Development of a CFD Capability for Full Helicopter Engineering Analysis

George Barakos

Department of Engineering
University of Liverpool

UKAA Consortium Conference
5/6 April 2006
Loughborough University

Collective effort of more that 10 person-years

- Ken Badcock, René Steijl, Alan Brocklehurst, John Miller, Adriano Gagliardi, Agis Spentzos, Jeremy Beedy, Romy Morvant, Stefano Rolfo, Geoffrey-Alexis Hakkens

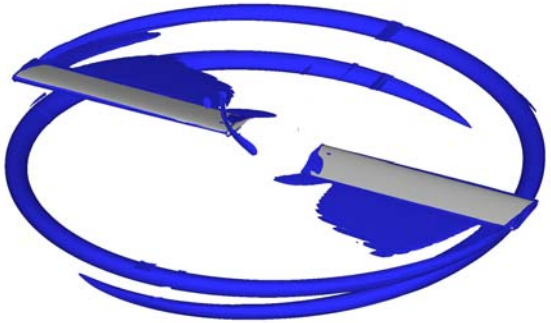
Outline of the presentation

Motivation and Objectives

CFD Method for Rotorcraft

Examples of Rotorcraft CFD

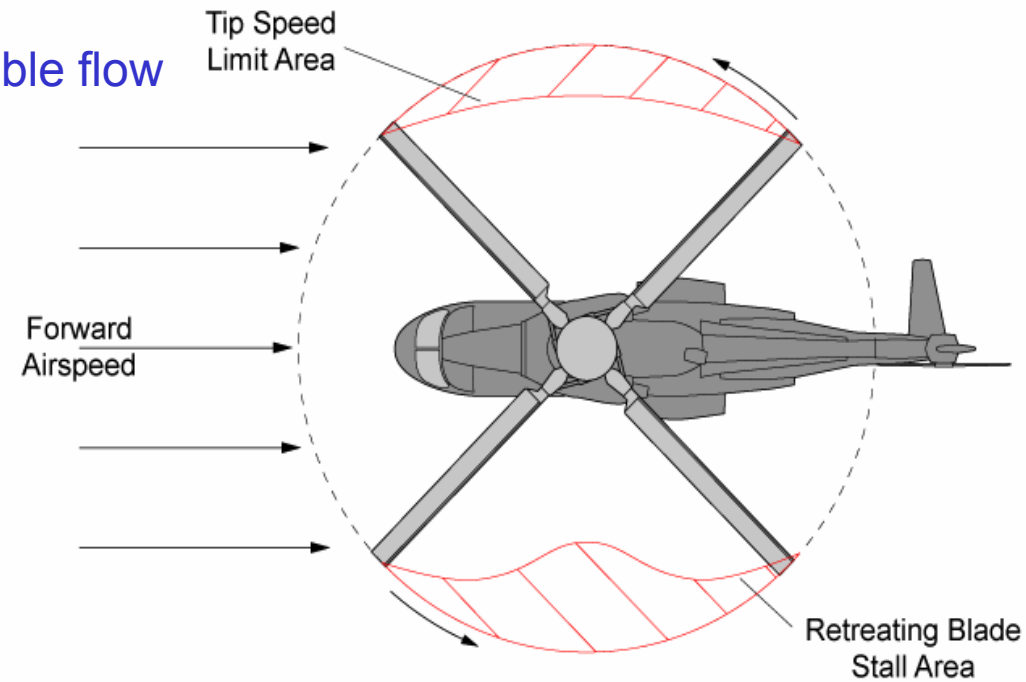
- Prediction of vortex locations
- Design optimisation of a flapped rotor
- Advancing side aerodynamics
- Dynamic stall on a rotating blade
- Combined Rotor/Fuselage Configuration



Summary and Future Steps

Motivation – Helicopter flows are interesting!

- Unsteady, turbulent, vortical, compressible flow
- Stall on retreating side
- Shock hysteresis on advancing side
- Blade-vortex interactions
- Complex blade motion
- Complex wake structure
- Bluff-body flow around the fuselage
- Transition to turbulence
- Main rotor/ tail rotor interactions
- Tail rotor power limitations



The aerodynamic design of helicopters must account for and balance all the above!

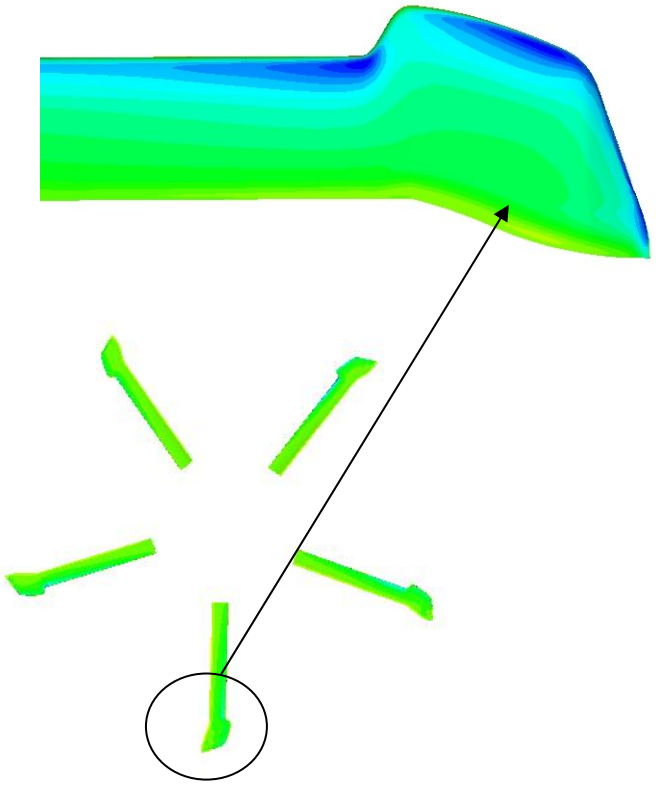
Objectives

- Non linear aerodynamics of rotor flows calls for CFD
- Need for detailed analysis of rotorcraft flows for:
  - *Design and Evaluation*
  - *Problem Solving*
  - *Understanding!*

- Rotorcraft problem is different

- CFD methods need extensions

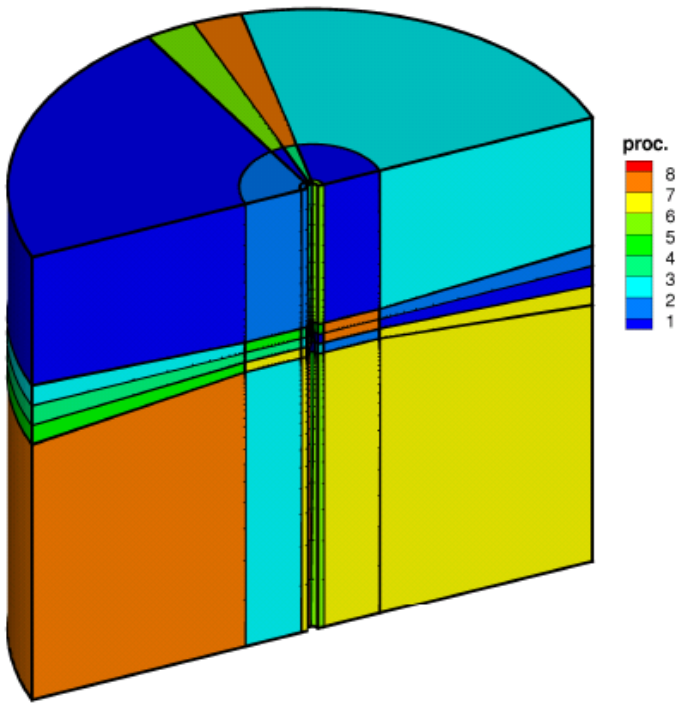
- Systematic approach is necessary to guarantee accuracy of results and efficiency of the method

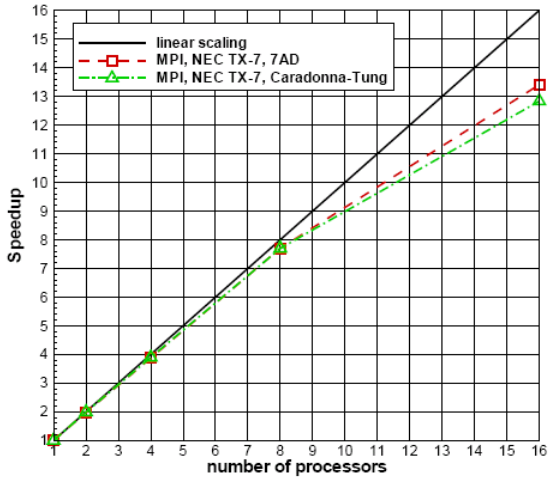


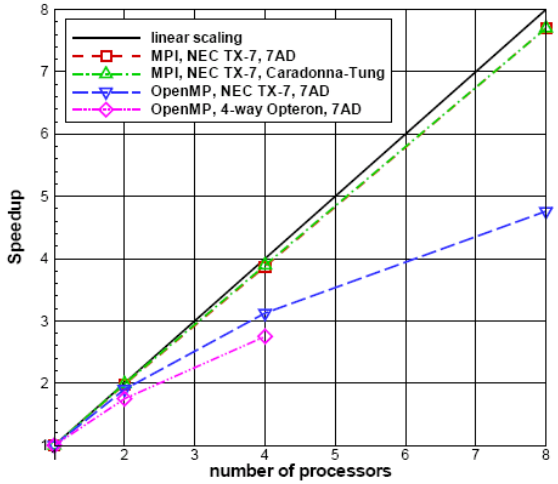
Outline of the CFD Solver

- Control volume method
- Parallel
- Multi-block (complex geometry) structured grids
- Unsteady RANS - Variety of turbulence models inc. LES/DES
- Implicit time marching
- Osher's and Roe's schemes for convective fluxes
- MUSCL scheme for formally 3rd order accuracy
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- Moving grids, sliding planes
- Hover formulation, rotor trimming, blade actuation
- Documentation
- Validation database

Parallel Computing

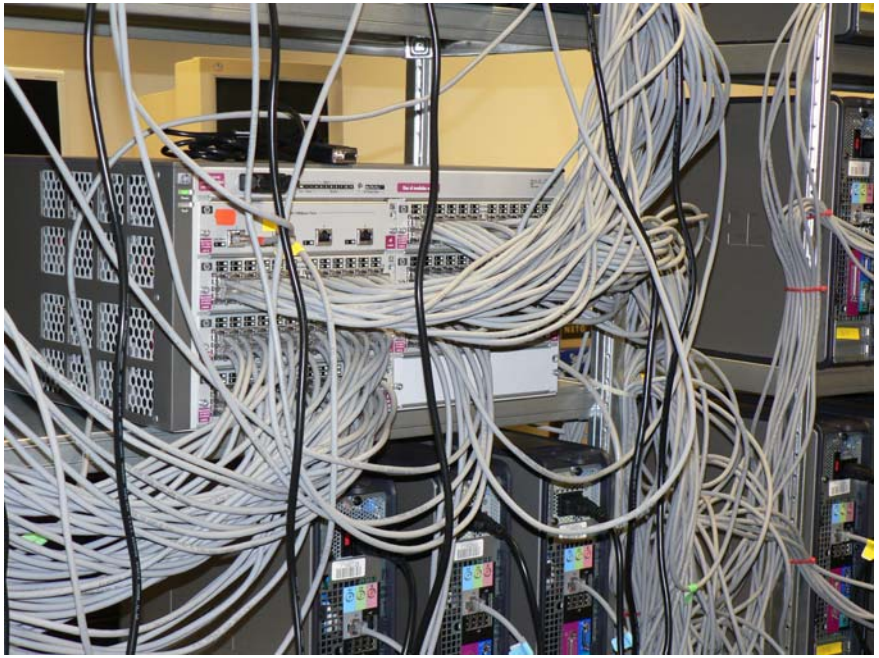






- Distributed and Shared Memory Machines
- MPI and OpenMP
- Linux Clusters
- CSAR, HPCX, NEC

Linux Cluster at Liverpool

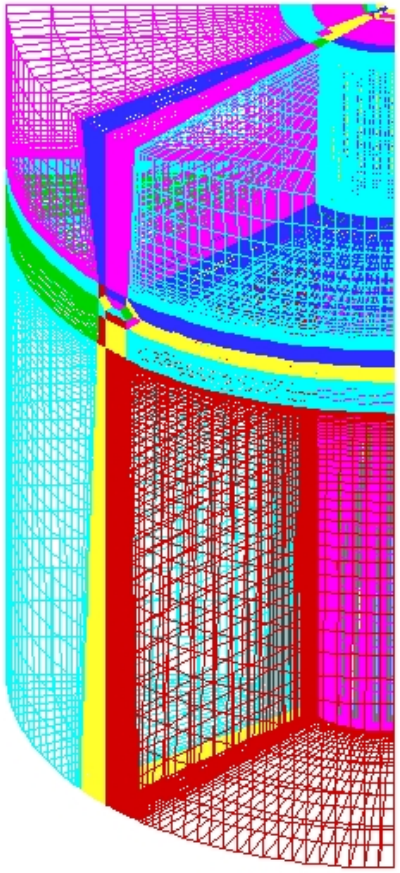


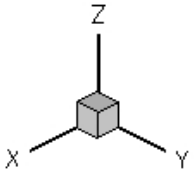
- **Jupiter 4**
- **Operational early 2006**
- **130 Pentium 4 machines, 3.0 GHz CPUs**
- **2 TB disk space**

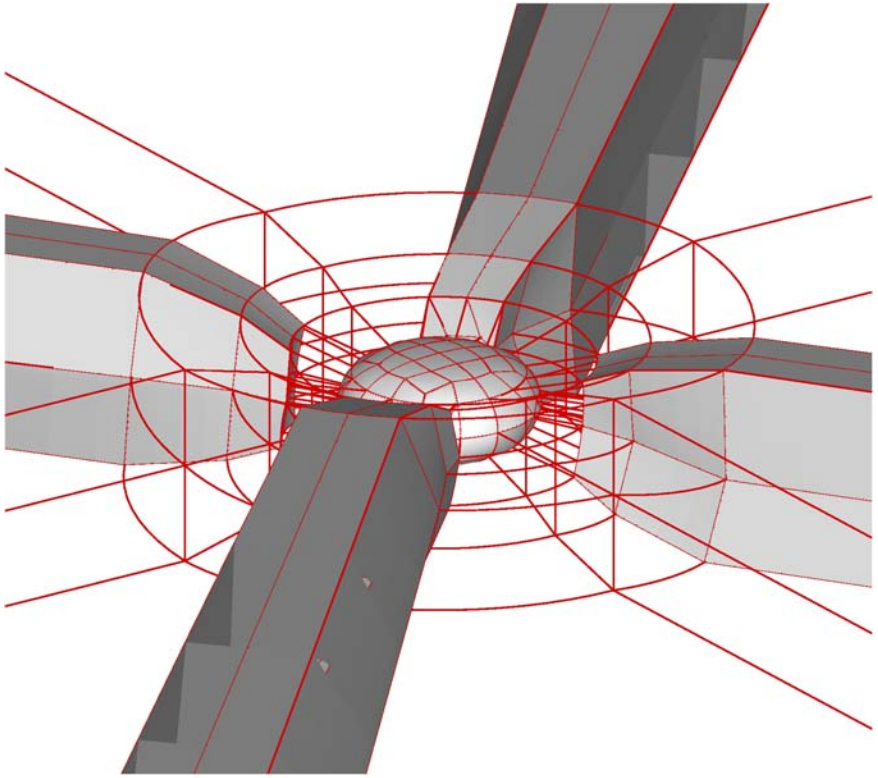
Example: Prediction of Vortex Locations

- Accurate representation of rotor wake is important
- Traditional wake methods predict vortex locations quite well for simple blade designs
- Few CFD investigations of wake locations exist
- Validation of CFD against data
- Typical grid size: 2-5 million points per blade
- Cost: 2 months using 36 P4 processors

Multi-block topologies for rotor cases



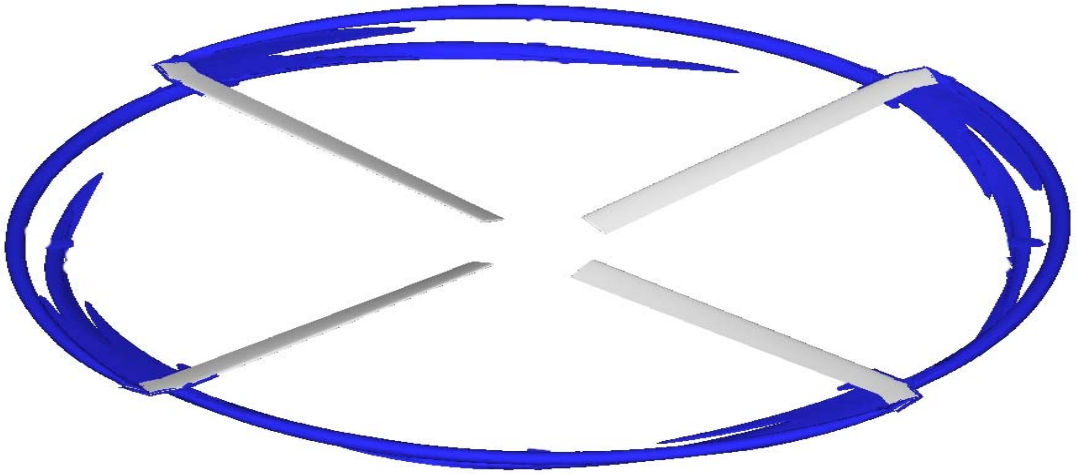


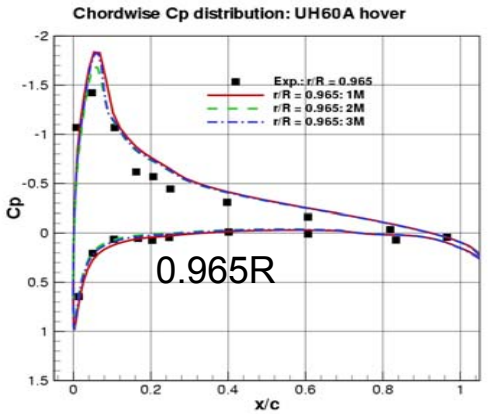


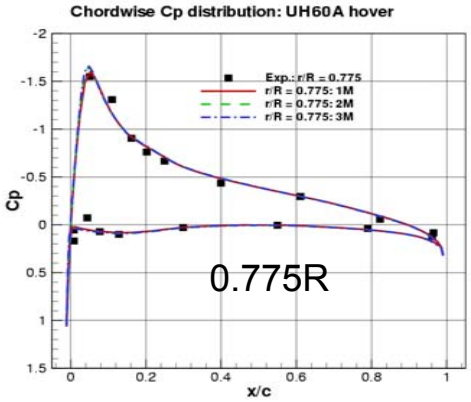
2-4.5M grid points per blade, blade actuation requires special topologies

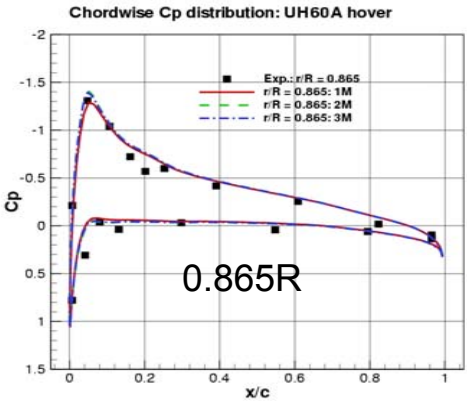
CFD – Validation - UH-60A Model Tail Rotor Tests (Lorber)

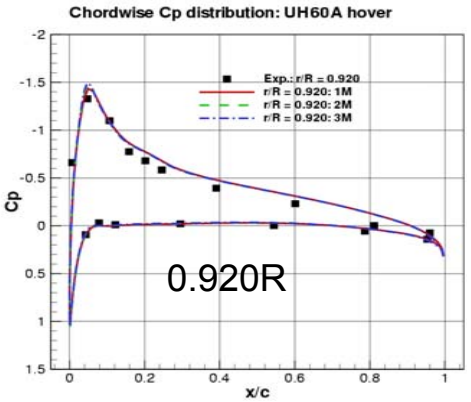
UH60A - Hover M_T = 0.626, 10.5° collective, 2.31° coning

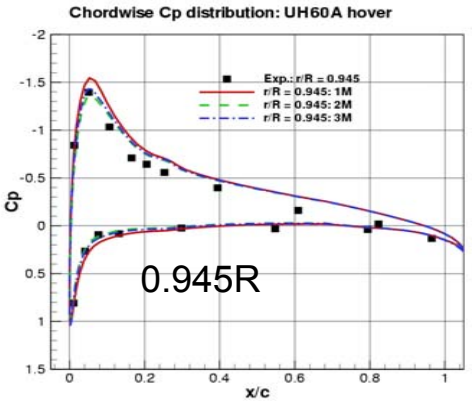




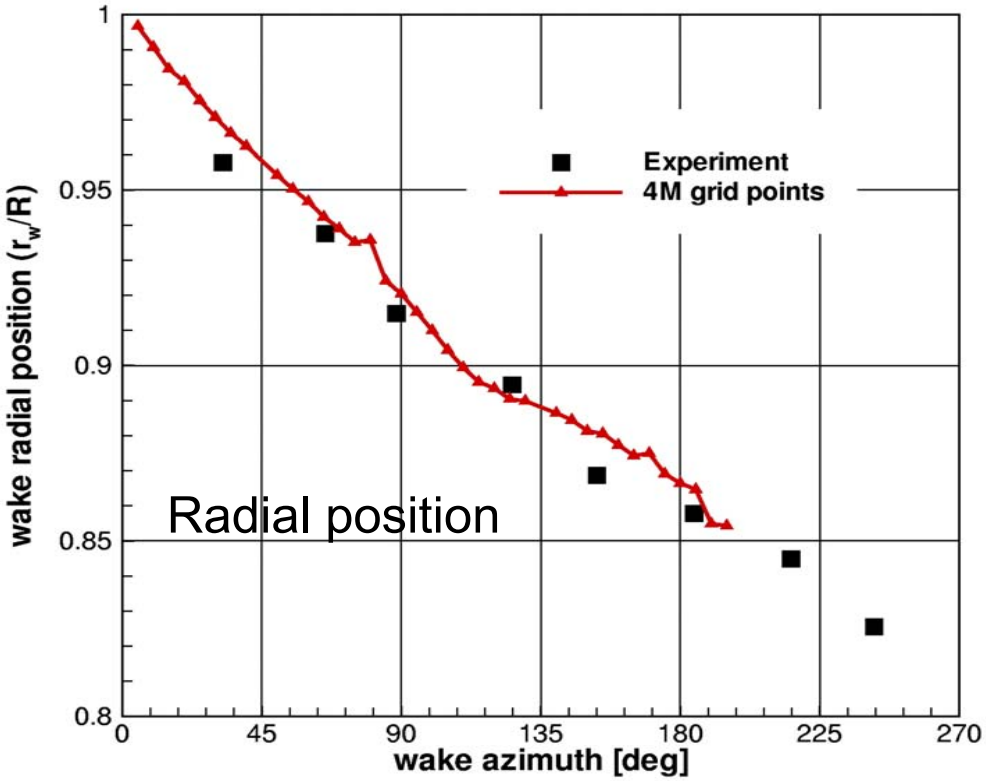


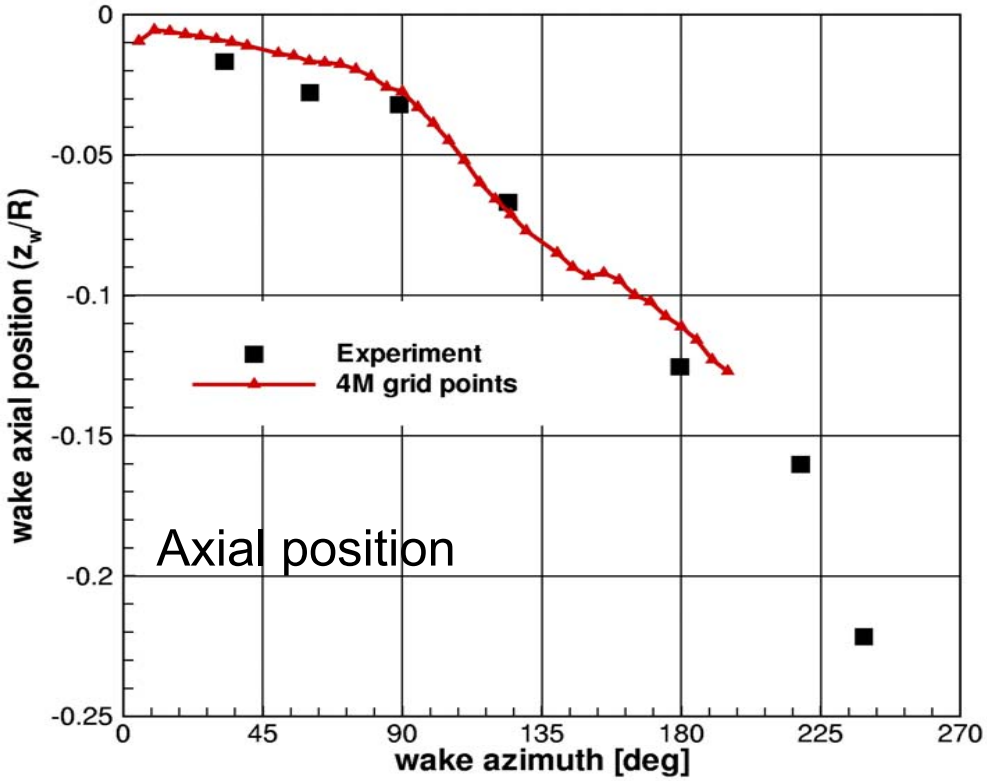






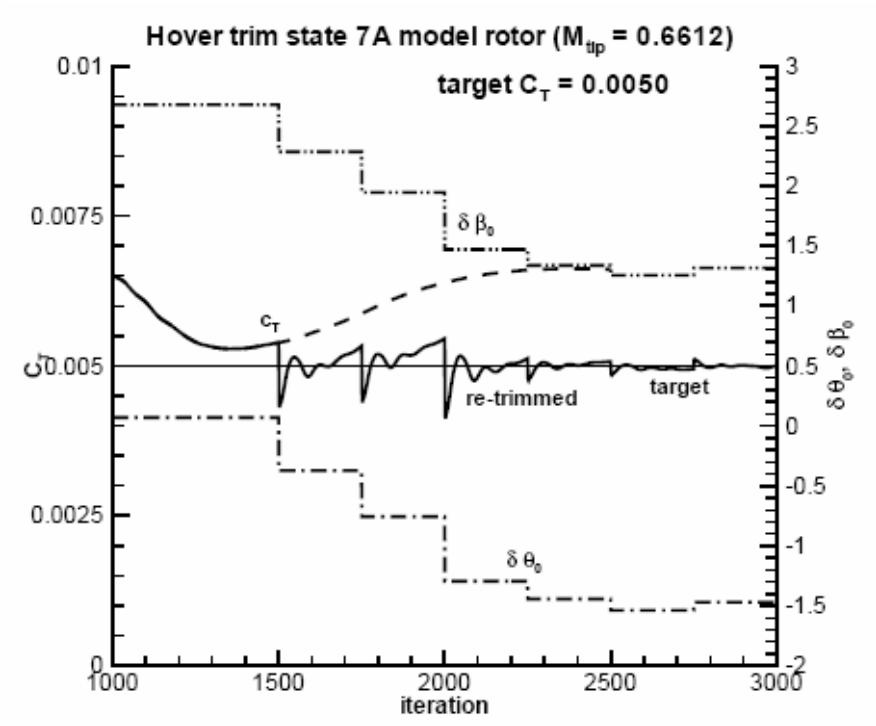
CFD – Validation - UH-60A Model Tail Rotor Tests (Lorber)





11.47° collective pitch, M_{tip} =0.628, inviscid, 240-block grid, 4.5M grid points

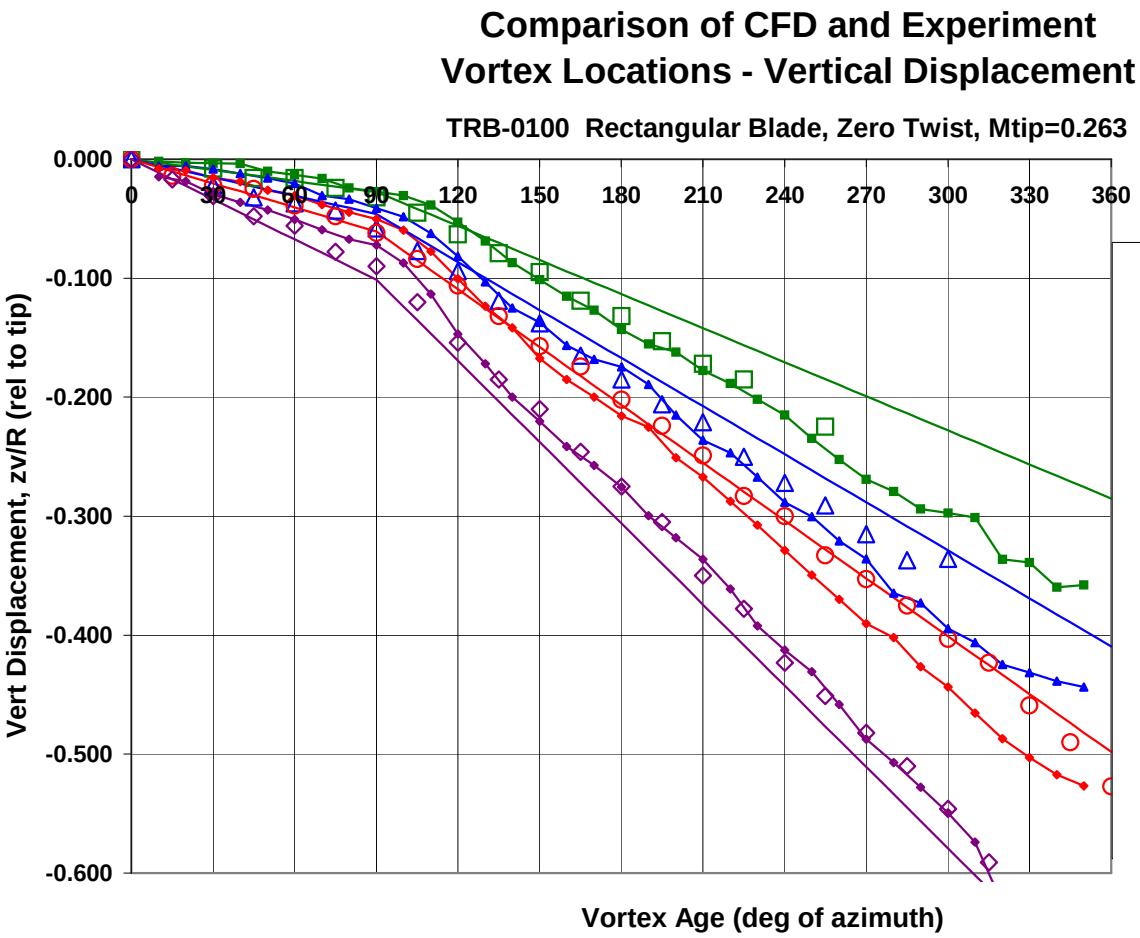
Hover computations are not steady-state!



- To trim the rotor, several iterations are needed
- Initial estimate of the control angles
- Collective and coning are needed for hover
- Cyclic inputs for forward flight
- Computations must be repeated at several thrust settings

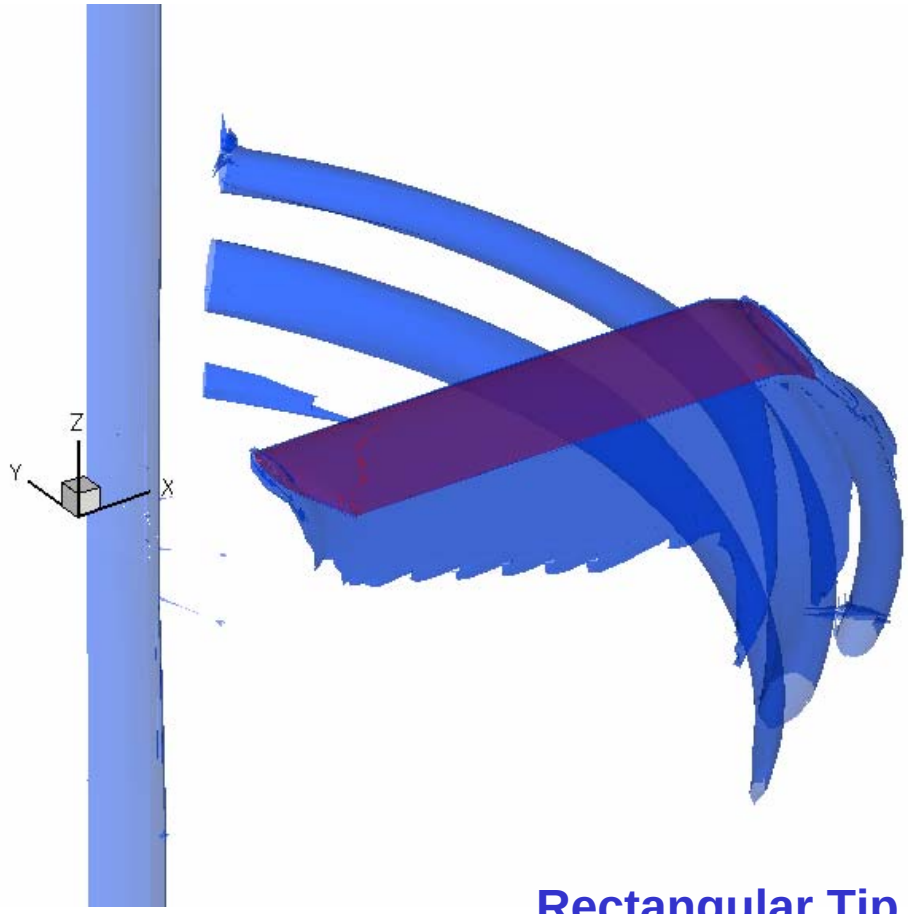
M_{tip}=0.6612, target C_T=0.0050

Comparison – Model Tail Rotor – Vortex Wake Trajectories



Vortex locations around the azimuth
Four blade designs

Iso-surfaces of Vorticity Magnitude

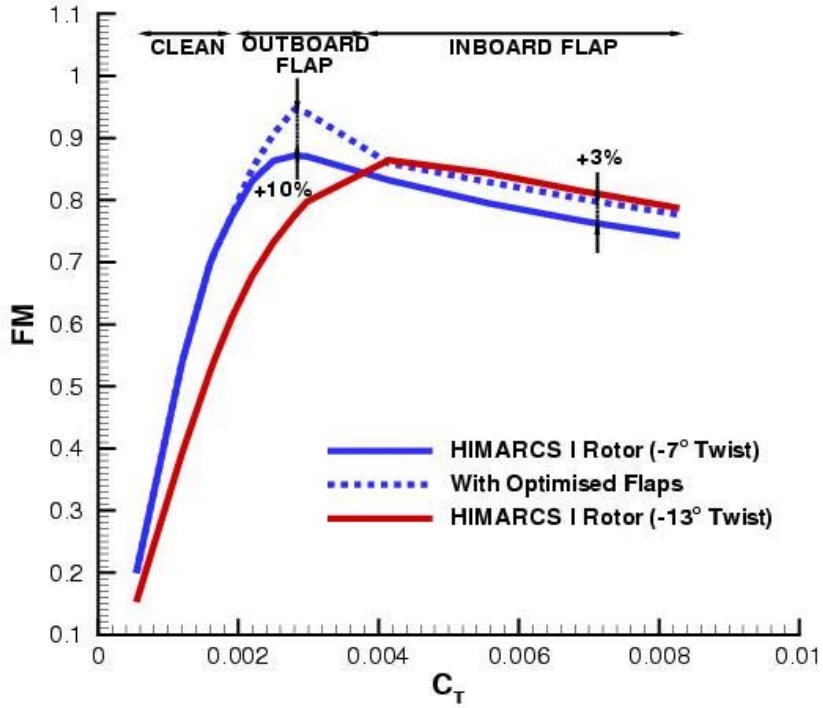


Rectangular Tip, Anhedral, 10 deg Pitch
Iso-surfaces of Vorticity Magnitude

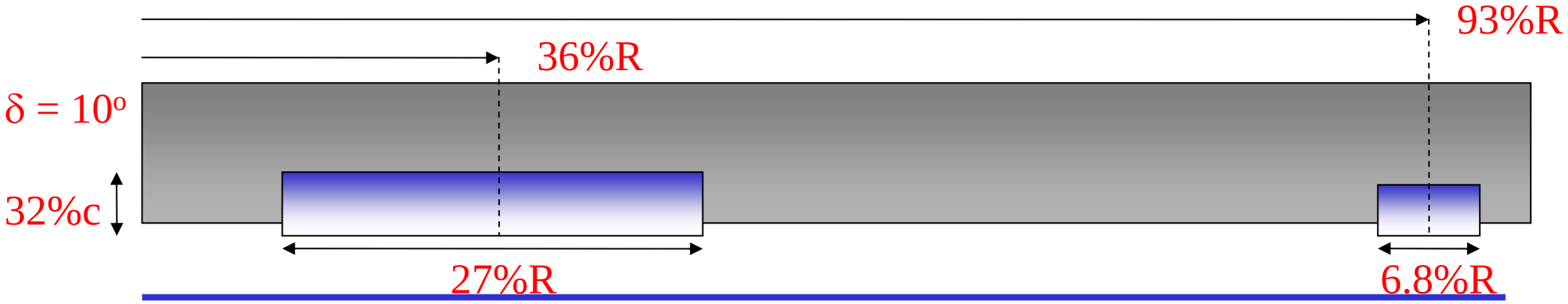
Example: Flapped Rotor Design

- Blade twist can help with hover performance of rotors at high loading
- Blade twist could have adverse effects in forward flight
- Design a rotor with moderate twist and use a flap to recover performance during hover
- Typical grid size: 2-5 million points per blade
- Cost: 4 months using 36 P4 nodes

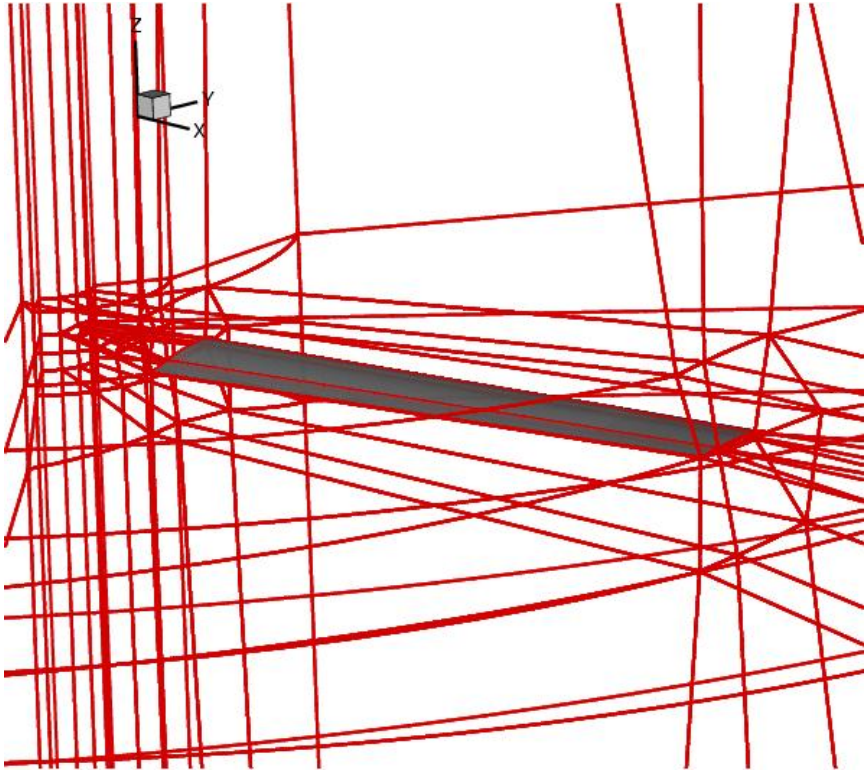
Optimum Flap Selections



Wind Tunnel Evaluation of a Helicopter Main-Rotor Blade with Slotted Airfoils at the Tips, Noonan *et al*., NASA TP 211260, December 2001

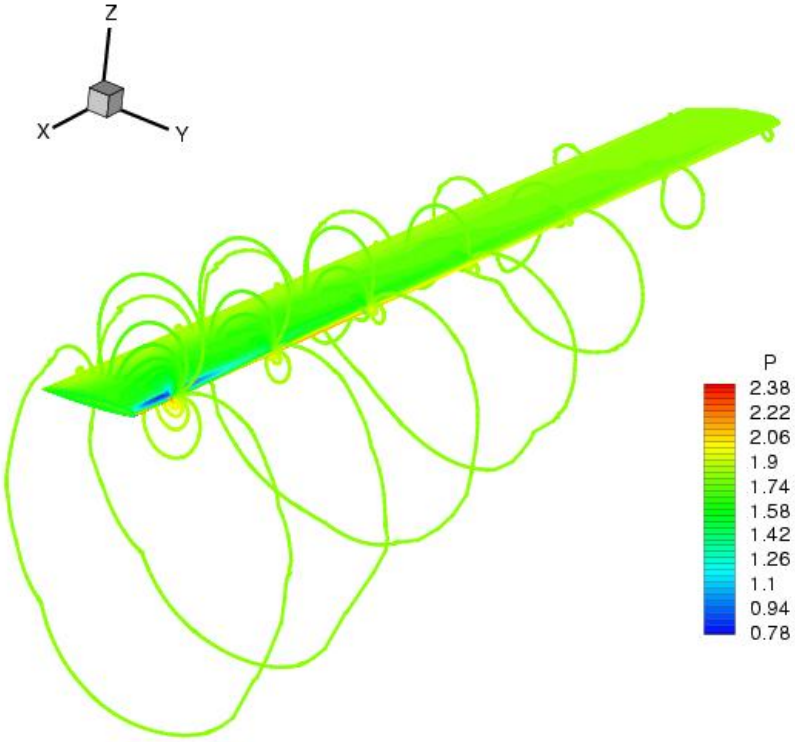


CFD Capability for Helicopter Analysis



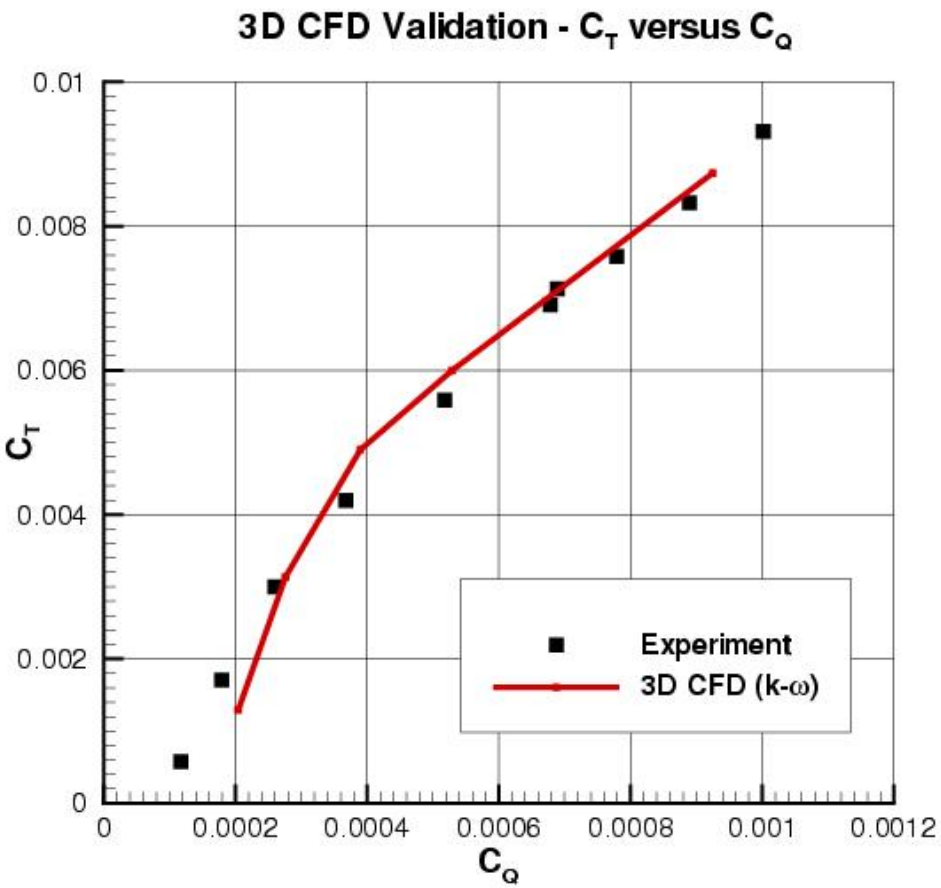
106 Blocks; 2mil+ grid points

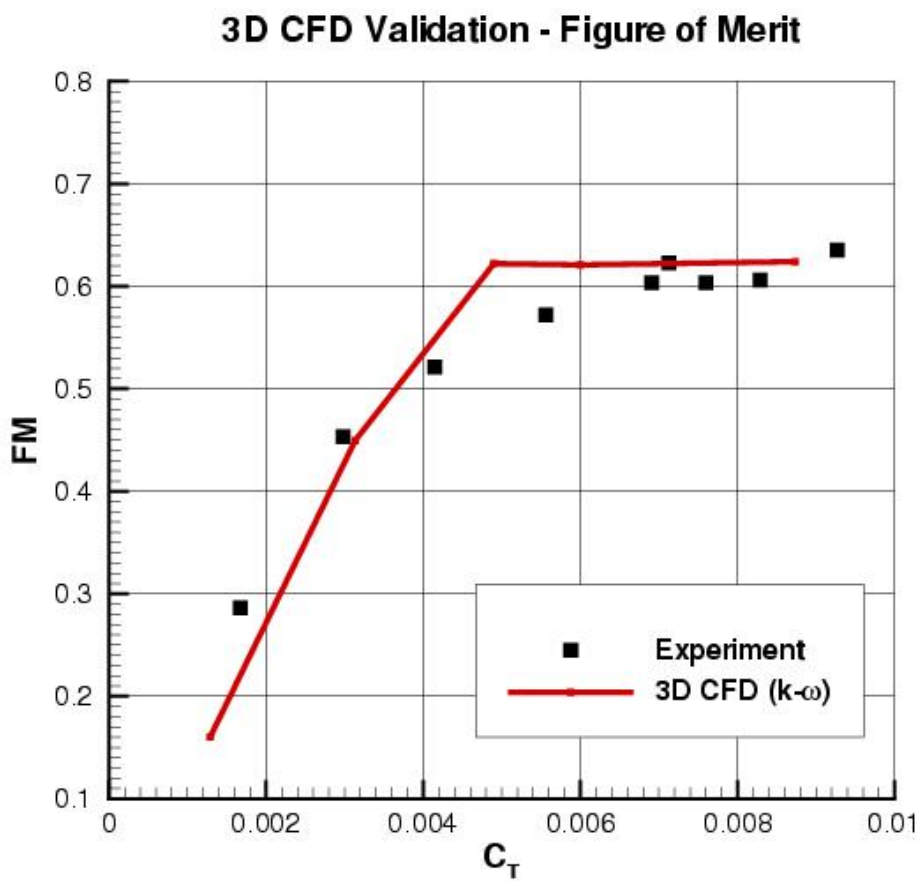
- Blocking for HIMARCS I Rotor
- Also used for varied twist blades



- Pressure Contours at $\theta = 13.11^o$ and $\tau = 3.124^o$ ($M_\infty = 0.627$ and $Re = 9x10^6$)

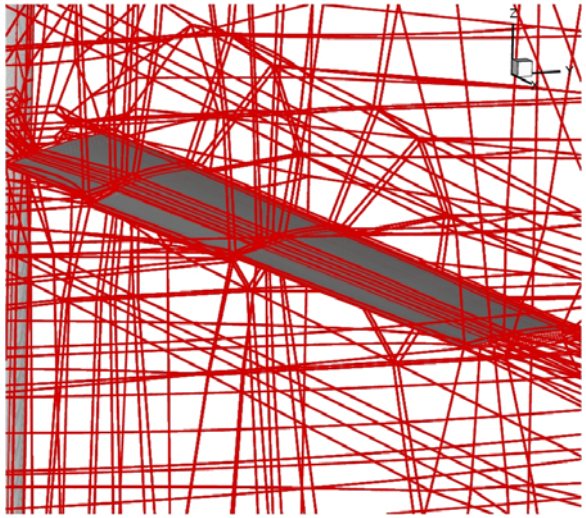
Validation against NASA Experiments

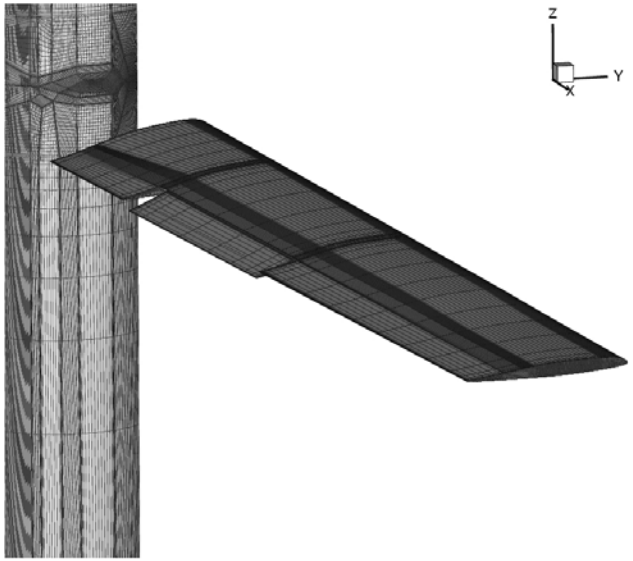


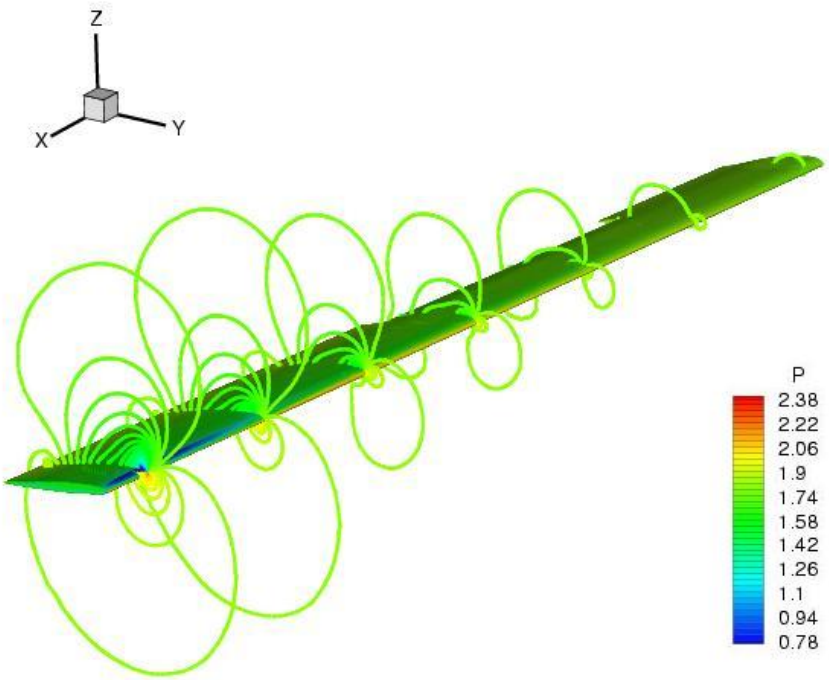


3D viscous computations at all thrust settings

Optimum Inboard Flap







- Pressure Contours at $\theta = 13.7925^{o}$ and $\tau = 3.304^{o}$ ($M_{\infty} = 0.627$ and $Re = 9x10^{6}$)

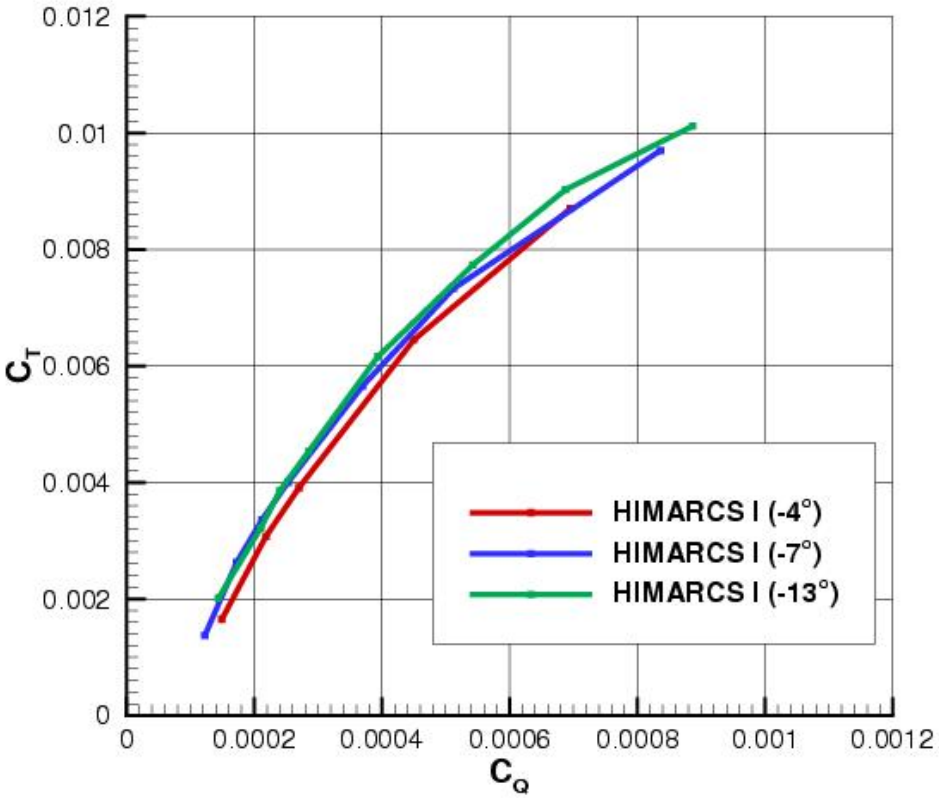
446 Blocks; 2.7mil+ grid points

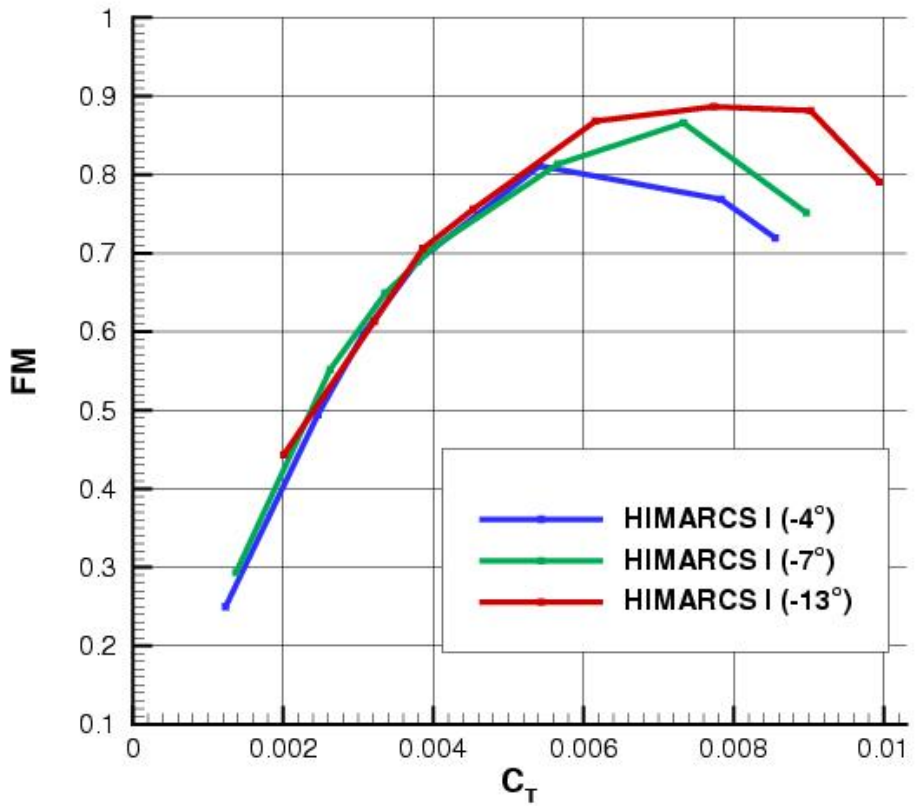
Test Cases Evaluated

- Both the clean and flapped rotor blades were evaluated at C_T settings ranging from 0.0007 to 0.01

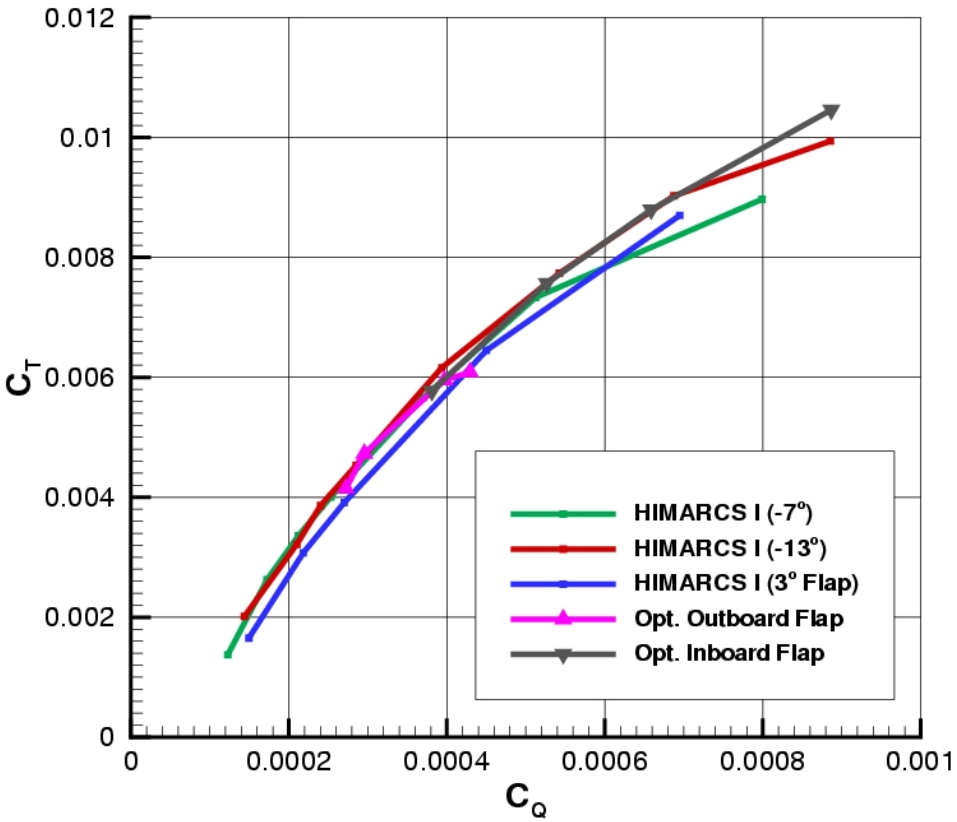
	Flap Location	Flap Span	Flap Chord	Flap Deflection	Number of Designs
Inboard	4.5%R-31.81%R	4.5%R-31.81%R	32%c, 22%c, 11%c	3°, 10°	396 at 15 C_T's
Outboard	88.6%R-95.45%R	2.27%R-11.36%R	32%c, 22%c, 11%c	3°, 10°	120 at 15 C_T's

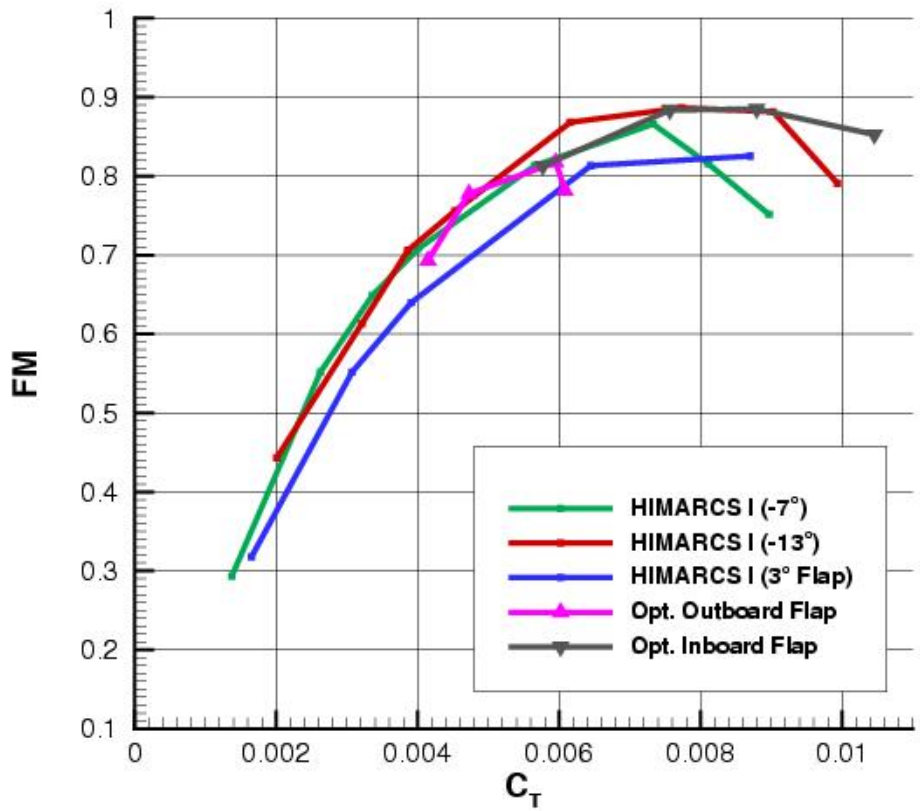
CFD Results - Blade twist study



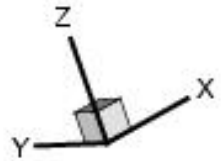


CFD Results - Blade performance

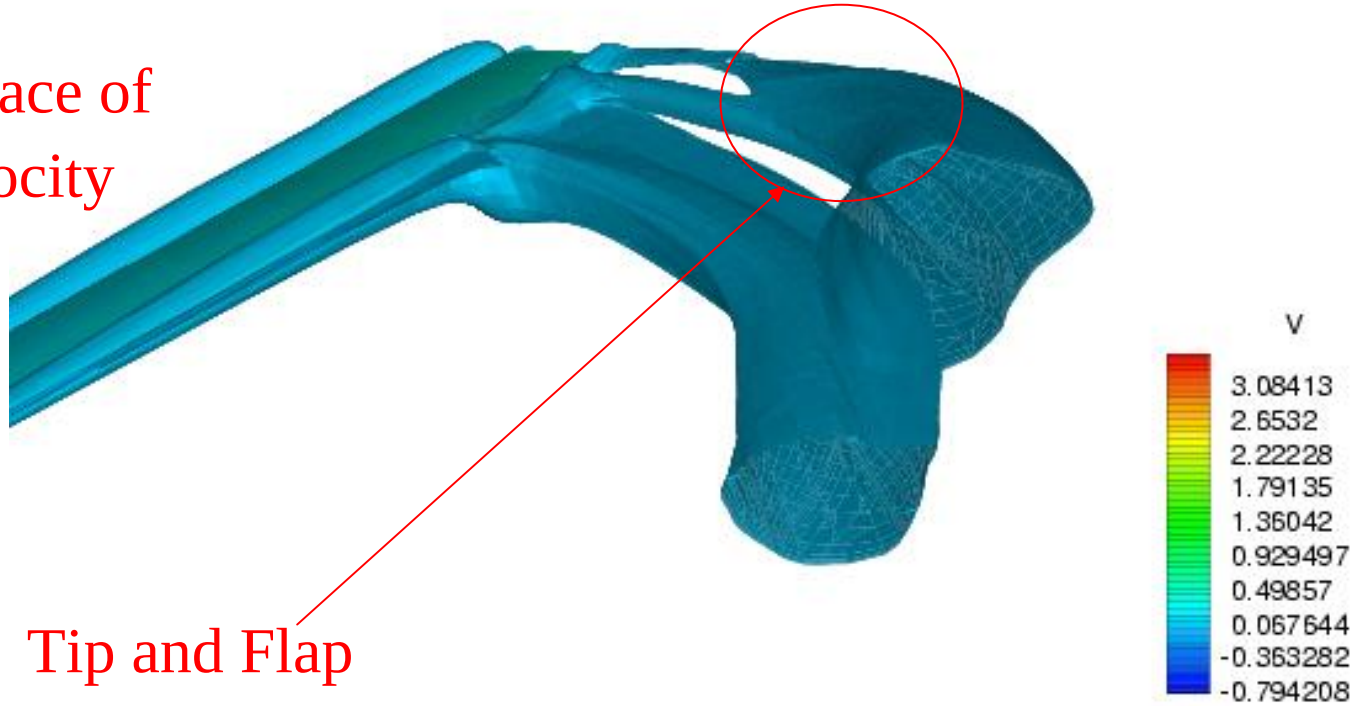




Wake Structure

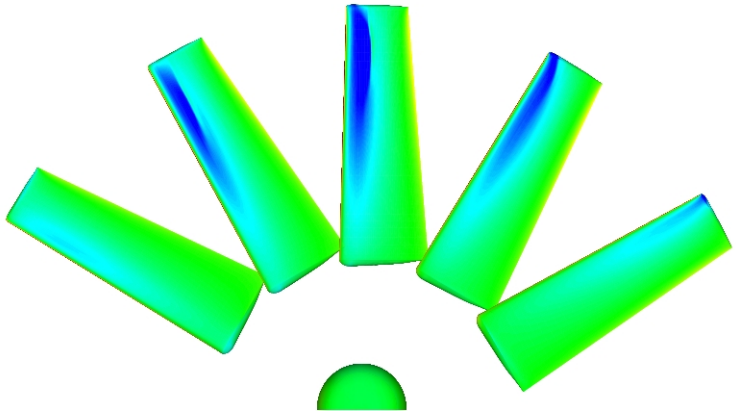


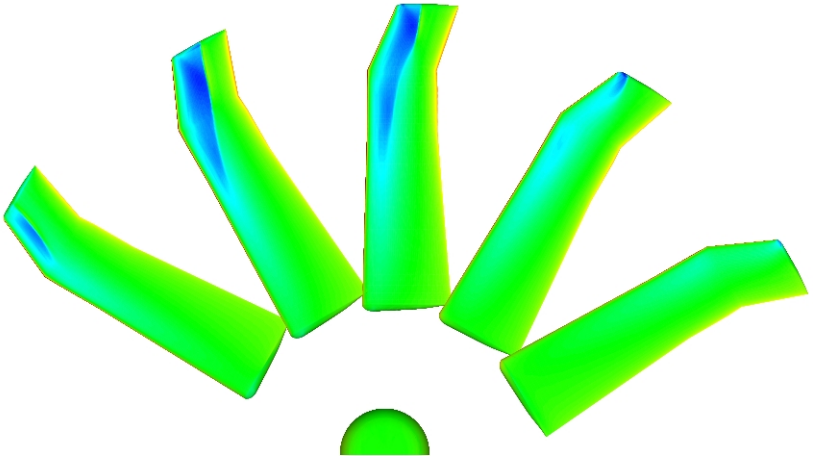
Iso-Surface of V-velocity



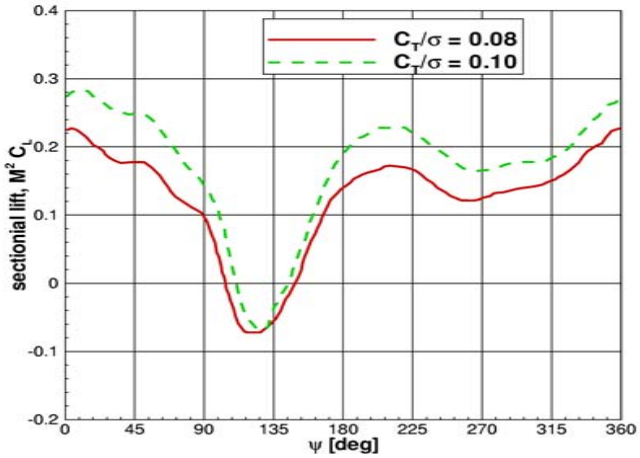
Tip and Flap Vortex Interaction

Example:
Advancing and Retreating Side Aerodynamics

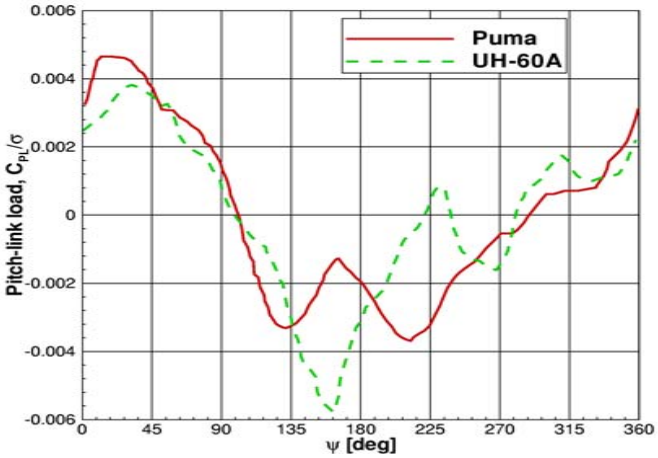




Example: Study of Advancing Side Aerodynamics



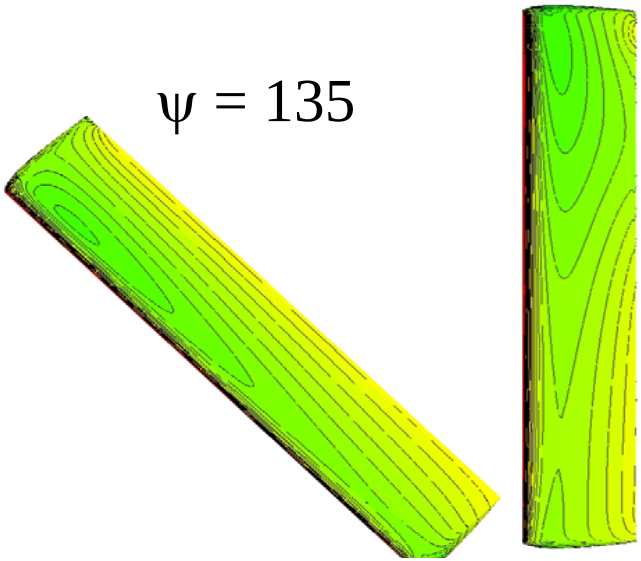
μ=0.37, 86.5% radius
(NASA TM-110396)

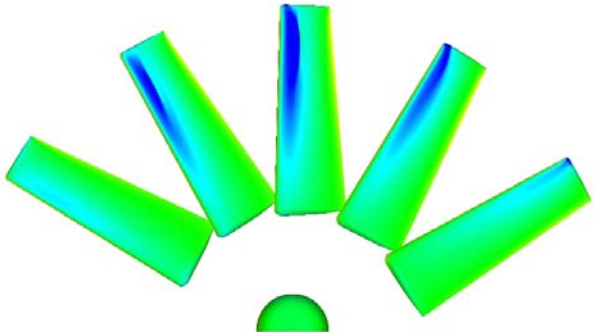


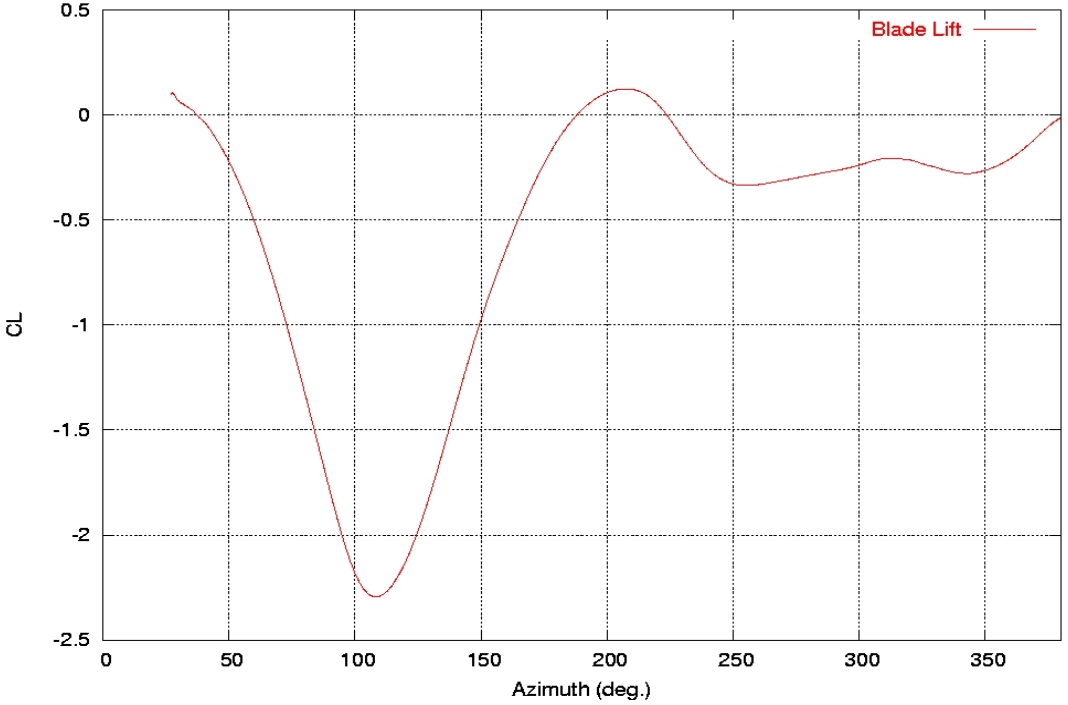
UH-60A: μ=0.355 and
Puma: μ=0.362 (NASA TM-104006)

- Advancing blade lift phase delay: minimum lift 40° beyond ψ = 90° at high μ
- Pitch-link load shows similar phasing
- Predictive methods based on reduced-order aerodynamics fail to predict this
- 3D unsteady transonic flow conditions on advancing side
- Grid size: 6-16 million points (four blades must be computed)
- Cost: 6 months using 36 P4 processors

Untwisted blade with cyclic pitch

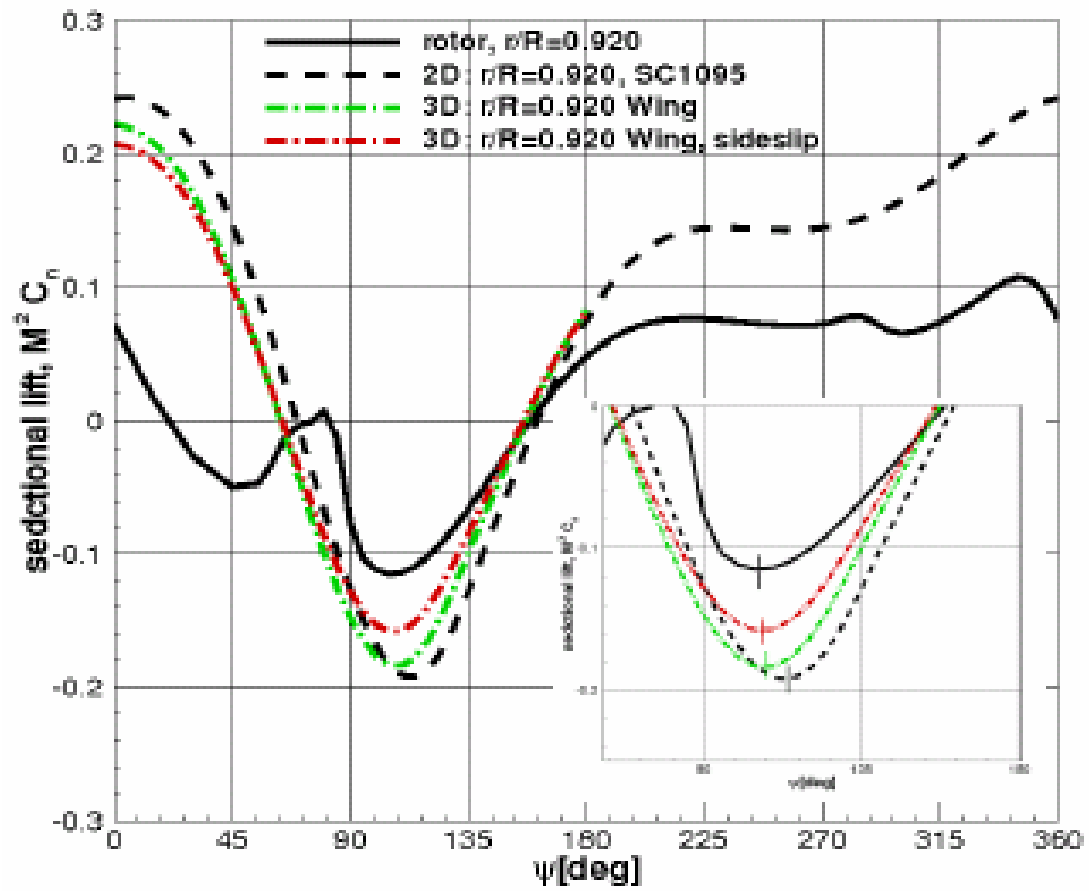






10 deg collective, 10 deg cyclics, turbulent flow

Advancing Side Aerodynamics



UH-60A rotor
High-speed forward flight
$\mu = 0.35$, $M_{tip} = 0.625$

$\theta_0 = 6.809$ deg.

$\theta_{1s} = 4.928$ deg.

$\theta_{1c} = -1.747$ deg.

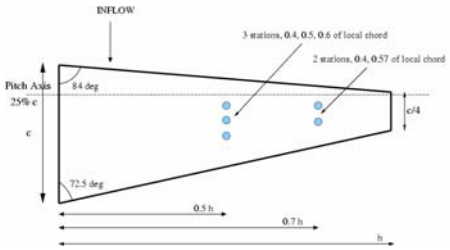
$\beta_0 = 1$ deg.

$C_T = 0.005$

Advancing Side Aerodynamics

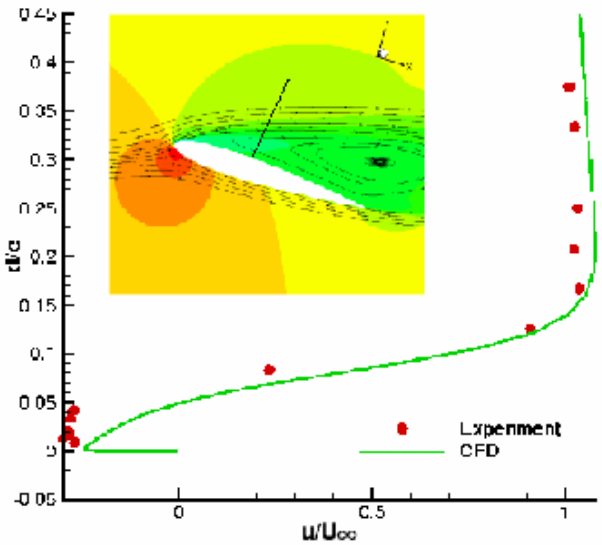
- Contributions from;
  - Cyclics: up to 10 degrees of delay
  - Impulsive Effects: up to 10 degrees of delay (at high tip Mach number)
  - dM/dt Effects: up to 10 degrees of delay (dominant effect)
  - Yawed Flow Effects: 5-6 degrees of delay (combined with 3D tip effects)
  - 3D Effects: 5-8 degrees of delay

3D Dynamic Stall – Validation Study – Wing cases

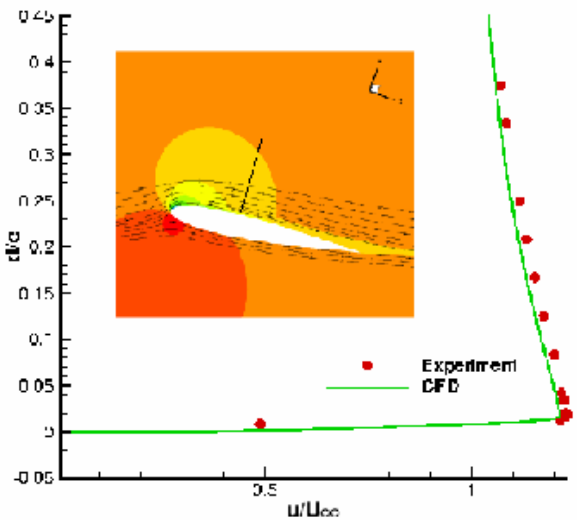


Comparison with oscillatory data from LABM

Pitching motion, k = 0.048
AoA=18 + 6 sin(wt)
x/c = 0.4
z/c =0.5

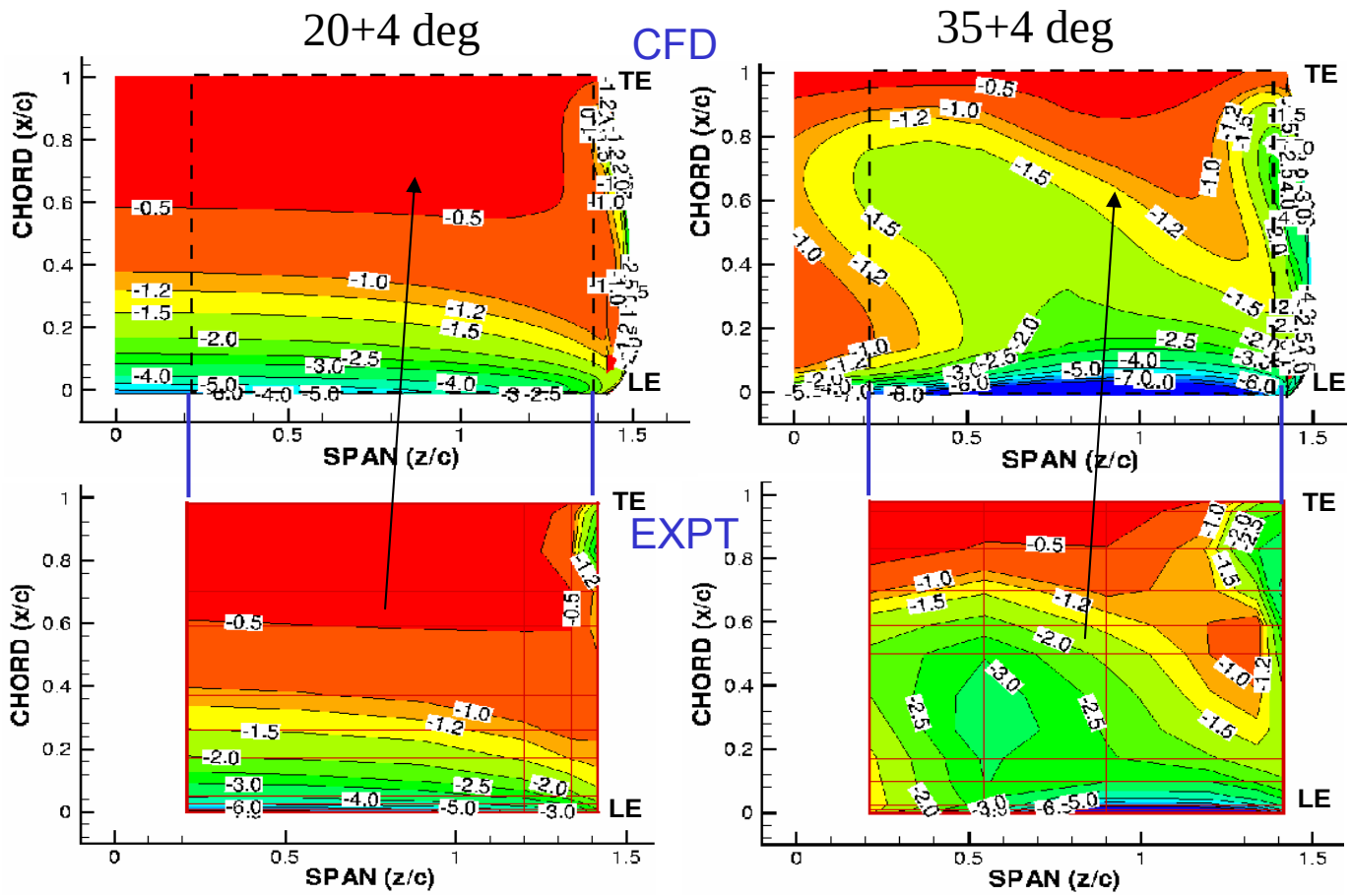


AoA = 18 deg downstroke

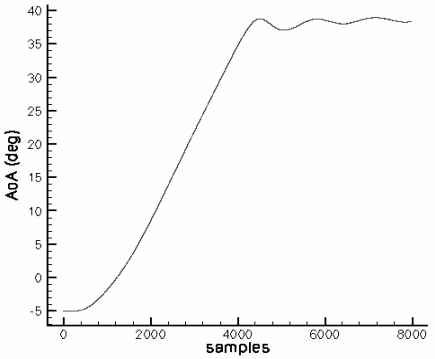


AoA = 12 deg

3D Dynamic Stall – Validation

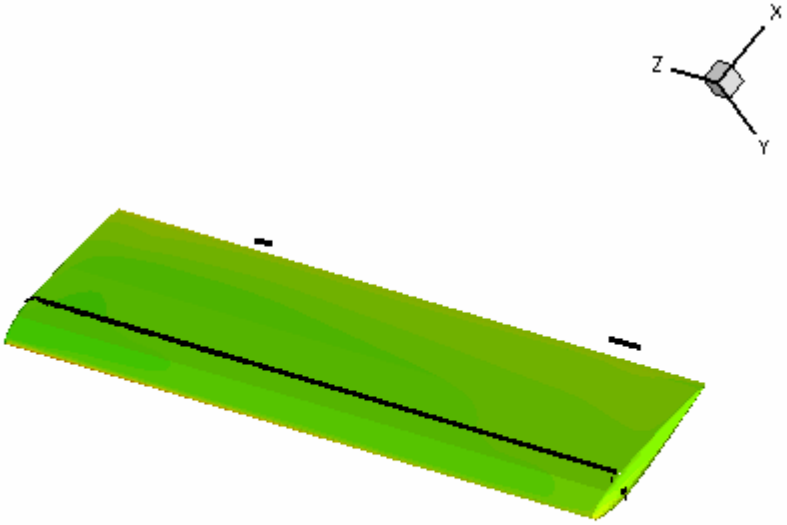


Coton and Galbraith
(Ramping Rect. Wing)



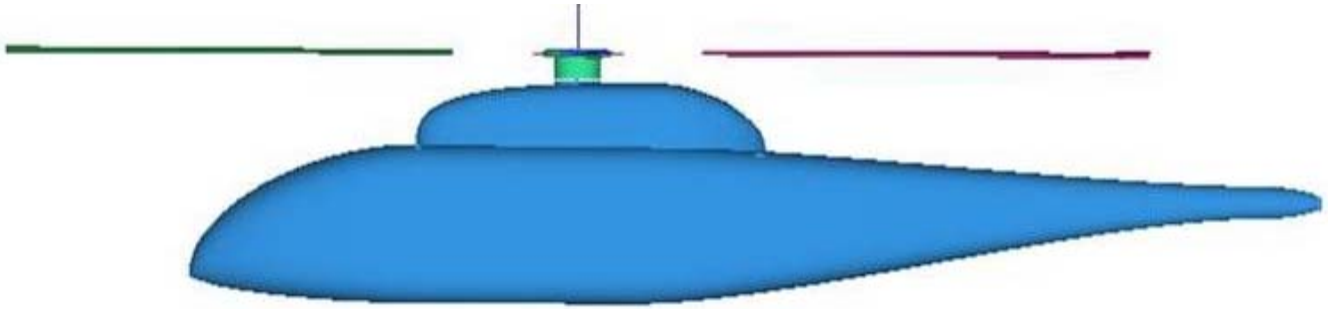
Ramping motion
$\alpha^+ = 0.027$
$-5^o \rightarrow 40^o$
$Re=1.45\times10^6$
$M=0.16$

Retreating Side – 3D Dynamic Stall



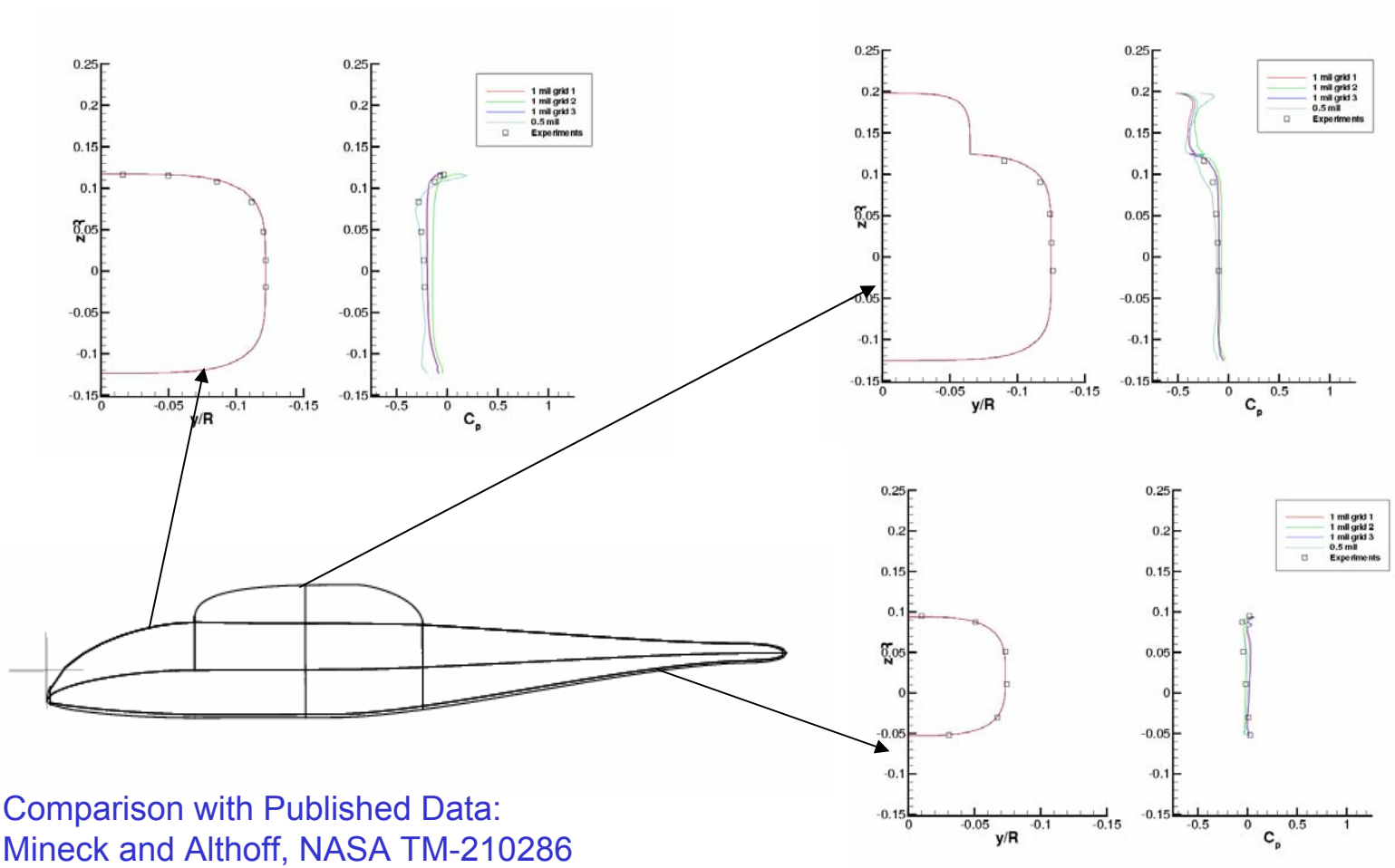
- Vortex cores for a retreating side computation
- untwisted blade
- 10 degrees of collective 10 degrees of cyclic
- Re=4million
- M=0.3
- 4 days on 36 CPUs

Demonstration: Combined Rotor/Fuselage Configuration



- CFD capability for rotor body
- Validation against data
- Derive some method for assessing rotor designs
- Typical grid size: 4-12 million points for fuselage + 3-4 million points per blade
- Cost: estimated 25-30 months using 36 P4 CPUs

Isolated Fuselage – Validation – ROBIN Body at -5 degrees

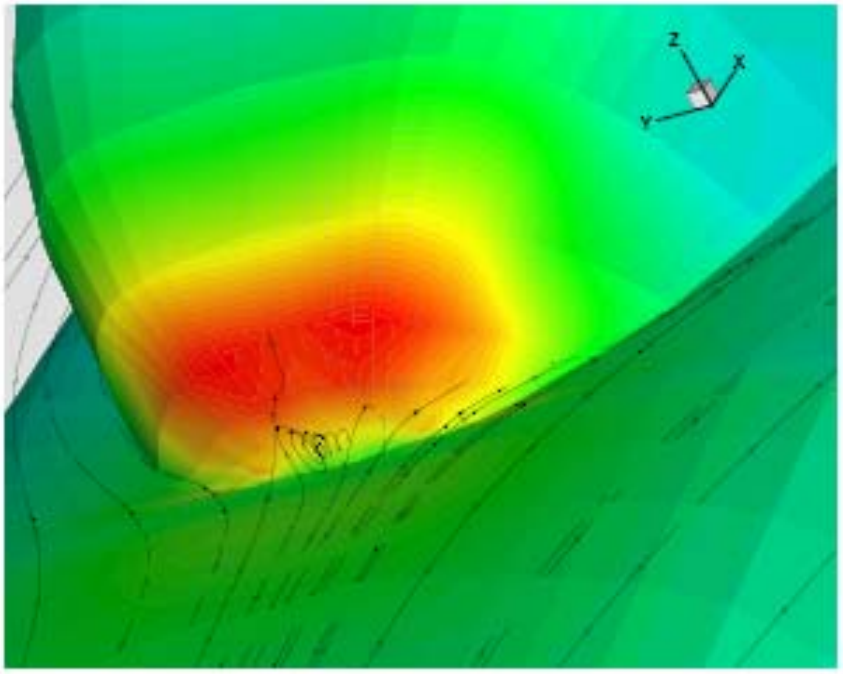


Comparison with Published Data:
Mineck and Althoff, NASA TM-210286

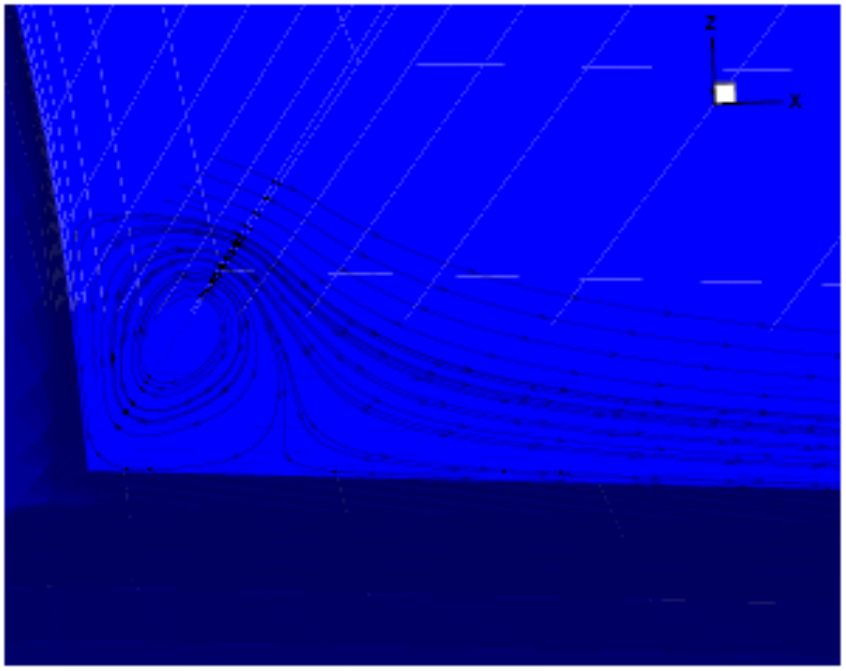
Isolated Fuselage – Validation – ROBIN Body at -10 degrees

Detailed Flow Features Captured

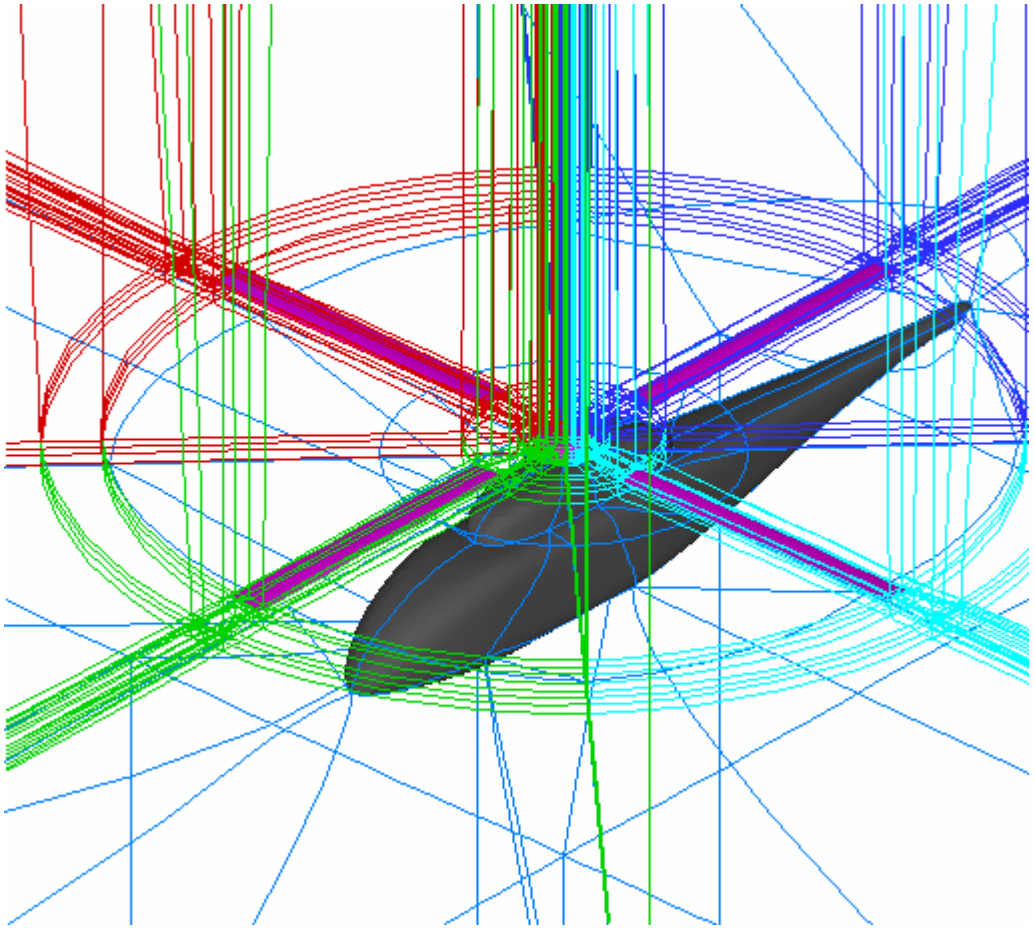
Vortex around the pylon



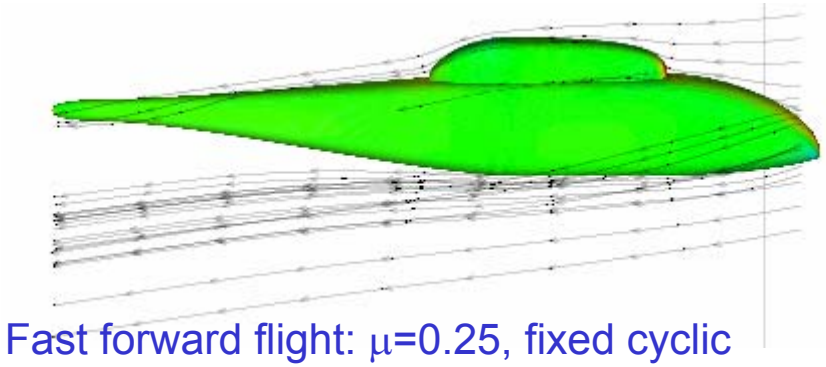
Recirculation after the pylon



Combined Rotor/Fuselage Configuration – Demonstration Case

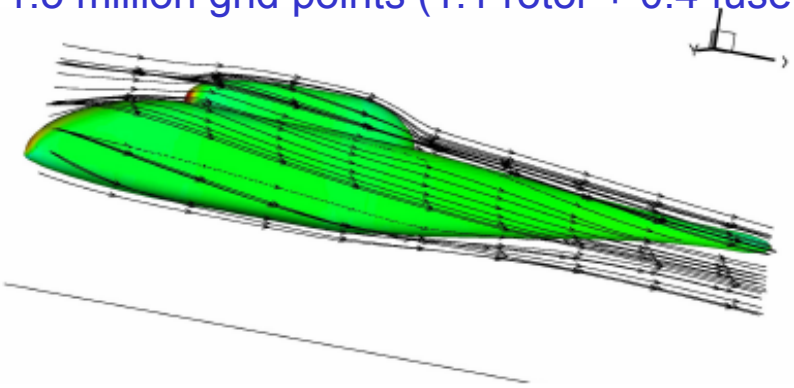


Combined Rotor/Fuselage Configuration – Demonstration Case

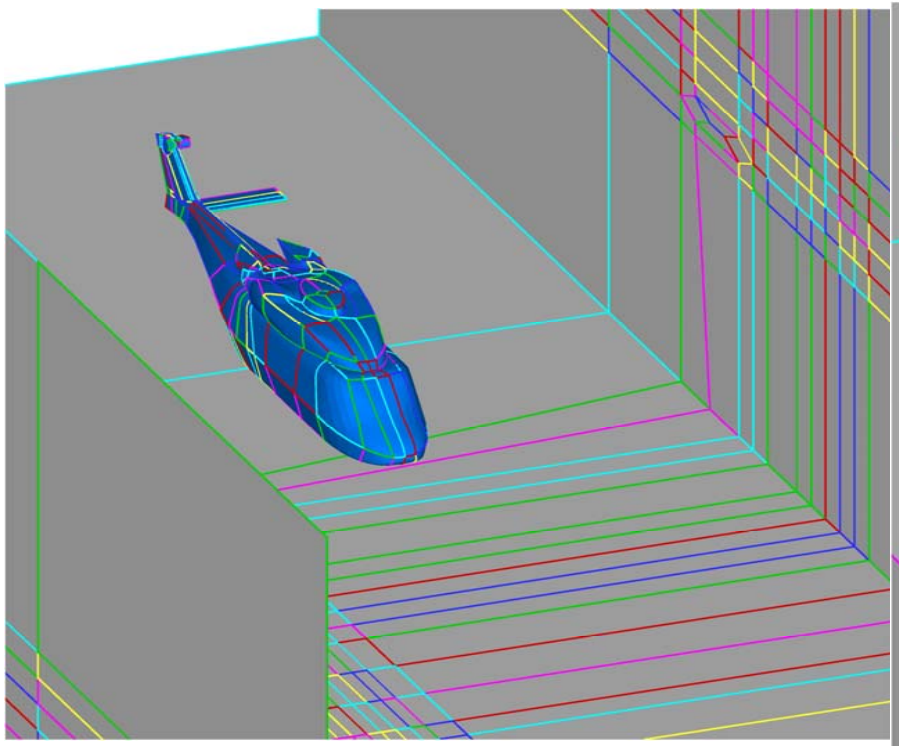


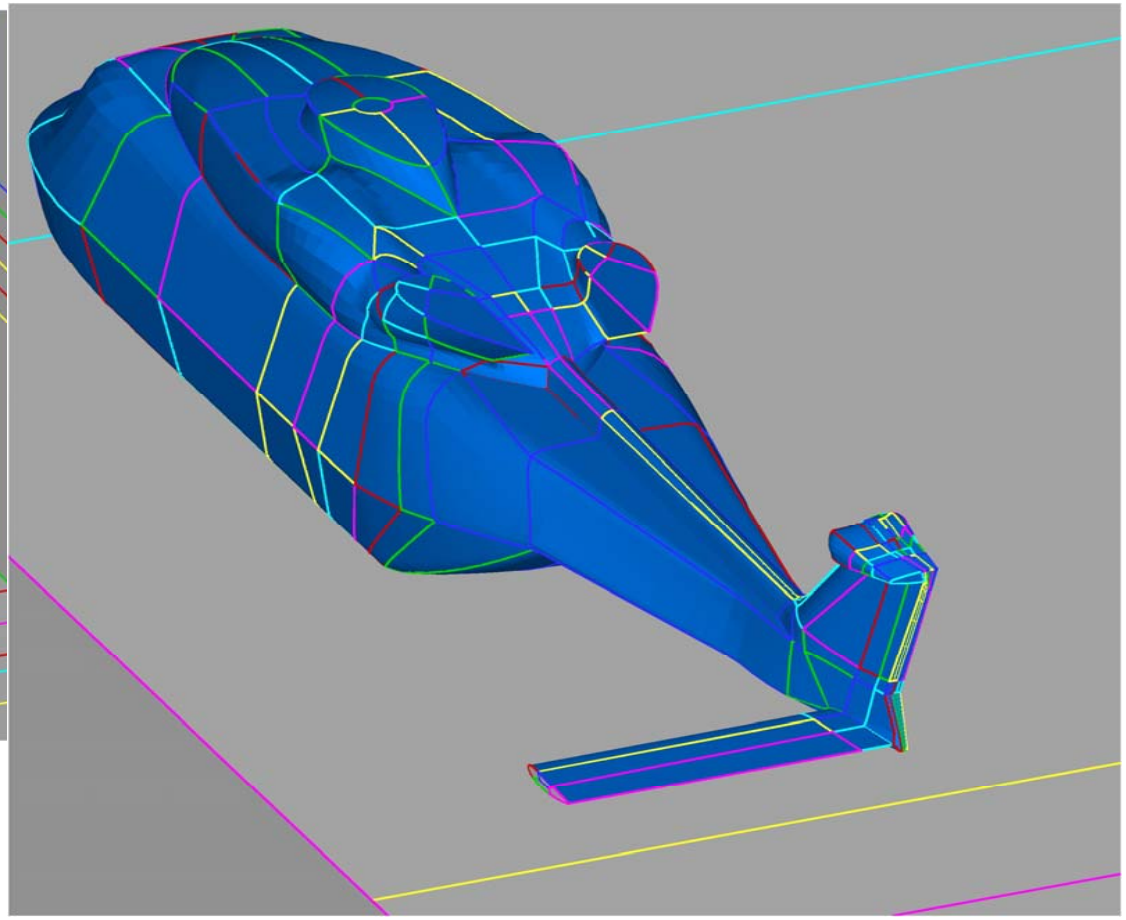
Fast forward flight: μ=0.25, fixed cyclic

1.5 million grid points (1.1 rotor + 0.4 fuselage)



GOAHEAD (F6 project) - Fuselage in wind tunnel section





Summary and future steps