Alfred Gessow Rotorcraft Center

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Review of Rotorcraft Technology & NASA Role

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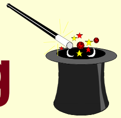
Rotorcraft Aeromechanics Research

Today's Technology Drivers

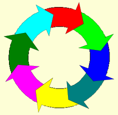
- All round desire to increase performance & efficiency
  SFC, Figure of merit, power loading, L/D, speed, etc

- Explosion of IT & wireless technology

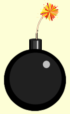
- Maturation of composite technology & upcoming smart structures and nano technologies



- Availability of sophisticated prediction tools

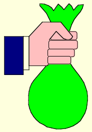


- Availability of miniaturized sensors & reliable measurement techniques

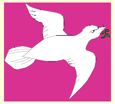


Today's Non-Technology Drivers

- 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

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

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***

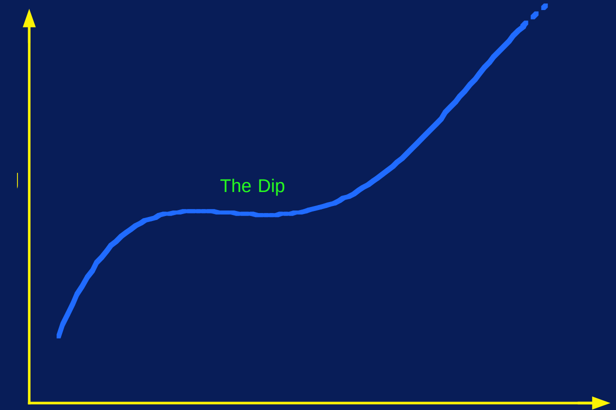
Postdictive Versus Predictive Capabilities

- ***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”?

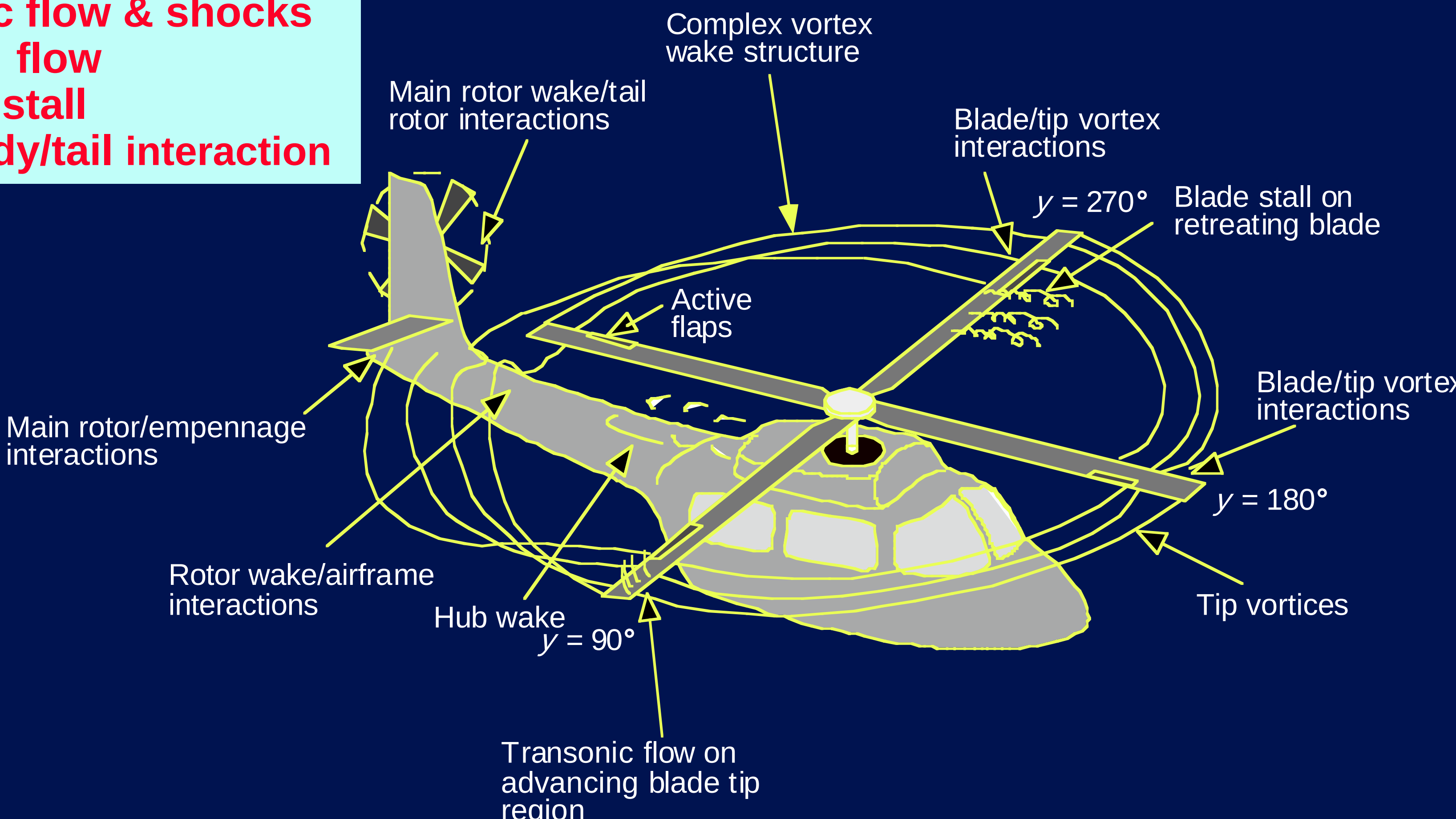
- ***R&D Funds***
  - *- Erratic flow of funds*
  - *- Following of milestones (creativity secondary)*
  - *- Too much bureaucracy!!*
- ***Future Rotorcraft***
  - *- Overindulgence in upgrades*
  - *- Pursuing infeasible projects*
  - *- Industry: too short sighted*
- ***Government Laboratories (Buyers)***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

Aerodynamics

Aerodynamics: Challenges

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

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



Aerodynamic Modeling: State-of-Art

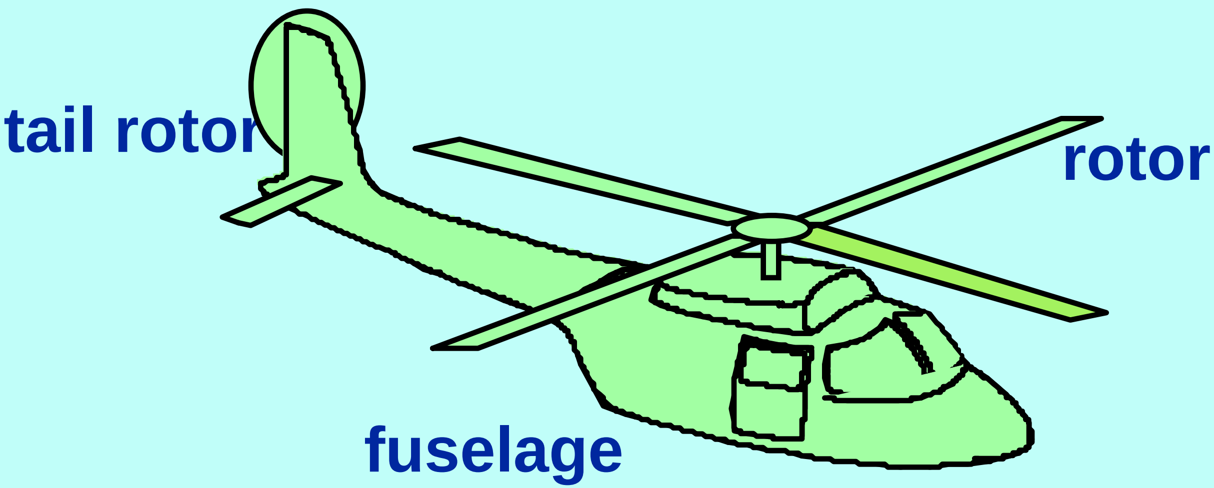
	Past	Present	Future
Blade Aero	Lifting line Table-lookup Empirical stall	Indicial response functions for unsteady and dynamic stall	CFD/CSD coupling
Rotor Wake	Linear inflow Prescribed	Free wake Frequency & time-domain	CFD-generated wake capture
Airframe	Flat plate area	Table lookup Panel method	CFD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

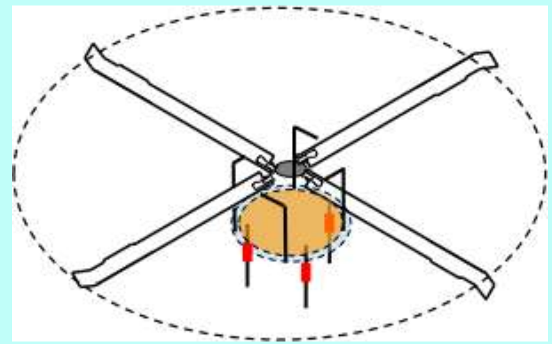
NASA played a key role in development of CFD tools; and future of rotorcraft is towards exploitation of CFD tools

Structural Modeling

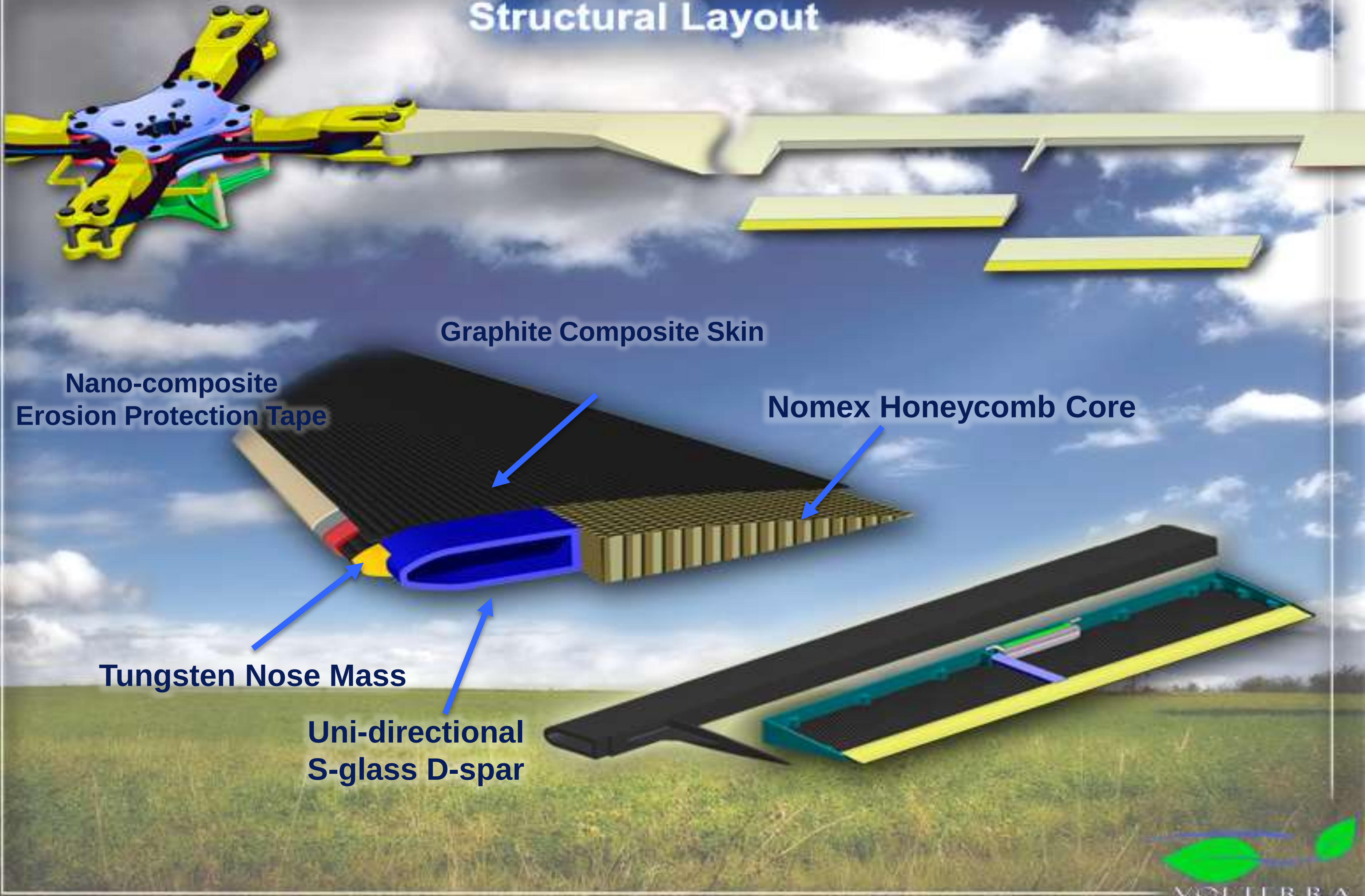
Structural Modeling: Challenges

- Rotor built of composites with redundant load paths and undergoing large deformations
- Airframe 3-D structure with complex joints and cutouts
- Complex couplings main-rotor/airframe/tail-rotor/engine
- Structural integrity, energy absorption and repair





Structural Layout



Airframe Assembly

Structural Modeling: State-of-Art

	Past	Present	Future
Deflections	Moderate-large	Moderate-large	Large (no ordering)
Blade Modeling	FEM/modal 1-D	FEM/Multibody 1-D	Multibody 3-D
Airframe	Stick model	3-D FEM/modal	Multibody Airframe/Rotor/Engine Coupled
Materials	Small strain Isotropic	Small strain Anisotropic	Large strain Ultra-light/multi-functional

NASA/Army played a key role in development of structural modeling. Future towards coupled rotor/airframe/engine models through active collaborations of NASA/Army/Industry/academia

Dynamics

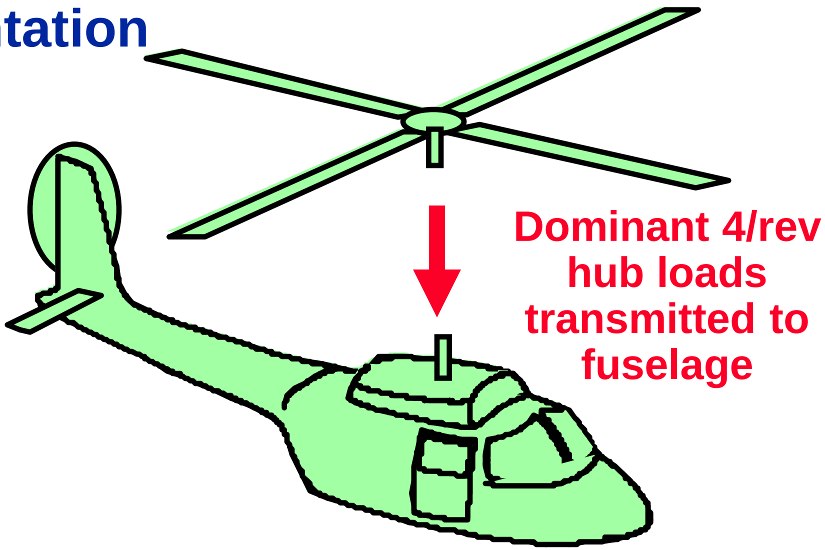
Dynamics

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)



High Vibration: Flight Conditions

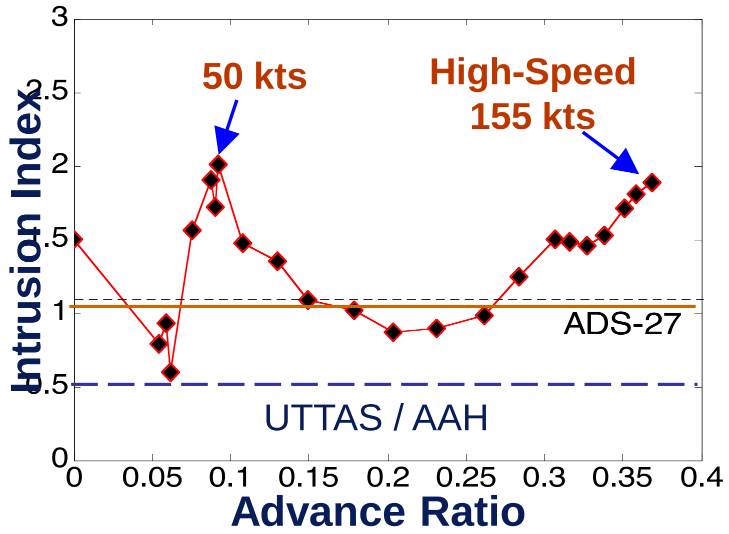
Sources of Vibration

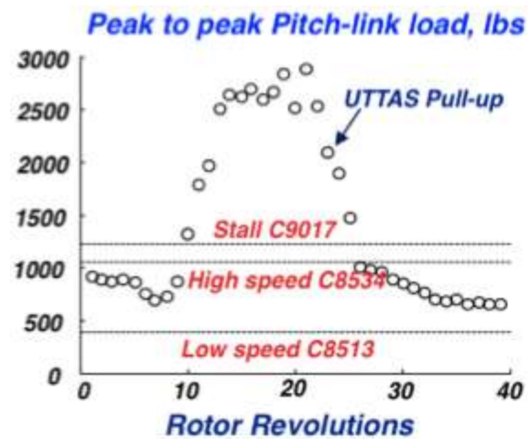
- Asymmetric flow in forward flight
- Complex wake
- Compressibility on advancing side and dynamic stall on retreating side

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

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

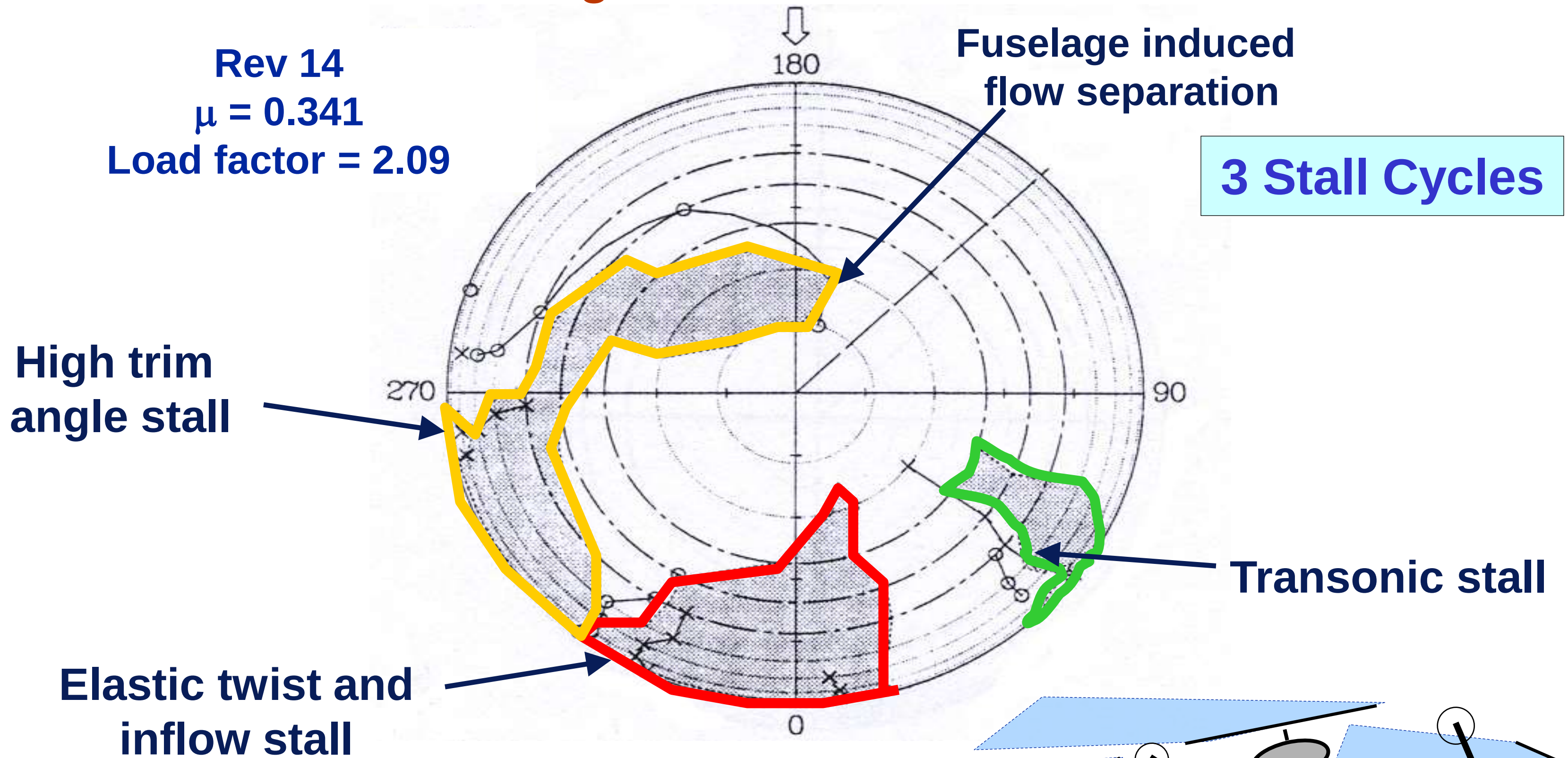
Measured Vibration at pilot floor
UH-60A 16,500 lbs



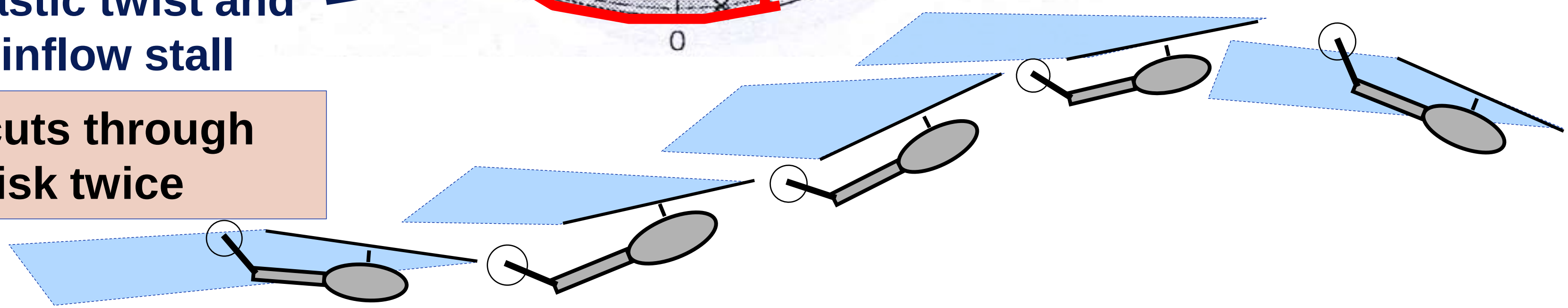


Flight 11029, Severest UH-60A Maneuver: Stall Map

Flight Test Measurement



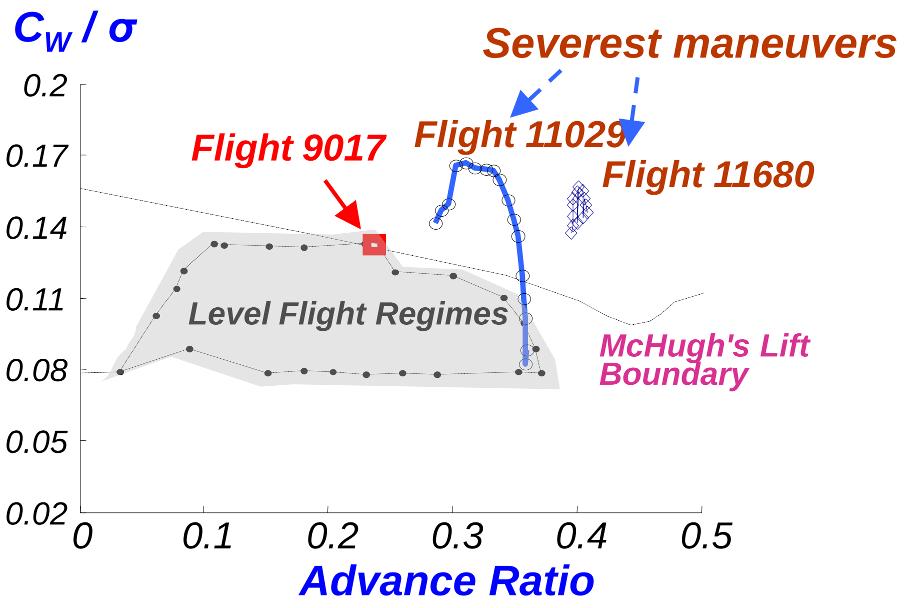
Wake cuts through rotor disk twice



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 Findings:

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

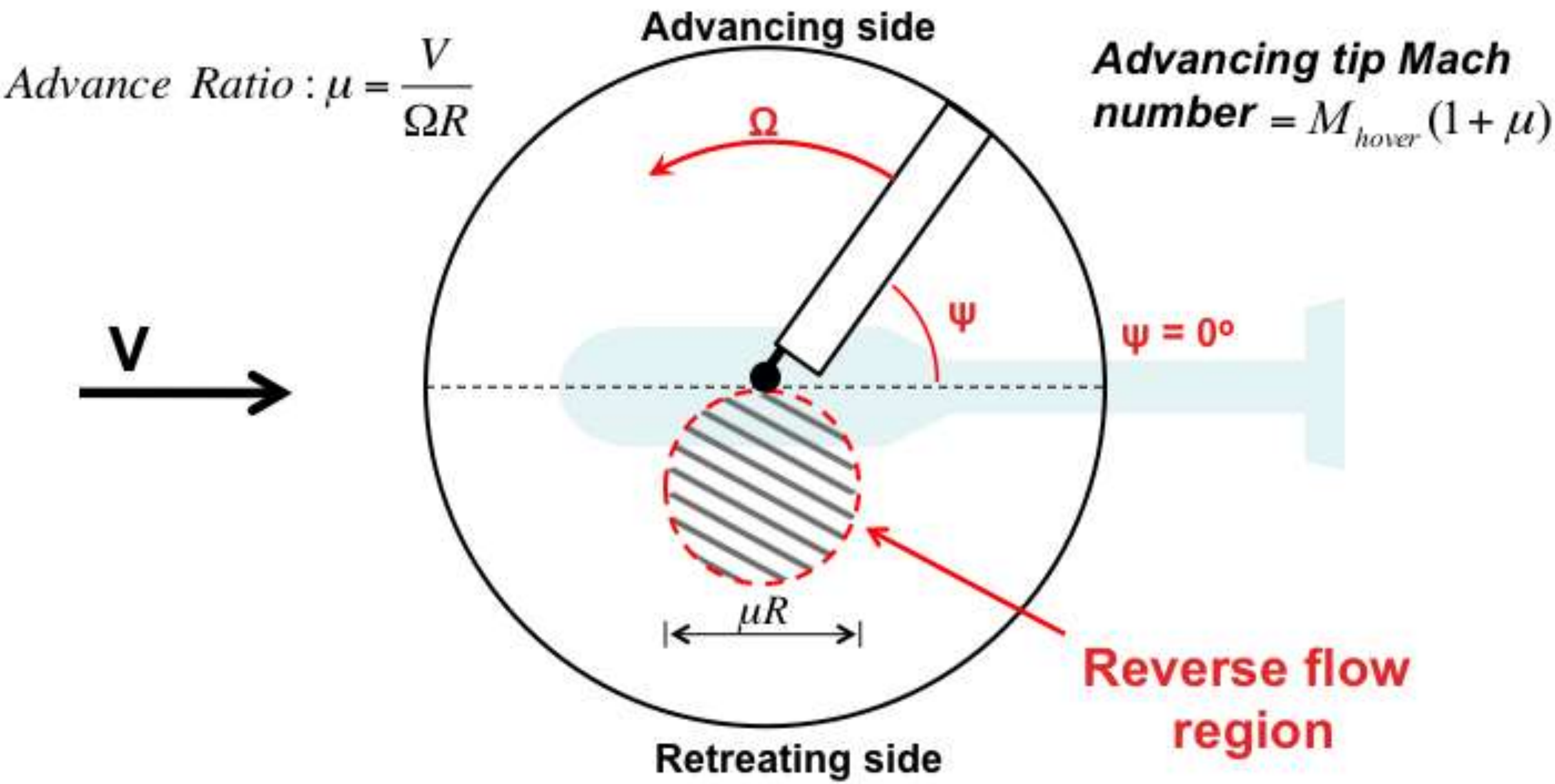
Dynamics: State-of-Art

	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
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

NASA/Army started a major initiative in 2001 "UH-60 Loads Prediction Workshop" actively involving industry, academia and Govt Labs, Continuously meet twice a year, solved many barrier problems and helped industry to refine their prediction capability (competitiveness)

High Speed Rotocraft

Advance Ratio

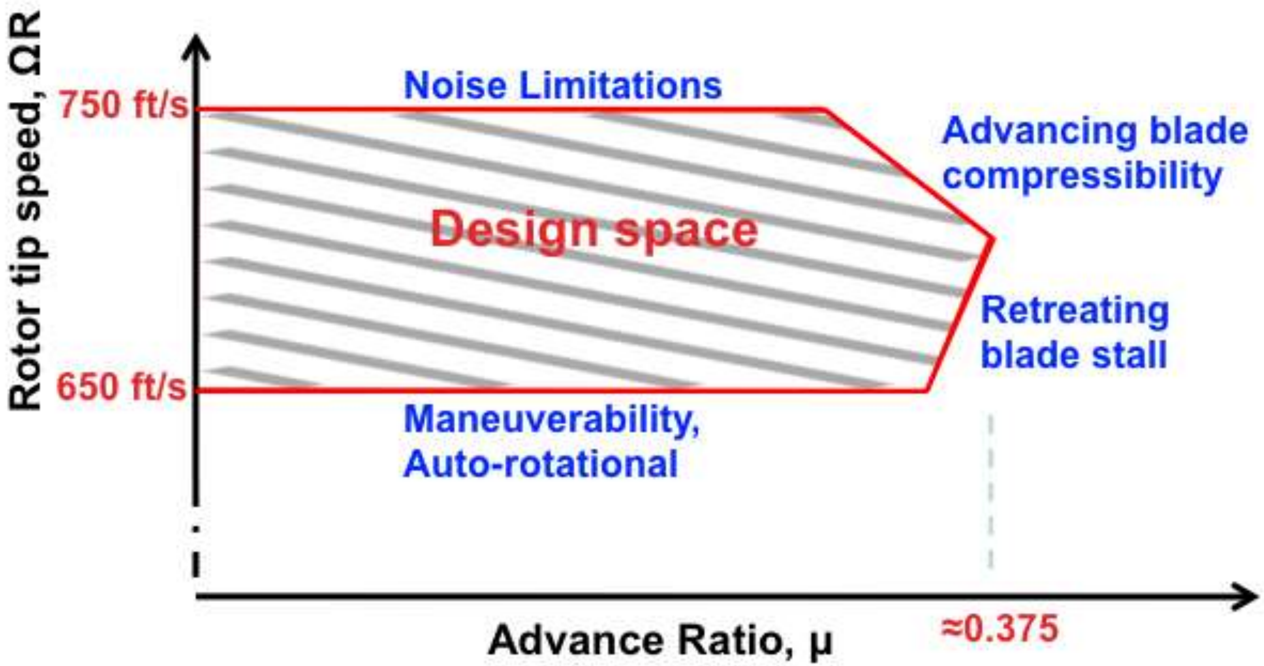


Because of compressibility effects on advancing side and reversed flow region on the retreating side, Max μ ≤ 0.35-0.4 for conventional rotors

Flight Envelope

Basic Design Considerations

For μ = 0.375, and tip speed = 700 ft/sec
Advancing tip Mach number = 0.85 (Drag Divergence ≈ 0.85-0.95)
Max speed = 260 ft/s ≈ <u>155 knots</u>



Basic Rotor Design Requirements

To achieve:	Design requires
Efficient hover	Low disc loading Low tip speed
High payload	Low disc loading High dynamic pressure Low empty weight fraction
High speed	Low tip Mach number
Autorotation	High rotor energy

Basic Rotor Design Requirements

To achieve:	Design requires
Efficient hover	Low disc loading: <- Minimize induced power Low tip speed: <- Minimize profile losses.
High payload	Low disc loading: <- Reduce blade stall High dynamic pressure: <- Reduce stall Low empty weight fraction:<- Parasitic weight
High speed	Low tip Mach number:<- Limit compressibility
Autorotation	High rotor energy: <- Increase rotor energy

High Advance Ratio Aeromechanics: Future Outlook and Needs

Slowed rotors can enable dramatic speeds and efficiency for all rotorcraft – helicopters, compounds, and tiltrotors

A160T (50%)

X2 (20%)

V-22 (19%)

- *Need rotor frequencies to be designed over 40-50% RPM variation*

  - Need innovative drive systems or gas turbine to support such a variation

Helicopters	Compounds	Tiltrotors
Hover	200 kt	350 kt

Model/Full-Scale Testing

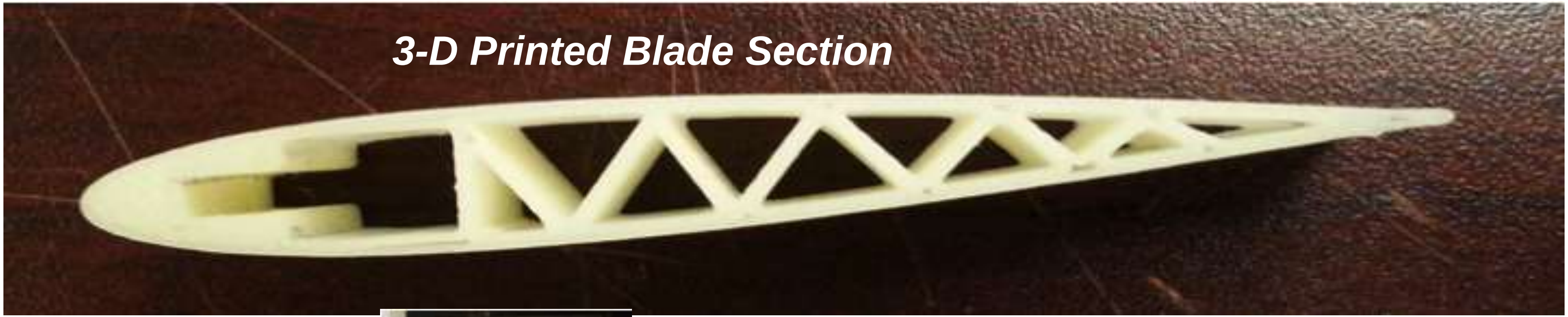
NASA/Army UH-60A Flight Test

- Acquired a comprehensive set of data with pressure instrumented blades
  - 31 test flights: 7 level, 3 maneuver, 9 ground acoustics, 6 inflight acoustics, 6 flight dynamics (480 sensors)
  - performance, structural loads, hub loads, airloads, blade deformations
- Documented complete rotor characteristics and flight test conditions
- Widely used by industry/academia/labs; provided competitiveness to industry

NASA High-Advance Ratio Full-Scale Wind Tunnel Tests

High Advance Ratio Aeromechanics: Future Outlook and Needs

- Need more detailed experimental data under high-μ reverse flow conditions with instrumented blades (strain gages, pressure sensors), Blade deflections, flow components
- New ways of fabrication of rotor blades using 3-D printing
- New ways of measuring blade deflection using VICON visual tracking



Vicon visual tracking

Rotorcraft Comprehensive Analyses

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

NASA/Army played a key role in development of modern comprehensive analyses (CAMRAD-II & RCAS)

Future is exploitation of robust coupled analyses for optimized designs

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*

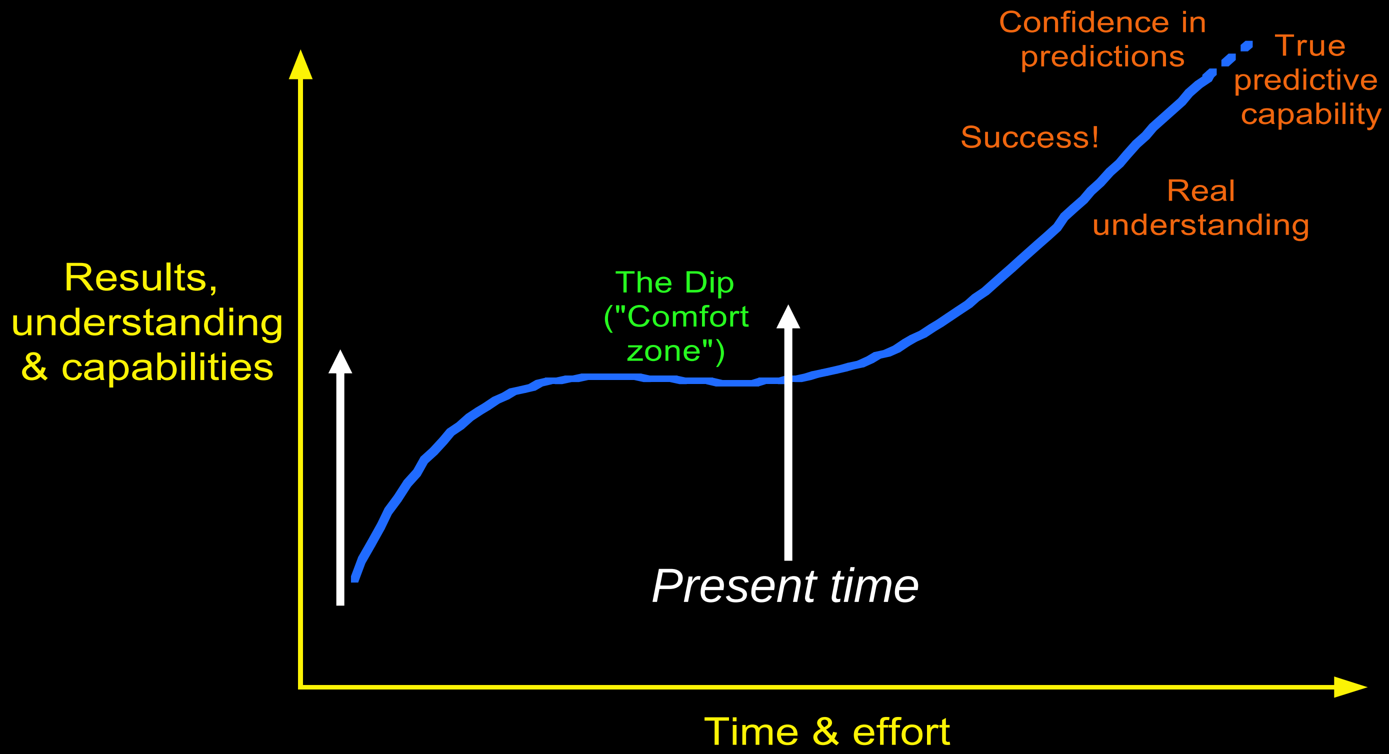
  - Carefully planned component and configuration tests under controlled flight environment and systematic validation by team (government, industry & academia)

  - 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!!!!)*
- *Experimental facilities are key to methodology robustness, product refinements and revolutionary designs (let us not close wind tunnels!!!)*
- *"Nurture active teams with NASA as lead (industry, labs and academia) validations of methodology (both at component & configuration level)"*
- *NASA/Army has to play a leadership role to nurture rotorcraft technology*

Crossing the Dip?



- ***Advances in aeromechanics appear poised for enormous potential in rotorcraft, especially towards the development of a mission adaptive rotors with a quantum leap in performance***
- ***Absolutely necessary for international competitiveness!!!!***