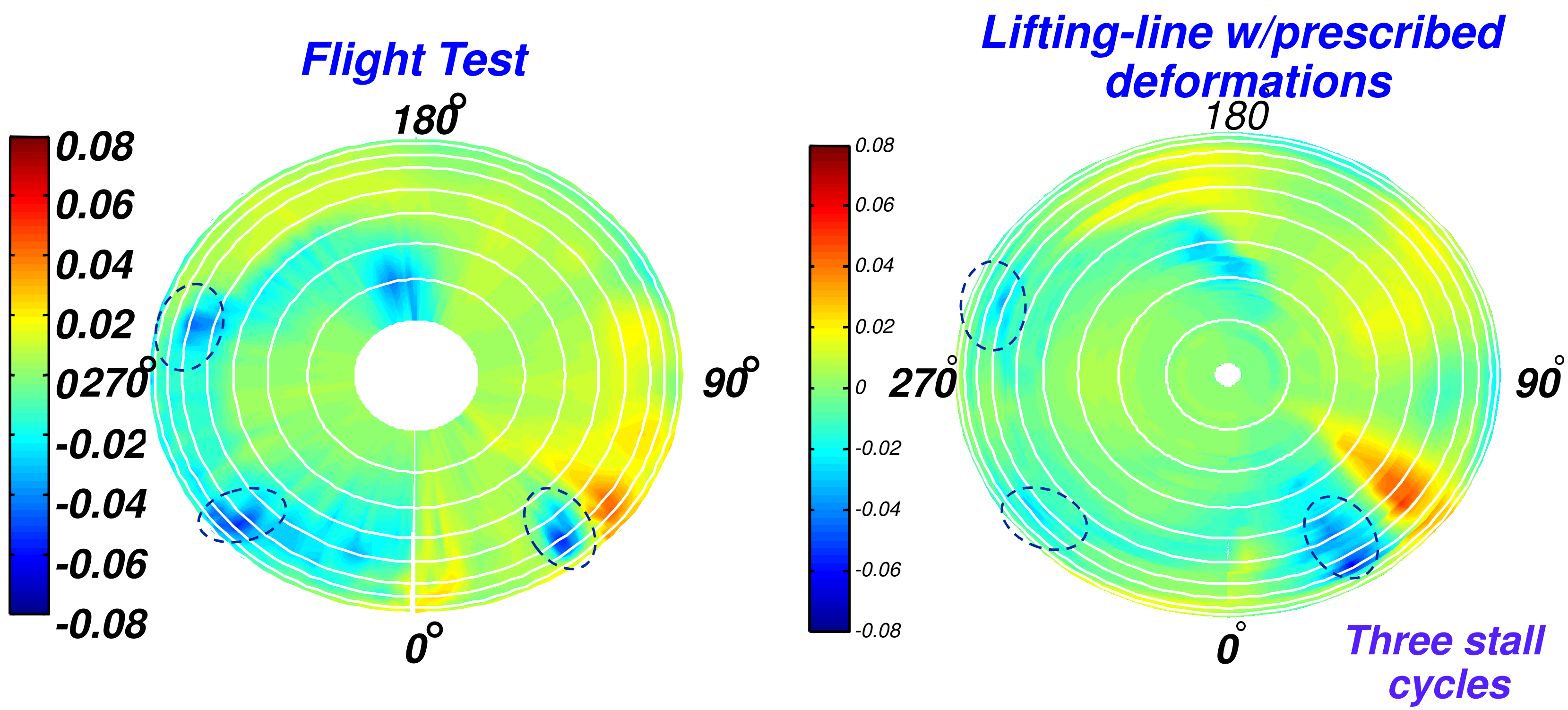
3 Stall Cycles



Wake cuts through rotor disk twice

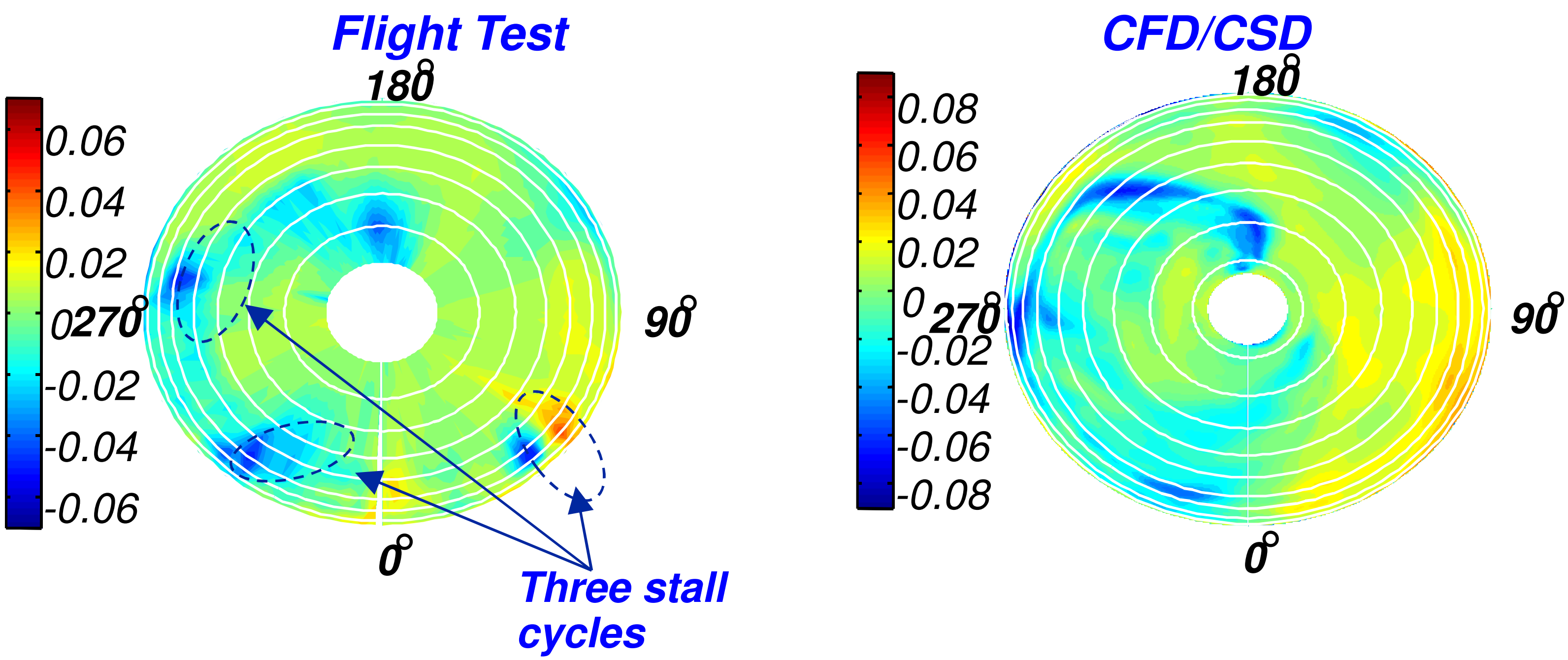


Pitching Moment C11029: Rev 18



Advancing blade stall predicted accurately using prescribed deformations

Pitching Moment: Maneuver Rev 14

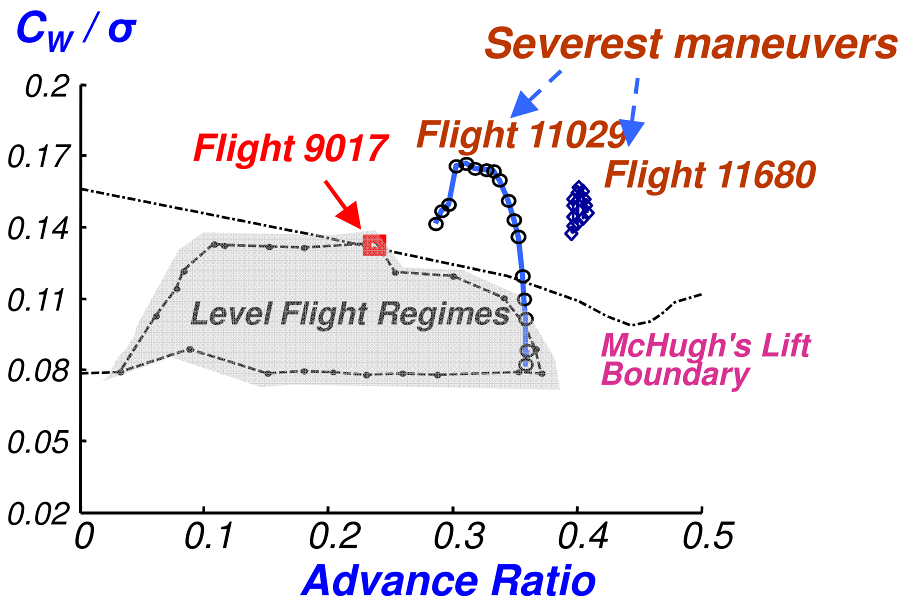


- ***Prediction with CFD/CSD shows good correlation for two stall cycles on retreating side -- advancing blade stall not predicted***

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

	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

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

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

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

	Past	Present	Future
Trim/Steady Response	Modal method/ Harmonic Balance	Modal/Complete FEM 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

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)

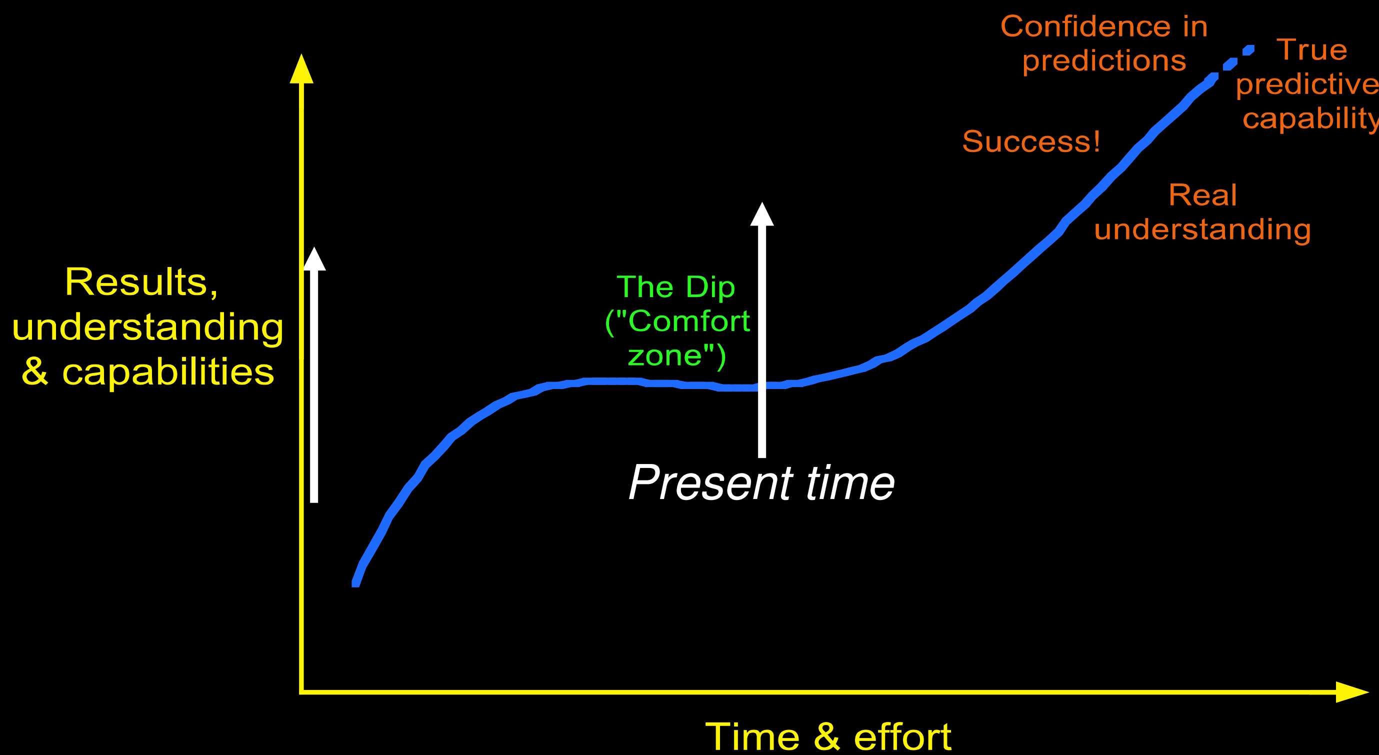
Technology Needs

- *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)"*

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***