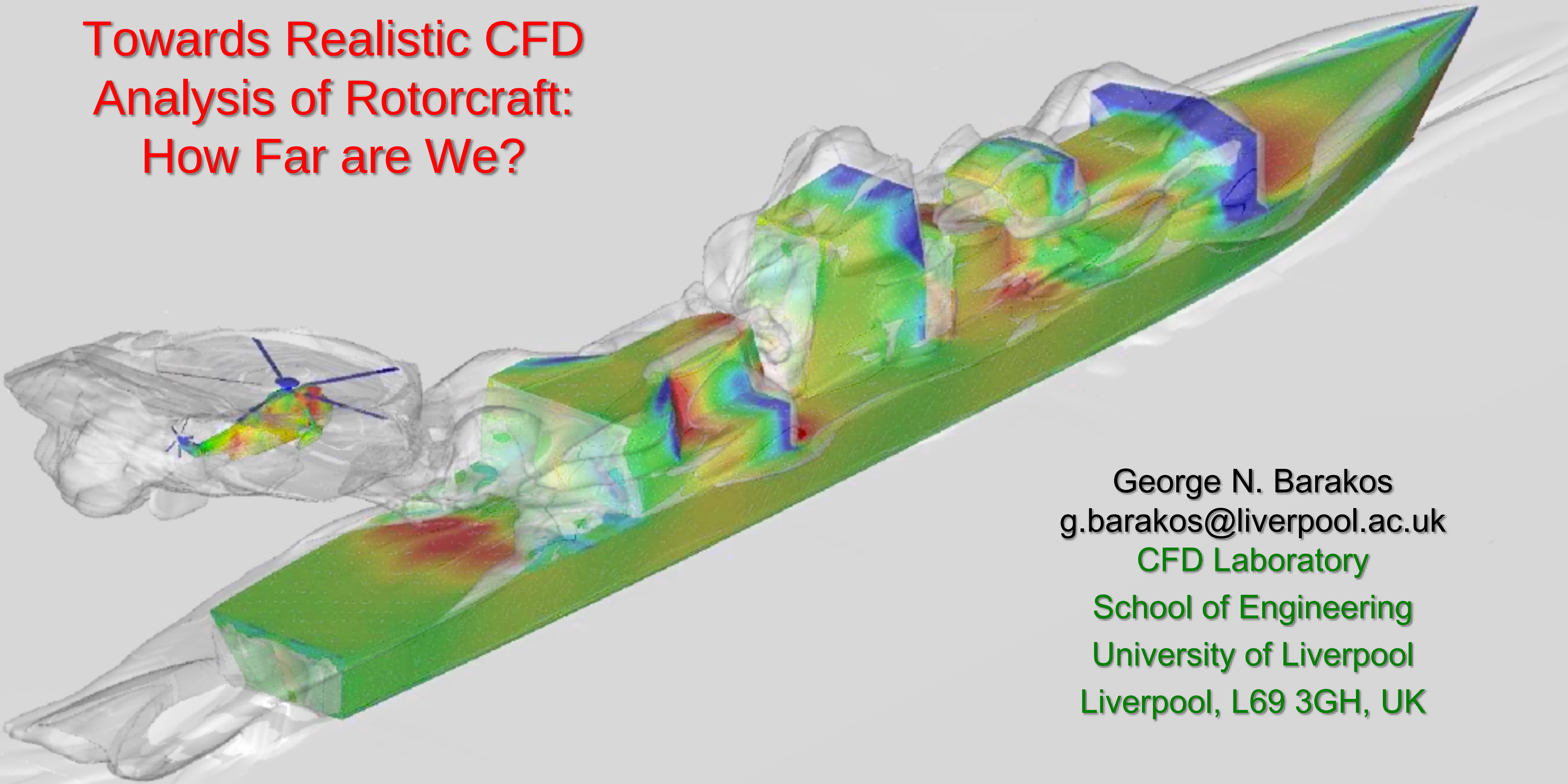
LABORATORY

Towards Realistic CFD Analysis of Rotorcraft: How Far are We?



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AgustaWestland A Finmeccanica Company
Advanced Rotorcraft Centre
UNIVERSITY OF LIVERPOOL

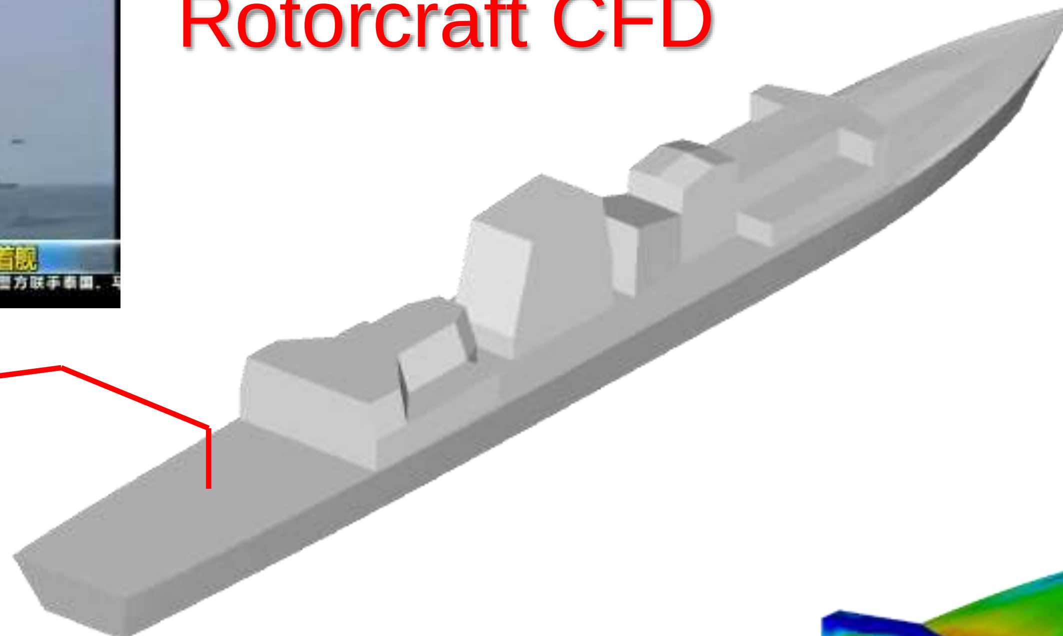
N8 Research Partnership High Performance Computing
STFC Hartree Centre

AgustaWestland A Finmeccanica Company
NGVLP
REACT Active Rotor Technology

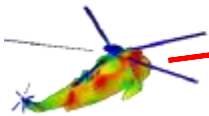
SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS
CENER

Ministry of DEFENCE
EPSRC
dti
QinetiQ

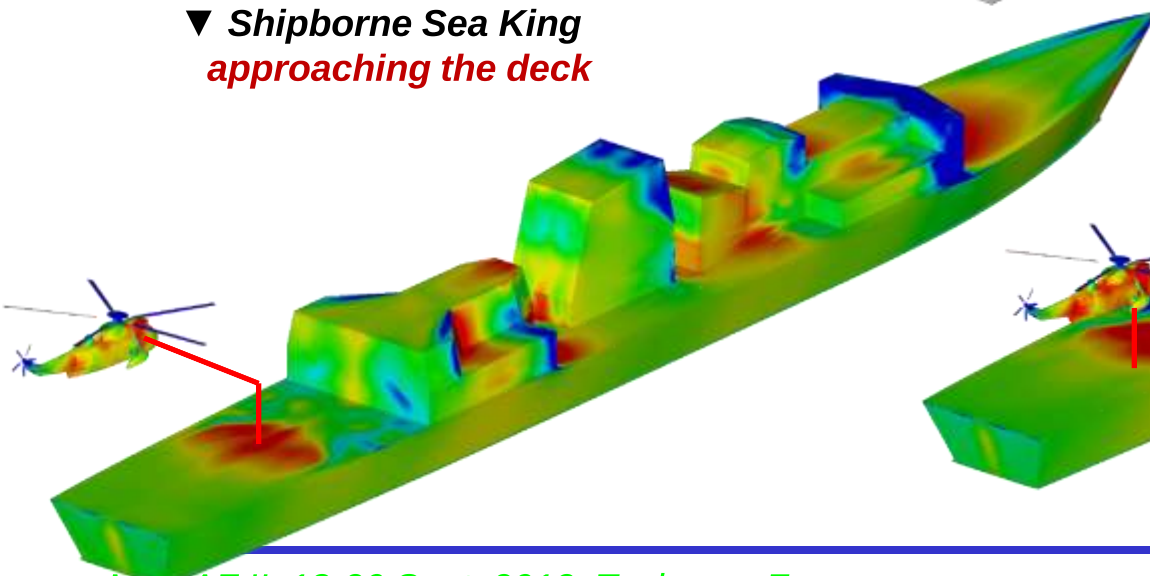
Rotorcraft CFD

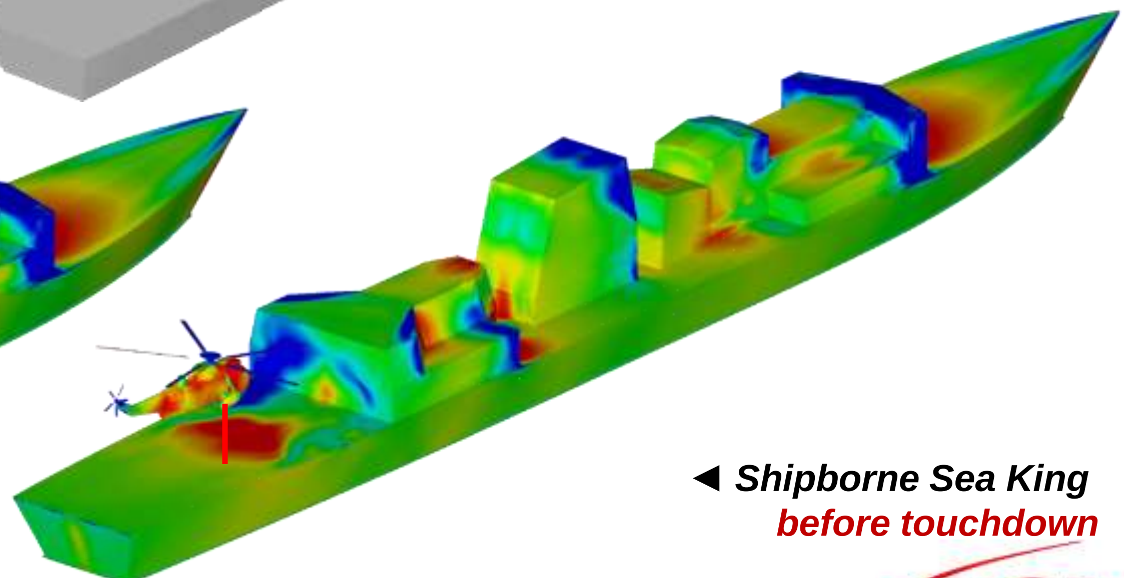


▼ *Isolated* ***Sea King in forward flight***



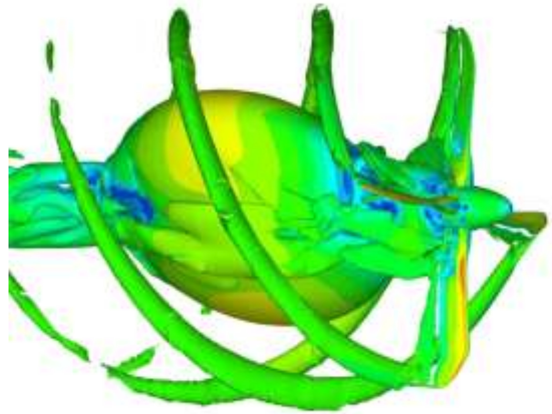
▼ ***Shipborne Sea King*** ***approaching the deck***

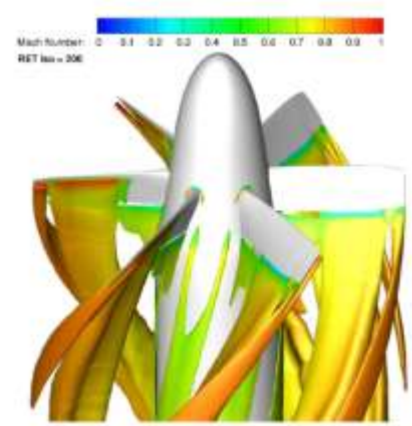


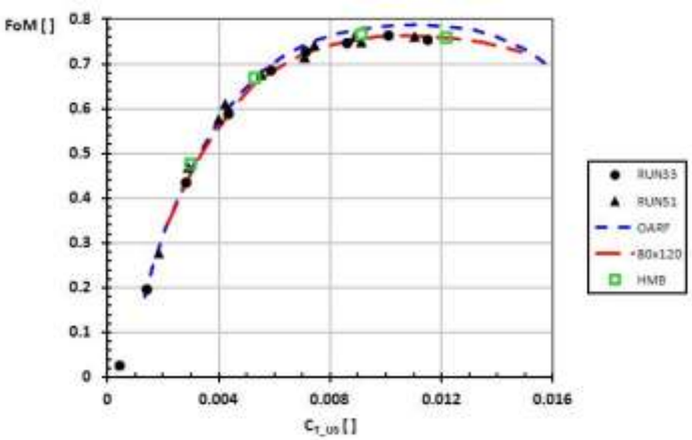


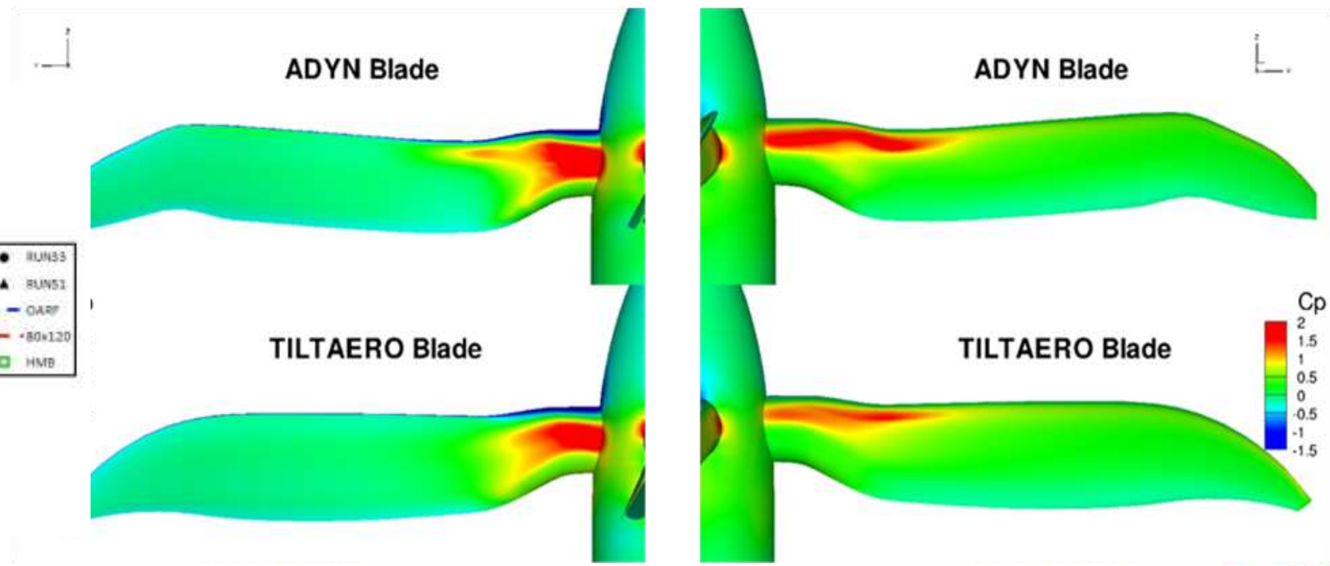
◄ ***Shipborne Sea King*** ***before touchdown***

Propellers and Tilt-Rotors





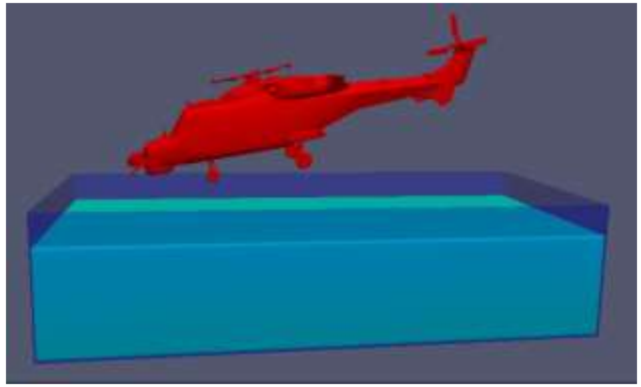
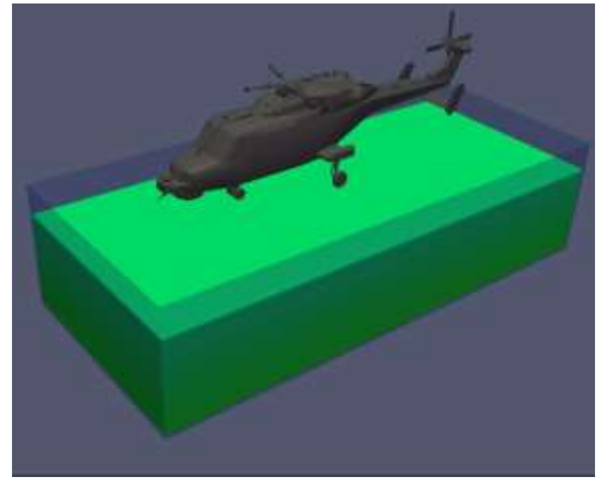
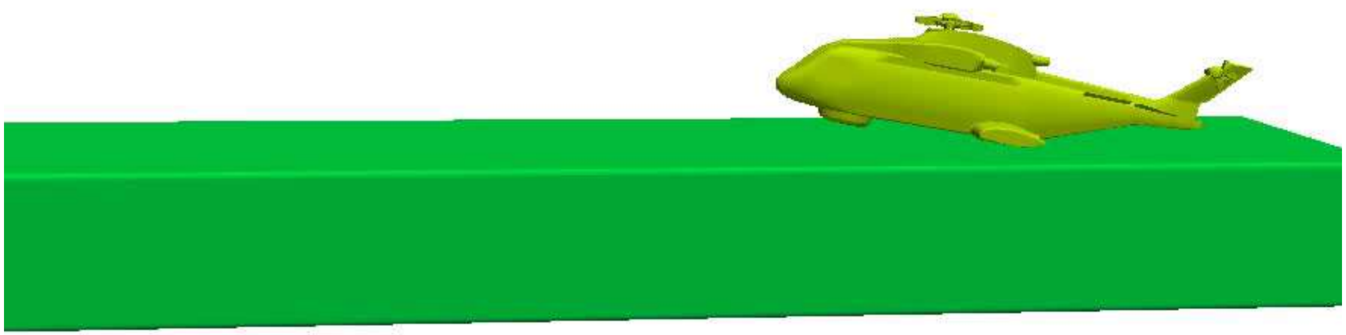




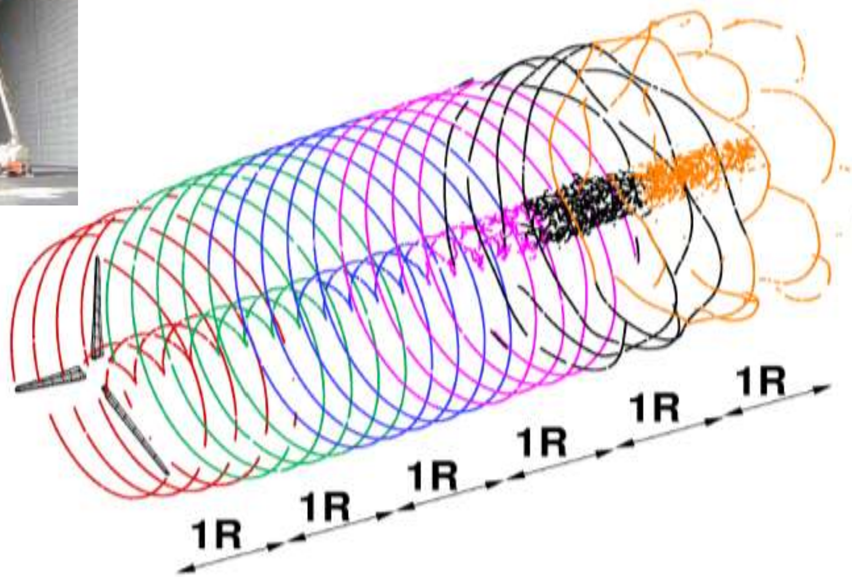
Lower side

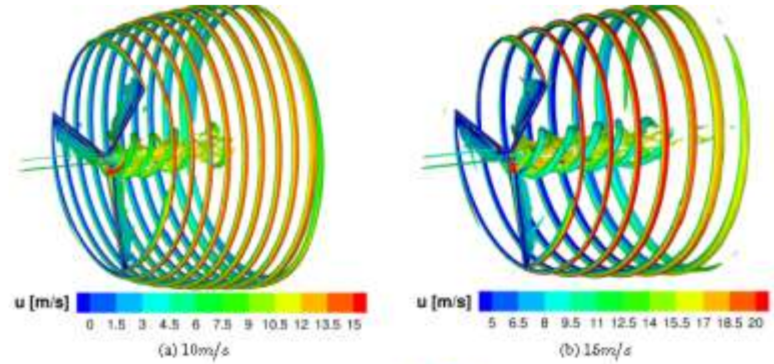
Upper side

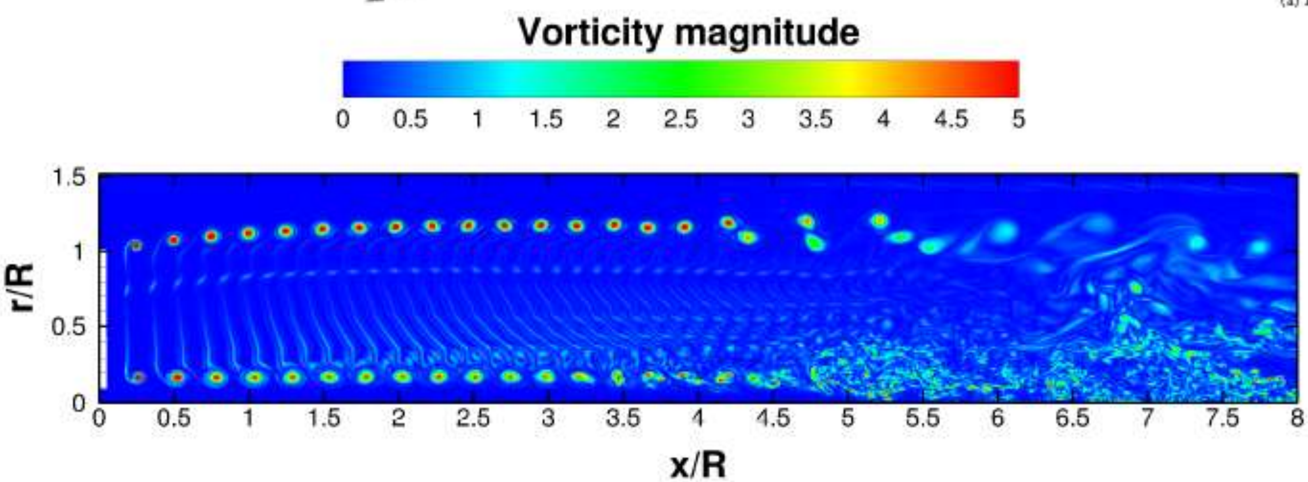
Helicopter Ditching

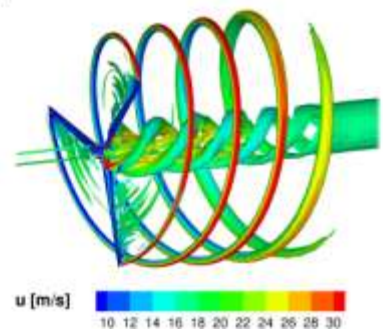





Wind Energy


1R
1R
1R
1R
1R
1R

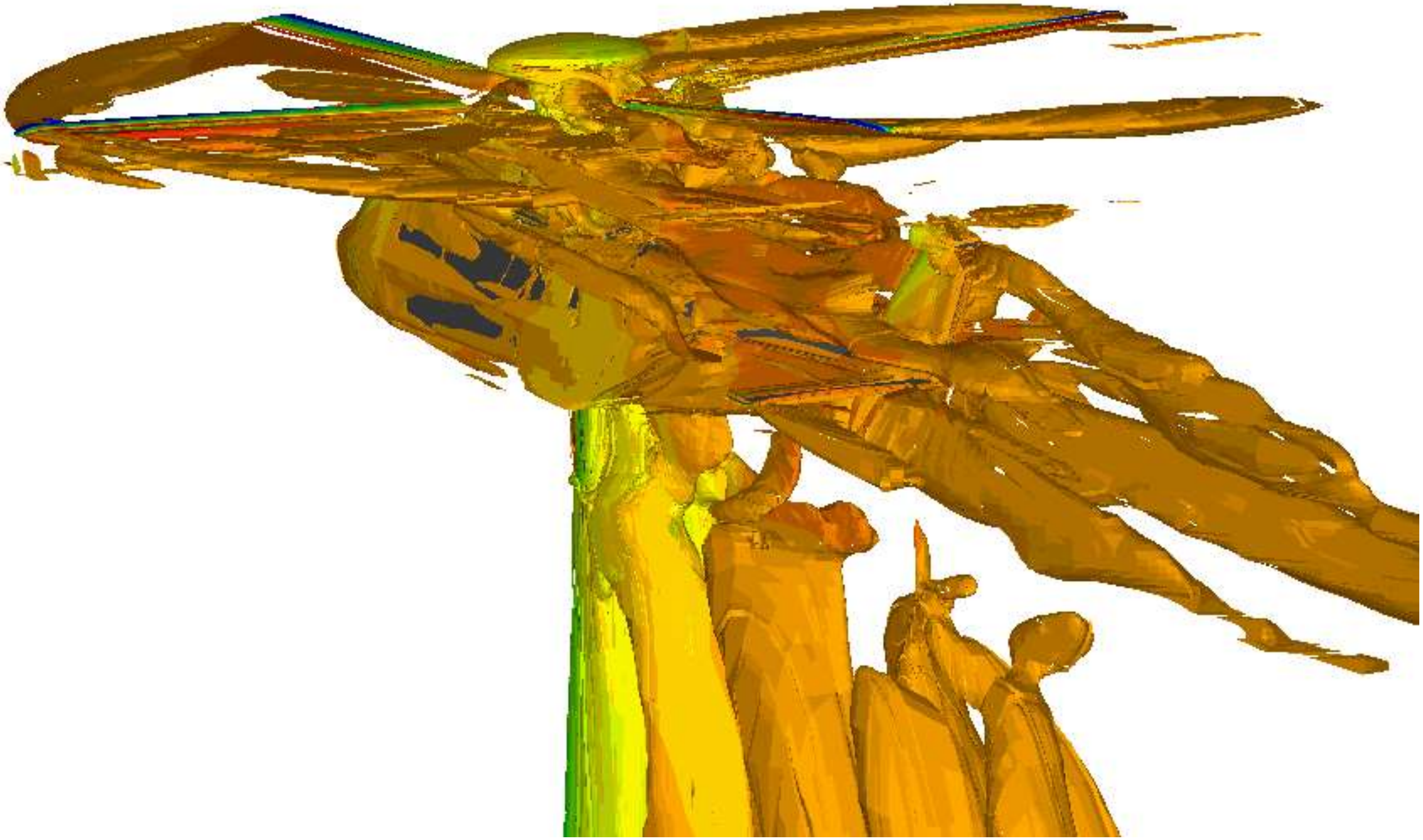

u [m/s]
0 1.5 3 4.5 6 7.5 9 10.5 12 13.5 15
(a) 10m/s
u [m/s]
5 6.5 8 9.5 11 12.5 14 15.5 17 18.5 20
(b) 15m/s


Vorticity magnitude
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
r/R
x/R

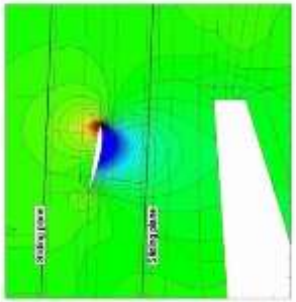

u [m/s]
10 12 14 16 18 20 22 24 26 28 30

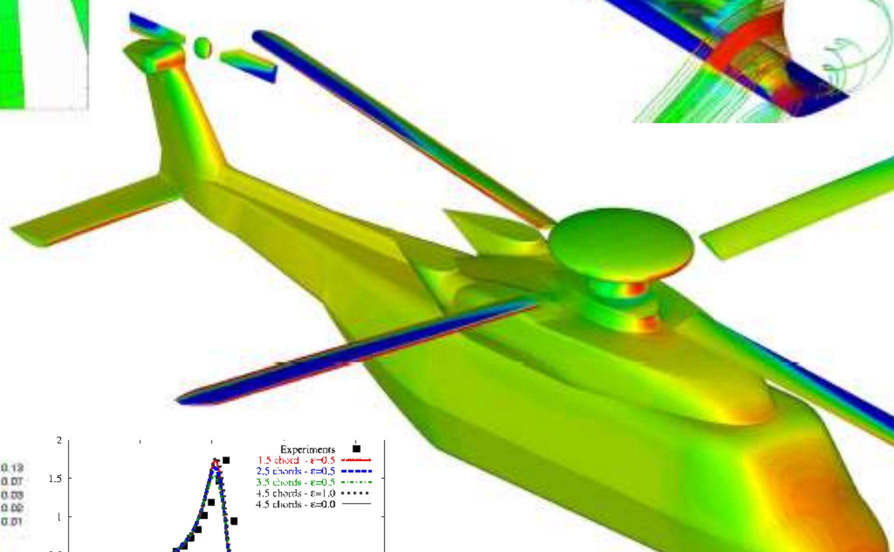
Rotorcraft is Different…

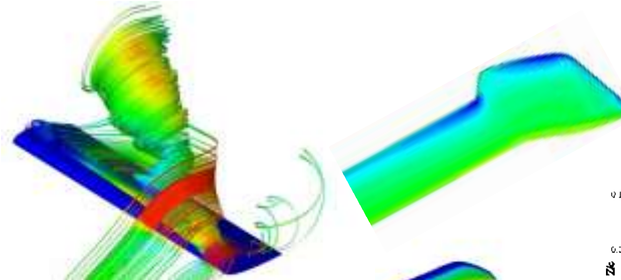
Tilt Rotors, Active Rotors, Compound Aircraft

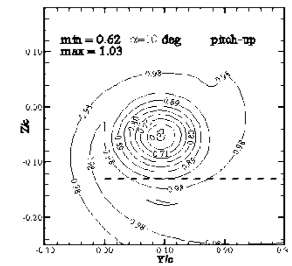


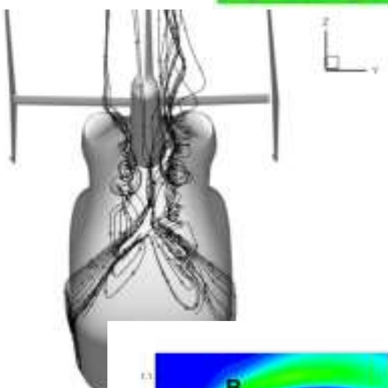
Flow Phenomena Associated with Helicopter Flow

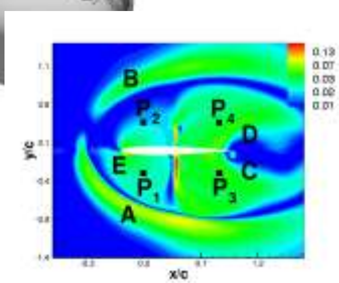


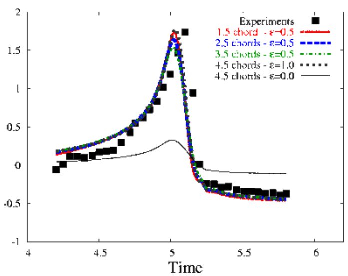


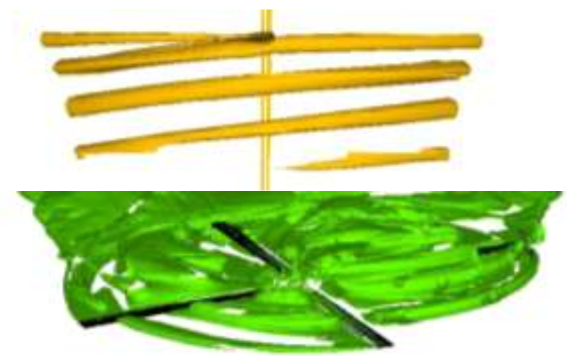


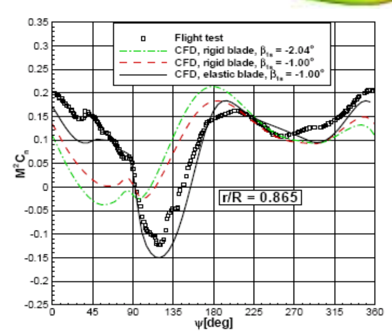






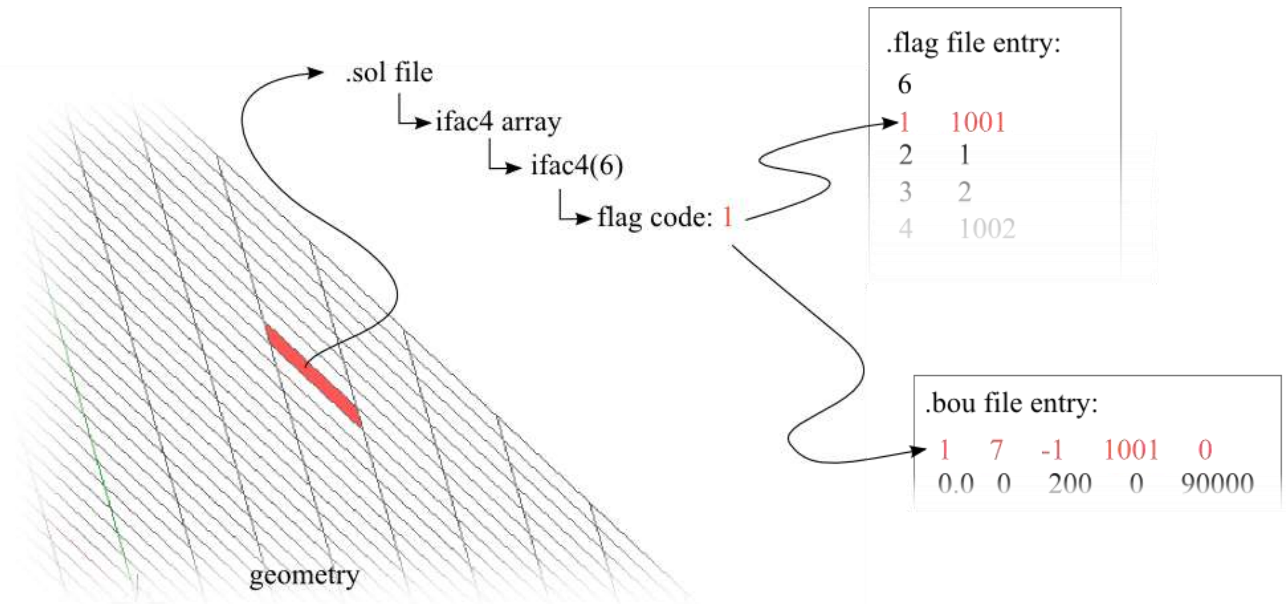




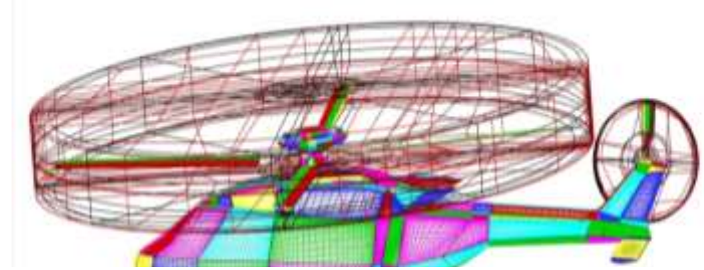


- Unsteady aerodynamics
- Wide range of Mach and Reynolds numbers
- Complex vortex wake
- Coupling between flow and structure

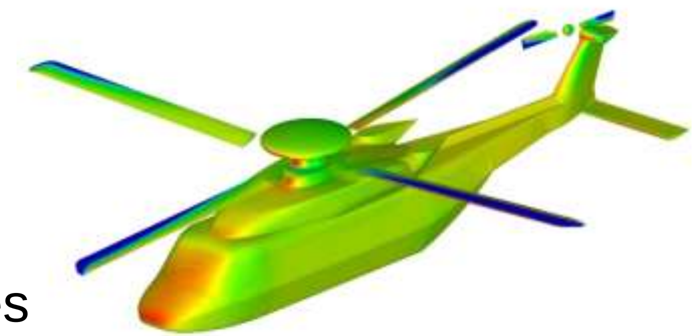
Time Marching CFD Method

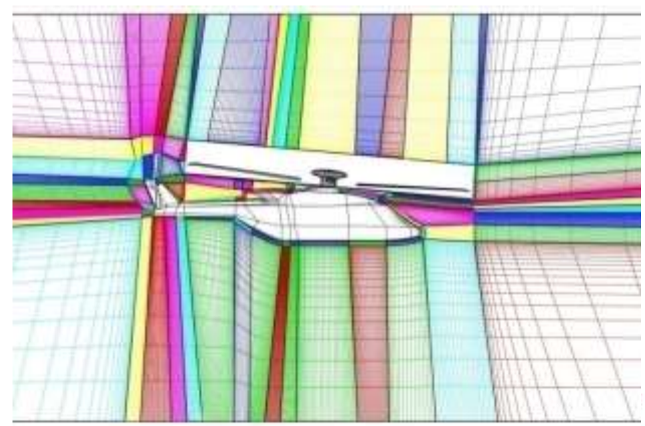


Solver – Overview of the core HMB features

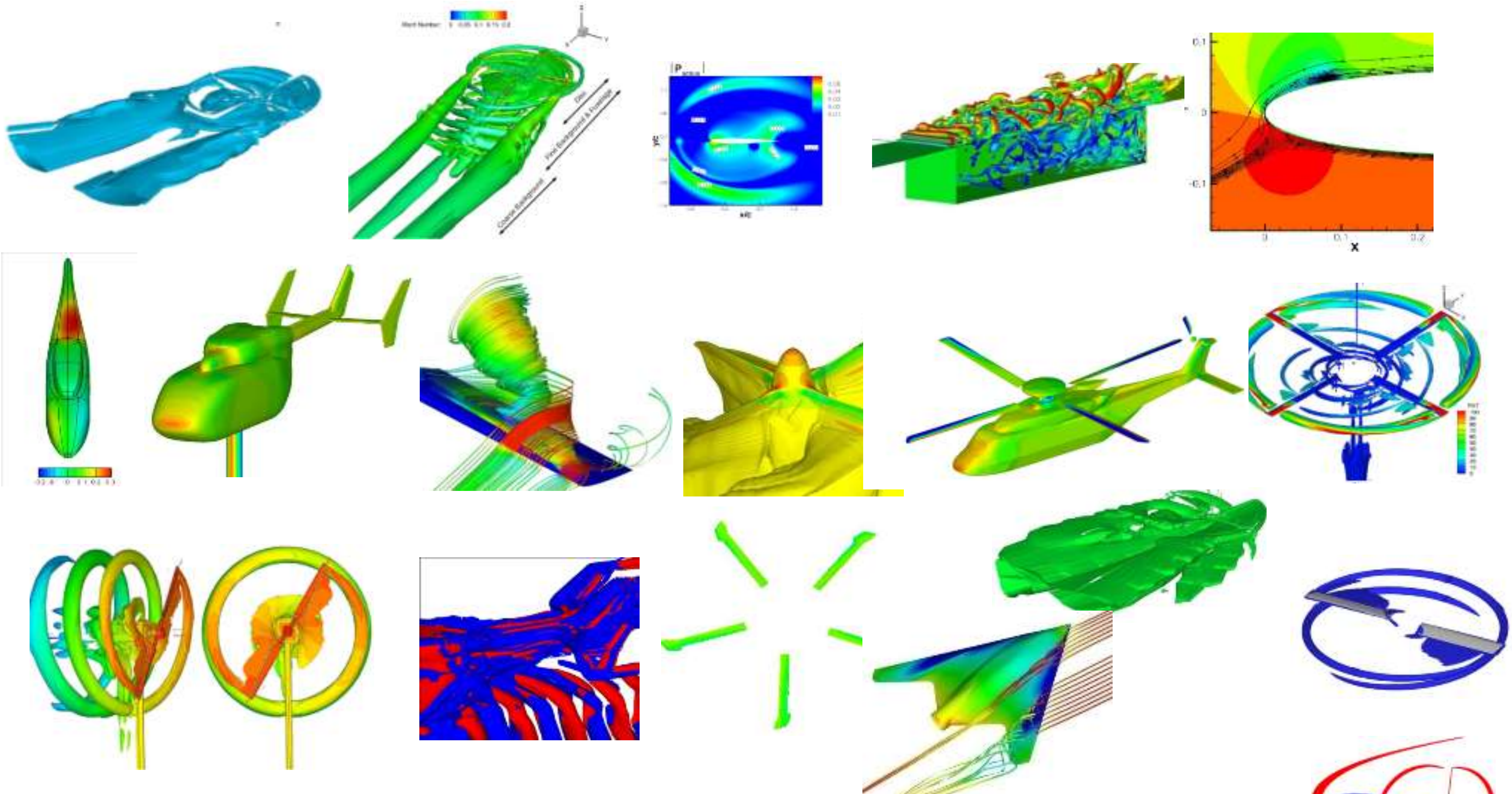


- Control volume method
- Parallel - Shared and Distributed memory
- Multi-block (complex geometry) structured grids
- Unsteady RANS - Variety of turbulence models including LES/DES
- Implicit time marching
- Osher, Roe, AUSM schemes for convective fluxes
- All Mach schemes
- MUSCL scheme for accuracy
- Central differences for viscous fluxes
- Moving grids, sliding planes
- Hover formulation, rotor trimming, blade actuation
- 1-1 face matching
- Overset grids
- Aeroelastic method





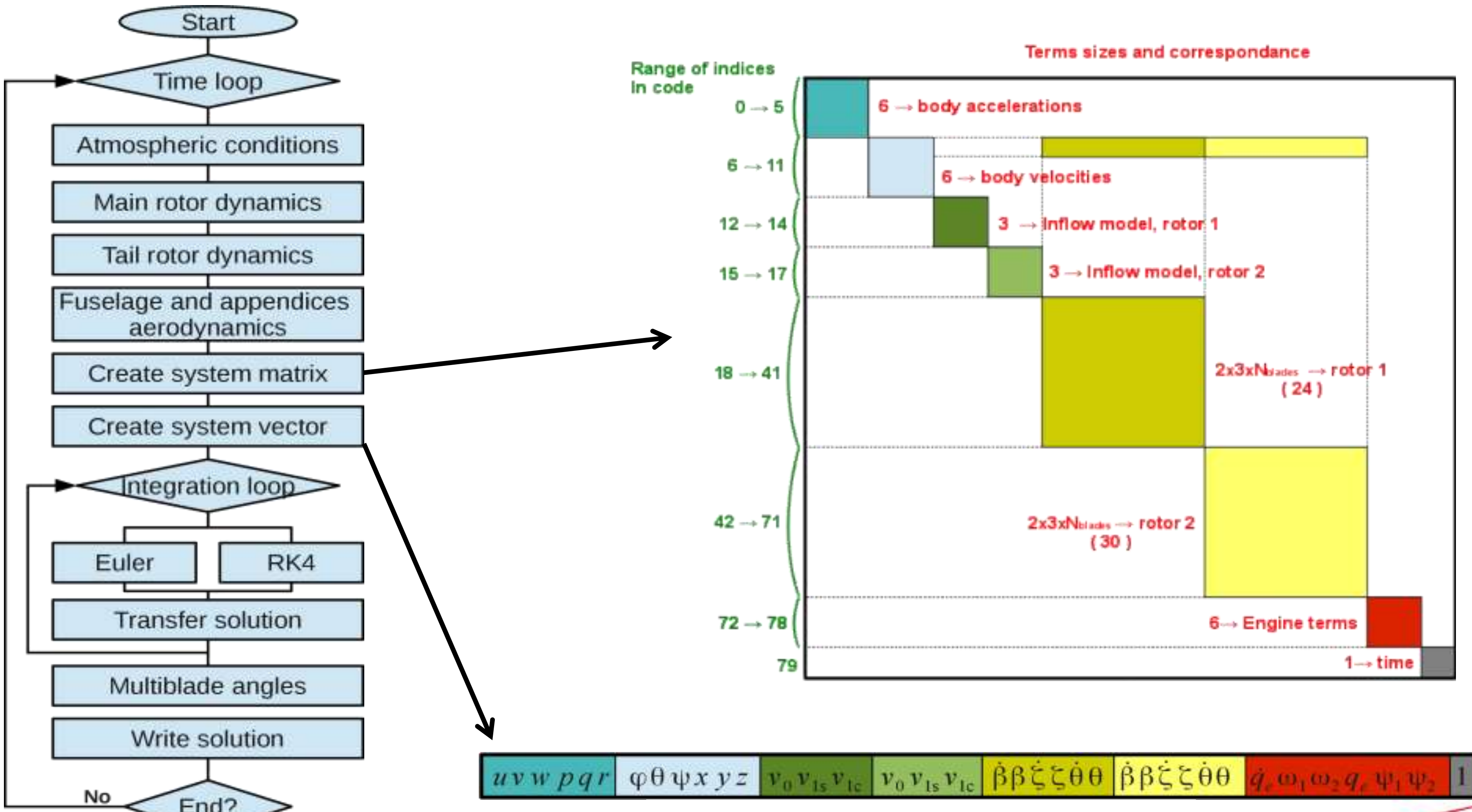
Some of the Flows Analysed with the Helicopter Multi-Block Method

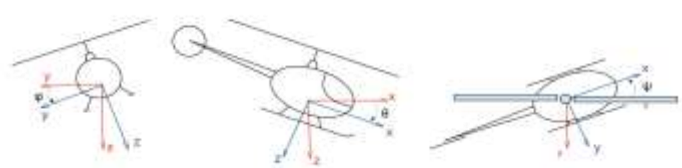


Blade Filmed During Flight

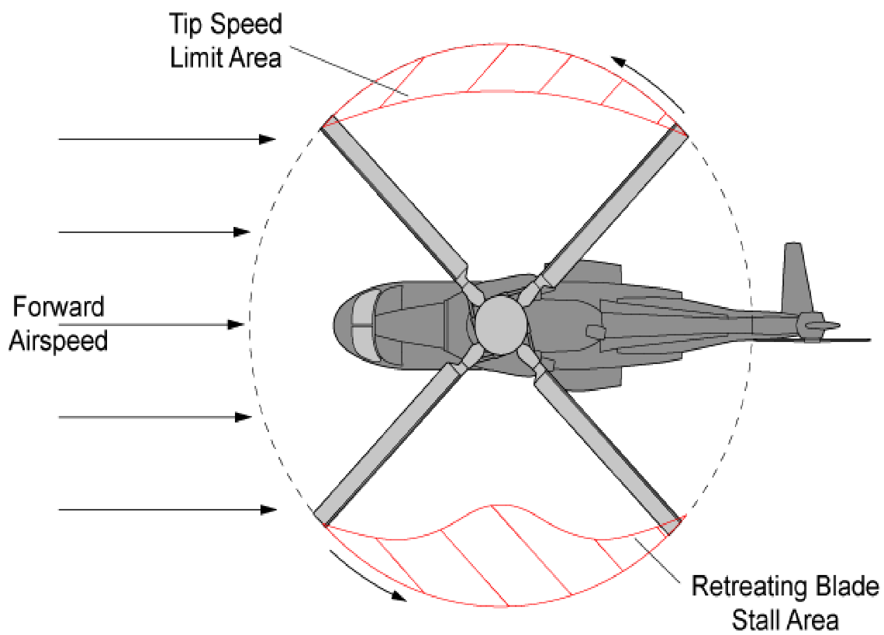
- Rotor motion is dictated by aerodynamics and blade dynamics
- Helicopter blades usually with high aspect ratio, therefore can not be considered as rigid
- Aerodynamic and centrifugal loads result in blade deformation
- High fidelity predictions should include the structural influence

Flight Mechanics Model

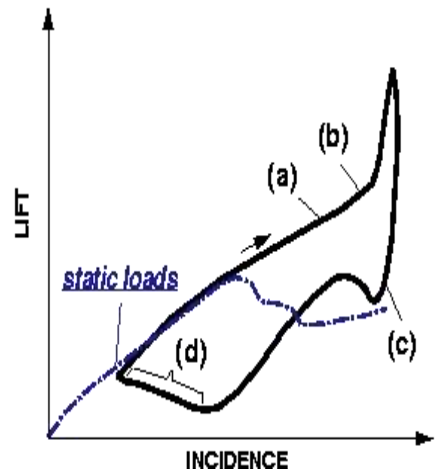


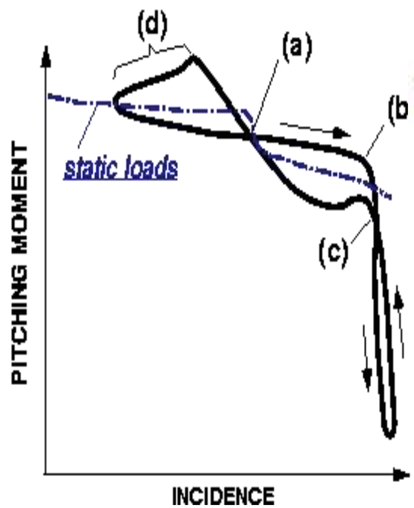


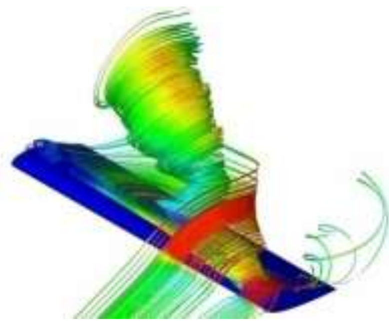
Fundamentals

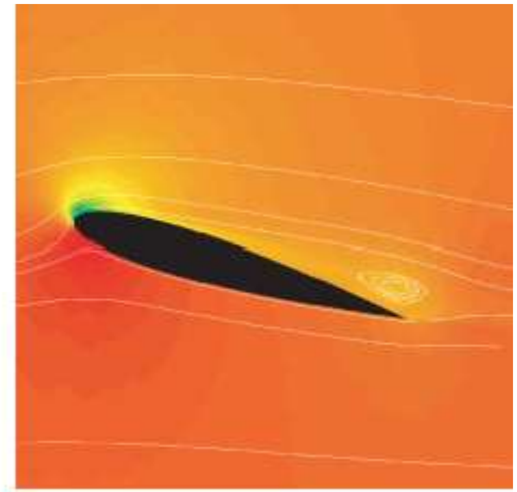


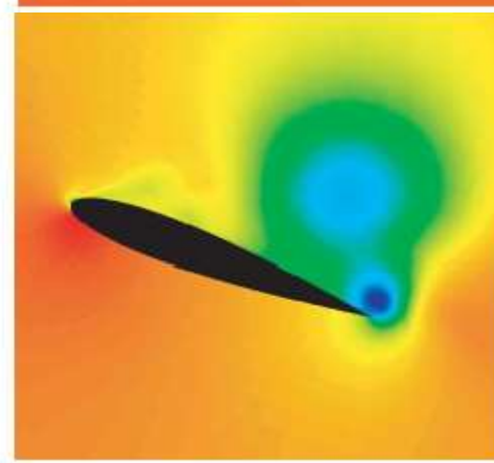
Dynamic Stall





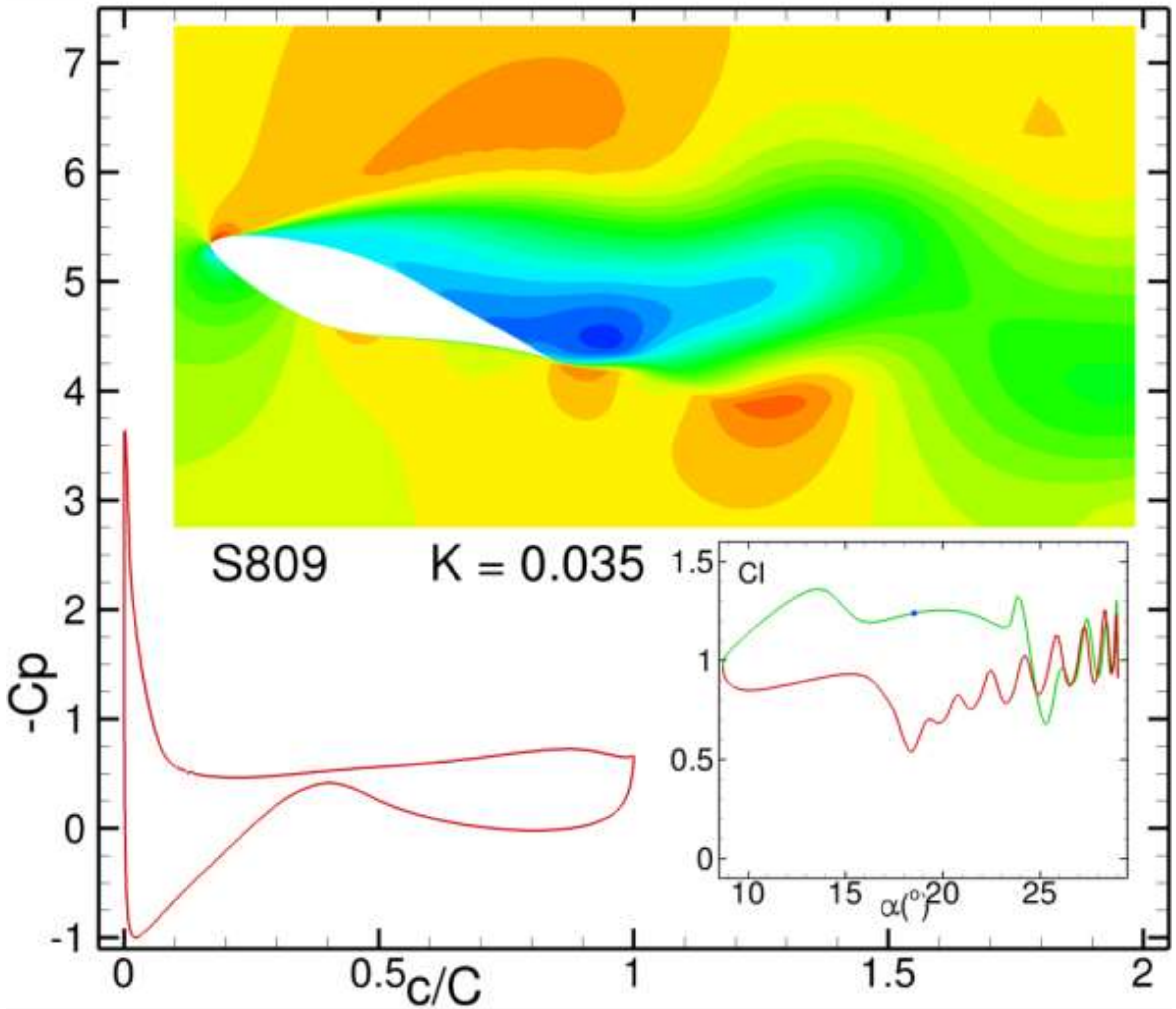




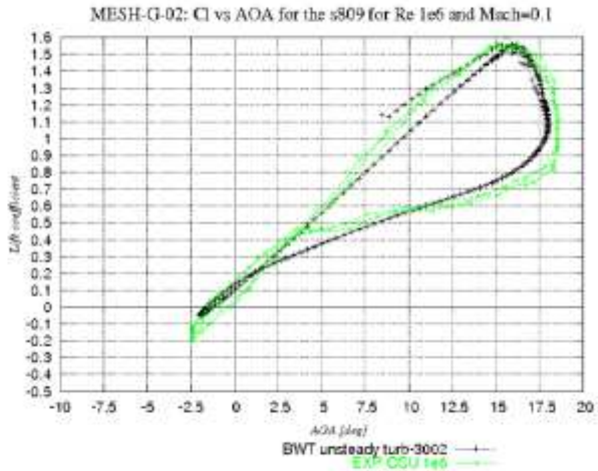


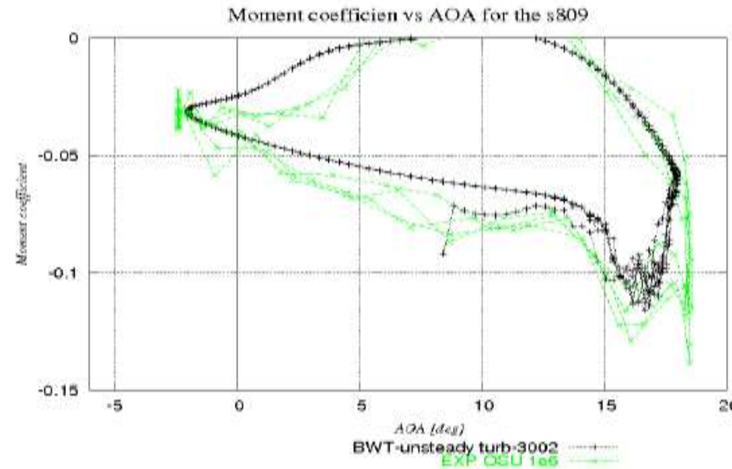
a—separation begins
b—leading-edge vortex forms
c—full stall
d—reattachment and return to static state

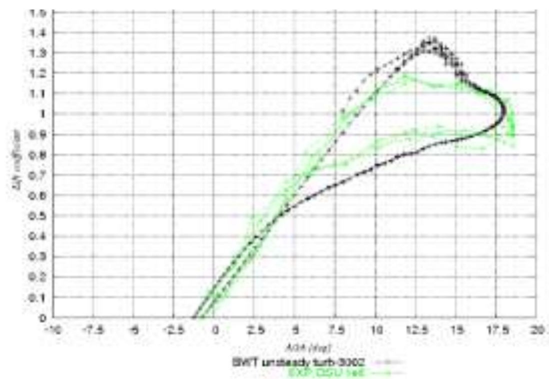
- ***Rapid motion and hysteresis produce increased lift***
- ***A great deal of work has been done on aerofoils, very little on wings***
- ***Important to any manoeuvering aircraft***

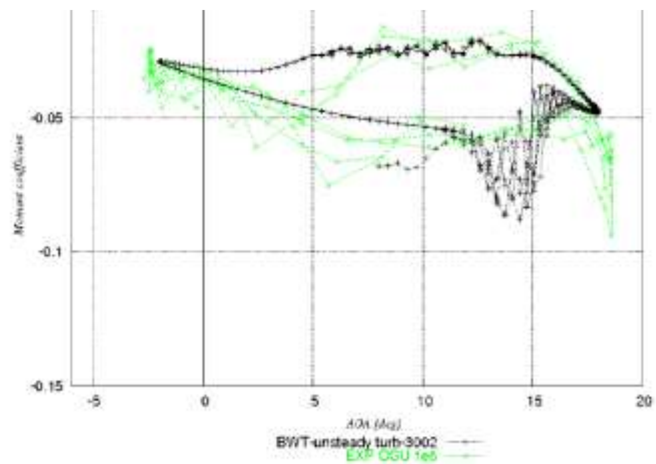

S809
K = 0.035
-Cp
c/C
Cl
α(°)

2D Dynamic Stall - Blind Comparisons







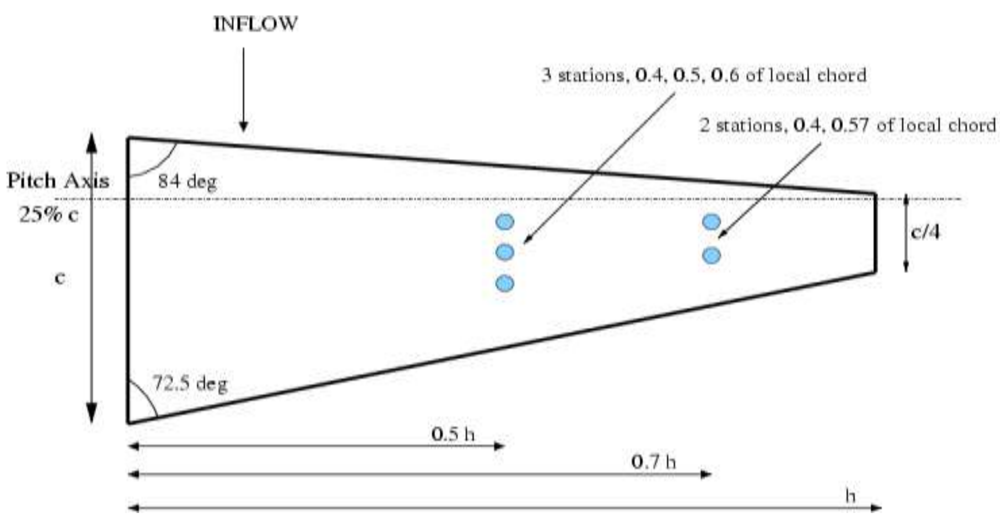


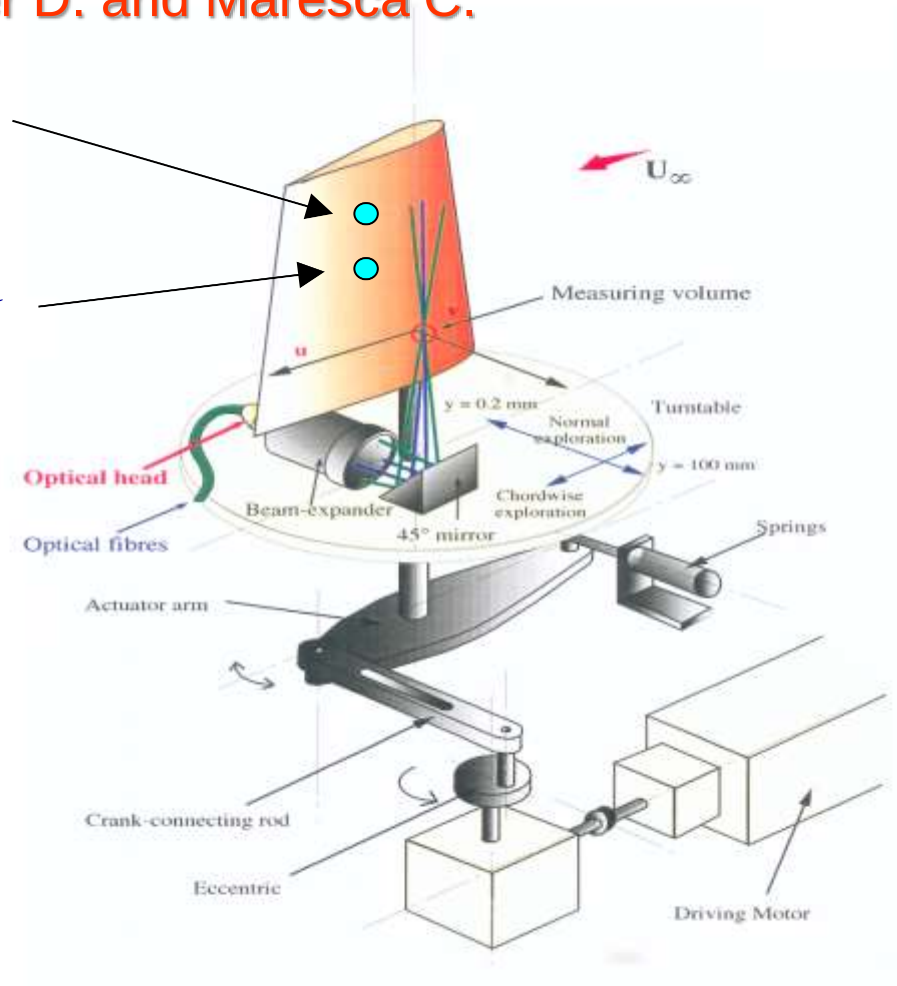
LABM

Berton E., Allain C., Favier D. and Maresca C.

z/c = 0.7 > *x/c* = 0.4, 0.57

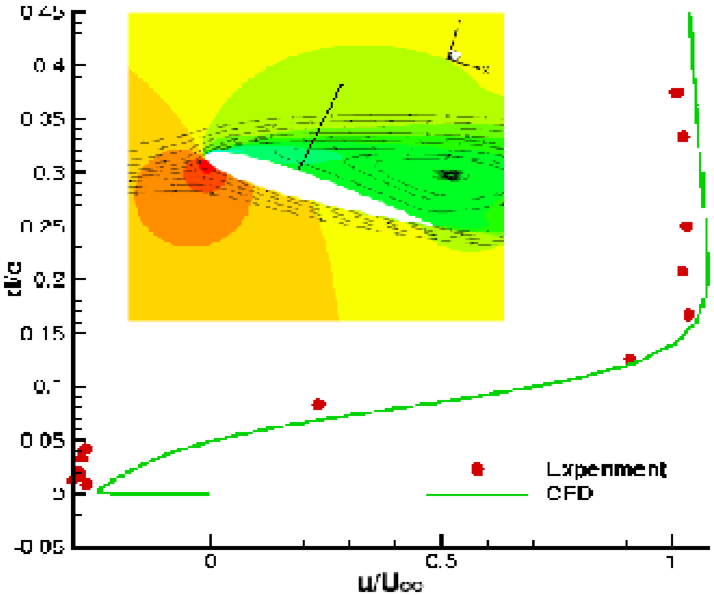
z/c = 0.5 > *x/c* = 0.4, 0.5, 0.6

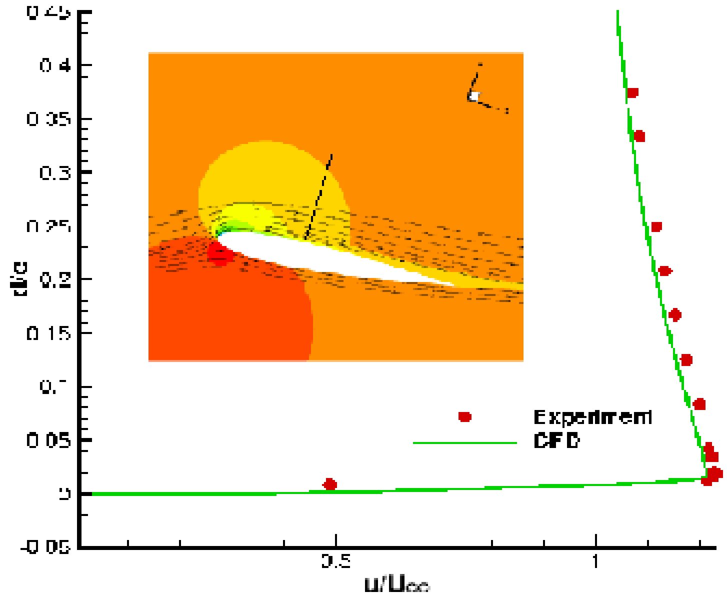




3D validation - LABM (ii)

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

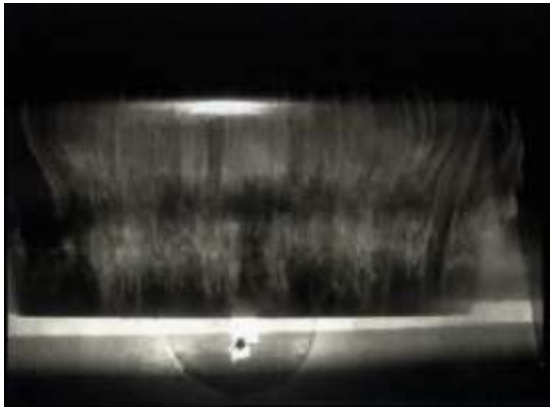


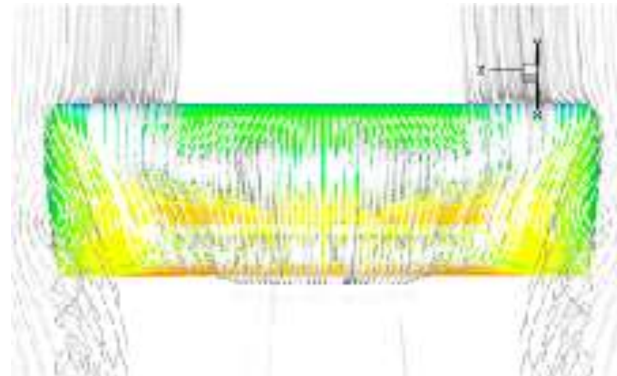


AoA = 18 deg downstroke

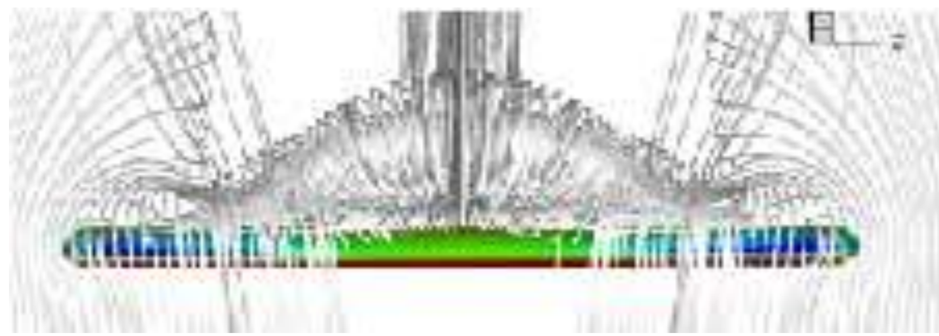
AoA = 12 deg

Experiments by Moir & Coton



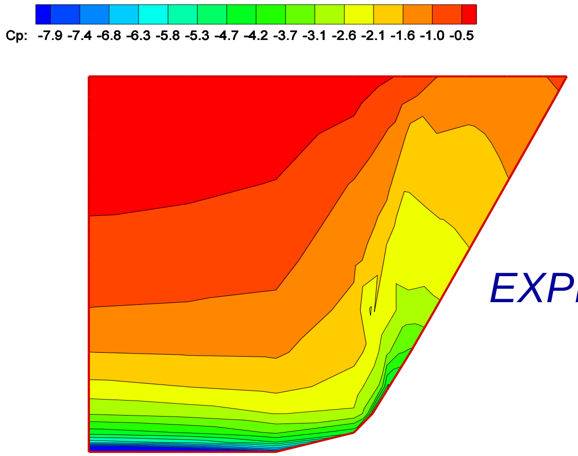


Top view, 30 degrees of pitch

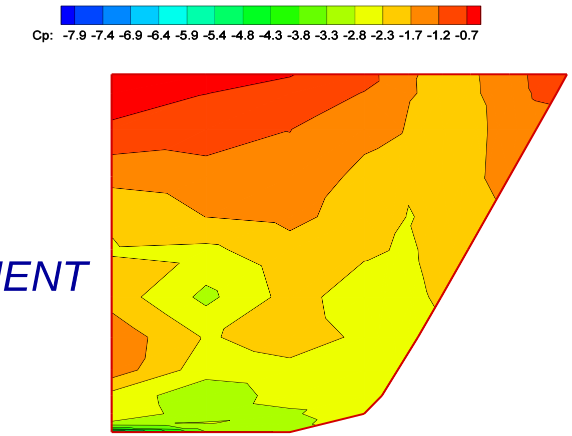


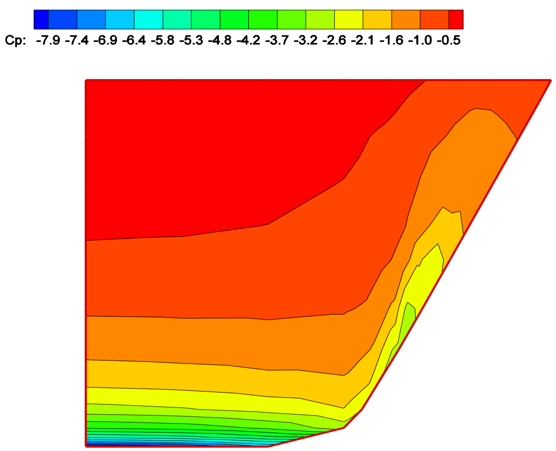
Leading edge view, 40 degrees of pitch

Experiements by Coton & Galbraith

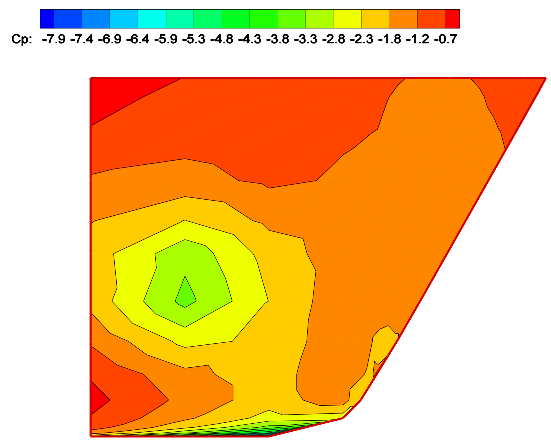


EXPERIMENT



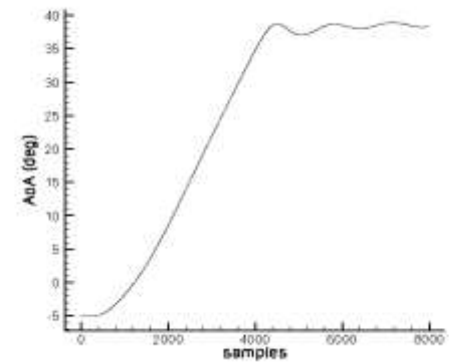


CFD



25deg

35 deg



Ramping motion

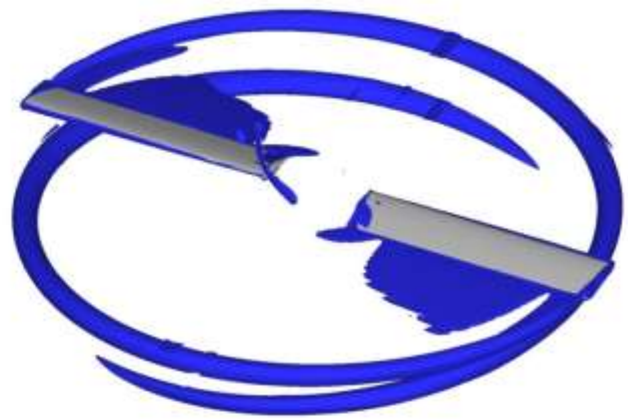
$a^+ = 0.027$

$-5^o \rightarrow 40^o$

$Re=1.45x10^6$

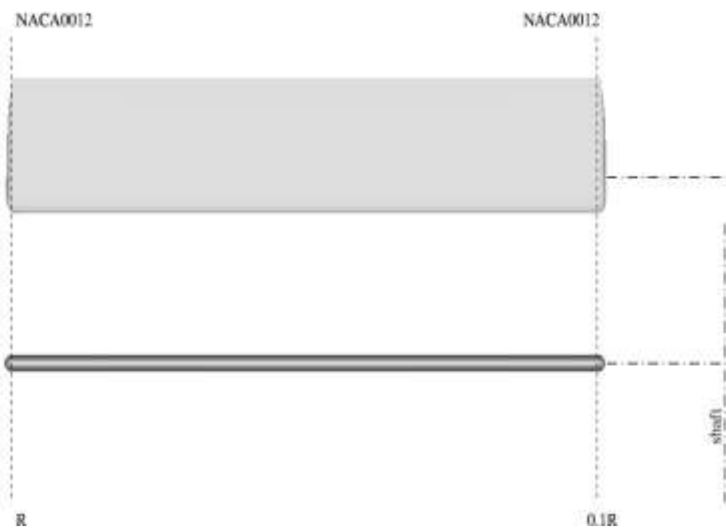
$M=0.16$

Hovering and Forward Flying Rotors

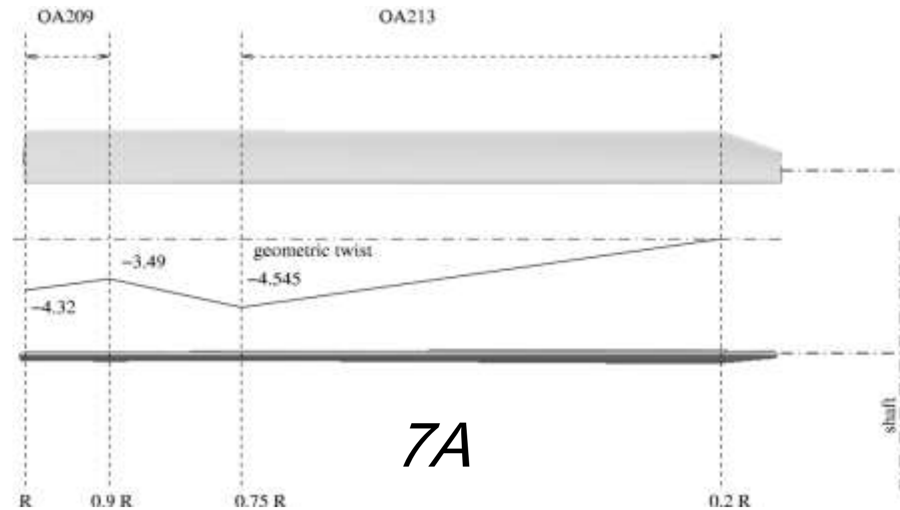


Isolated Rotor – Hover Validation

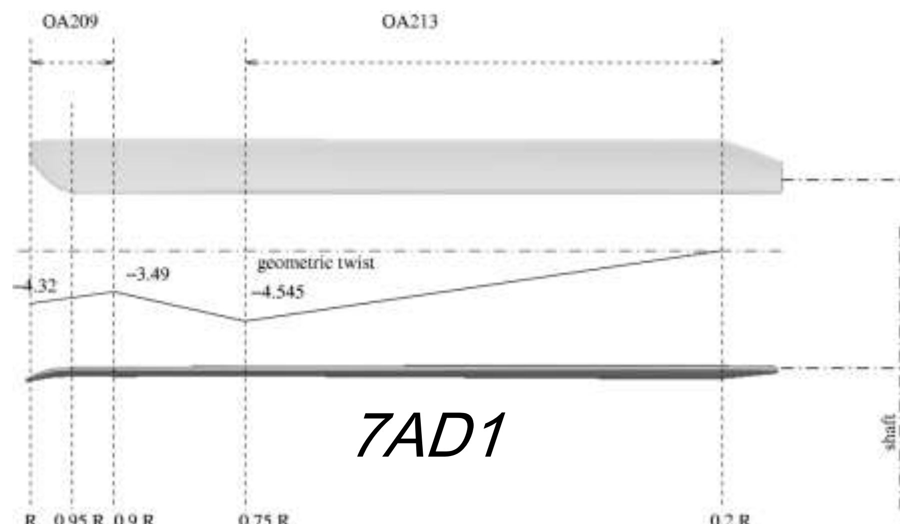
Validation test cases: blade geometries



Caradonna-Tung

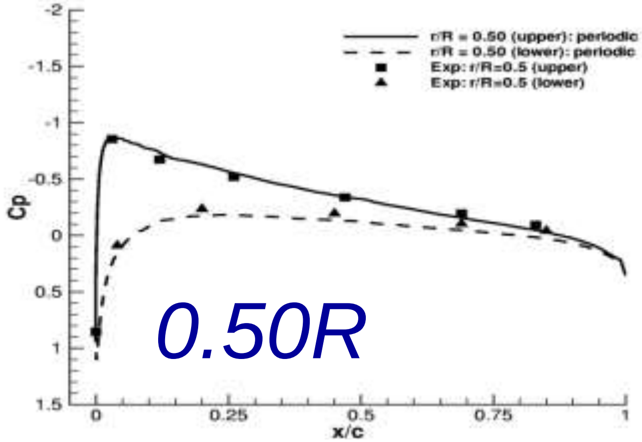


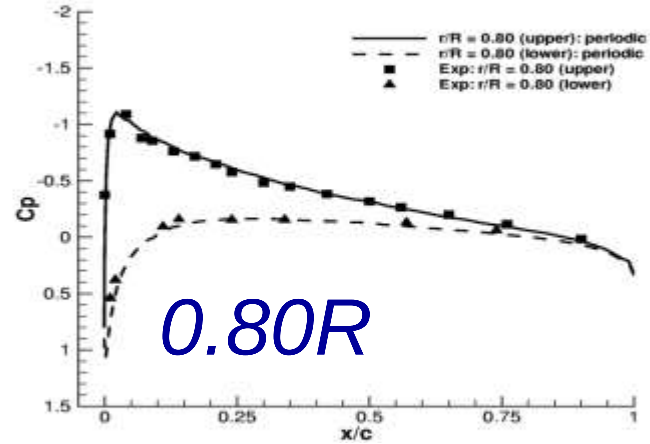
7A



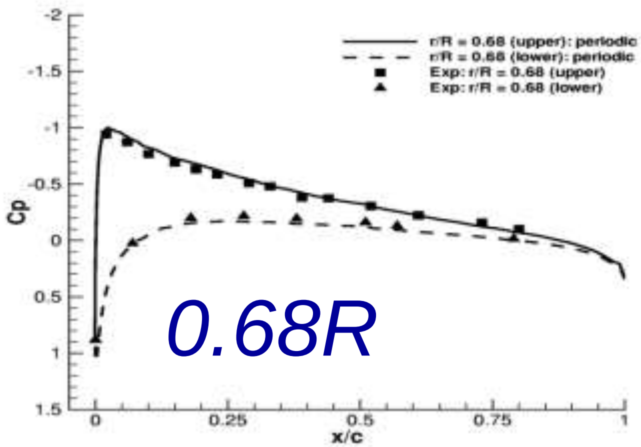
7AD1

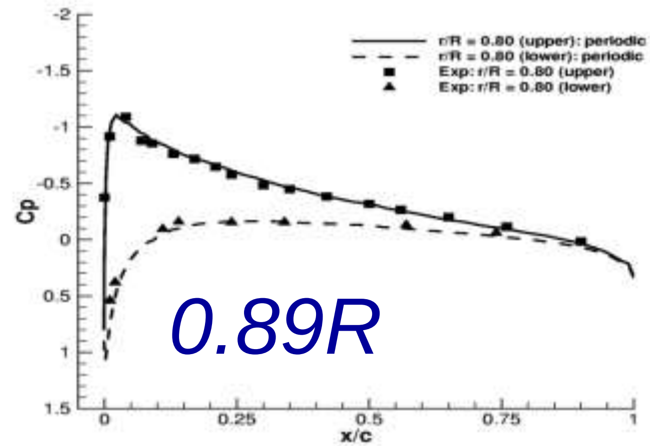
Isolated Rotor – Hover - Validation





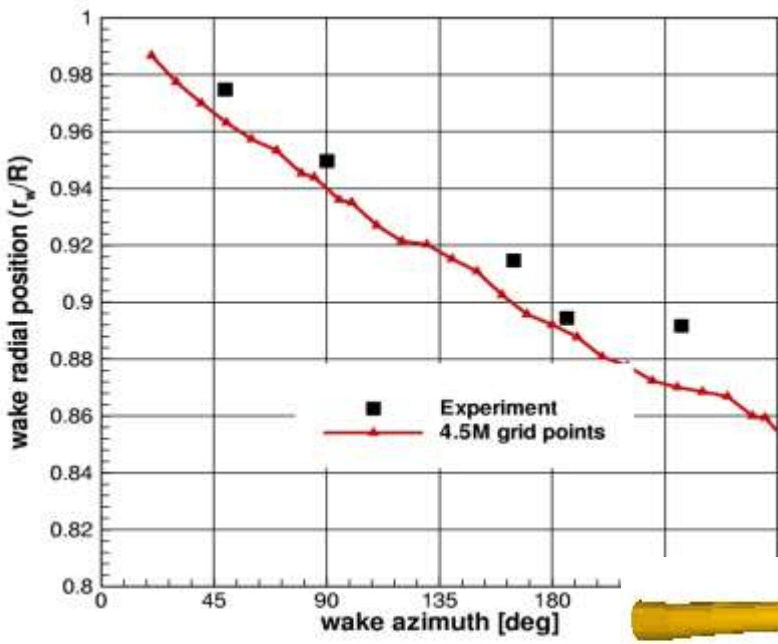
Validation test case: Caradonna&Tung rotor in hover (ii) lifting



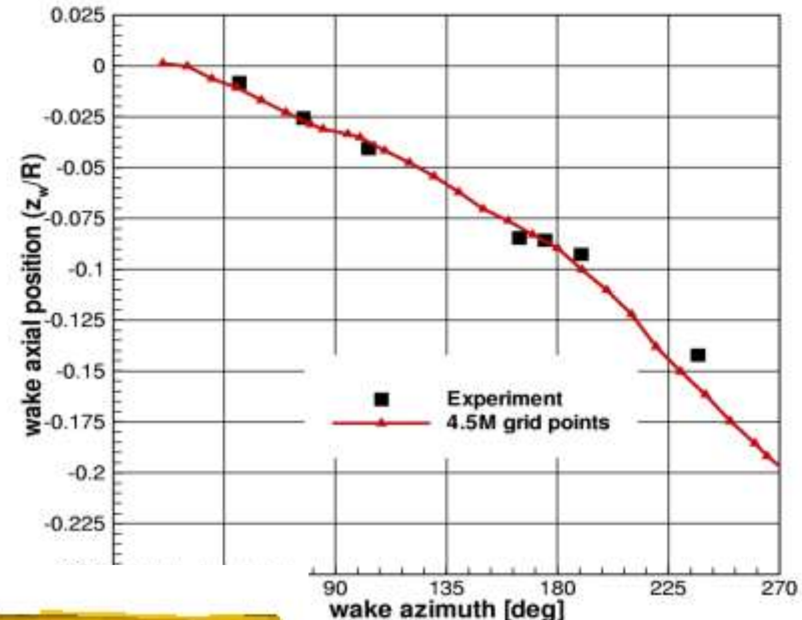


8º collective pitch, M_{tip} =0.44, inviscid, 74-block grid, 1.1M grid points

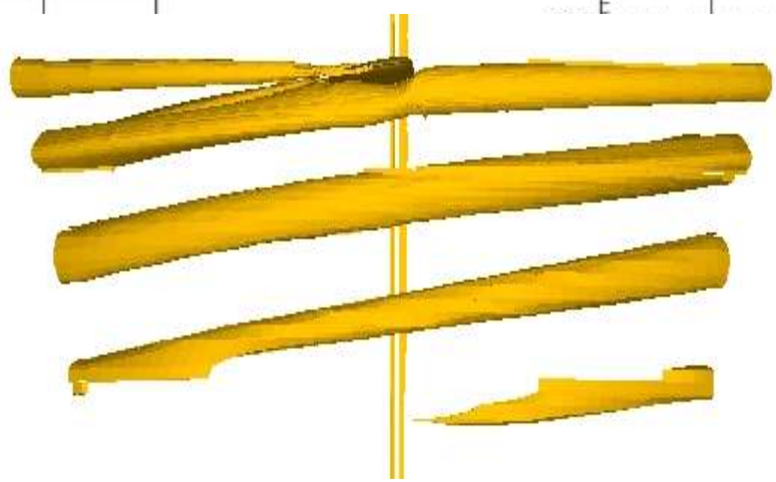
Caradonna & Tung Rotor in Hover



Radial position

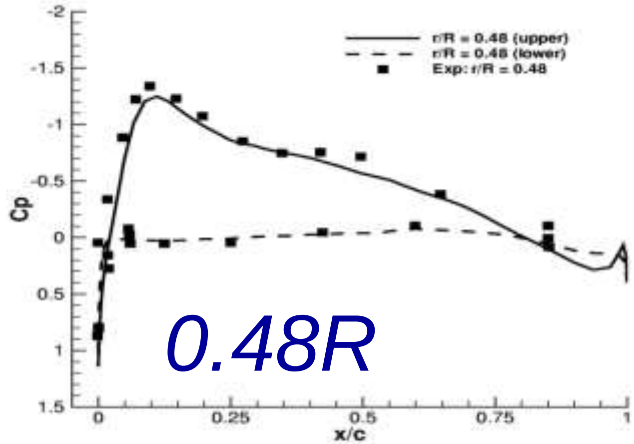


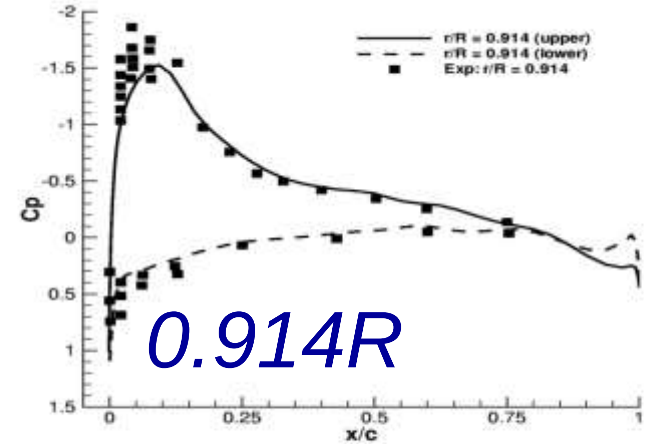
Axial position



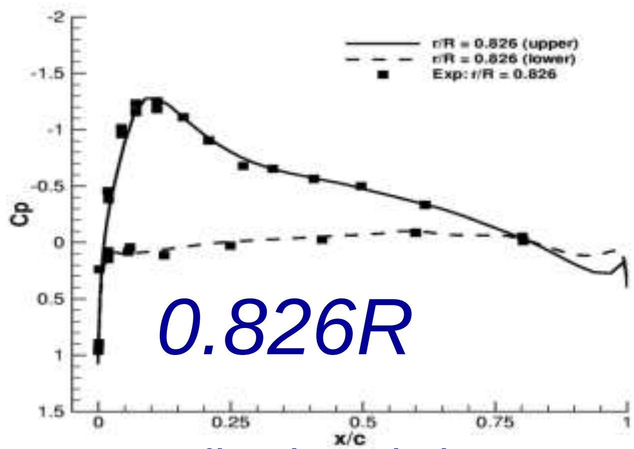
8^o collective pitch, M_{tip} =0.44, i74-block grid, 4.5M grid points

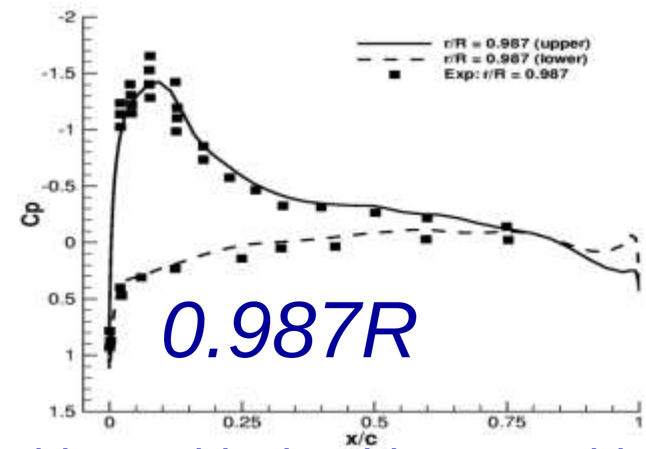
Isolated Rotor – Hover Validation





Validation test case: ONERA 7A rotor in hover

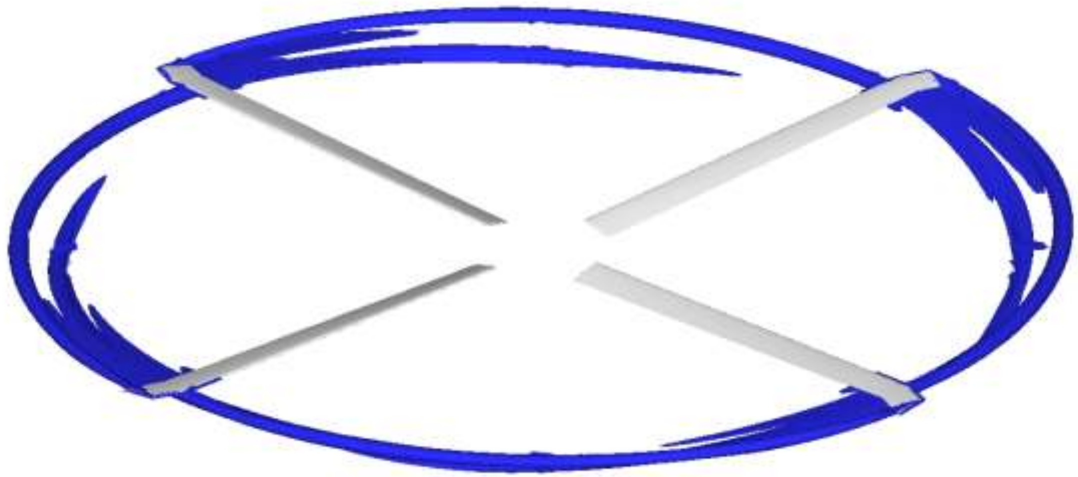


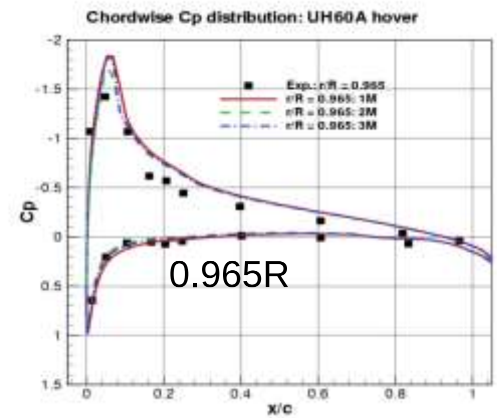


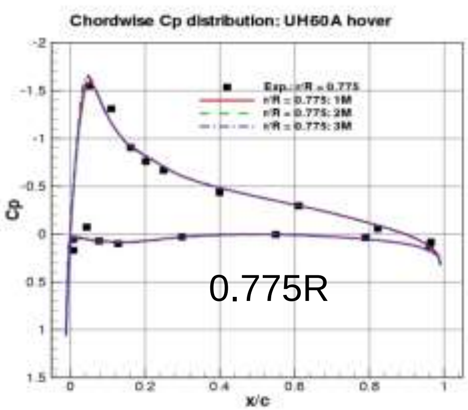
7.5º collective pitch, M_{tip} =0.6612, inviscid, 140-block grid, 0.6M grid points

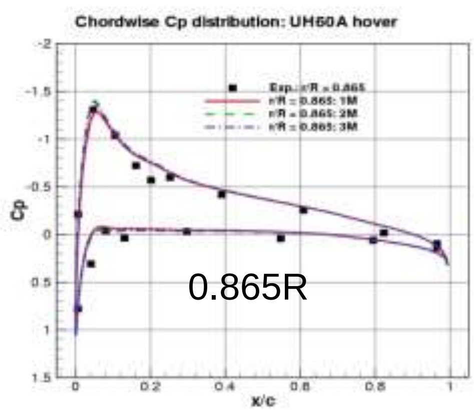
CFD – Validation - UH-60A Model Tail Rotor Tests (Lorber)

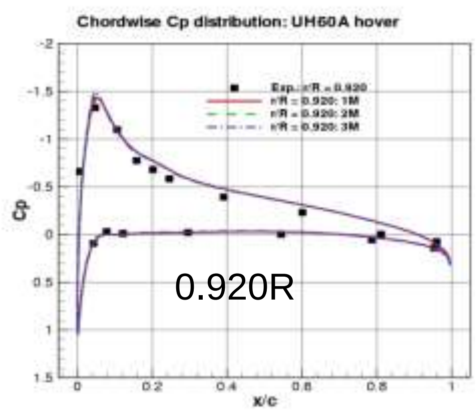
UH60A - Hover M_T = 0.626, 10.5° collective, 2.31° coning

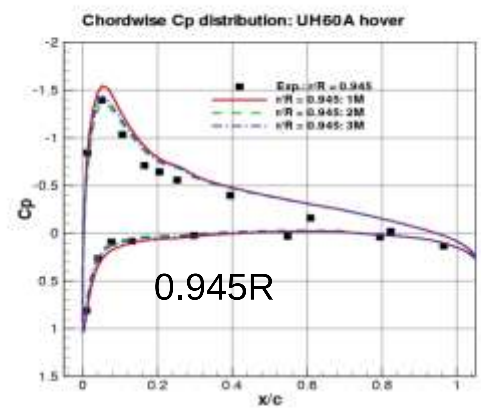




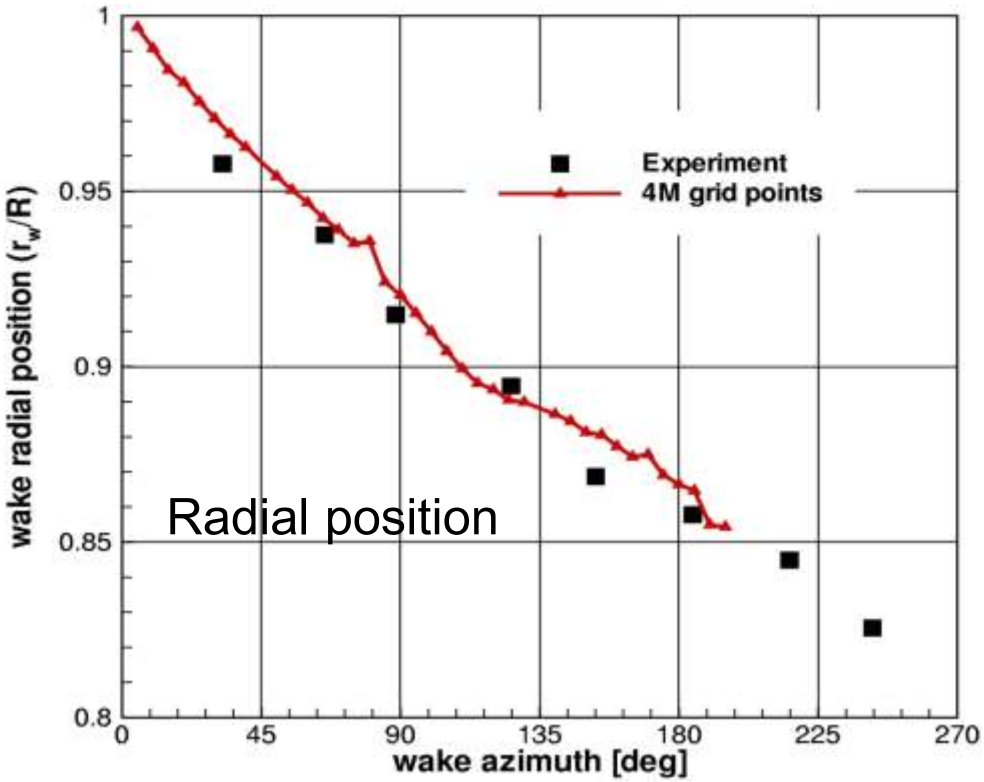


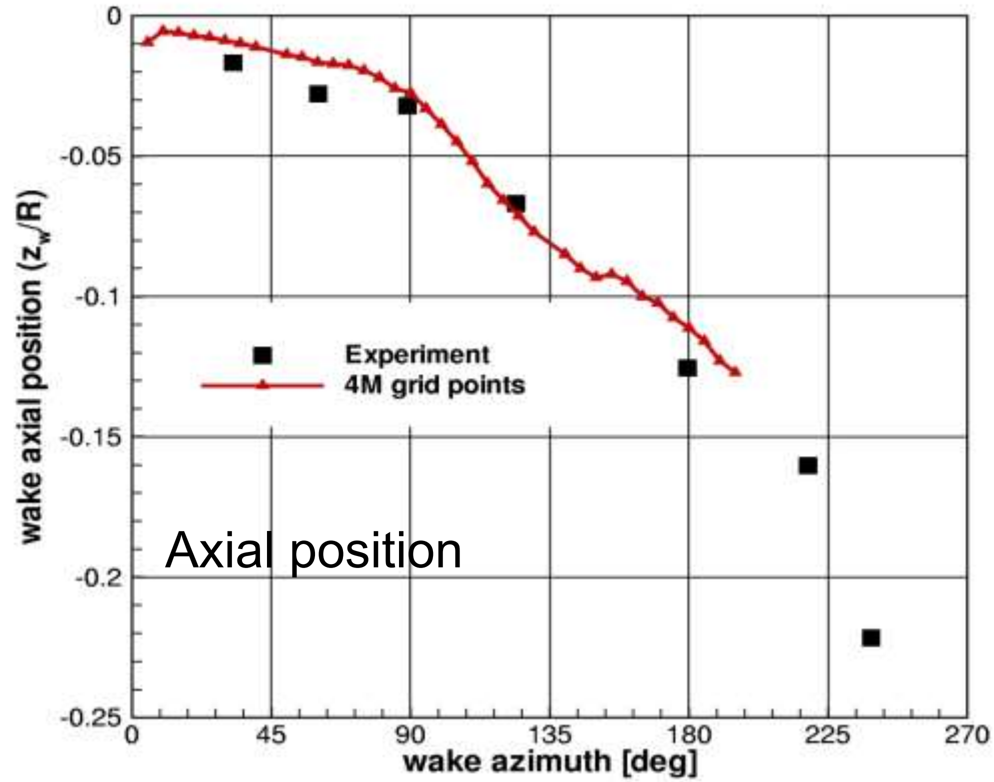






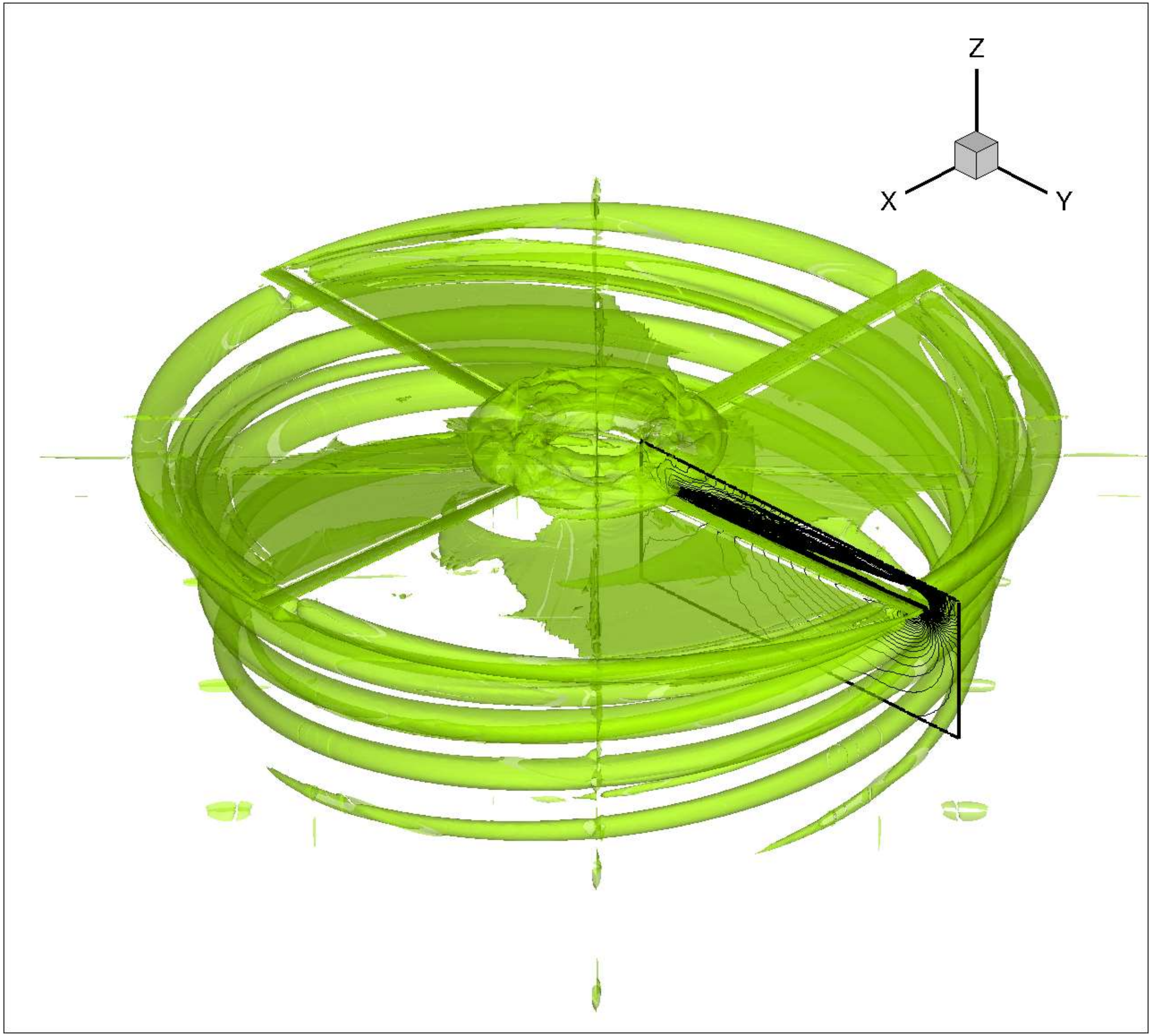
Isolated Rotor – Hover - Validation

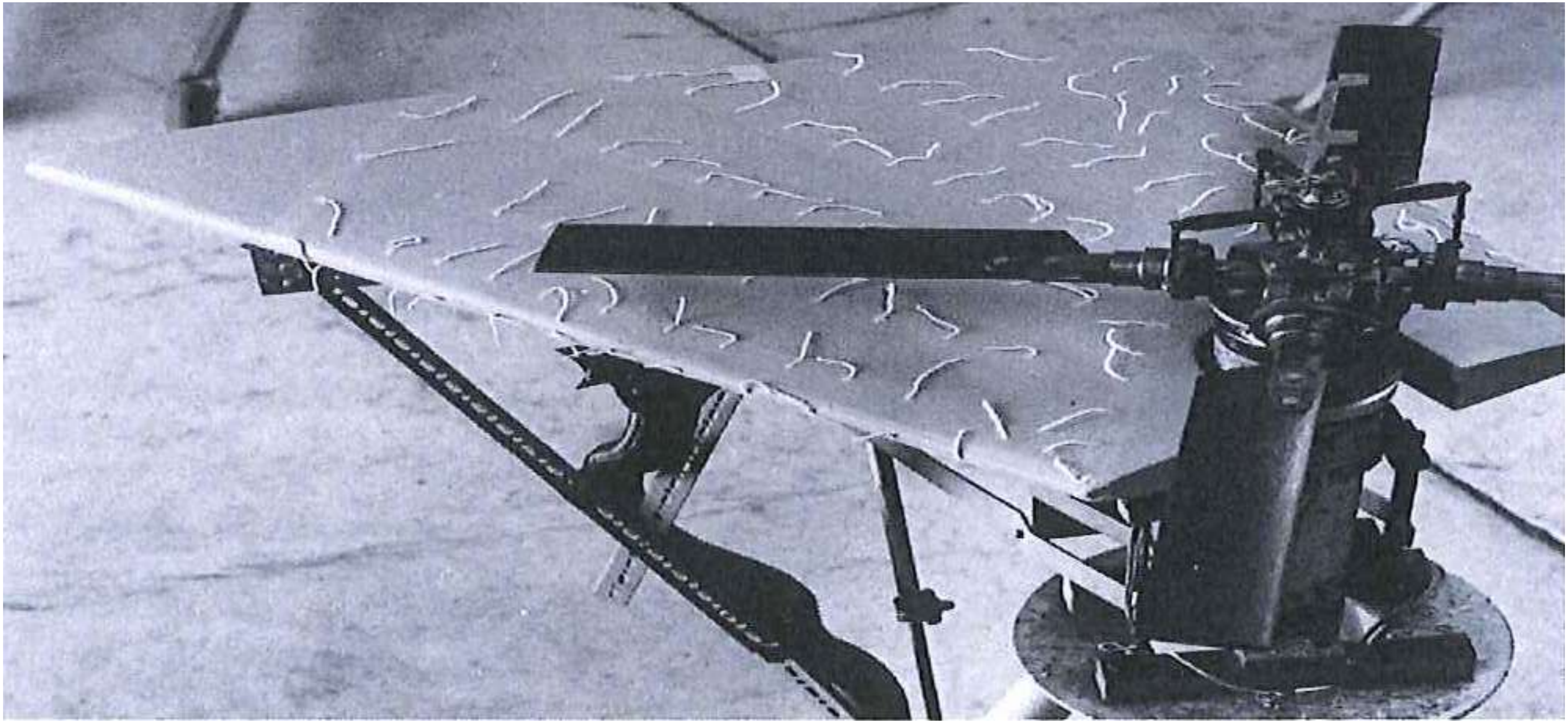




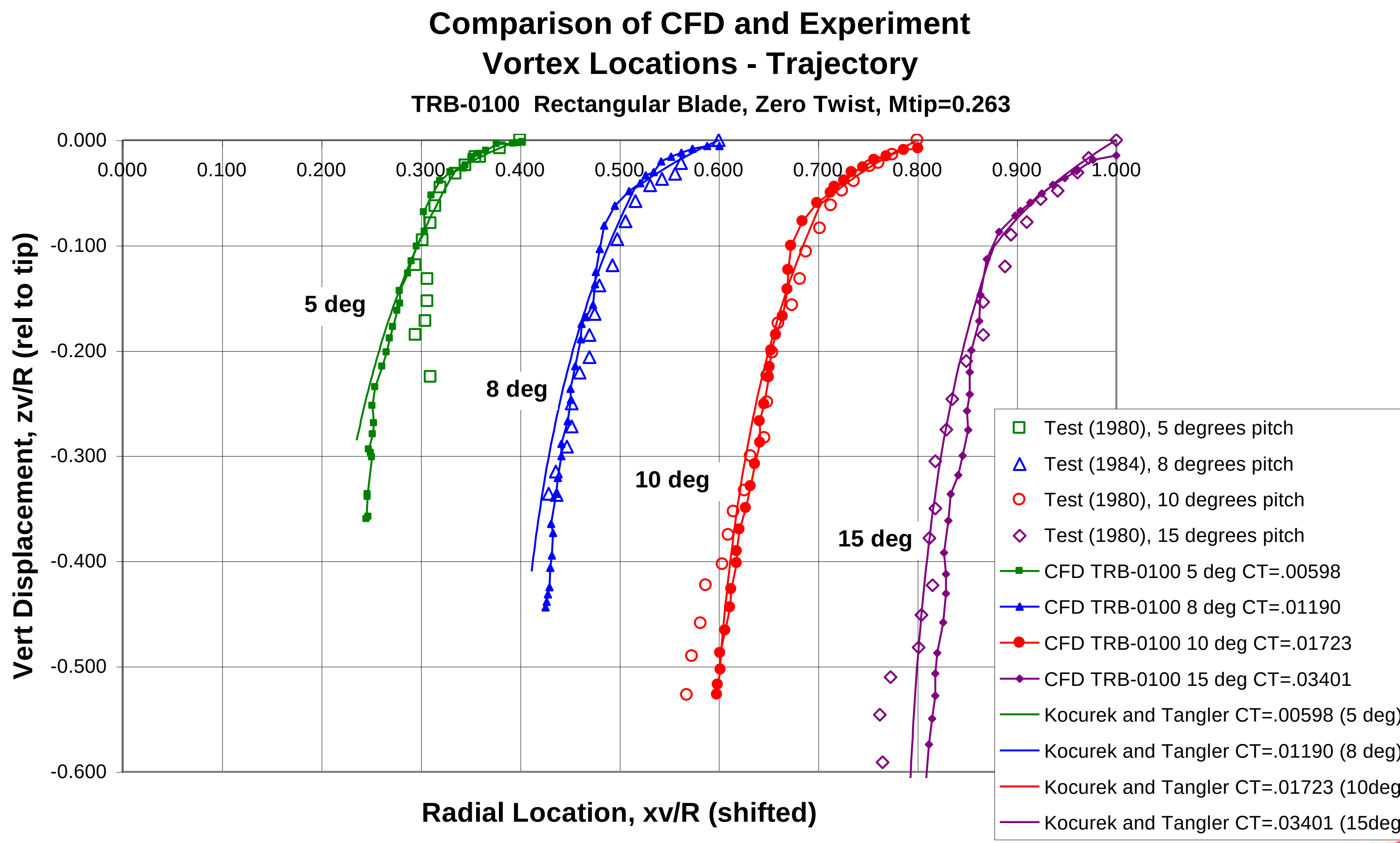
UH-60A rotor in hover: wake vortex position

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

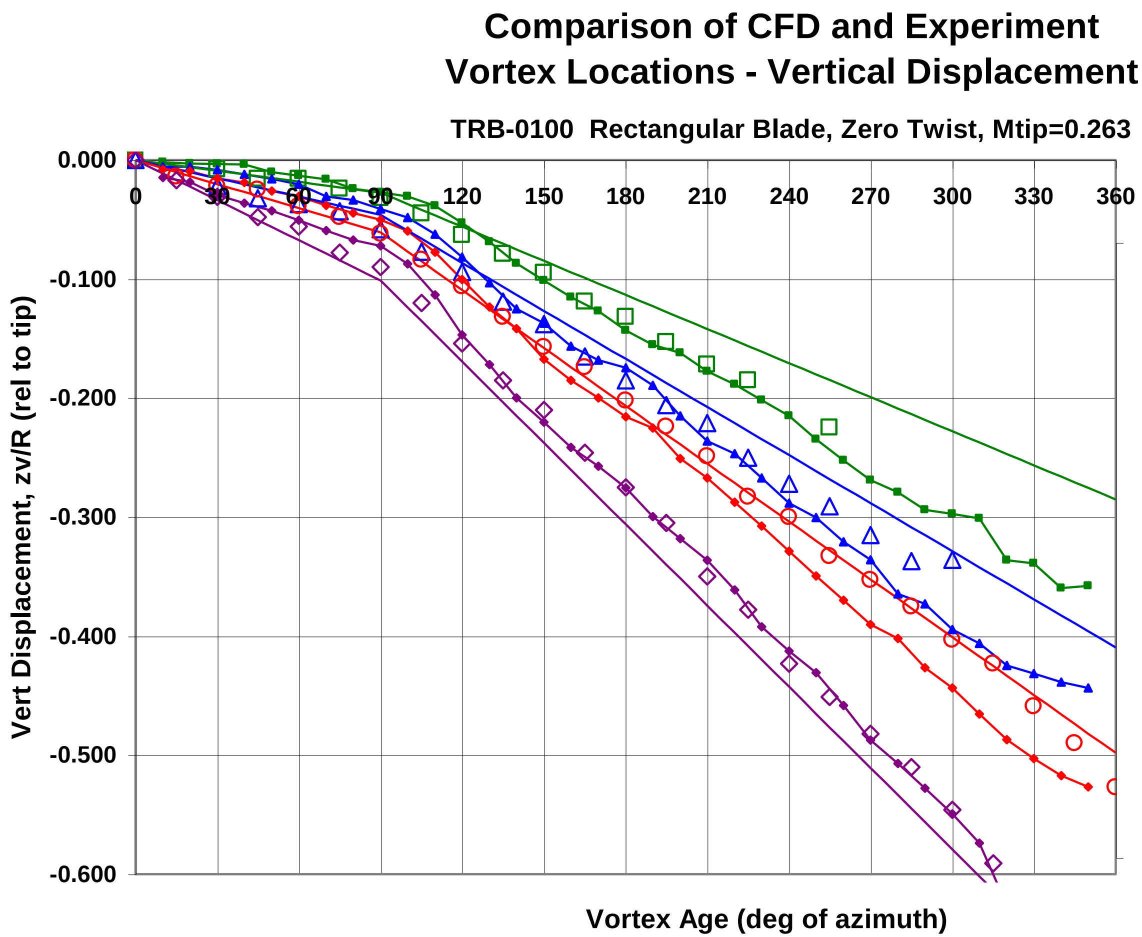

Z
X
Y



Comparison with Model Rotor Wake Flow Visualisation Tests



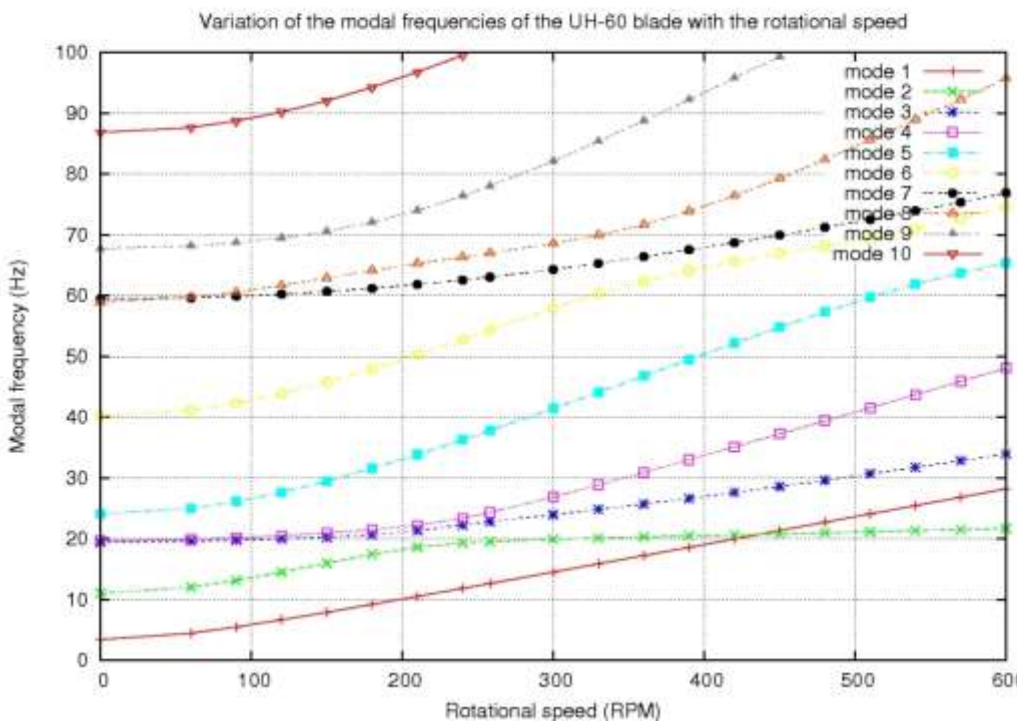
Comparison – Model Tail Rotor Vortex Wake Trajectories



Vortex locations around the azimuth

Structural models – "UH-60A blade"

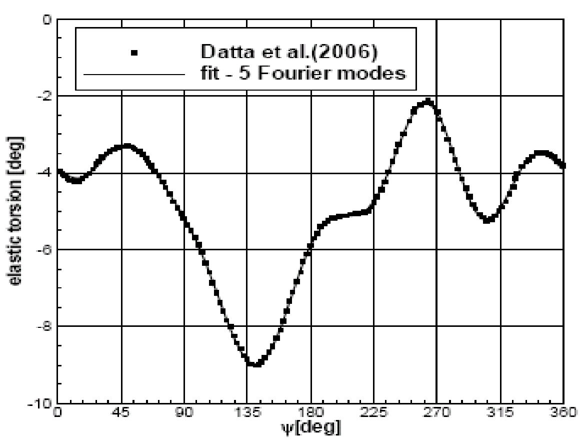
	Flap 1	Flap 2	Flap 3	Flap 4	Flap 5	Flap 6	Chord 1	Chord 2	Torsion 1	Torsion 2
Experiment	4.80	12.82	25.61	41.97	64.46	95.83	26.09	69.57	45.80	83.85
NASTRAN	4.36	12.81	25.09	41.17	65.52	95.97	25.55	69.81	44.42	84.05

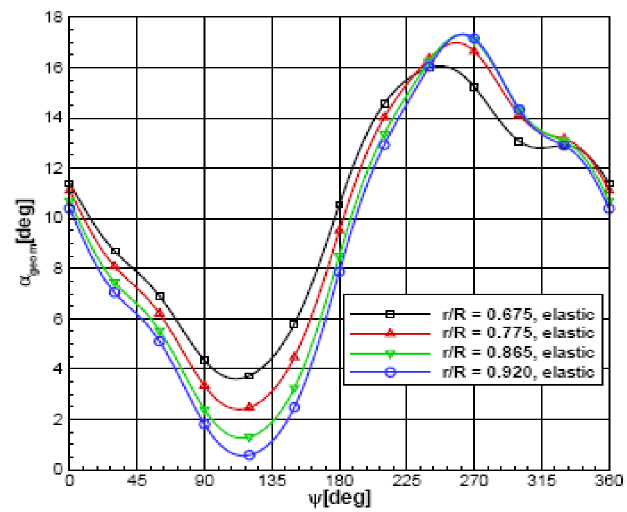


UH-60A Blade

Case	rotor	μ	M_{tip}	θ_{shaft}	θ_0	θ_{1s}	θ_{1c}	β_0	β_{1s}	β_{1c}
UH-60 baseline	UH-60A	0.368	0.648	7.3	14.6	8.63	-2.39	3.43	-2.04	-0.70
UH-60 red.flap	UH-60A	0.368	0.648	7.3	14.6	8.63	-2.39	3.43	-1.04	-0.70
UH-60 elastic	UH-60A	0.368	0.648	7.3	14.6	8.63	-2.39	3.43	-1.04	-0.70

Case	r/R=0.775			r/R=0.865			r/R=0.920		
	θ	M^2C_n	M^2C_M	θ	M^2C_n	M^2C_M	θ	M^2C_n	M^2C_M
UH-60 baseline	84^o	60^o	85^o	85^o	95^o	110^o	85^o	95^o	115^o
UH-60 red.flap	92^o	62^o	85^o	93^o	100^o	115^o	93^o	100^o	117^o
UH-60 elastic	113^o	120^o	120^o	115^o	120^o	130^o	116^o	120^o	140^o



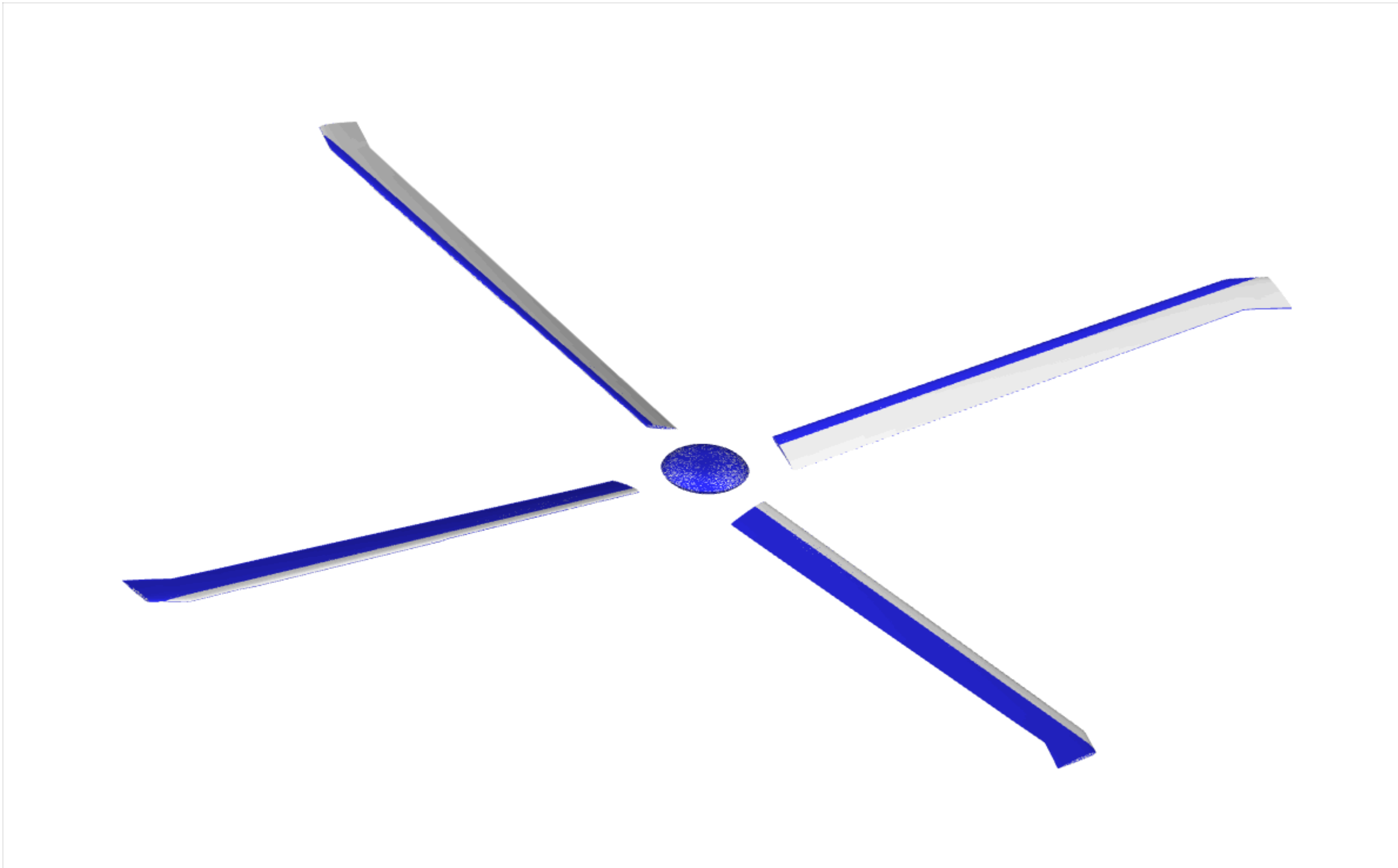


Torsional Mode

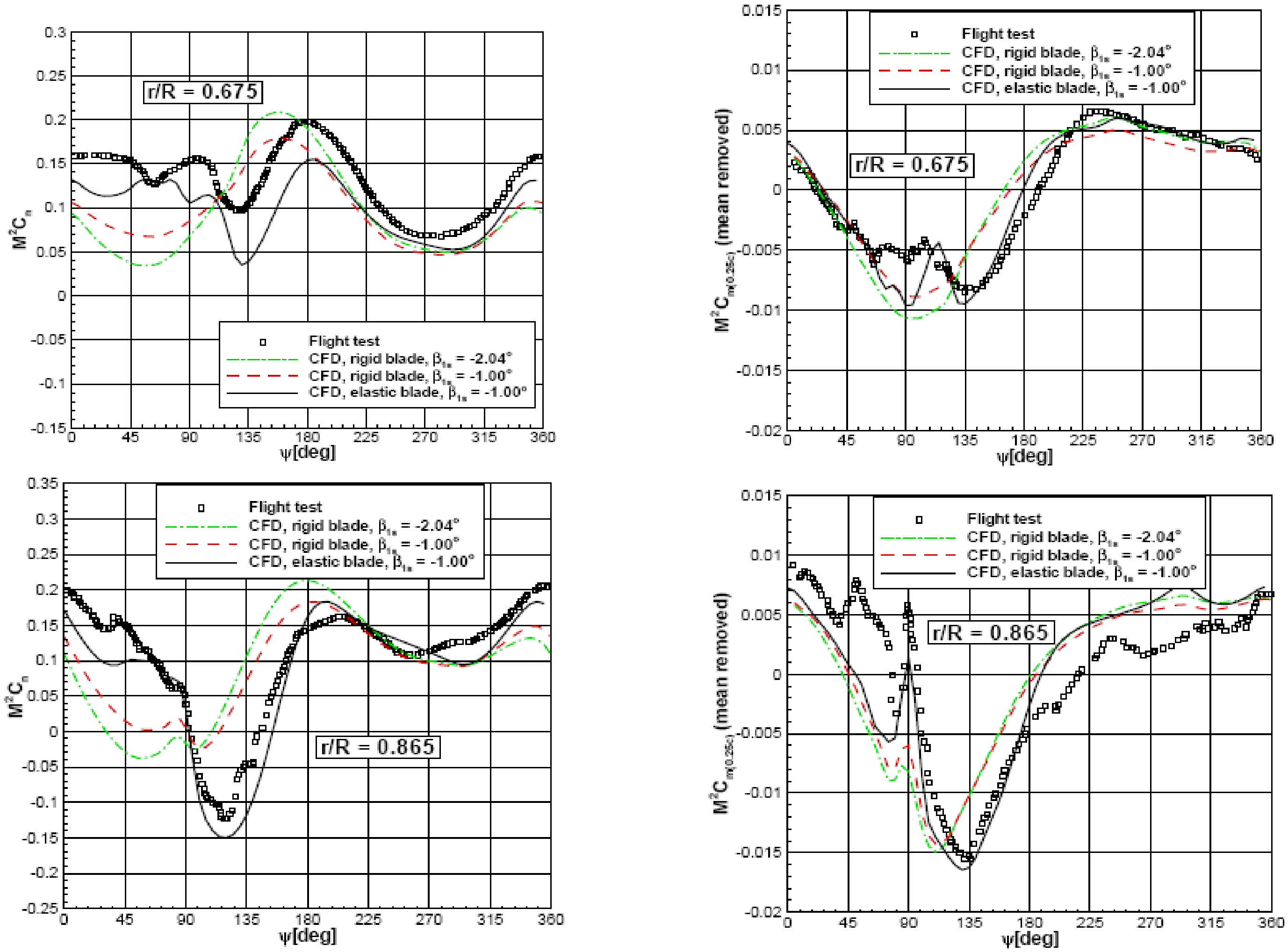
Reconstructed from Datta et al., 2006

Aeroelastic Computation

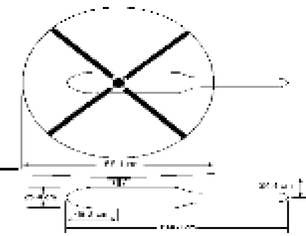
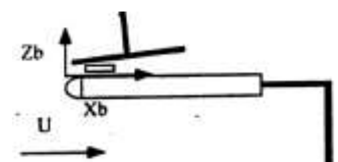
Grey: rigid
Blue: elastic



Comparison with Flight Test Data

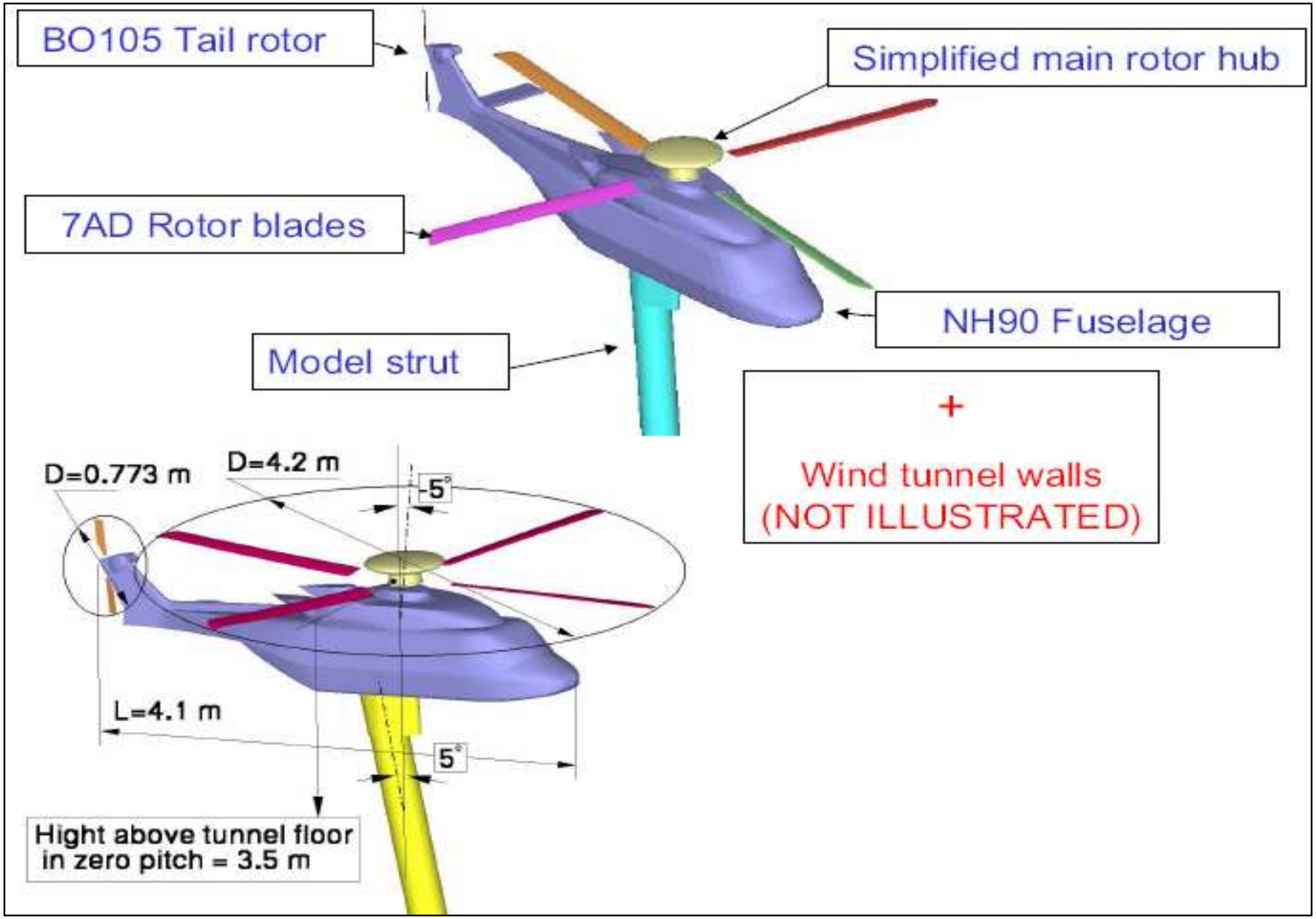


Rotor-Fuselage Studies – validation cases for HMB

	Complex Geometry			Simpler Geometry
More detailed data				
				
Less detailed data				

Sources: GIT, NASA, U Maryland, JAXA, DNW, ONERA

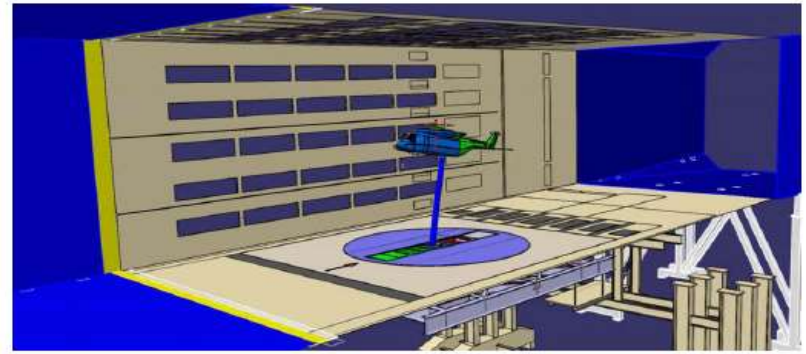
The GOAHEAD Model



[W. Khier, HPCN Workshop - Braunschweig 14.06.2009.DLR]

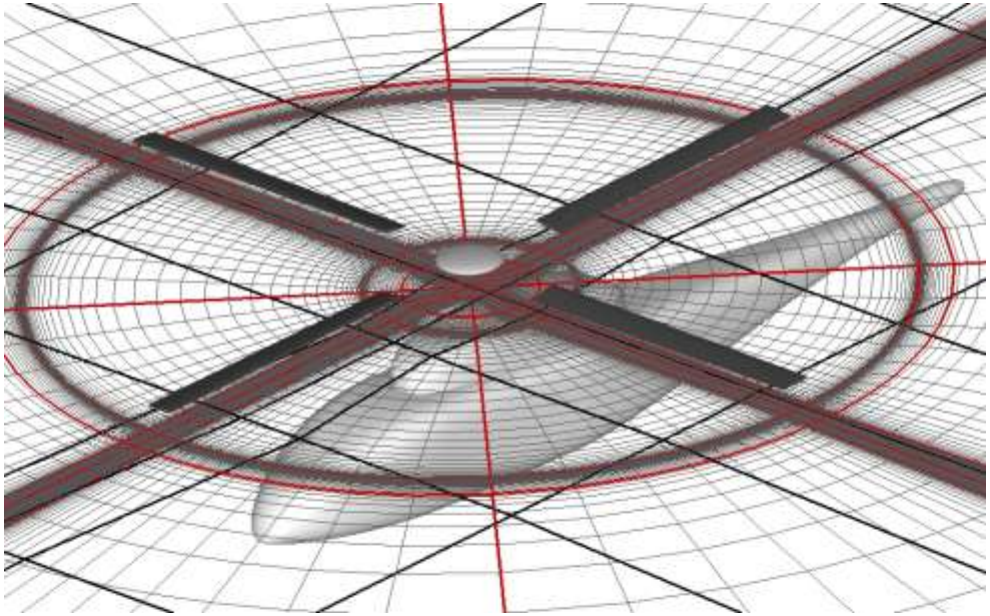
GOAHEAD

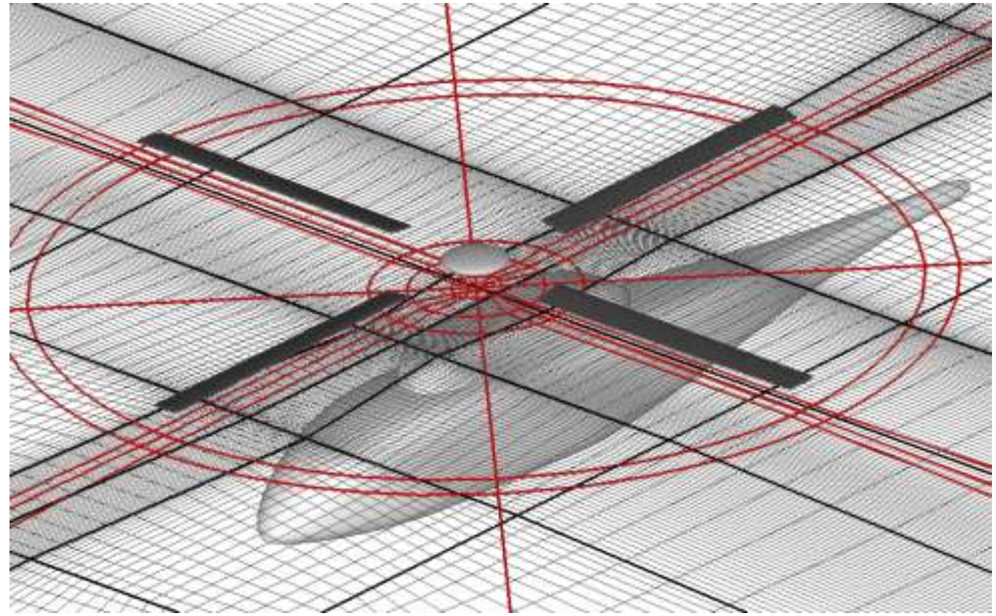
- F6 EC Project
- Exploited by few EC partners
- Fuselage based on he NH90 aircraft
- Main rotor based on the Puma aircraft
- Tail rotor from the BO105 aircraft
- Experiments by DNW
- Many partners with different methods
- Perhaps the most complete database of measurements ever conducted for helicopter
- Realistic configuration



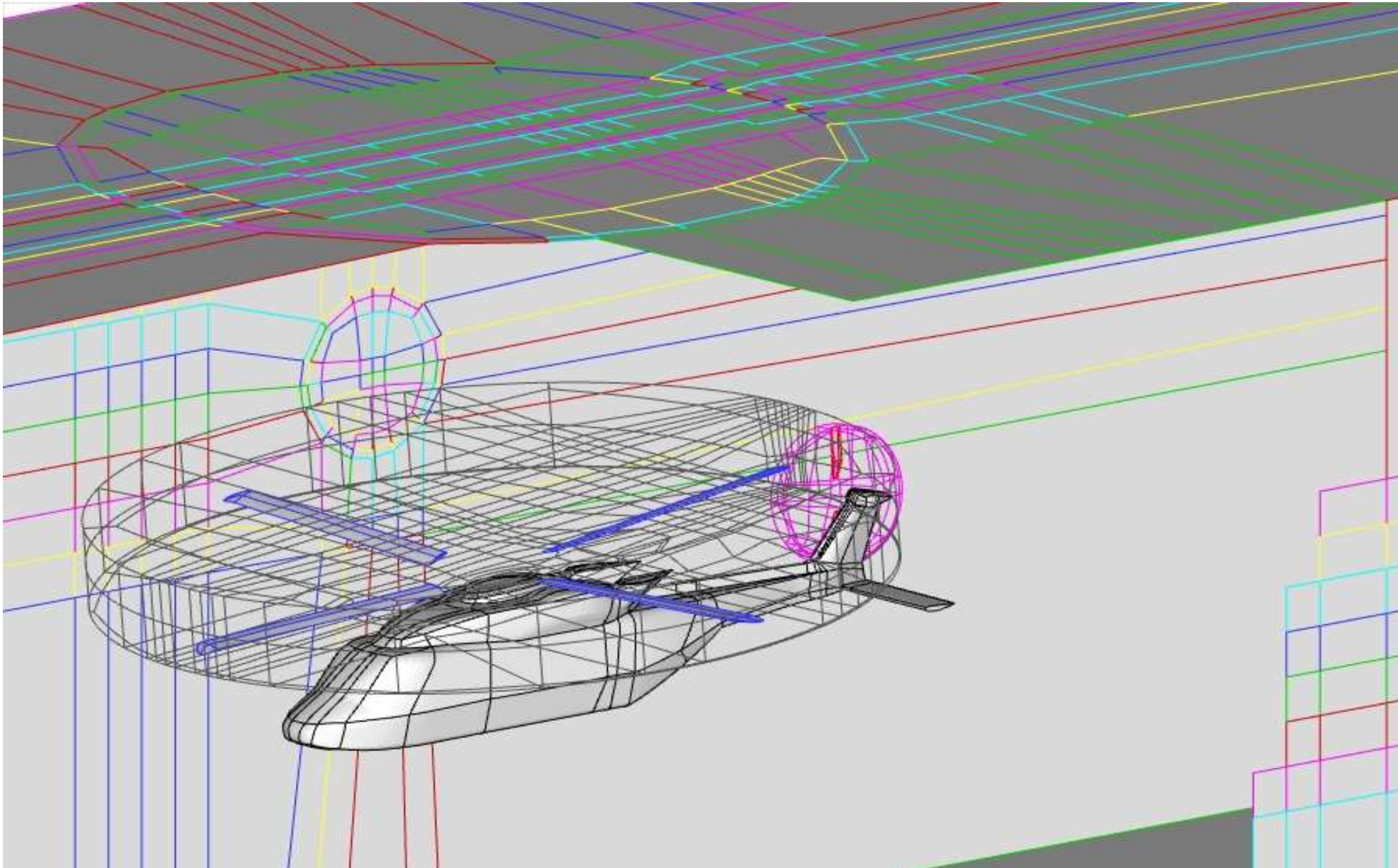
Video Clip from GOAHEAD

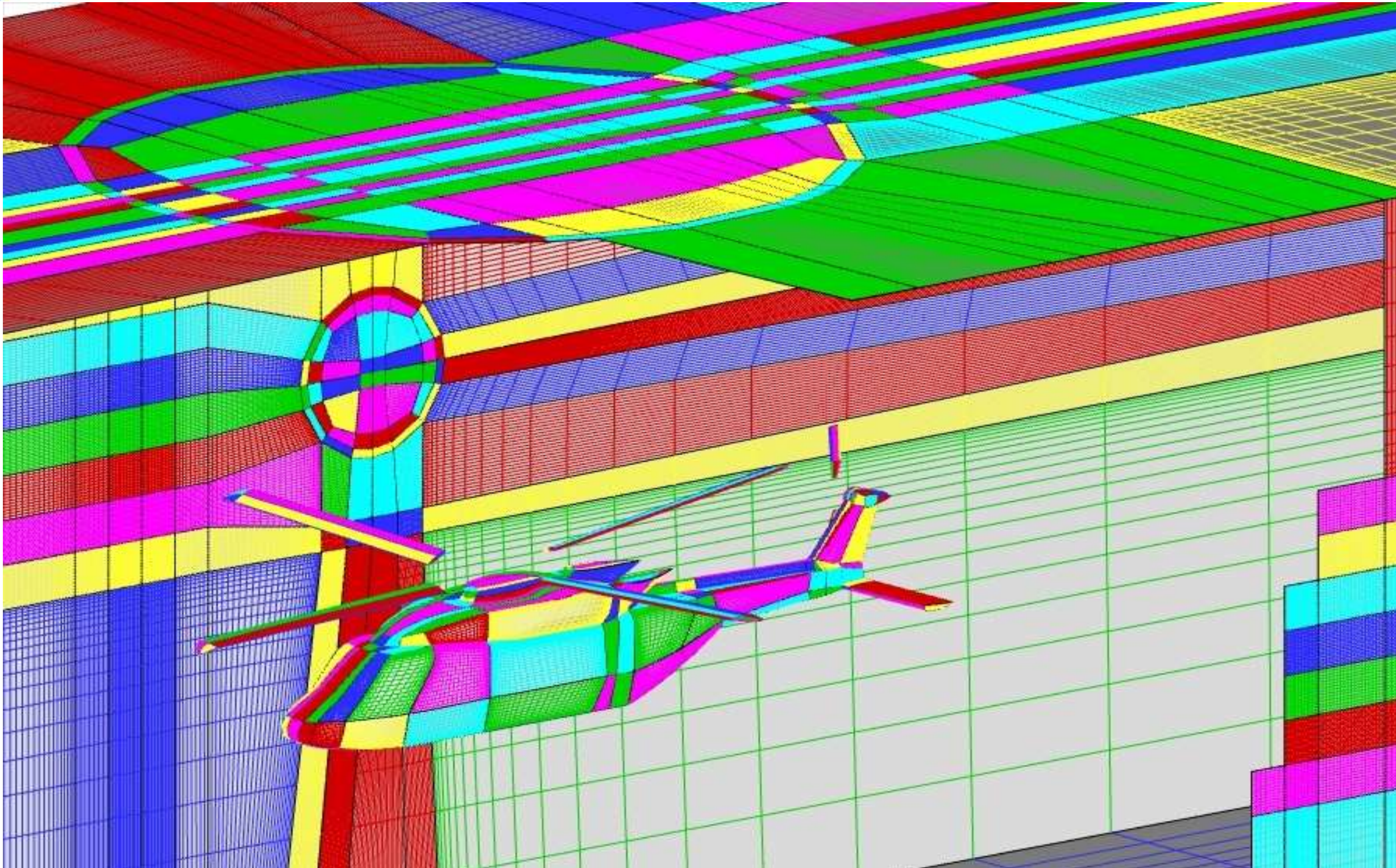
Sliding Plane Approach

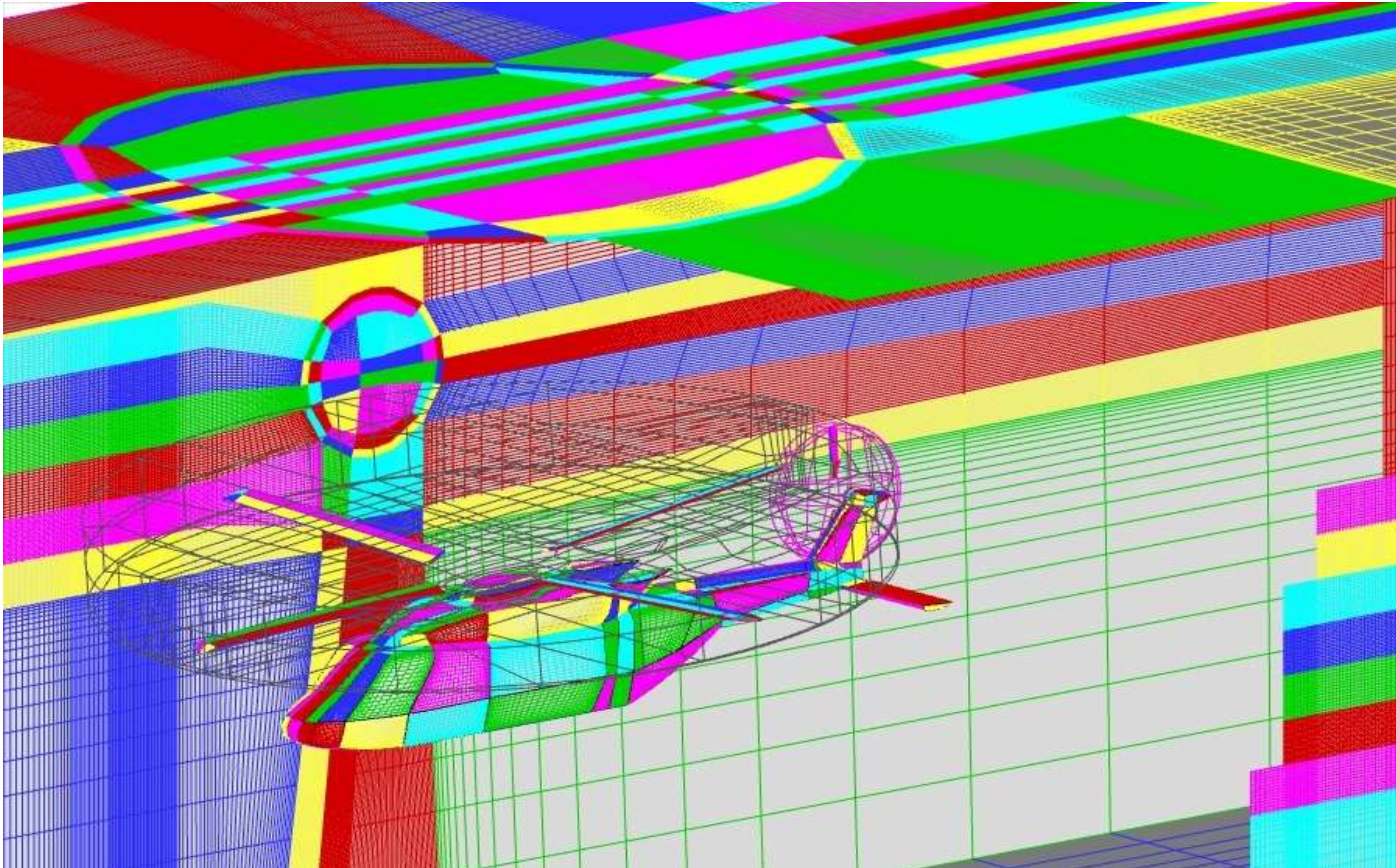


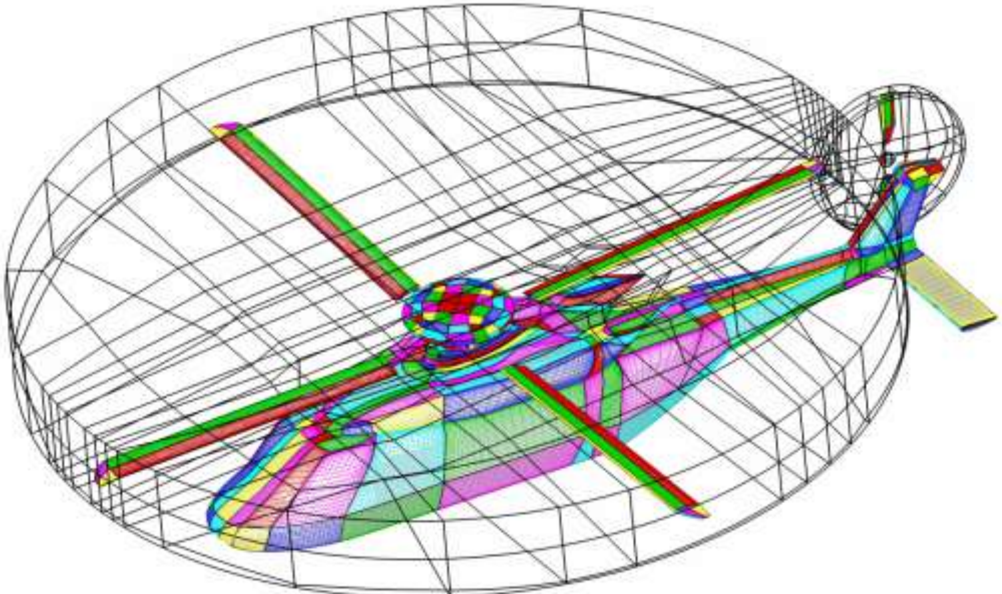


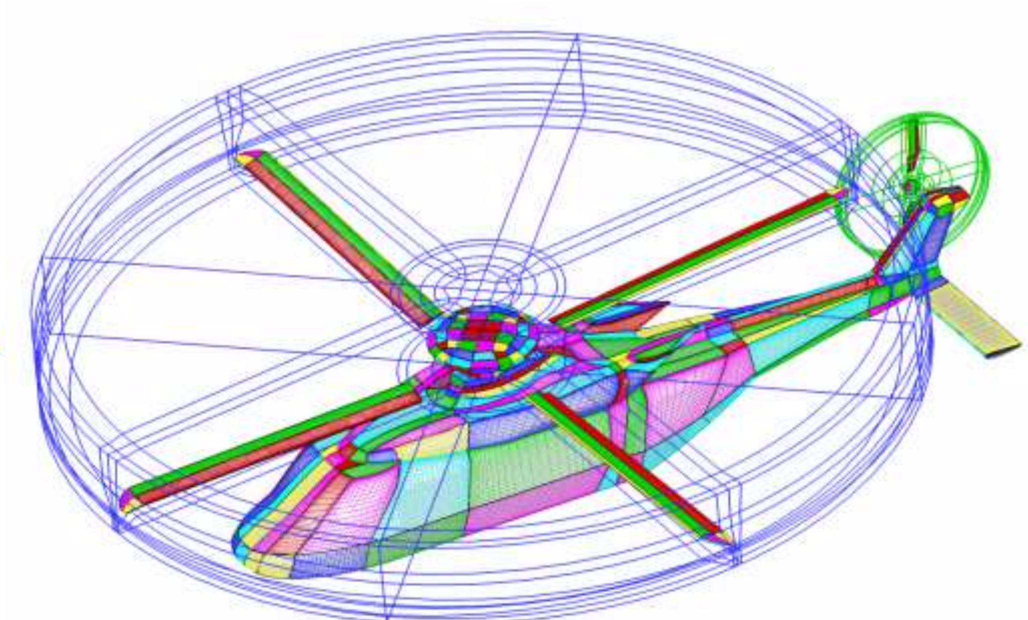
- Sliding-plane method can be regarded as an extension to the regular multi-block approach
- Halo cells are formed on both sides of interface
- Two steps are involved:
  - identification of neighbours
  - interpolation of neighbour cell centre values to form halo value





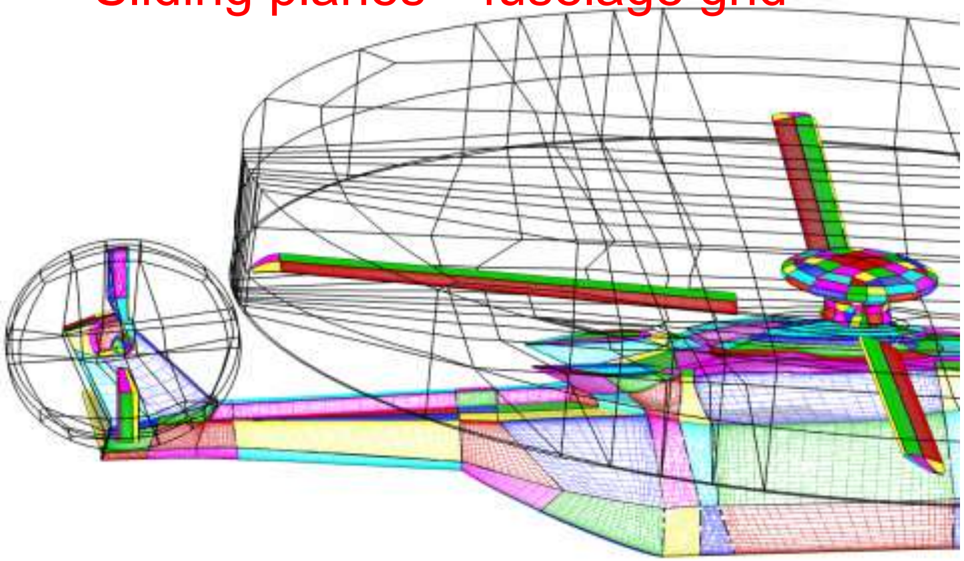


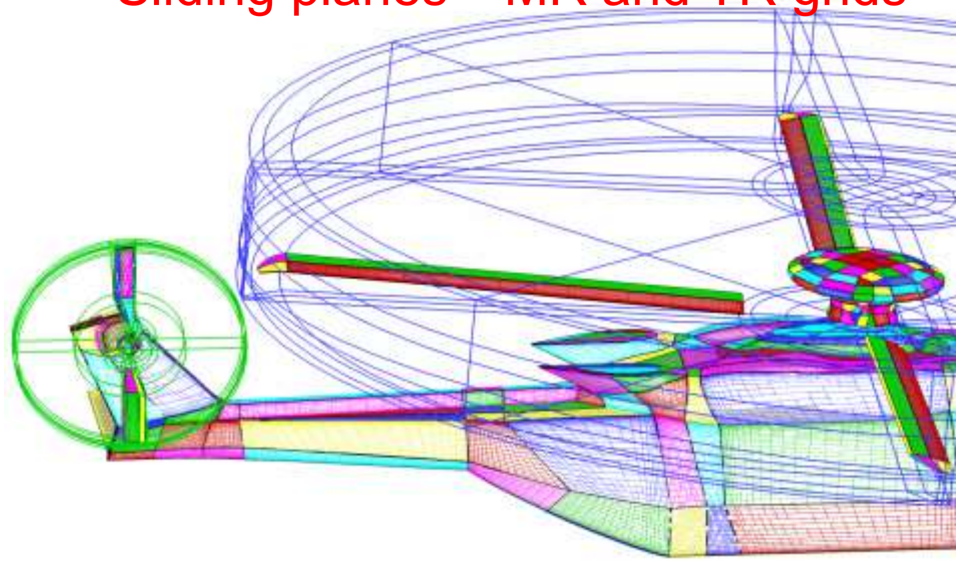




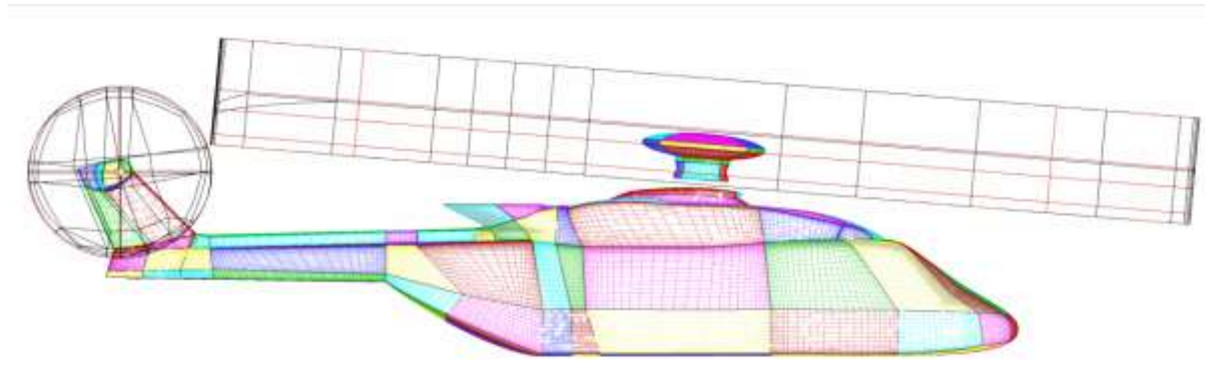
Sliding planes – fuselage grid

Sliding planes – MR and TR grids

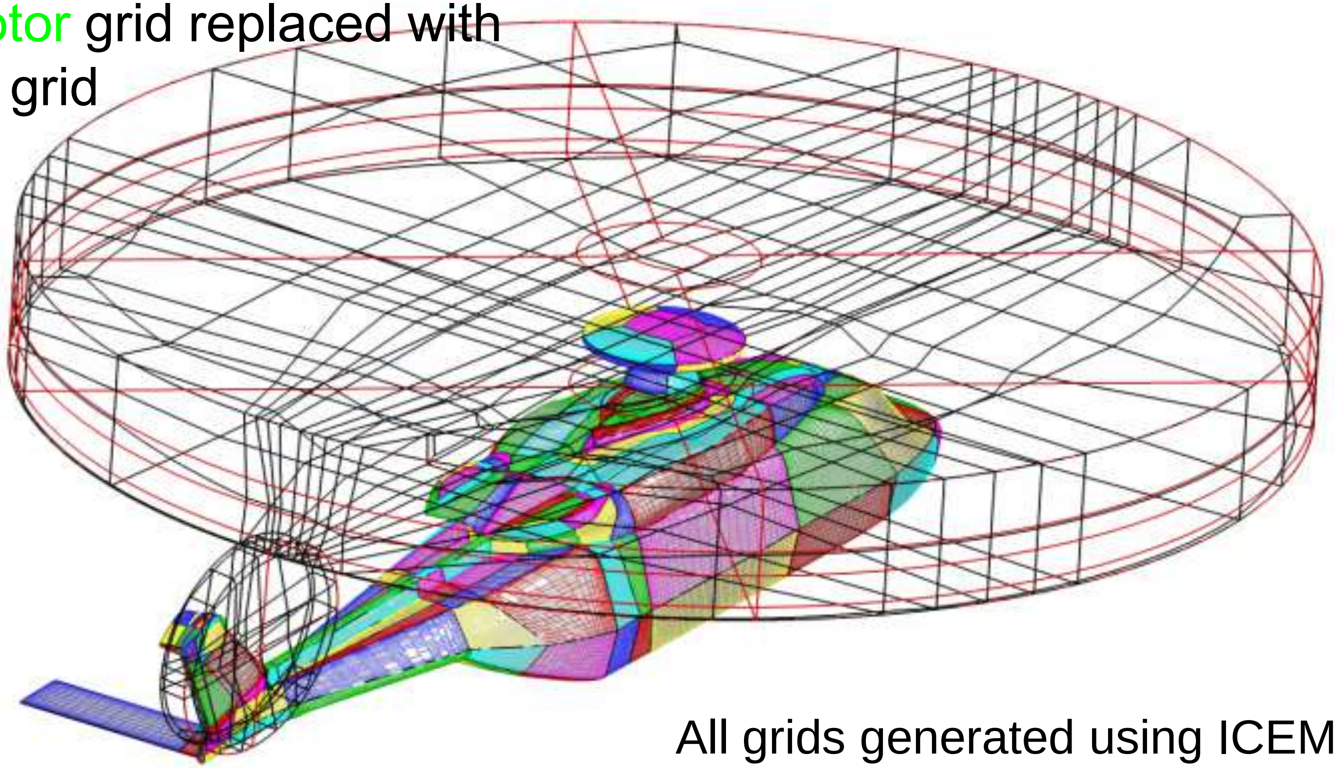




‘isolated’ fuselage mesh



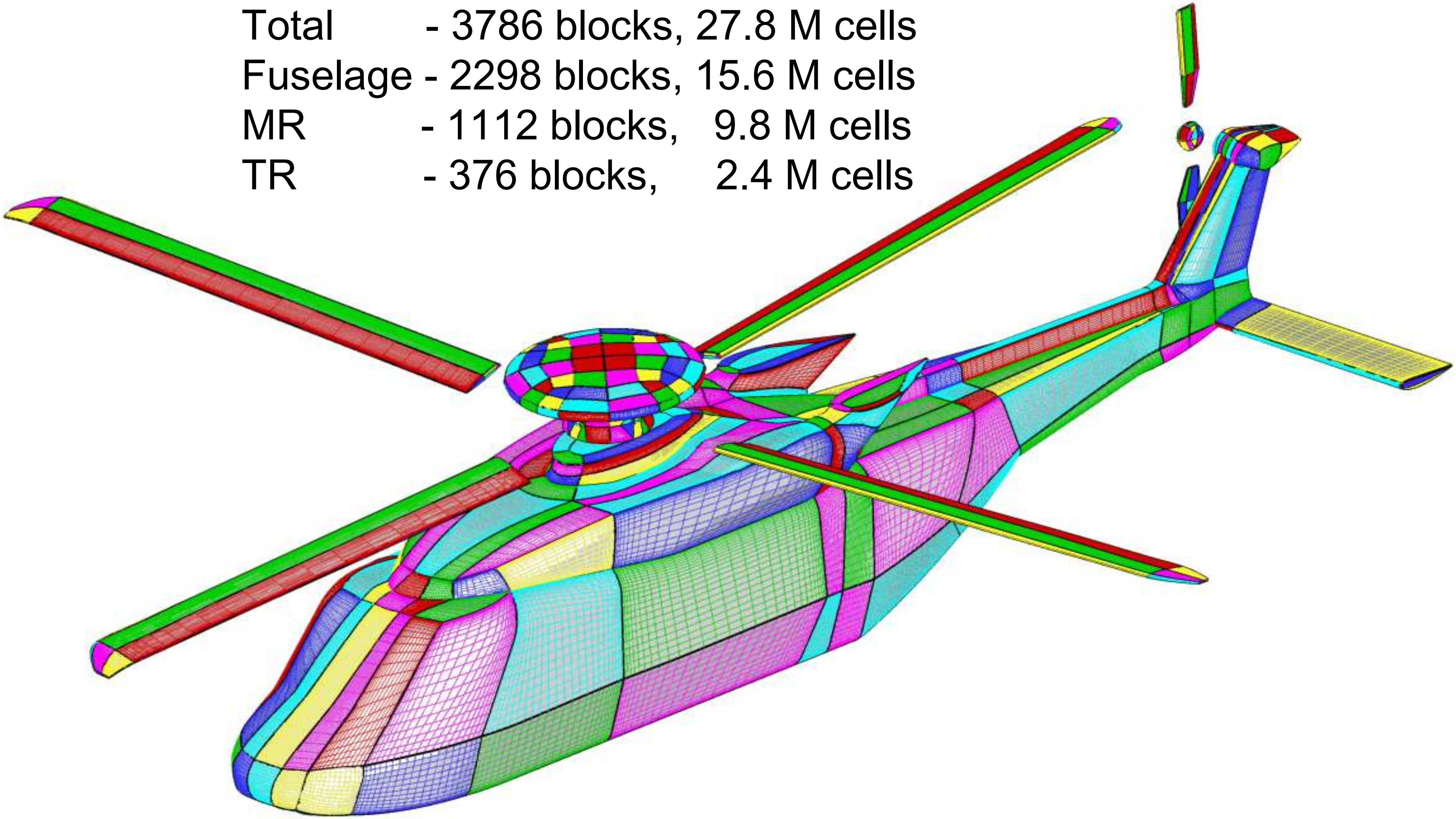
- Re-use of fuselage grid of full geometry
- Main rotor grid replaced with mesh for rotor head
- Tail rotor grid replaced with ‘empty’ grid

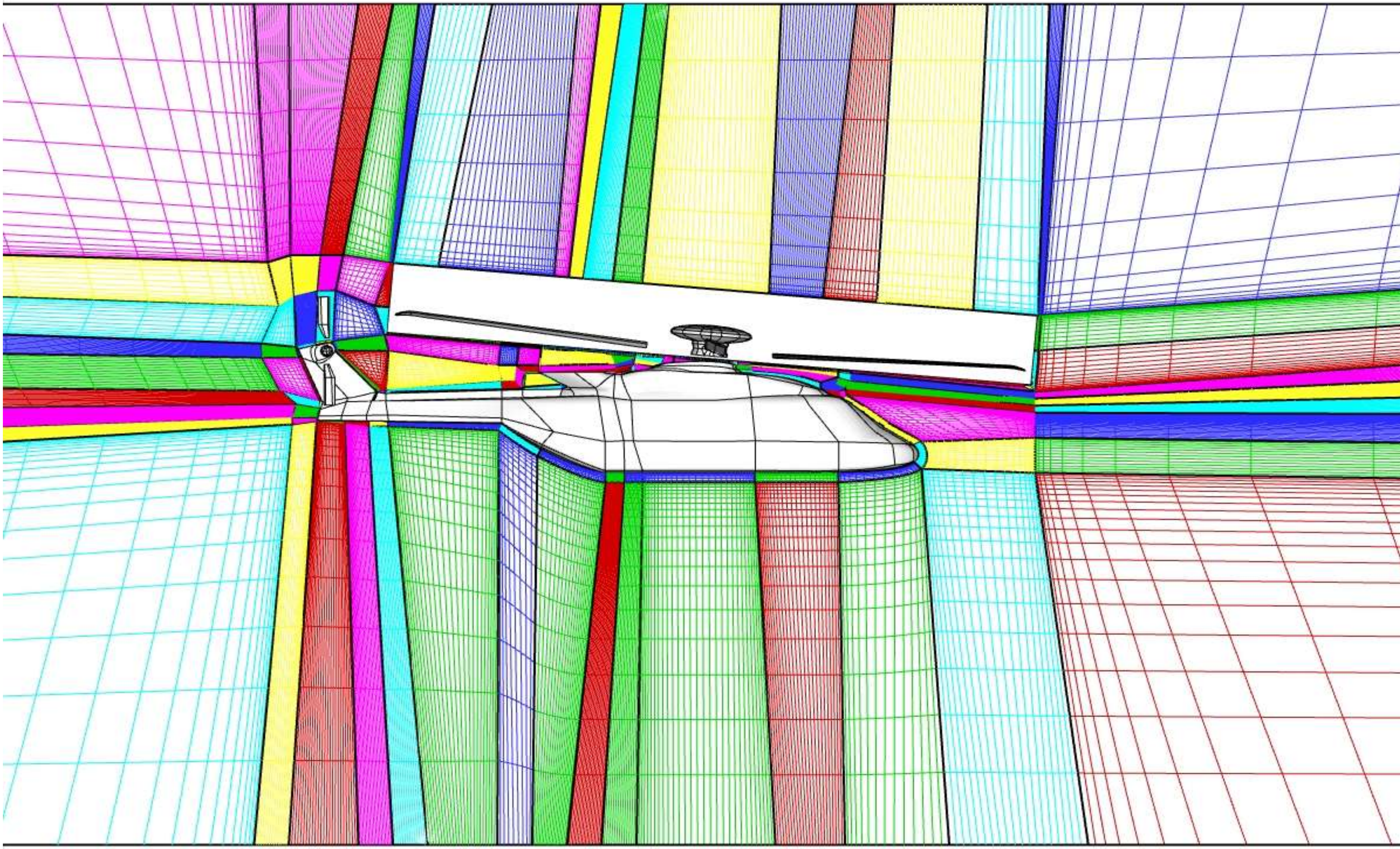


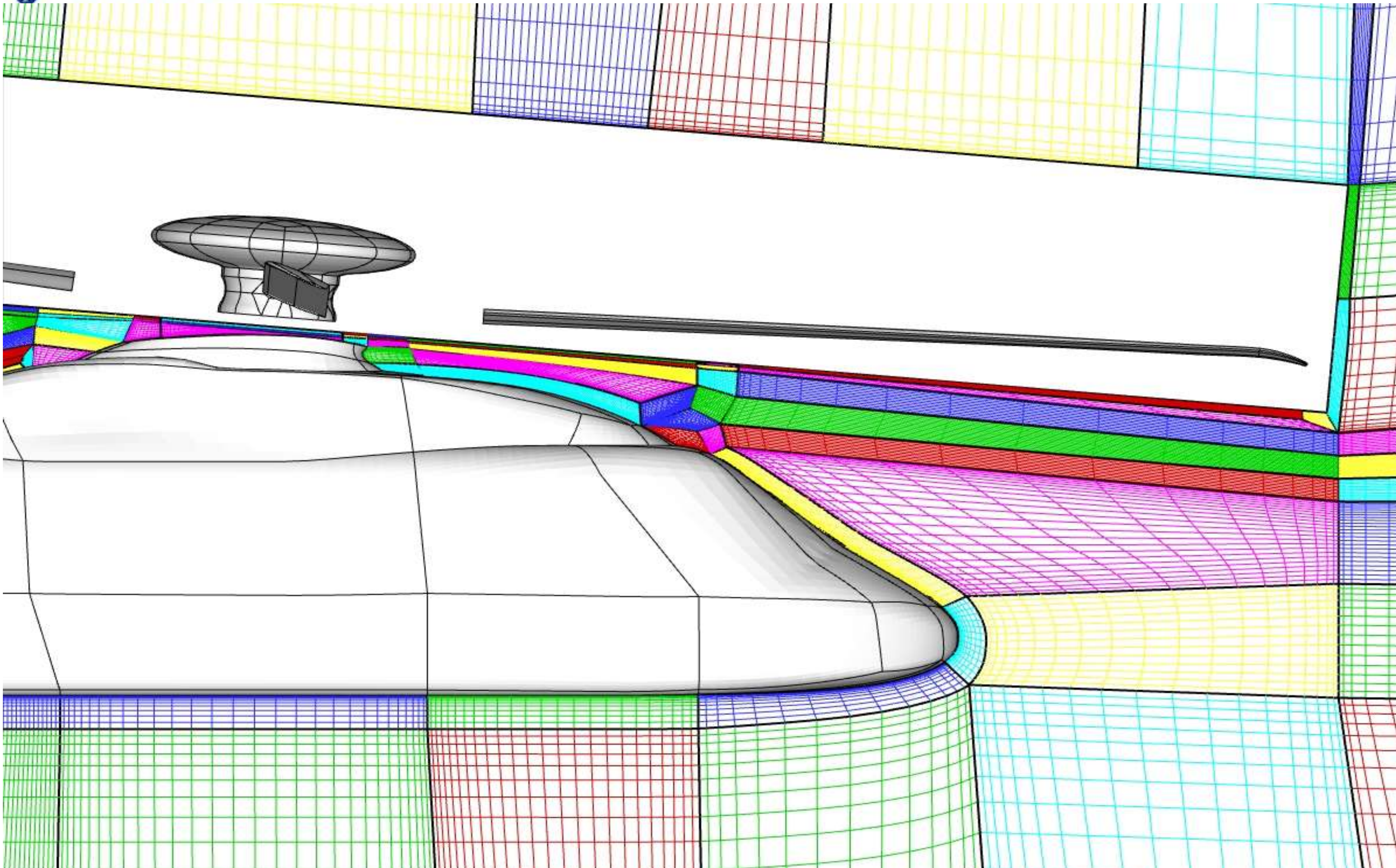
All grids generated using ICEMCFD

Multi-block mesh for full geometry

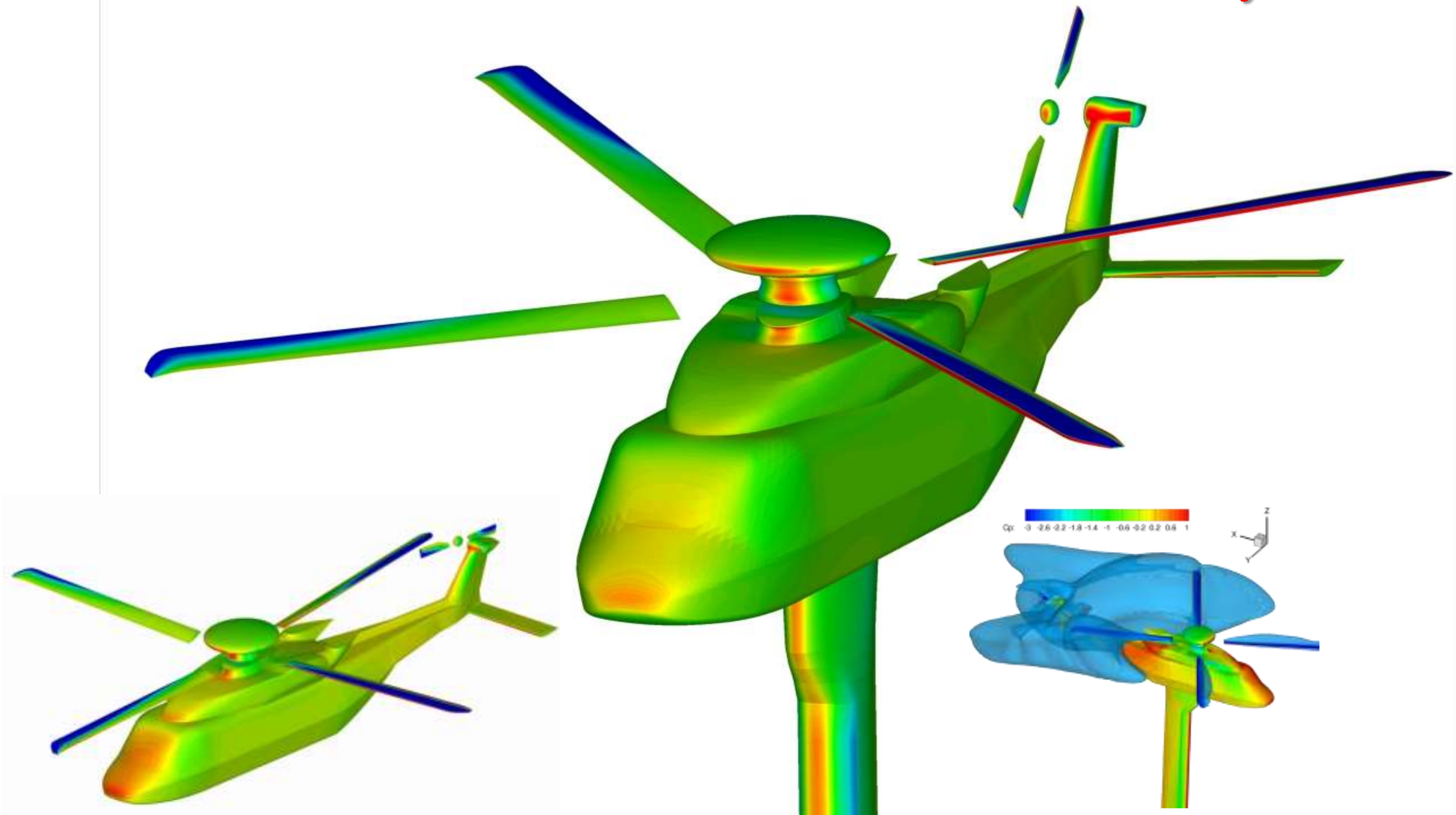
Total - 3786 blocks, 27.8 M cells
Fuselage - 2298 blocks, 15.6 M cells
MR - 1112 blocks, 9.8 M cells
TR - 376 blocks, 2.4 M cells





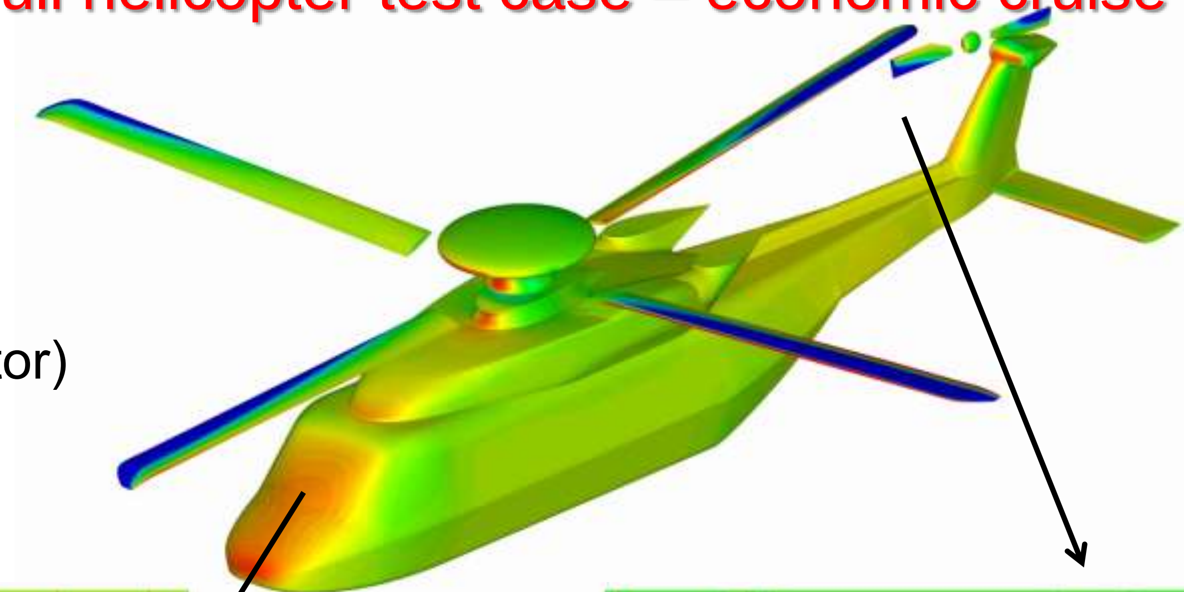


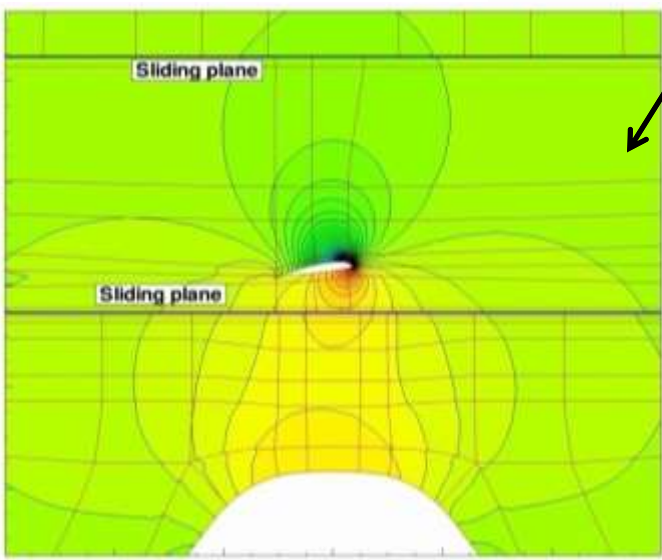
TC 3 : Economic Cruise – Full Geometry

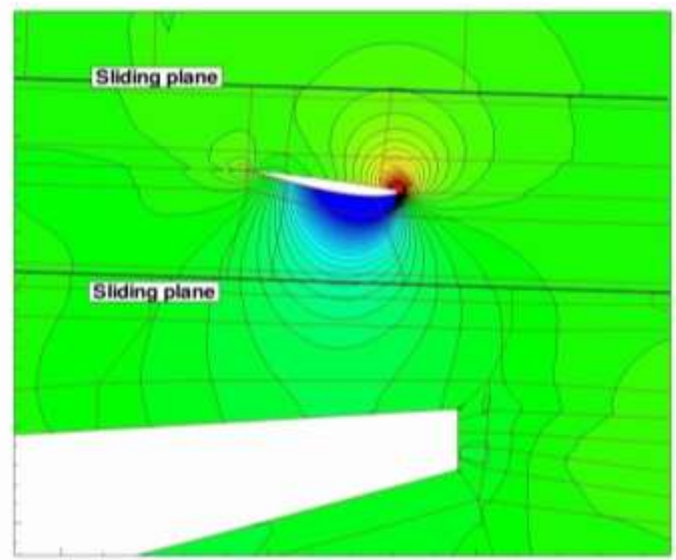


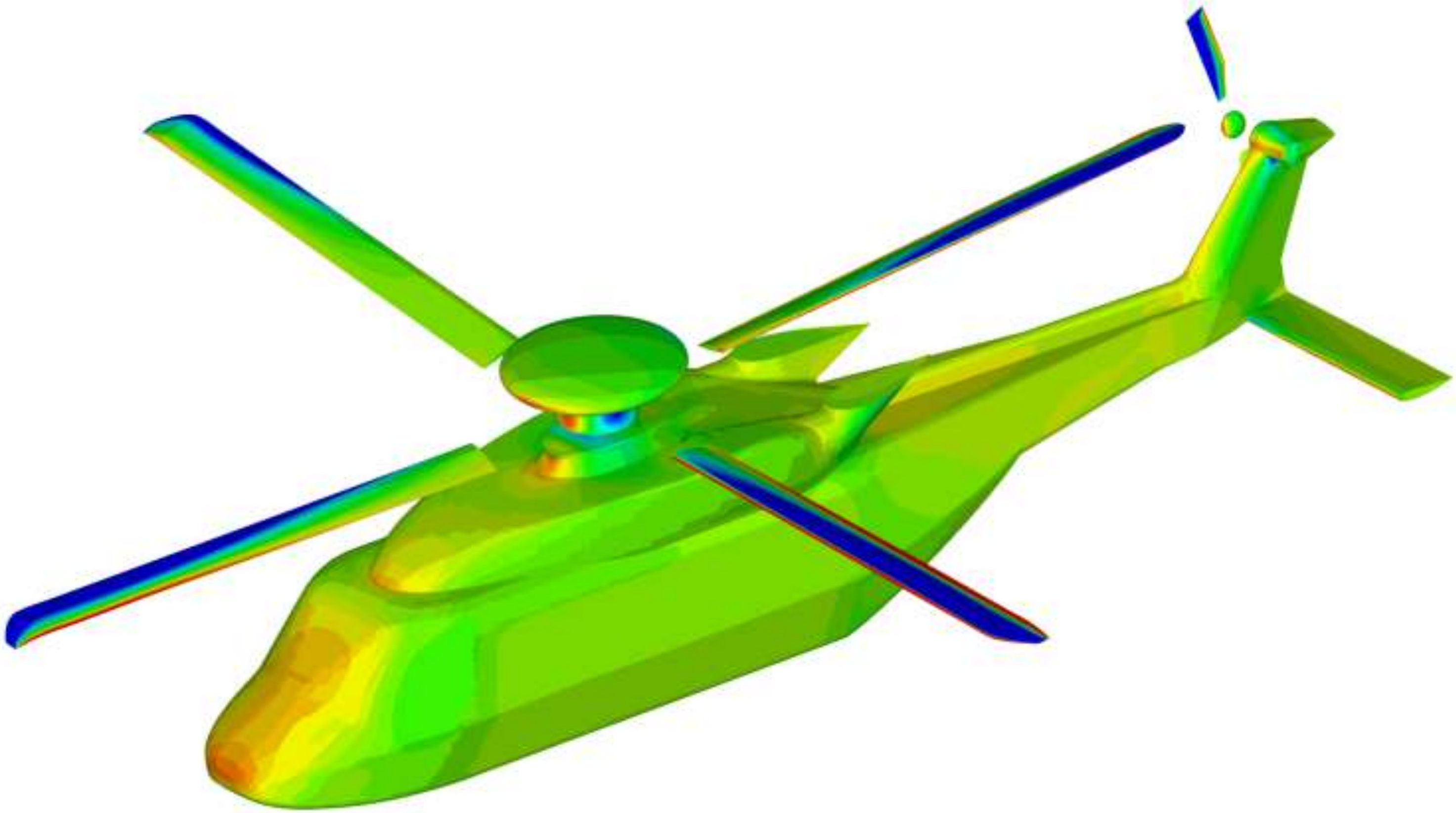
GOAHEAD full helicopter test case – economic cruise

μ = 0.33
k-ω model
0.25° steps (main rotor)

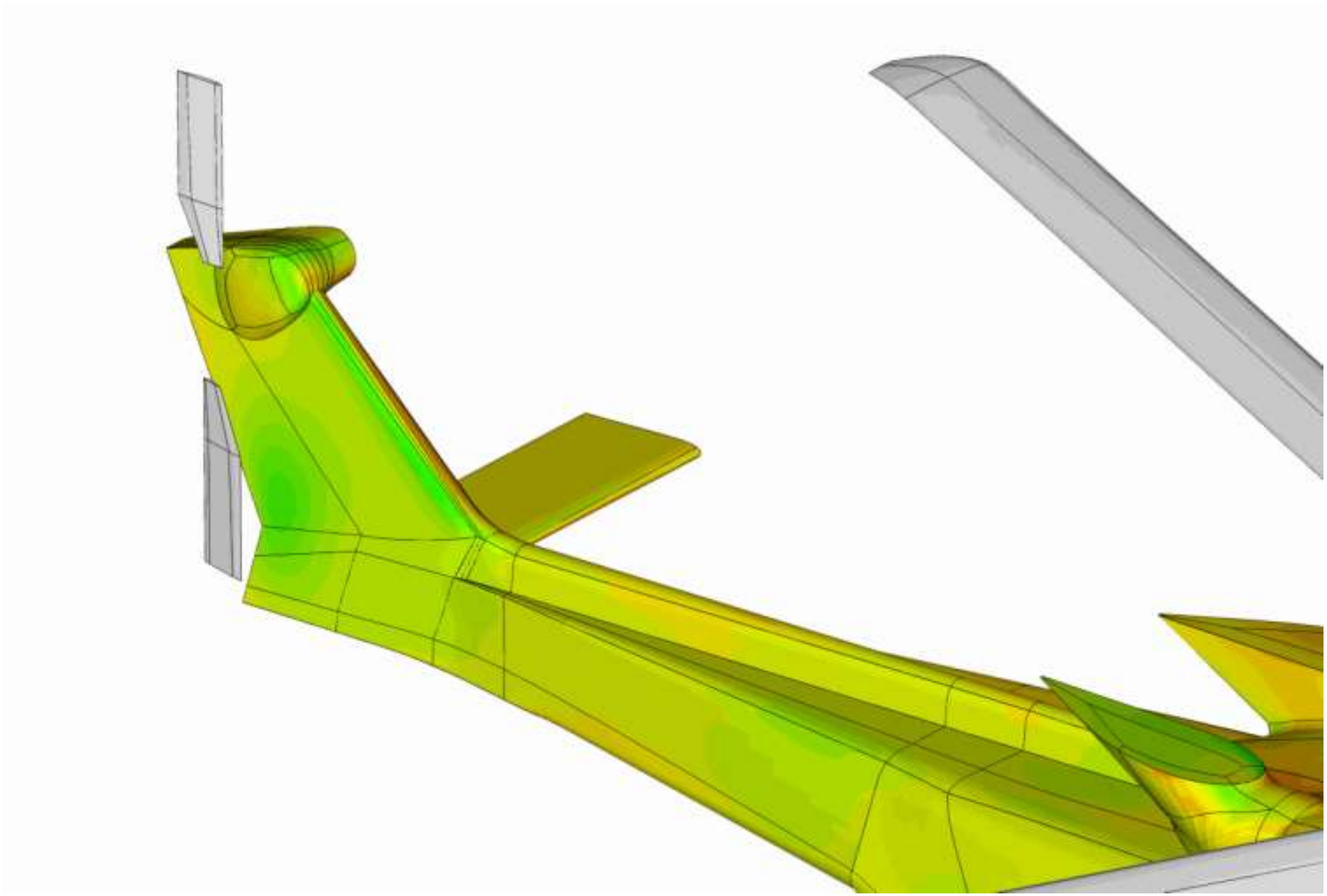


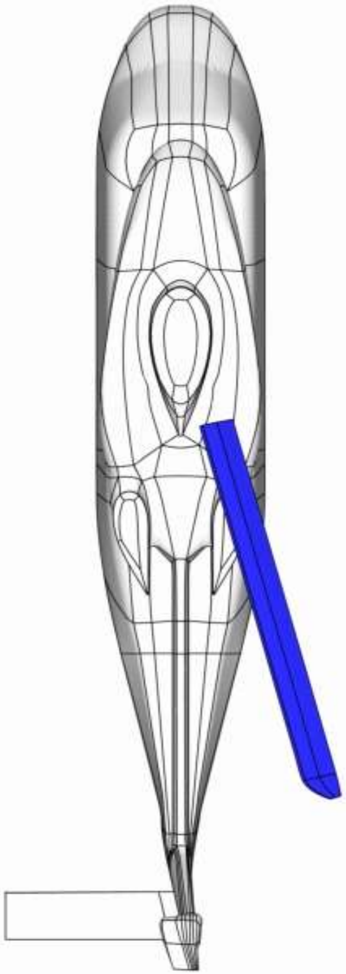


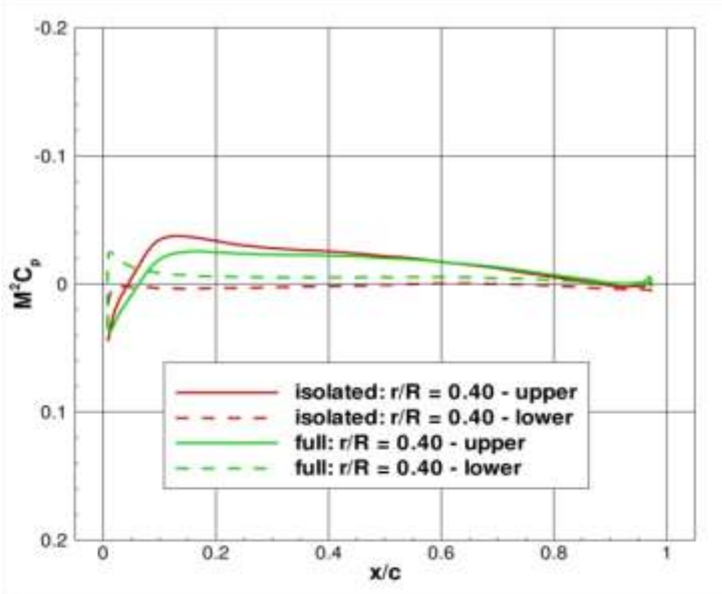


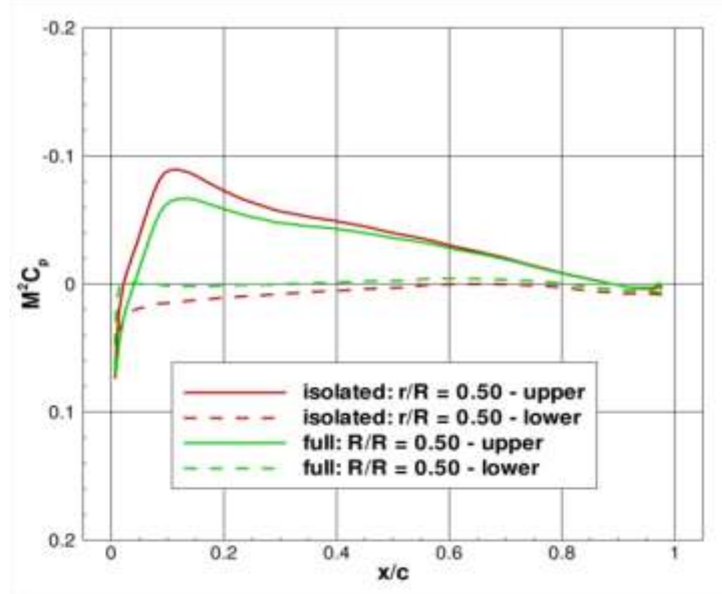


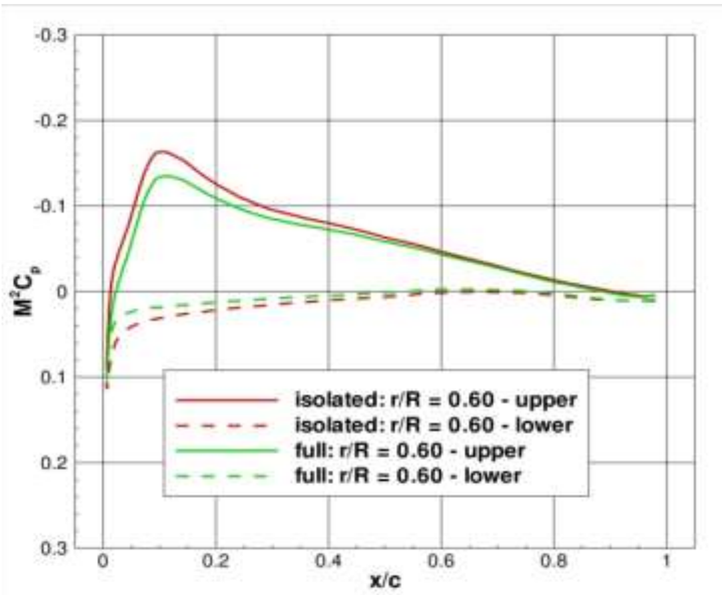
‘Unsteady’ pressure – instantaneous minus mean taken over 1 full TR revolution ‘blind’ results






-0.2
-0.1
0
0.1
0.2
M²C_p
0
0.2
0.4
0.6
0.8
1
x/c
isolated: r/R = 0.40 - upper
isolated: r/R = 0.40 - lower
full: r/R = 0.40 - upper
full: r/R = 0.40 - lower


-0.2
-0.1
0
0.1
0.2
M²C_p
0
0.2
0.4
0.6
0.8
1
x/c
isolated: r/R = 0.50 - upper
isolated: r/R = 0.50 - lower
full: R/R = 0.50 - upper
full: R/R = 0.50 - lower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-0.2
-0.1
0
0.1
0.2
0.3
M²C_p
0
0.2
0.4
0.6
0.8
1
x/c
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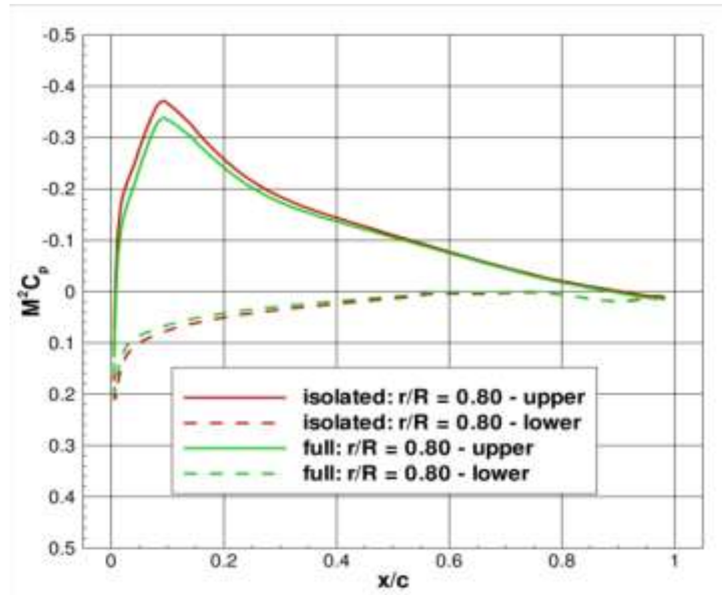
isolated: r/R = 0.60 - lower
full: r/R = 0.60 - upper
full: r/R = 0.60 - lower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-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
M²C_p
0
0.2
0.4
0.6
0.8
1
x/c
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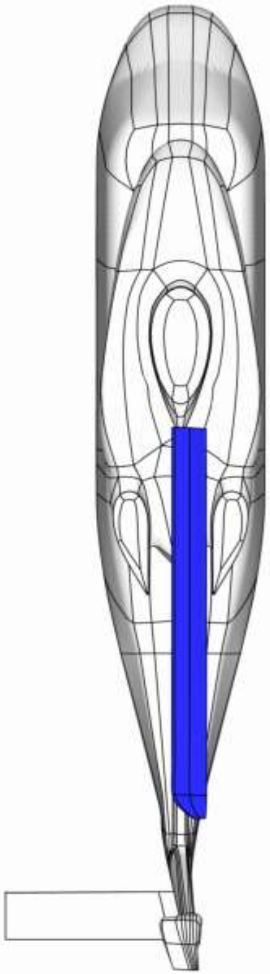
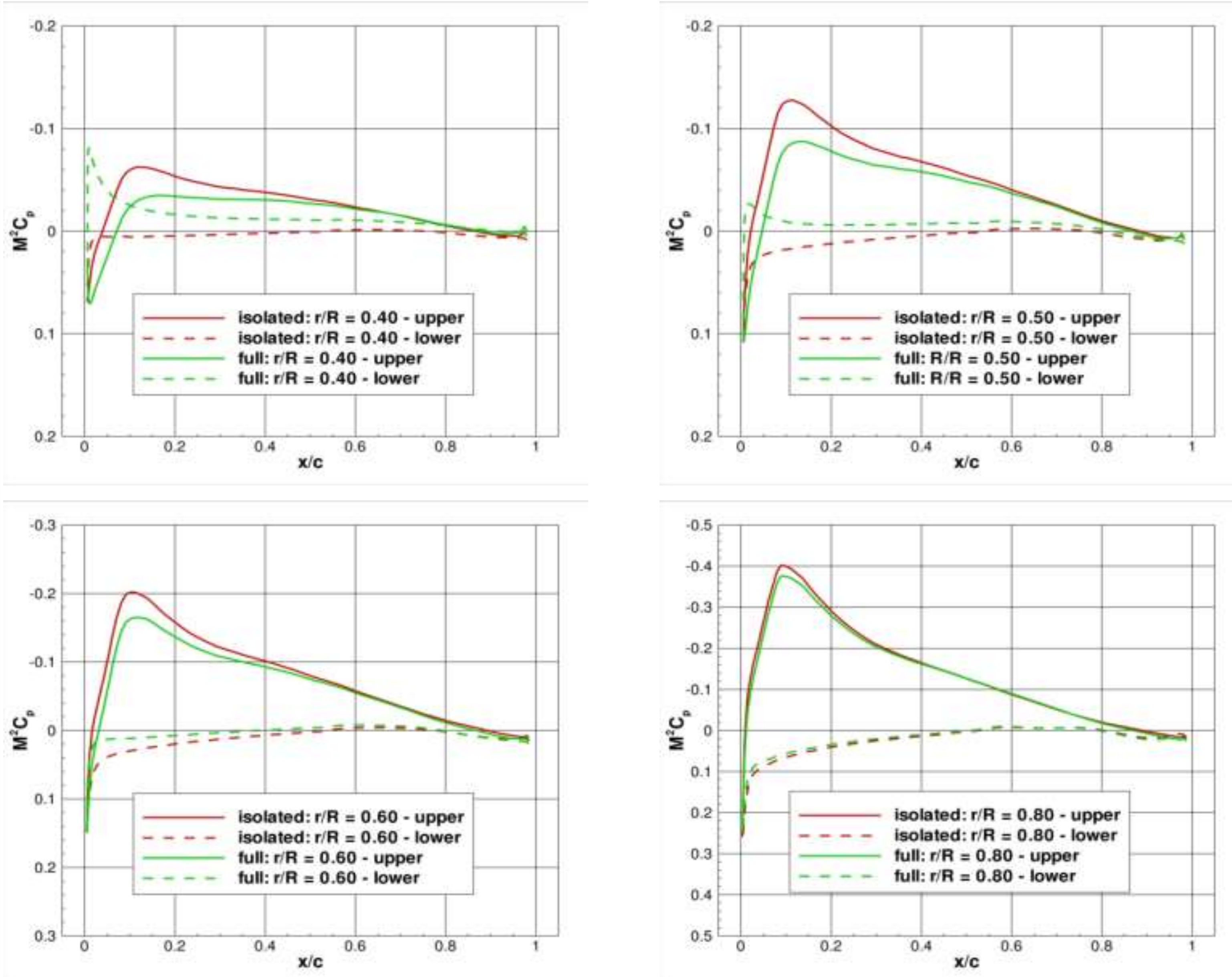
isolated: r/R = 0.80 - lower
full: r/R = 0.80 - upper
full: r/R = 0.80 - lower




M²Cp
x/c
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isolated: r/R = 0.40 - lower
full: r/R = 0.40 - upper
full: r/R = 0.40 - lower
isolated: r/R = 0.50 - upper
isolated: r/R = 0.50 - lower
full: R/R = 0.50 - upper
full: R/R = 0.50 - lower
isolated: r/R = 0.60 - upper
isolated: r/R = 0.60 - lower
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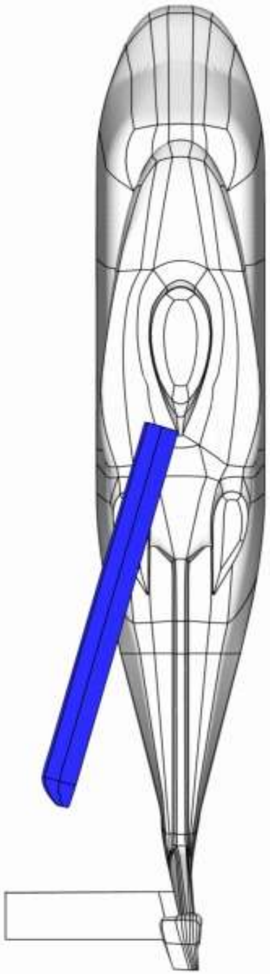
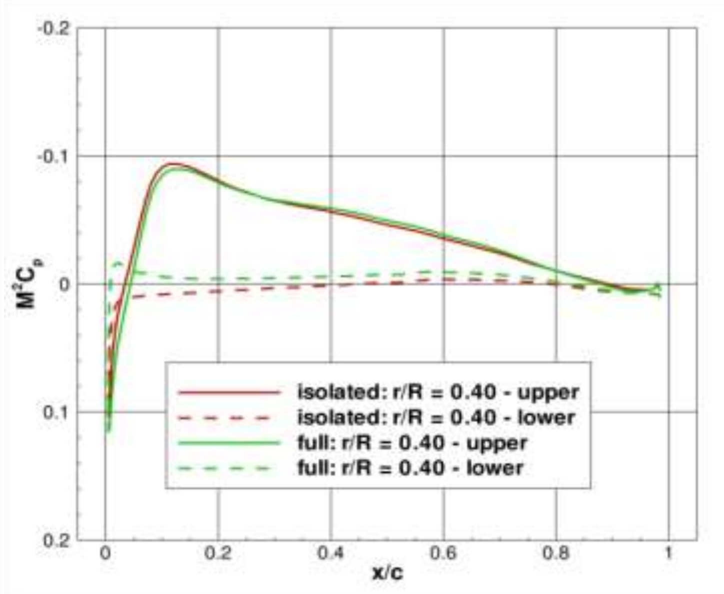
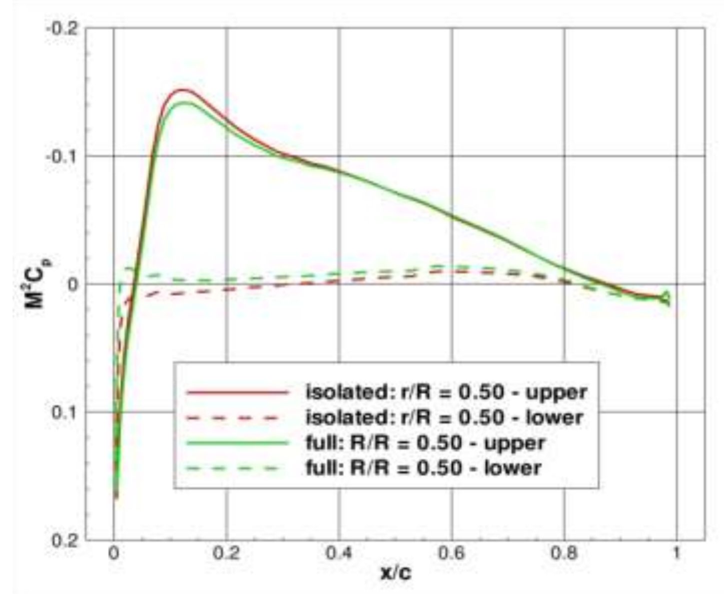
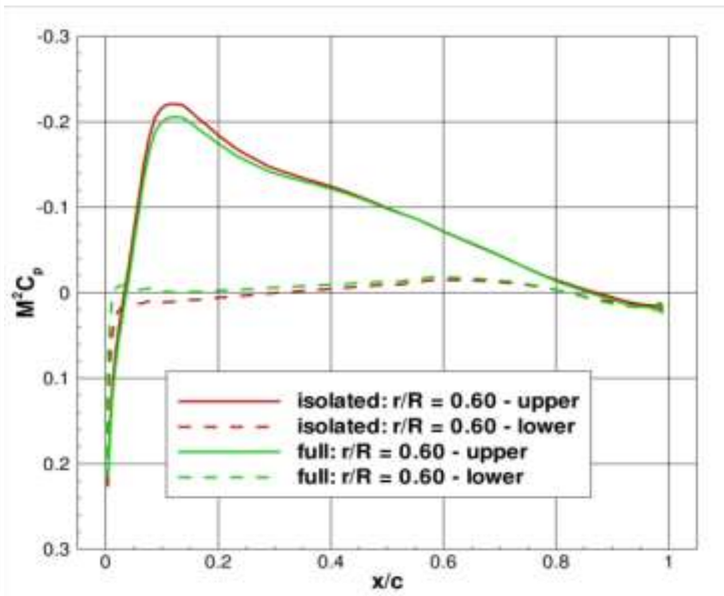
full: r/R = 0.80 - upper
full: r/R = 0.80 - lower




M²Cp
x/c
isolated: r/R = 0.40 - upper
isolated: r/R = 0.40 - lower
full: r/R = 0.40 - upper
full: r/R = 0.40 - lower


M²Cp
x/c
isolated: r/R = 0.50 - upper
isolated: r/R = 0.50 - lower
full: R/R = 0.50 - upper
full: R/R = 0.50 - lower


M²Cp
x/c
isolated: r/R = 0.60 - upper
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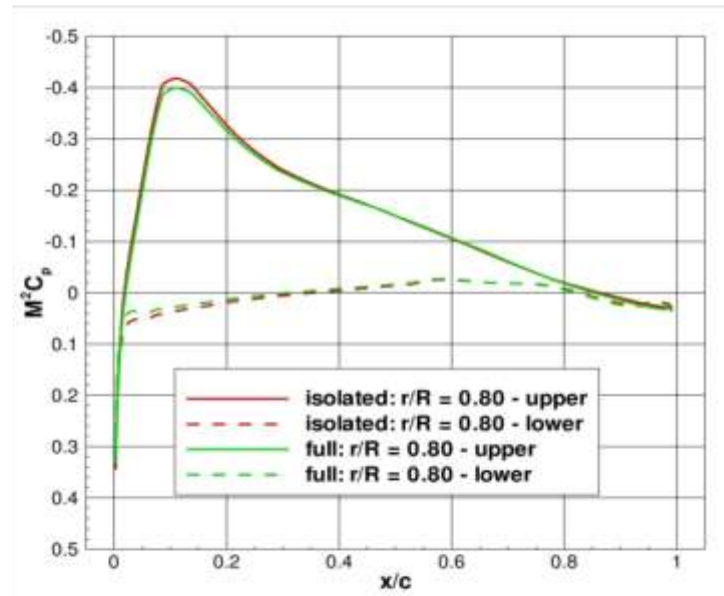
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x/c
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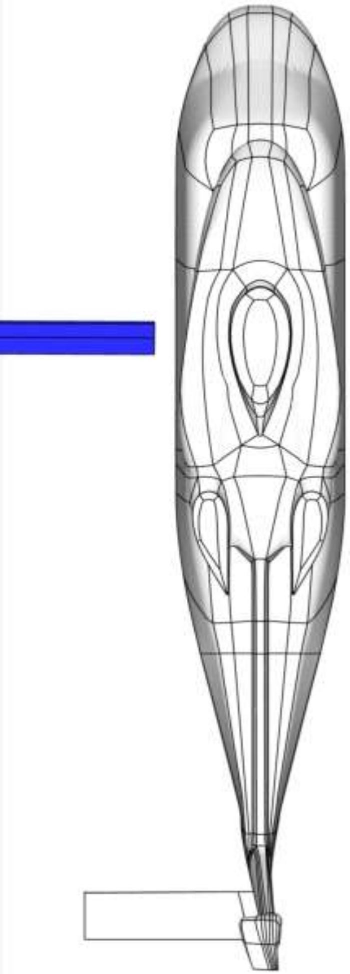

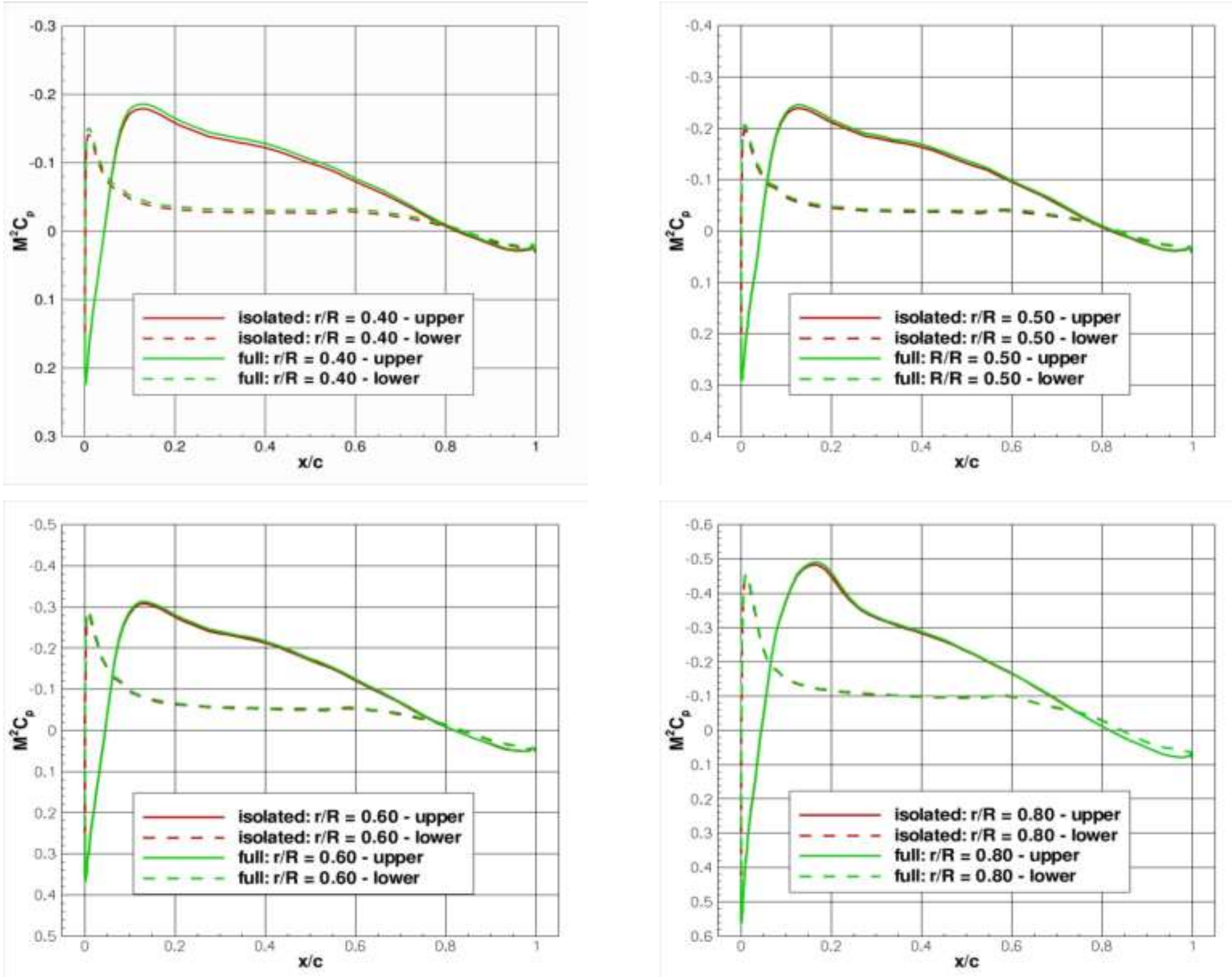

M²Cp
x/c
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isolated: r/R = 0.40 - lower
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full: r/R = 0.40 - lower
isolated: r/R = 0.50 - upper
isolated: r/R = 0.50 - lower
full: R/R = 0.50 - upper
full: R/R = 0.50 - lower
isolated: r/R = 0.60 - upper
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full: r/R = 0.60 - upper
full: r/R = 0.60 - lower
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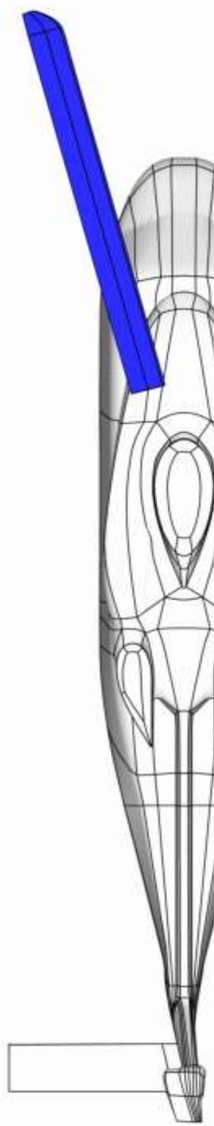
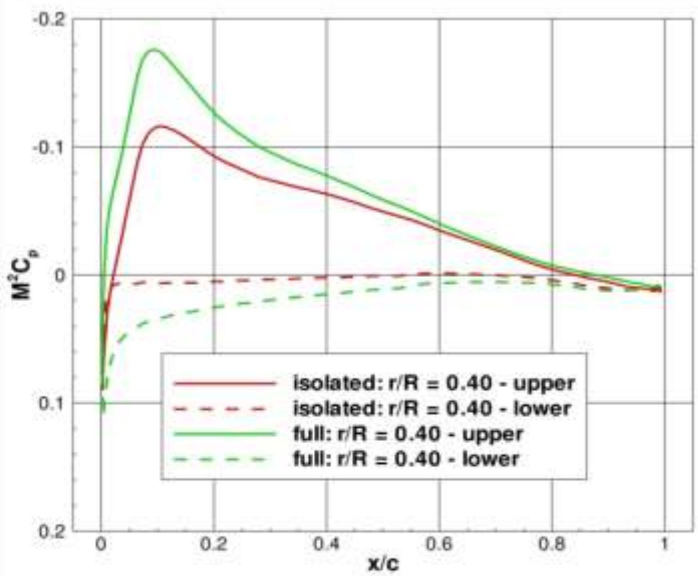
full: r/R = 0.80 - lower





M²Cp
x/c
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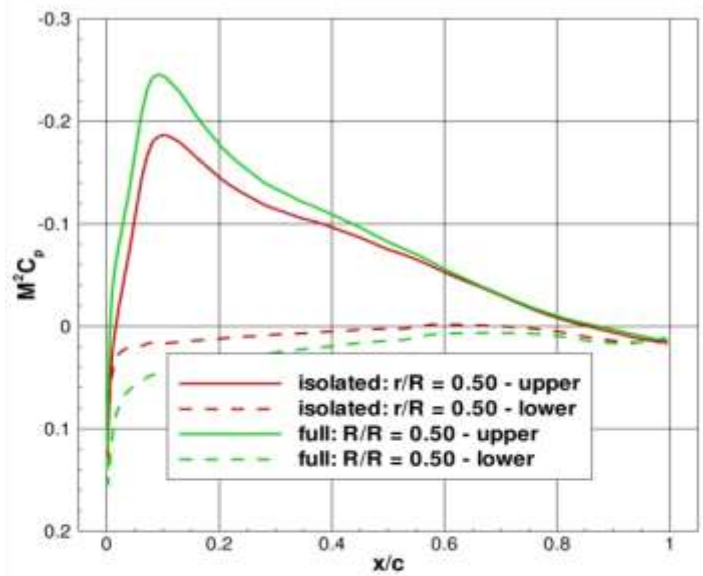

M²Cp
x/c
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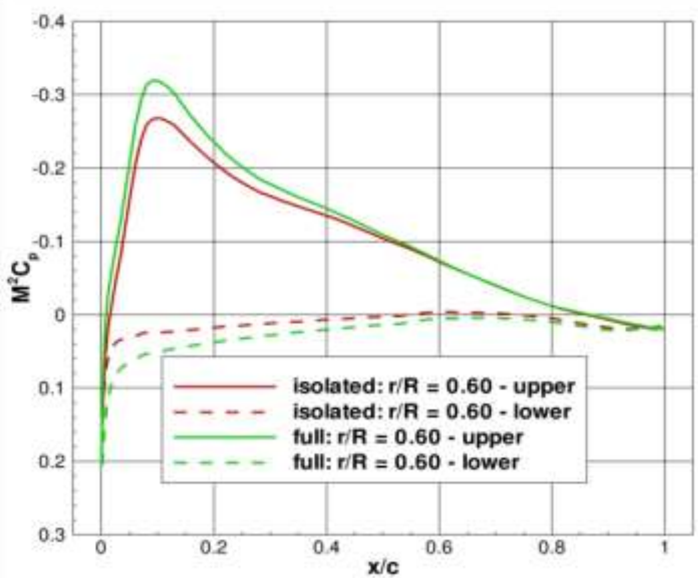

M²Cp
x/c
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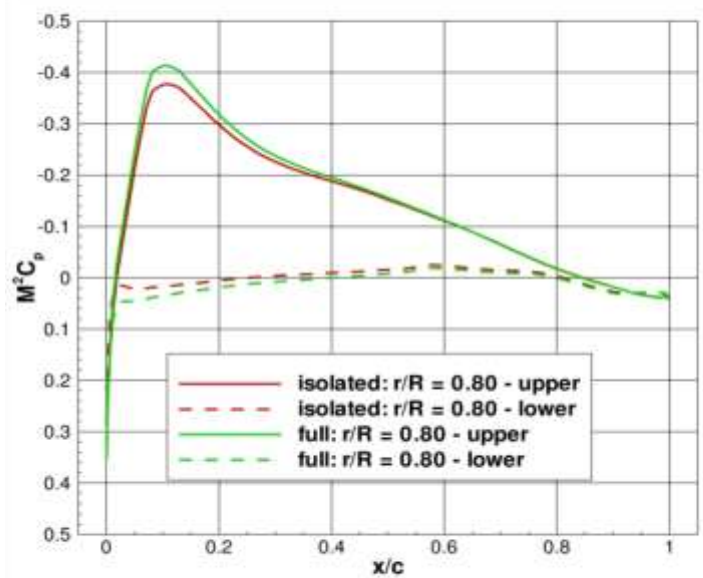

M²Cp
x/c
isolated: r/R = 0.80 - upper
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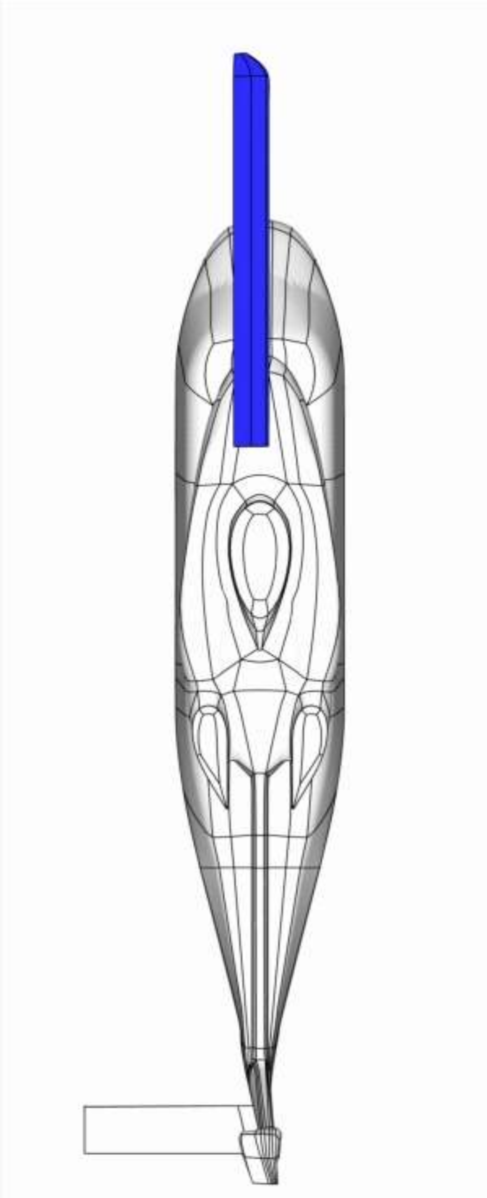

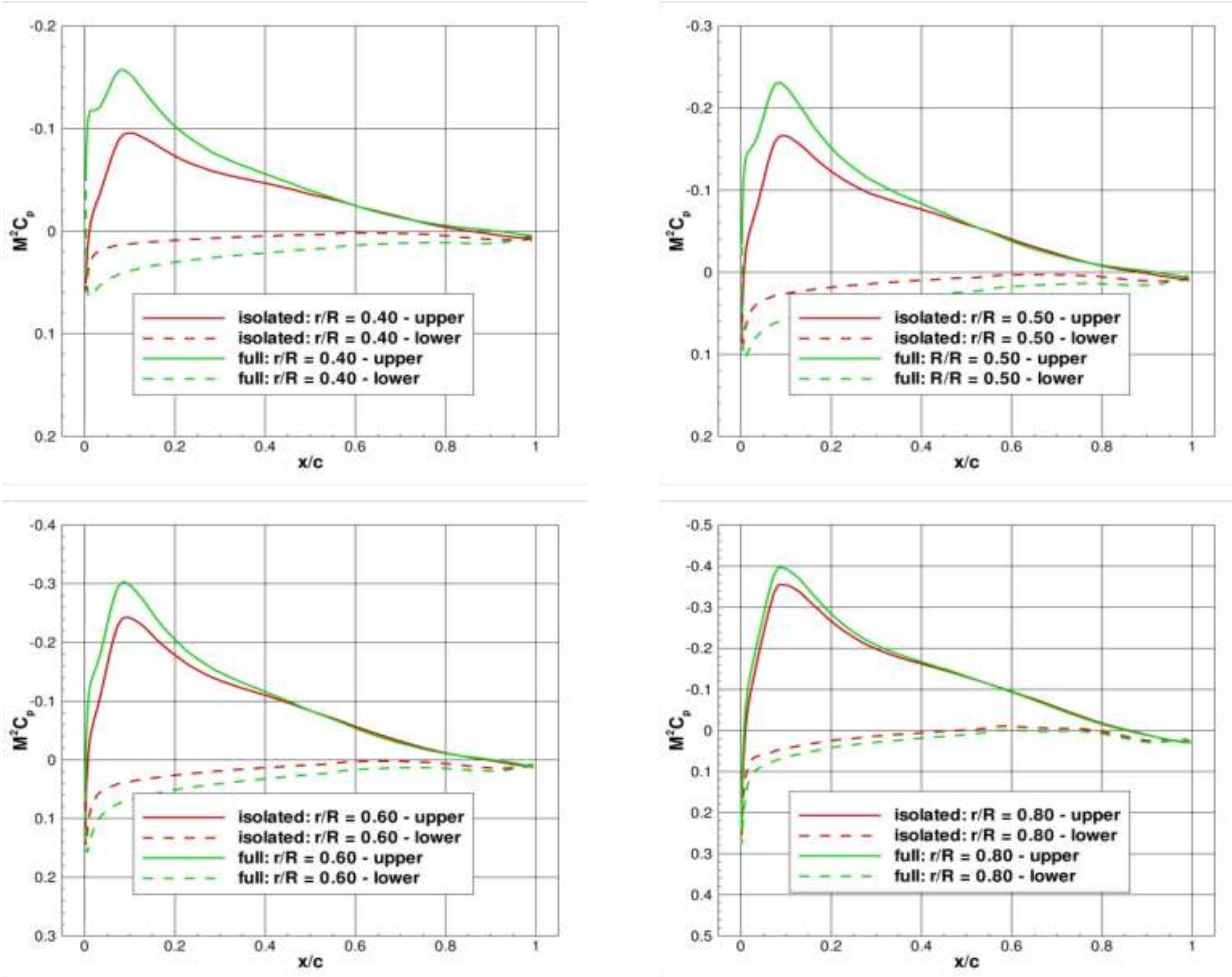
M²Cp
x/c
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isolated: r/R = 0.60 - upper
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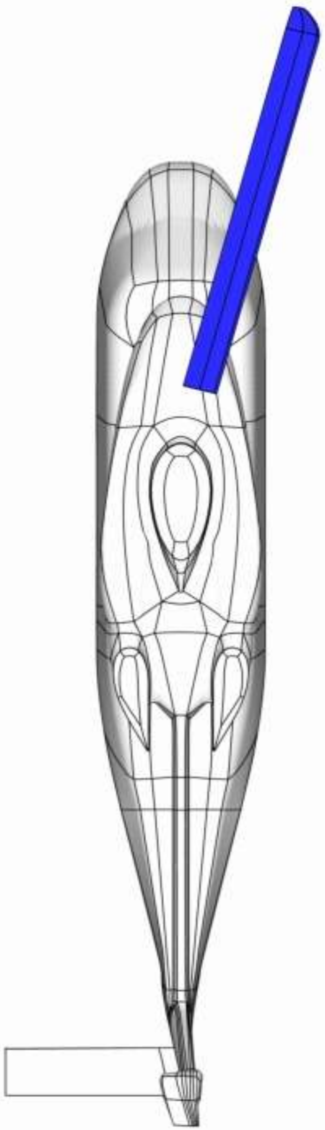

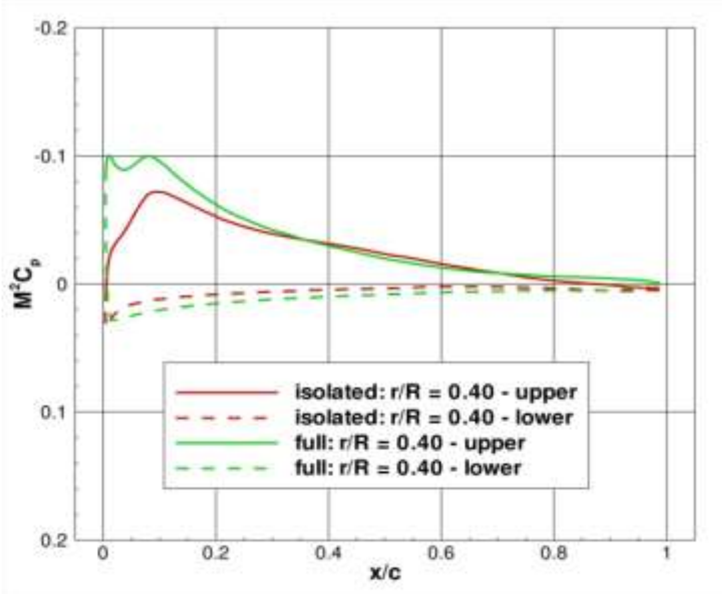
M²Cp
x/c
isolated: r/R = 0.40 - upper
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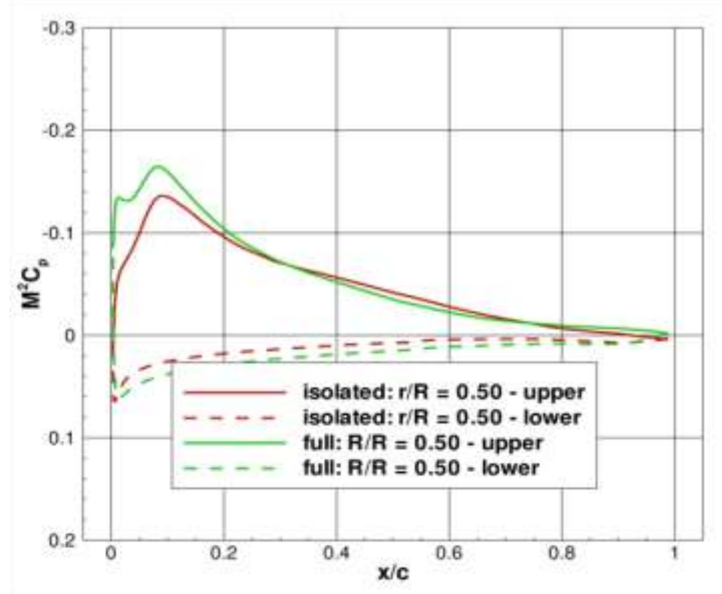
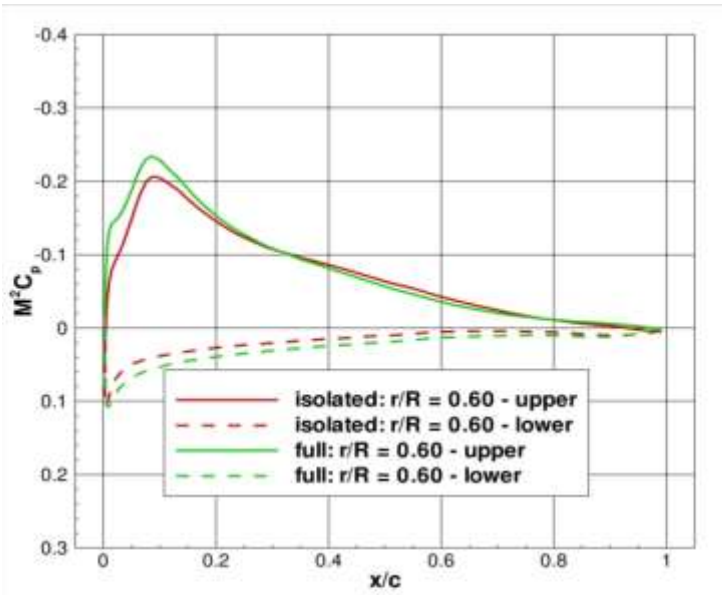

M²Cp
x/c
isolated: r/R = 0.50 - upper
isolated: r/R = 0.50 - lower
full: R/R = 0.50 - upper
full: R/R = 0.50 - lower


M²Cp
x/c
isolated: r/R = 0.60 - upper
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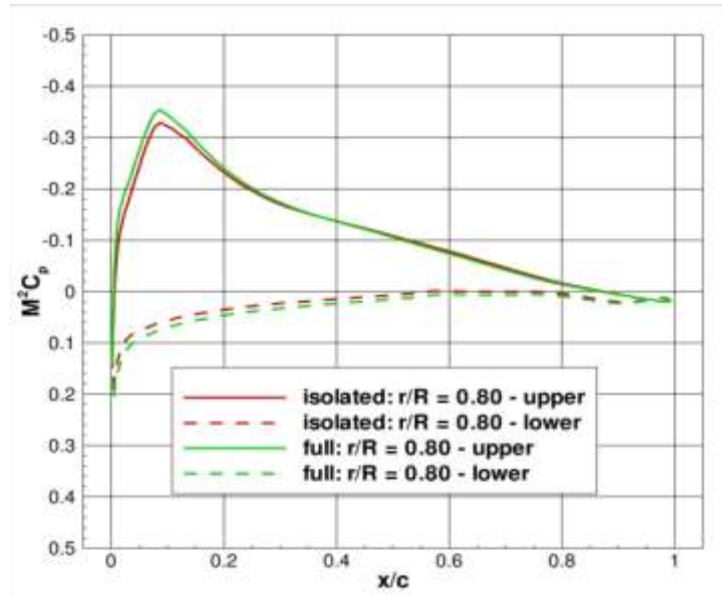
M²Cp
x/c
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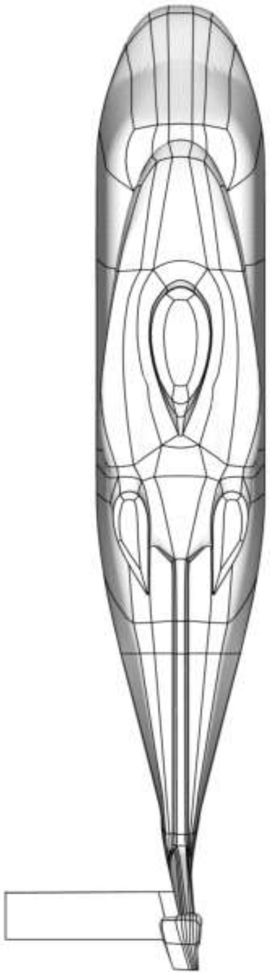

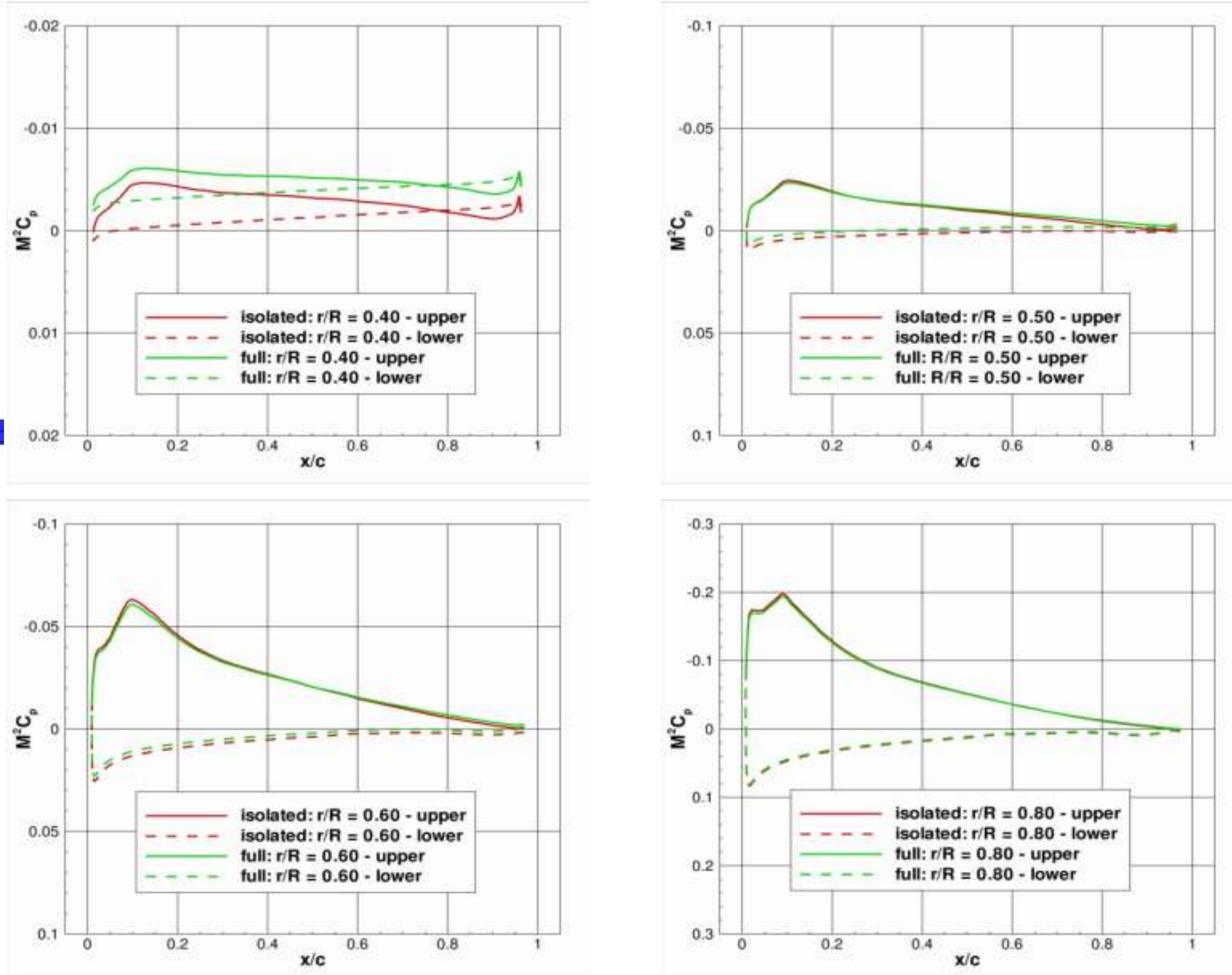
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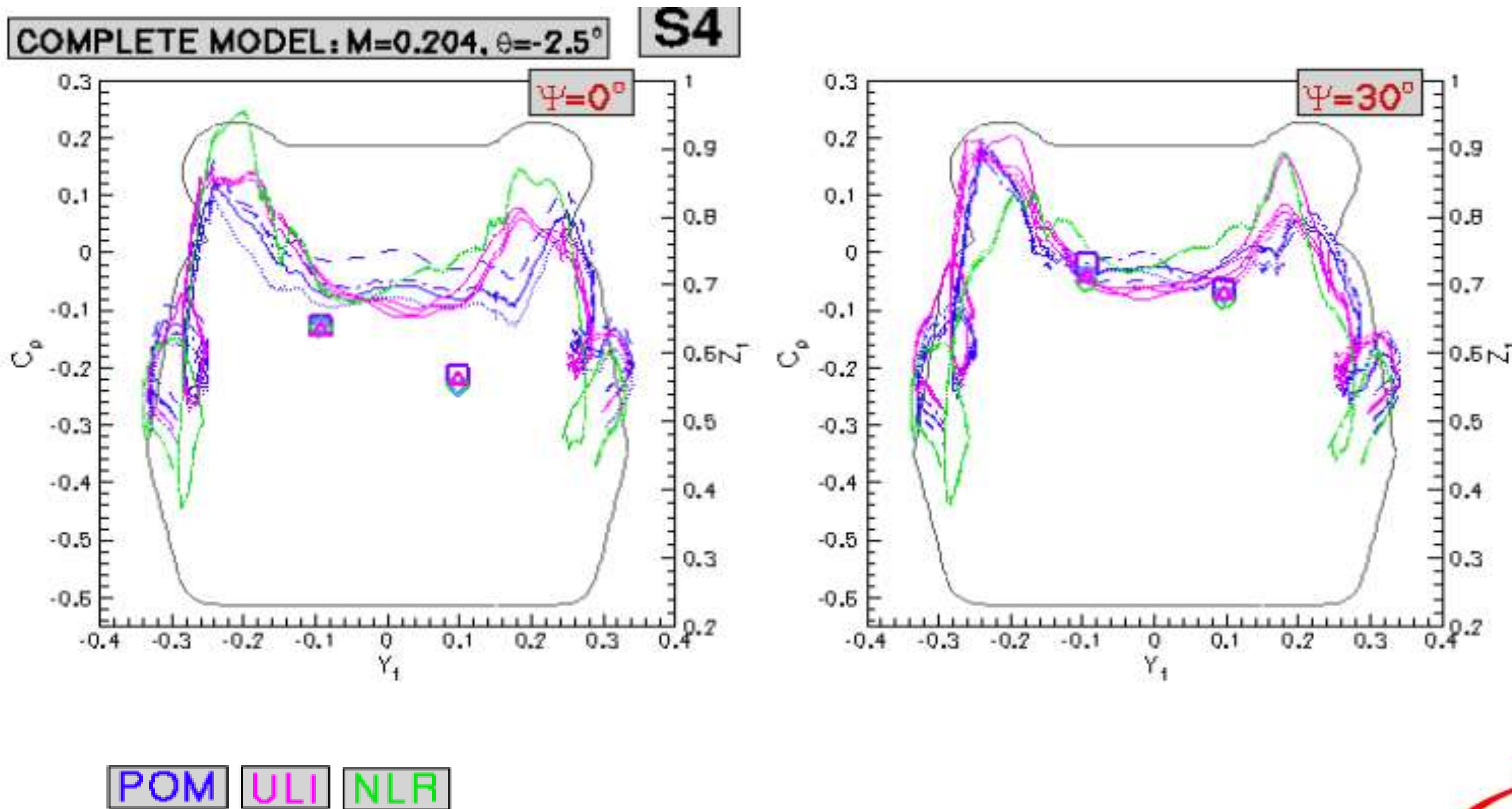
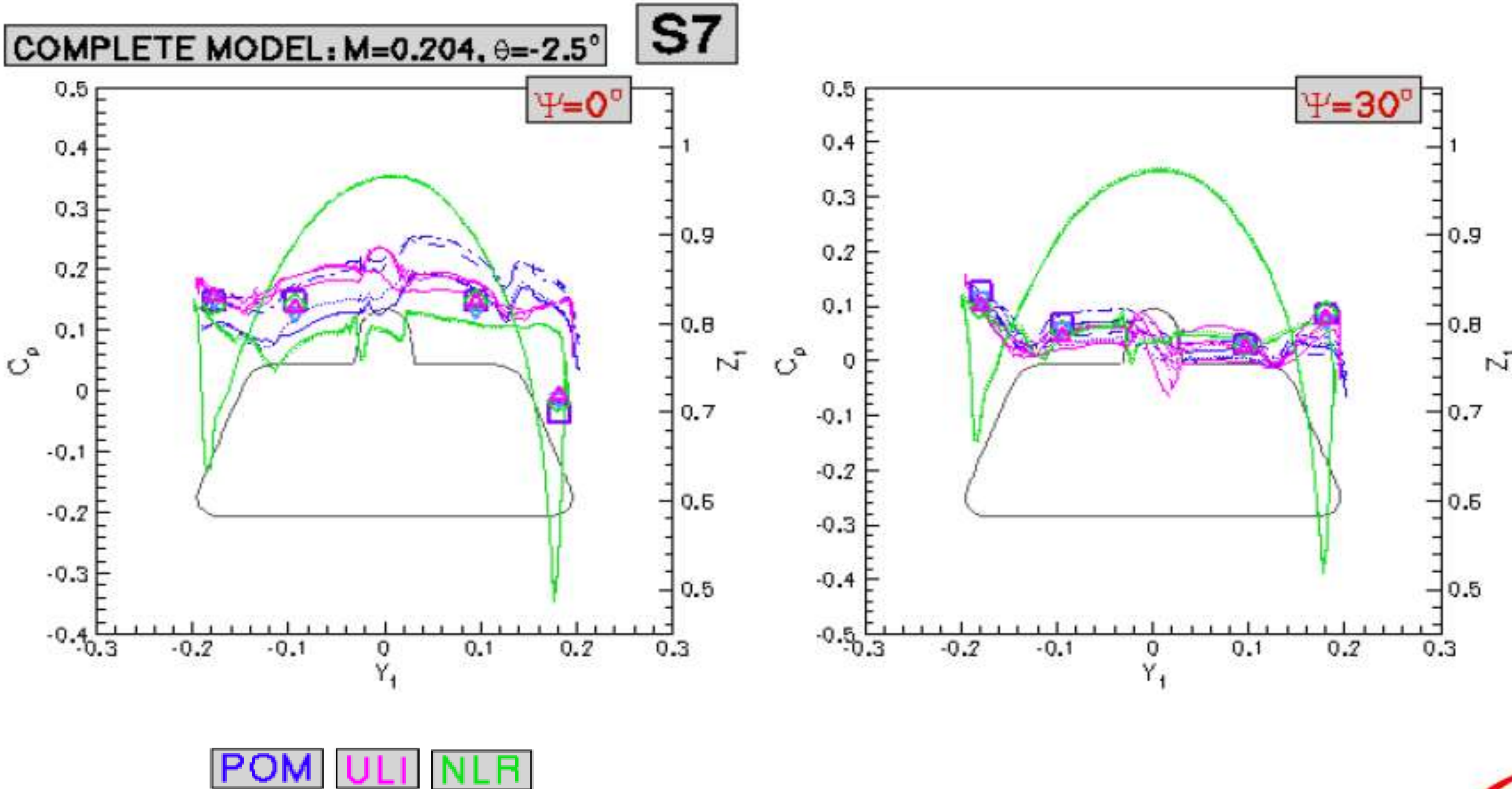
isolated: r/R = 0.60 - upper
isolated: r/R = 0.60 - lower
full: r/R = 0.60 - upper
full: r/R = 0.60 - lower
isolated: r/R = 0.80 - upper
isolated: r/R = 0.80 - lower
full: r/R = 0.80 - upper
full: r/R = 0.80 - lower
M²Cp
x/c

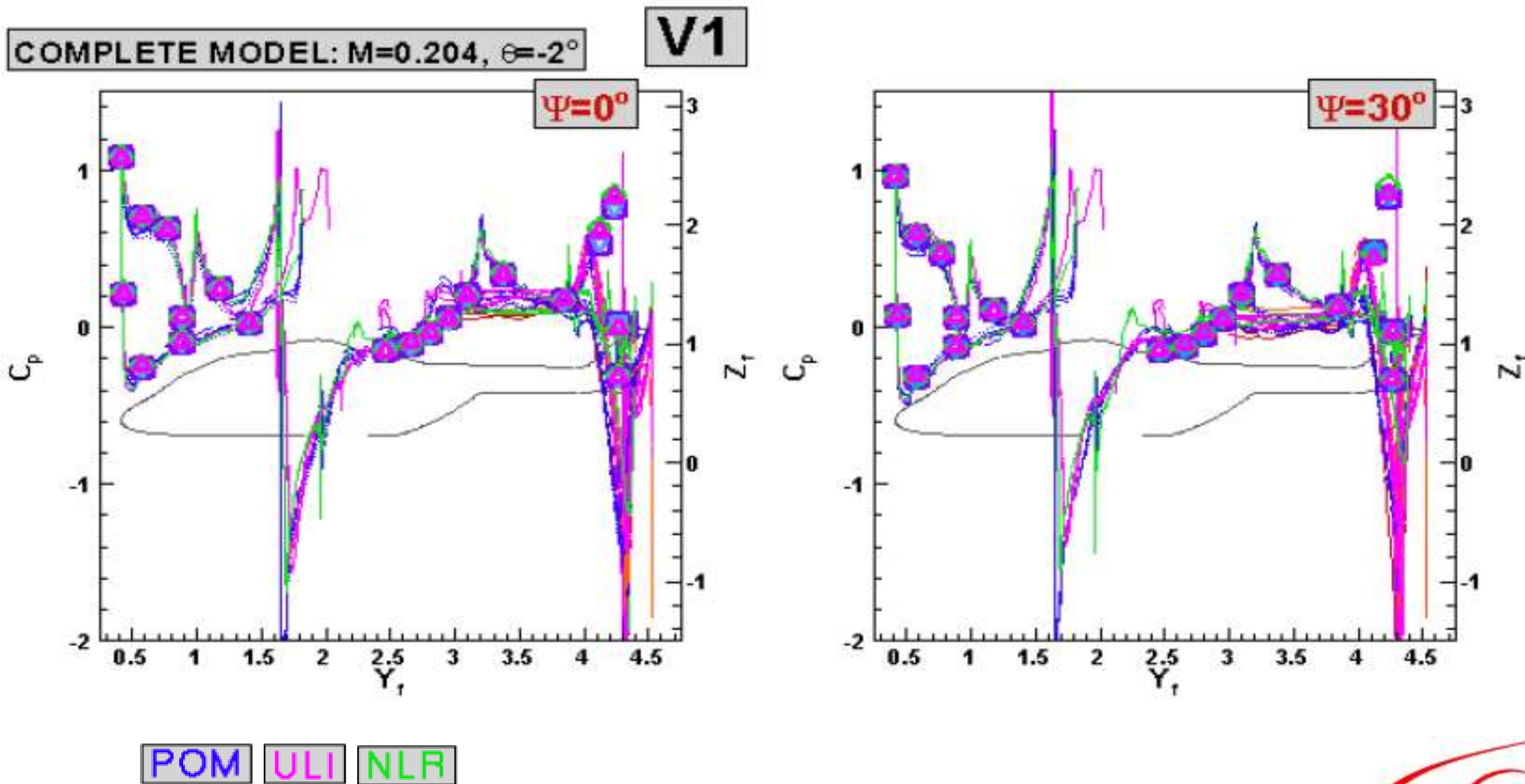
Economic Cruise Case



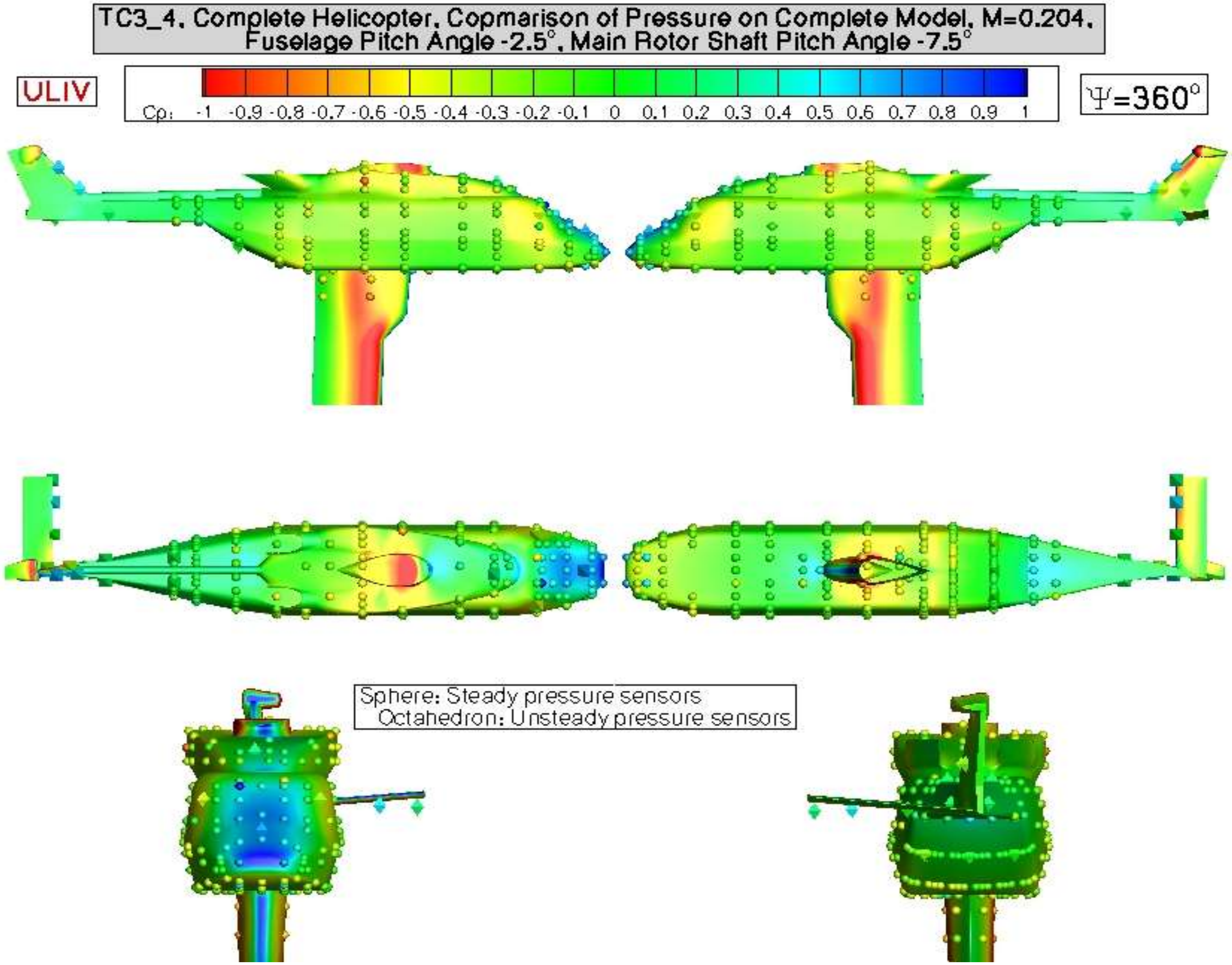
Economic Cruise



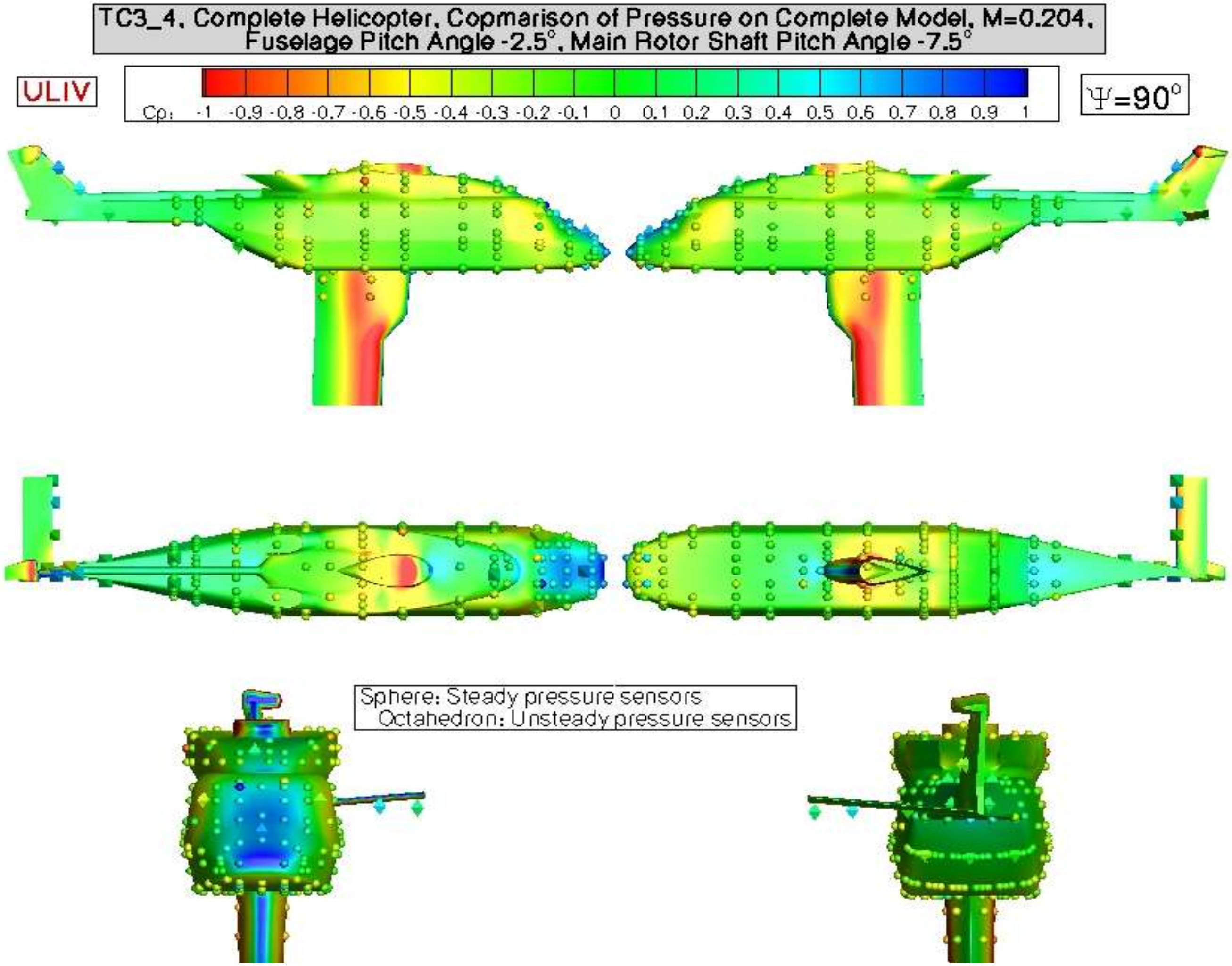
Post Test – Economic Cruise



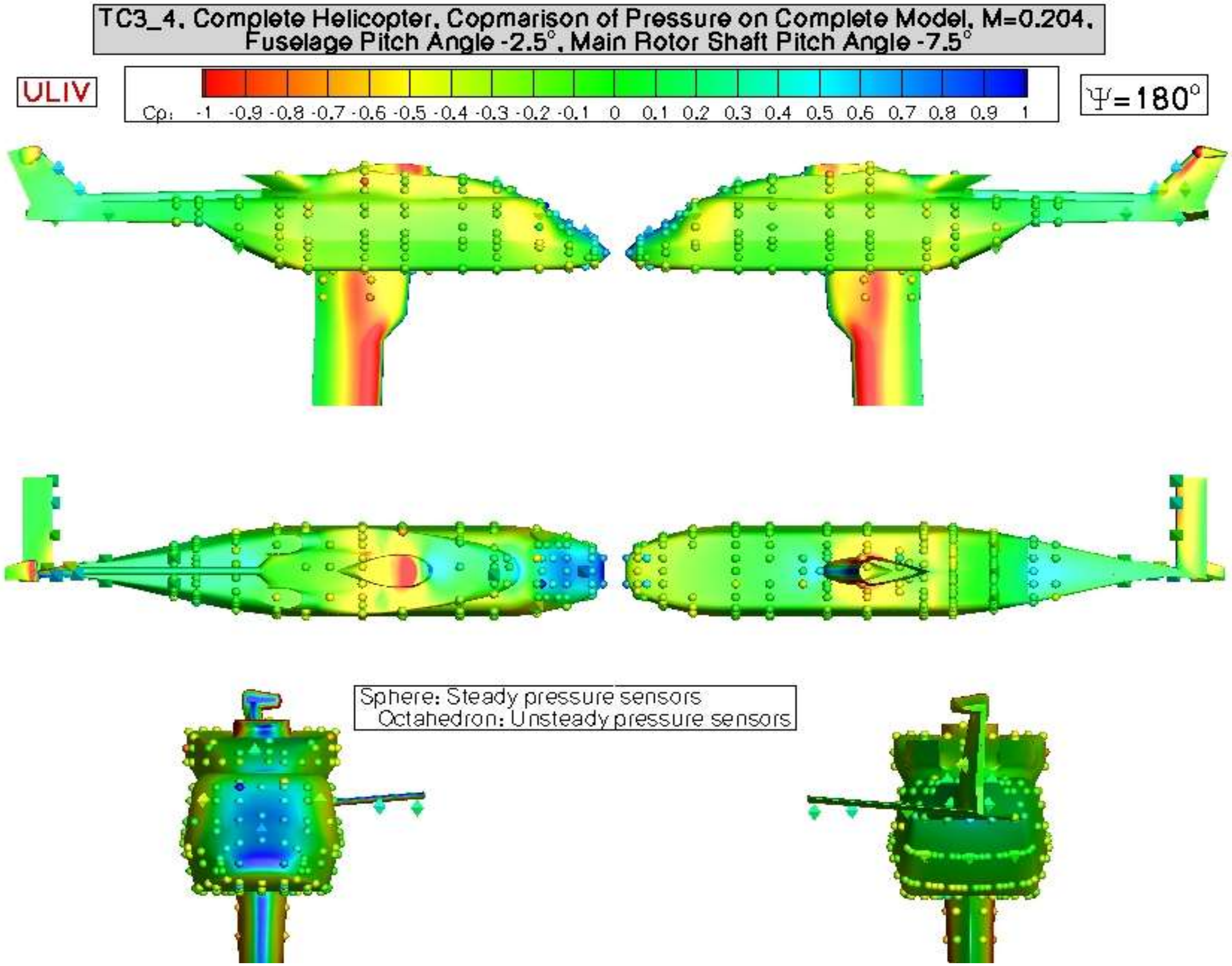
Experiments and CFD for complete configuration



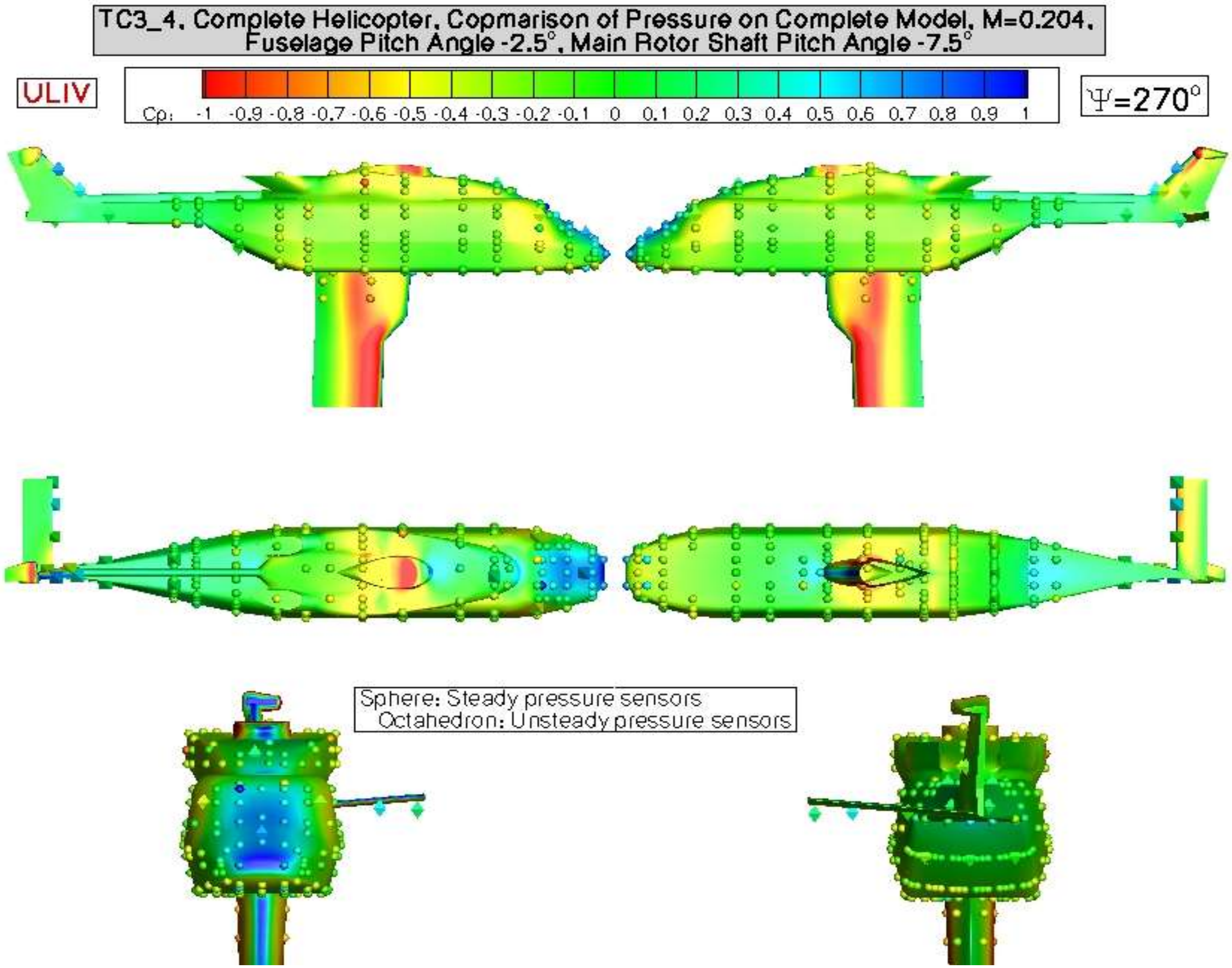
Experiments and CFD for complete configuration



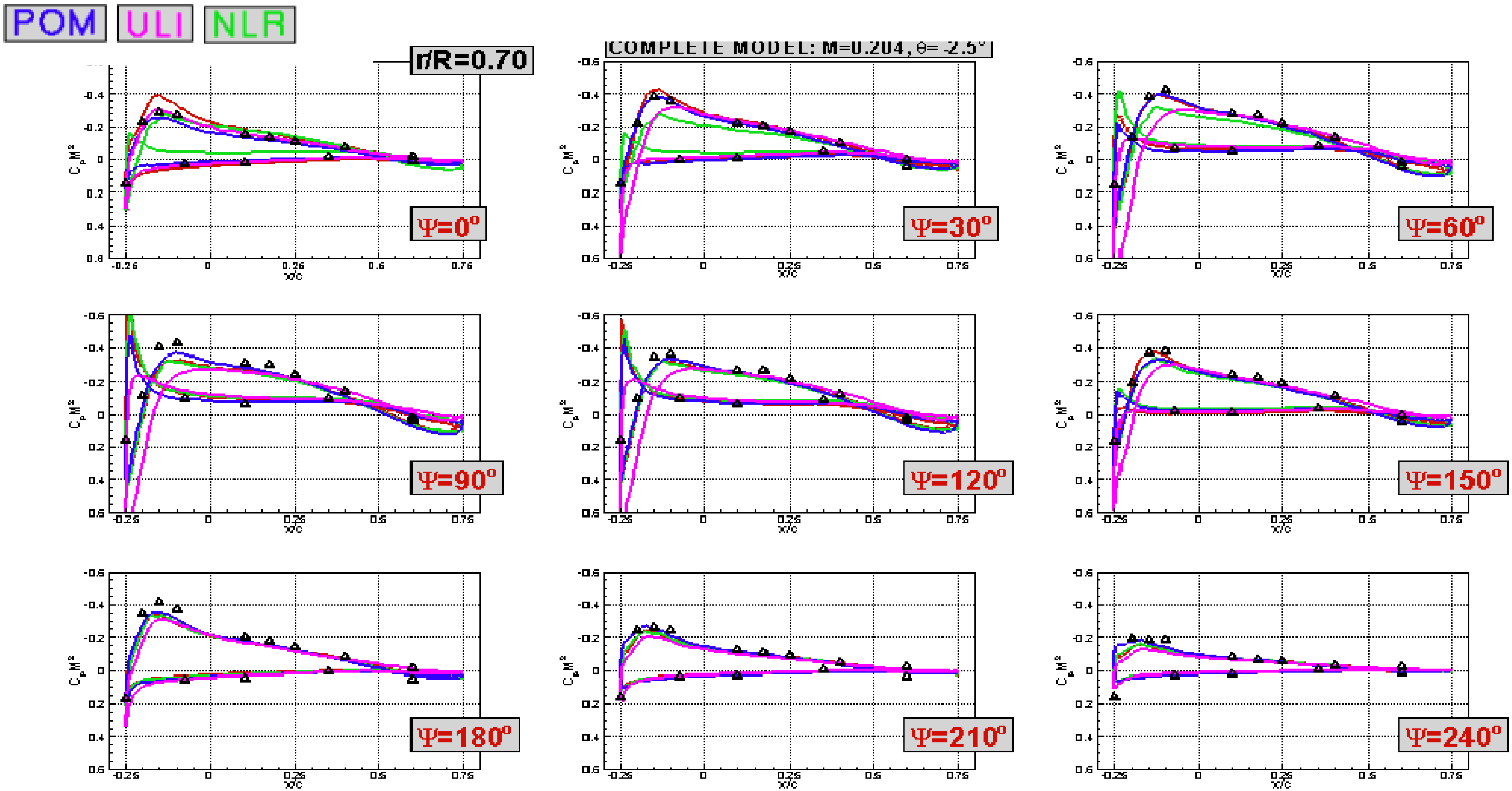
Experiments and CFD for complete configuration



Experiments and CFD for complete configuration

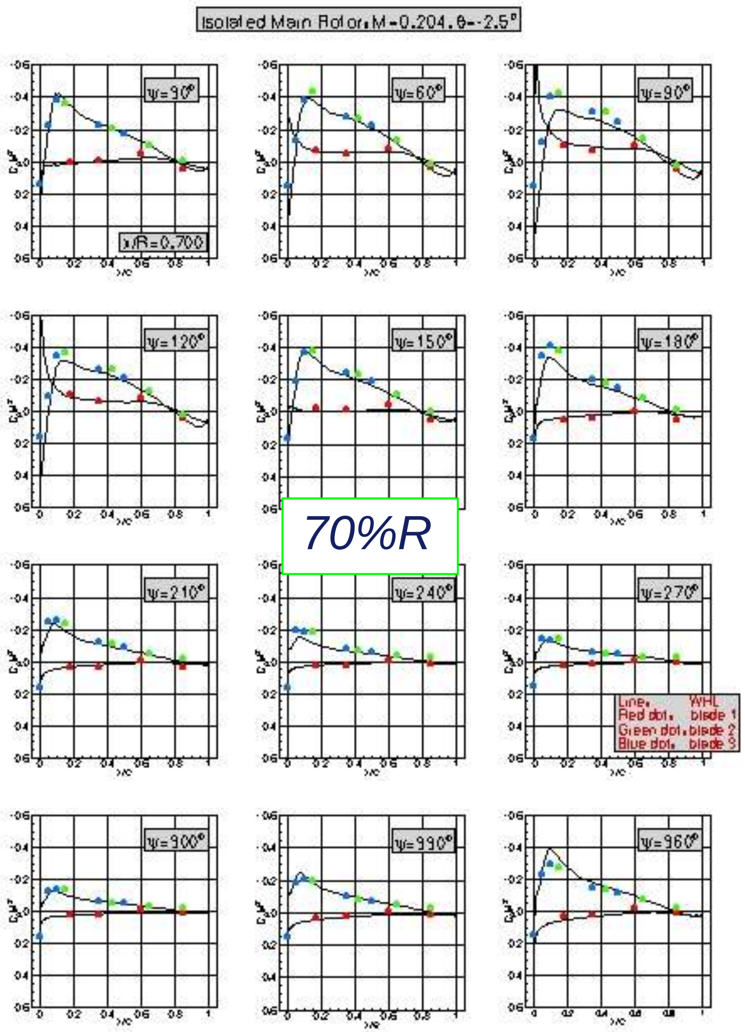


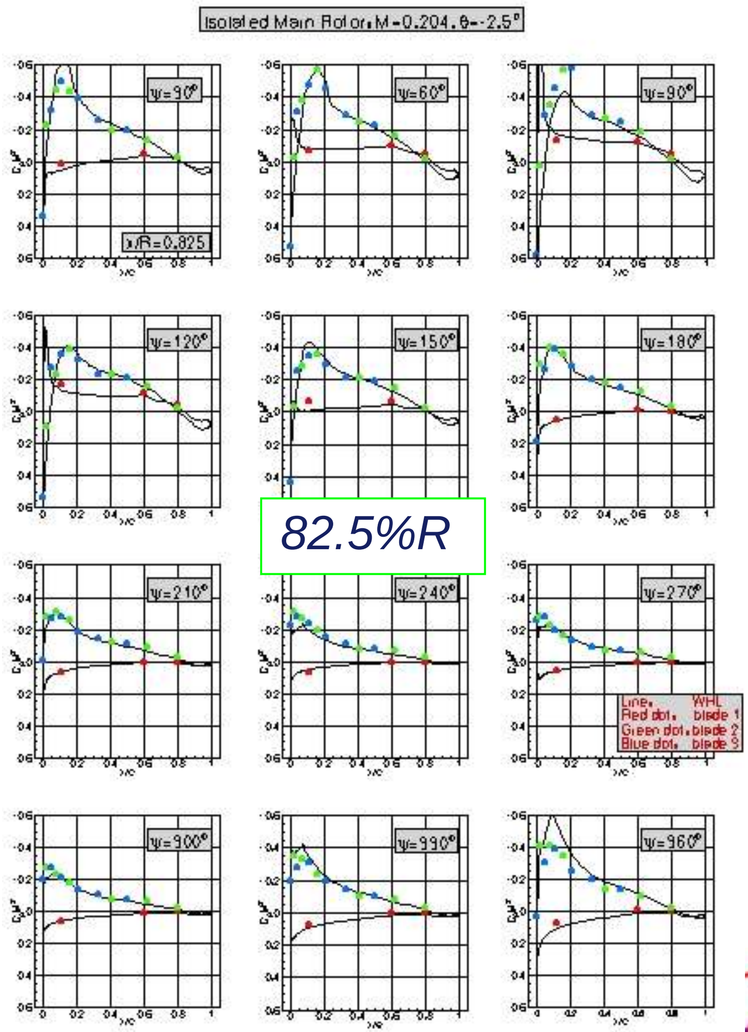
Some Comparisons – Economic Cruise



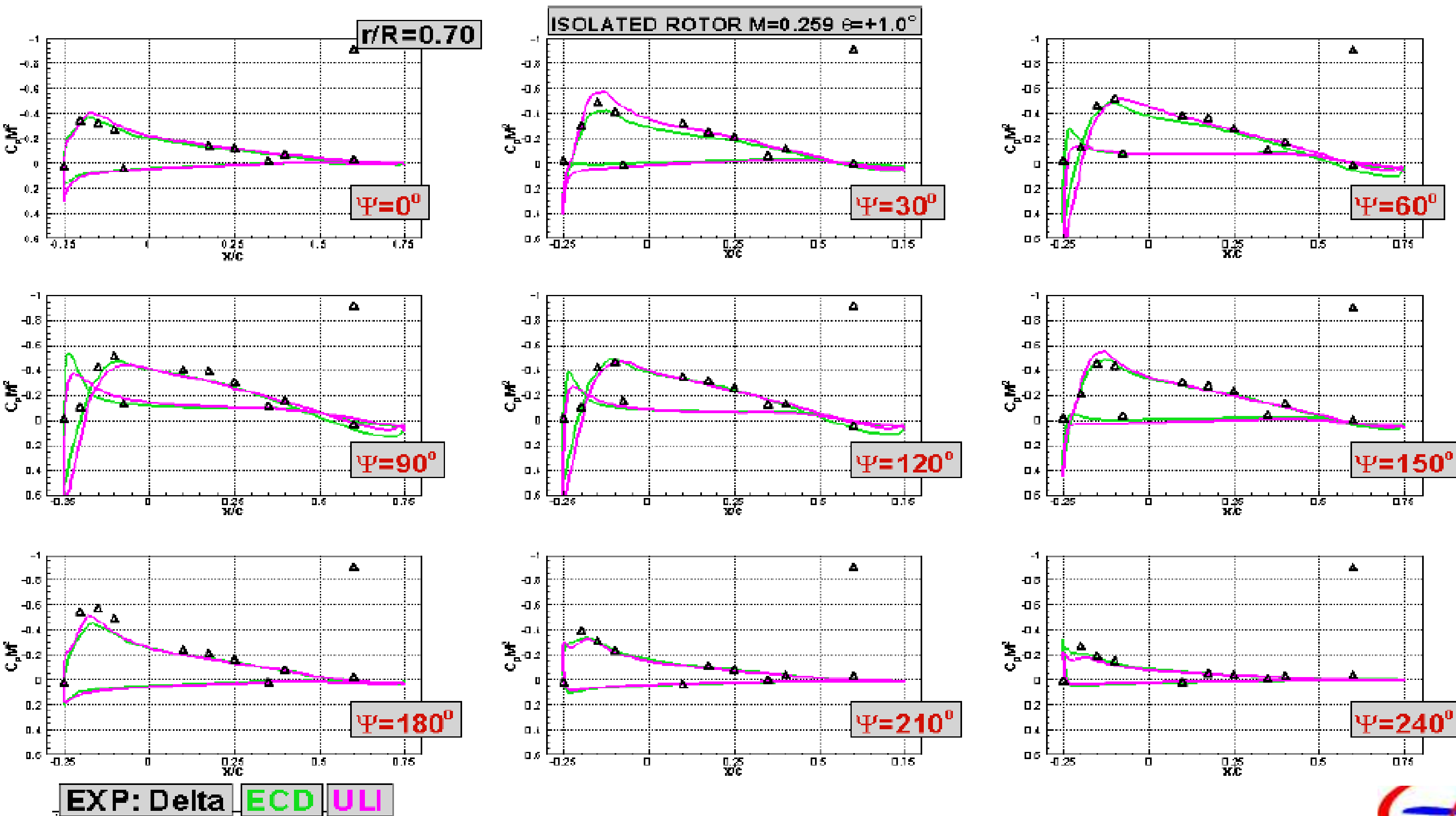
HMB, Post-Test Cruise Condition, TC3

Cp.M² vs x/c - Isolated Rotor – Navier-Stokes Simulation in Cruise Conditions



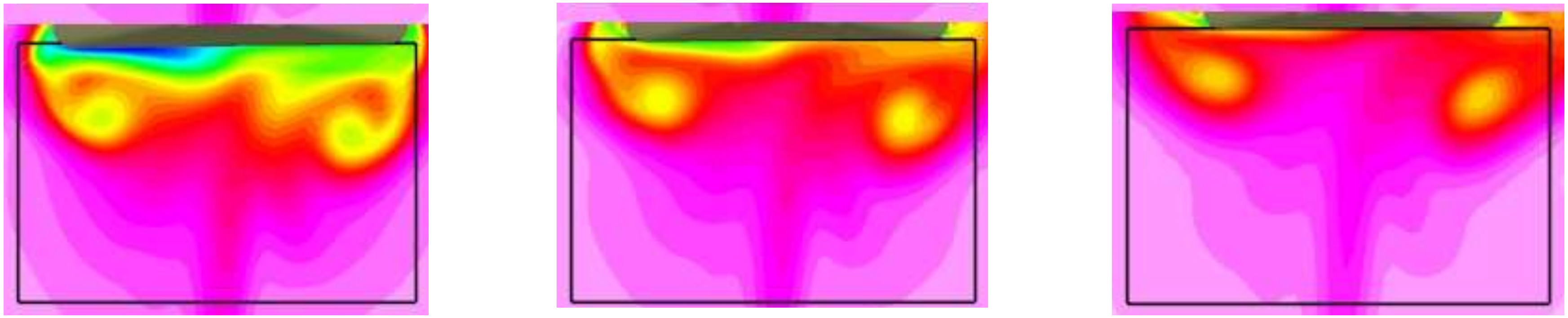


Dynamic Stall Case

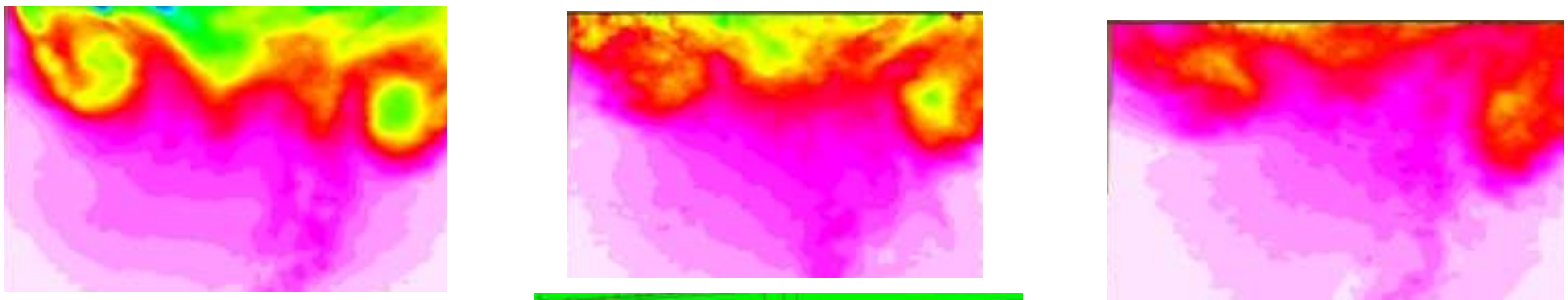


GOAHEAD TC3 – Economic Cruise

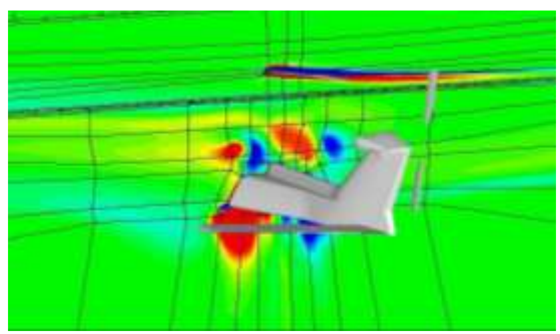
CFD

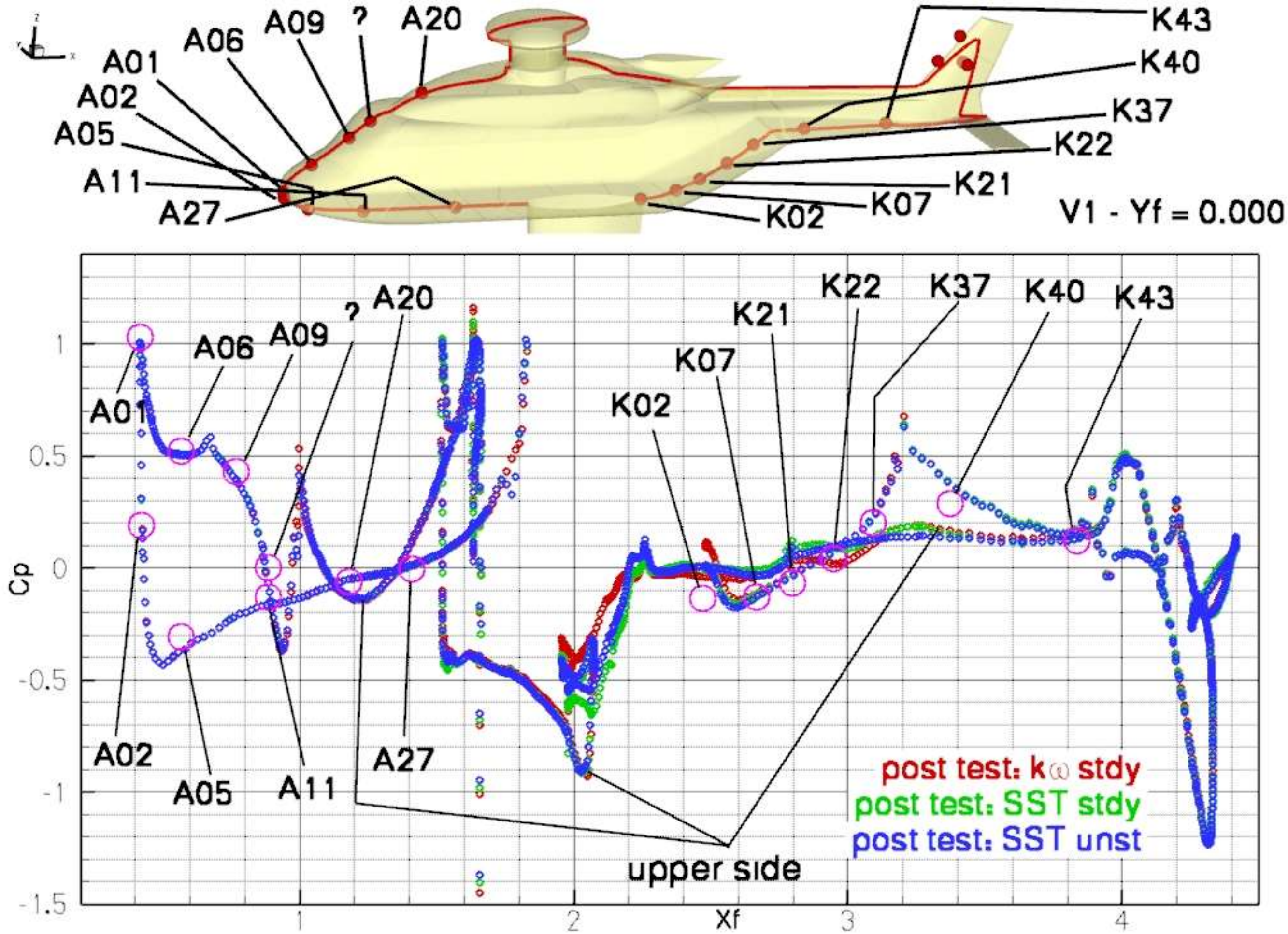


PIV planes below tail boom - Stream-wise velocity



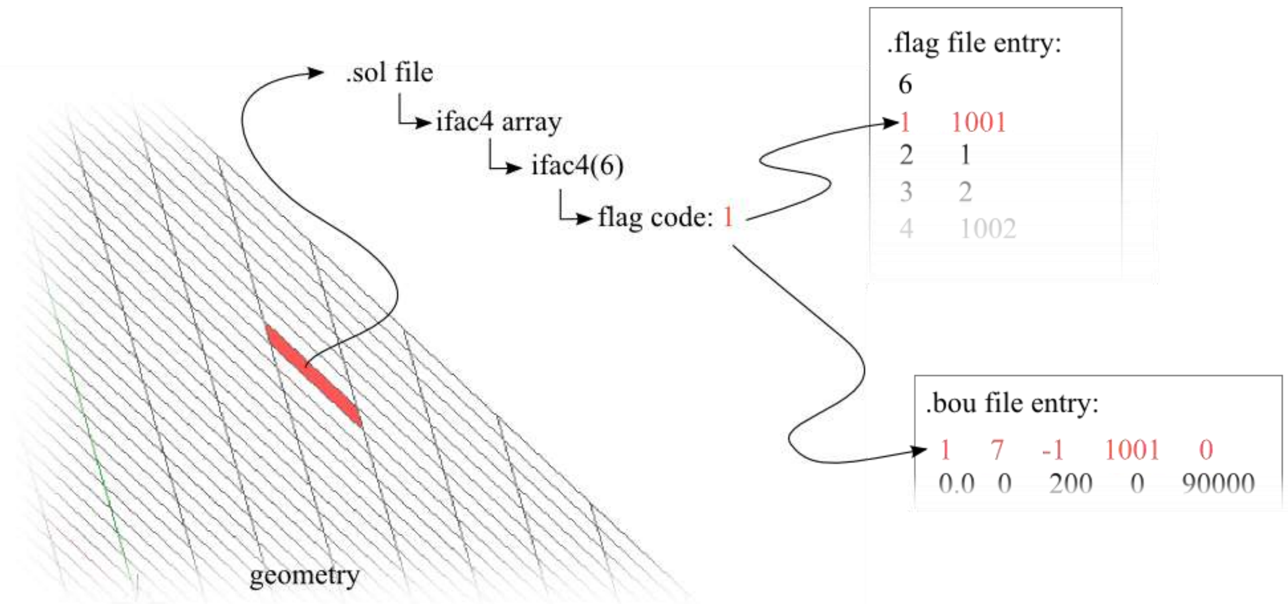
Experiments





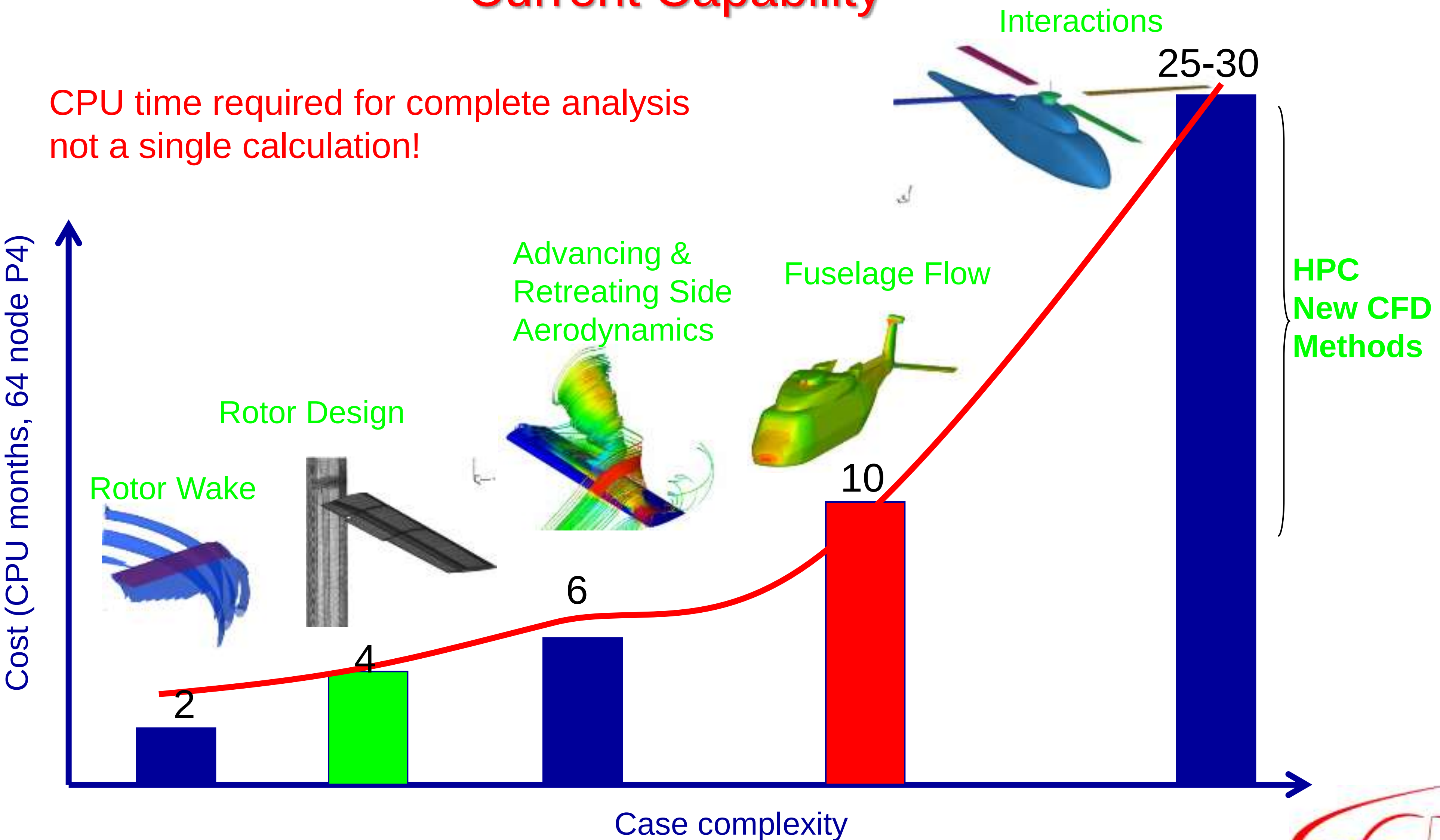
A01
A02
A05
A06
A09
?
A20
A11
A27
K43
K40
K37
K22
K21
K07
K02
V1 - Yf = 0.000
Cp
Xf
upper side
post test: kω stdy
post test: SST stdy
post test: SST unst

HPC and CFD Methods



Current Capability

CPU time required for complete analysis
not a single calculation!



Overview of the HMB Implicit CFD Scheme

Conservation of Mass
Newton's Second Law
Conservation of Energy
Turbulence Model
Transition Model
No Slip Wall B.C.
Far-field B.C. etc

Governing PDEs + B.C.s

Semi –Discretised

Density
Velocity (u,v,w)
Pressure
k, ω,
Passive scalars,
Transition quantities

$$\frac{\mathrm{d}}{\mathrm{d}t}(W_{ijk}V_{ijk}) = -R(W_{ijk})$$

Implicit

$$\frac{W_{ijk}^{n+1} - W_{ijk}^{n}}{\Delta t} = -\frac{1}{V_{ijk}} R(W_{ijk}^{n+1})$$

Linearize

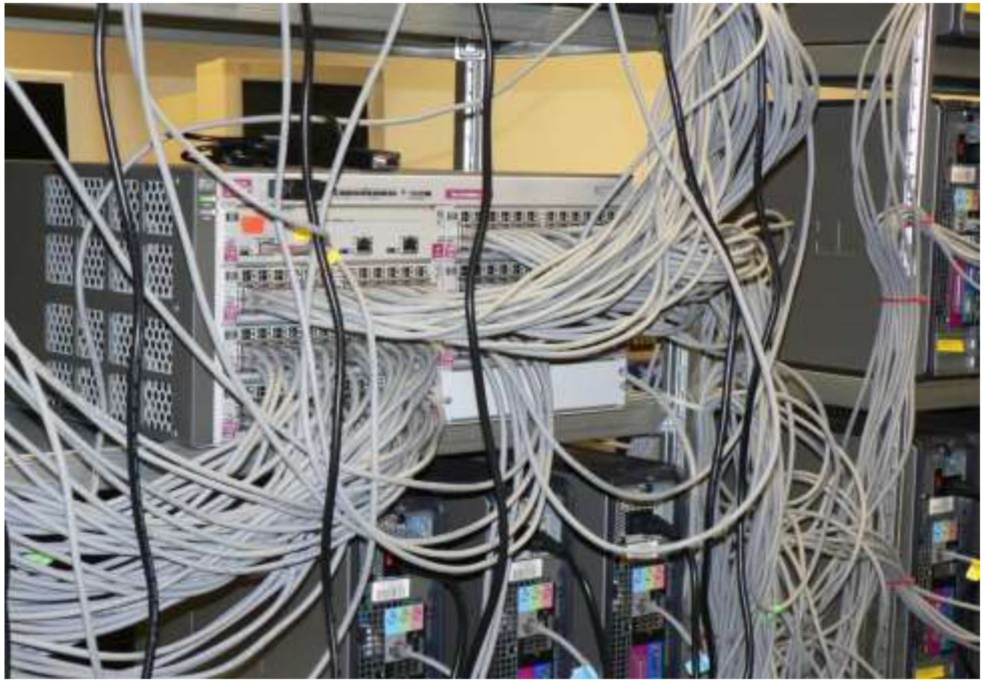
$$W_{ijk}^{n+1} = W_{ijk}^{n} - \left[\frac{V_{ijk}}{\Delta t} + \left(\frac{\partial R}{\partial W}\right)_{ijk}^{n}\right]^{-1} R(W_{ijk}^{n})$$

Jacobian Matrix

As time step gets very large, the implicit method recovers the convergence rate of Newton's method

An approximate Jacobian matrix solved using iterative method

Parallel Computer – Low Cost Clusters

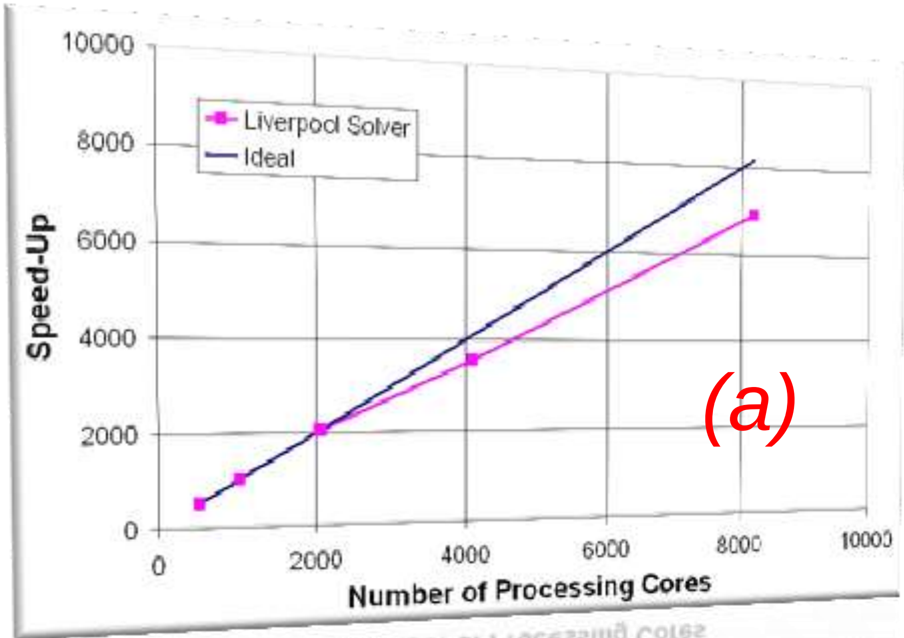



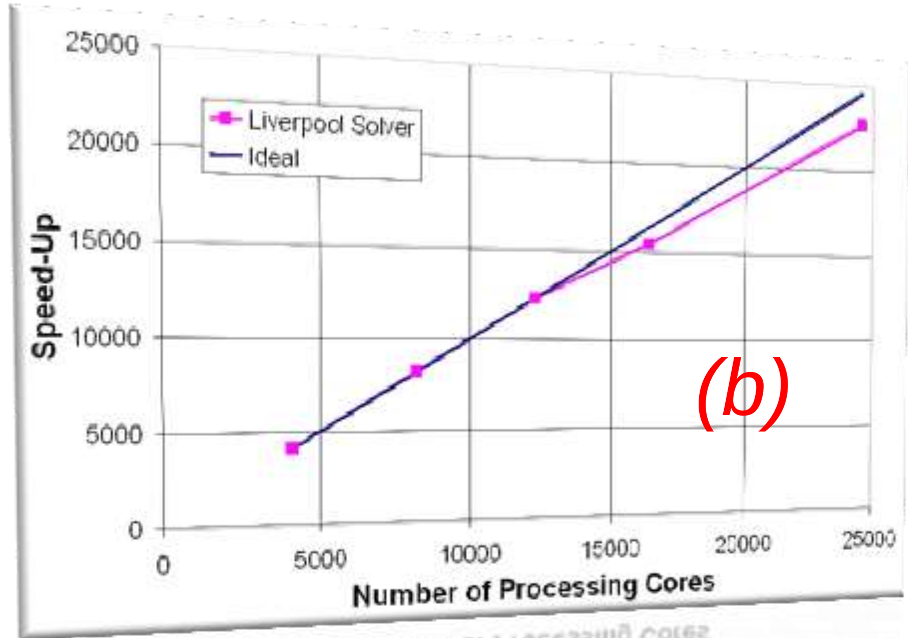
Parallel PC Cluster exclusive to CFD Lab

- –1997 jupiter 1 16, 200MhZ nodes
- –2000 jupiter 2 32, 700 MHz nodes
- –2003 jupiter 3 130, 2.5 GHz nodes
- –2006 jupiter 4 196, 3.0 GHz nodes
- –2008 jupiter 5 512, 3.2 GHz nodes
- **–2013 jupiter 6, 2048 3.1 GHz cores**

Hector Phase 2B

- Current capability at Liverpool as a result of AAC2





Helicopter Multi-Block solver using (a) 105 million point mesh with 24576 blocks and (b) 1100 million point mesh with 196608 blocks

Harmonic Balance / Time Spectral Method

$$V\frac{\mathrm{d}W}{\mathrm{d}t} + R(W) = 0$$

Assume Period with $T = \frac{2\pi}{\omega}$

Expand in Fourier series

$$\sum_{k=-\infty}^{\infty} (ik\omega V\hat{W}_k + \hat{R}_k)e^{ik\omega t} = 0$$

Orthogonal basis implies

$$ik\omega V\hat{W}_k + \hat{R}_k = 0, \quad \forall k$$

Infinite number of steady state equations in frequency domain – McMullen et al solved subset yielding non linear frequency domain method

May be impossible to determine an explicit expression, so transform back into time domain (Hall et al. / Gopinath and Jameson)

Harmonic Balance / Time Spectral Method

Truncate the series to N_h Modes and use uniform sampling

$$W = \begin{pmatrix} W(t_0 + \Delta t) \\ W(t_0 + 2\Delta t) \\ \vdots \\ W(t_0 + T) \end{pmatrix} \qquad W_n = \sum_{k=-N_h}^{N_h} \hat{W}_k e^{ik\omega n\Delta t} \qquad 1 \le n \le 2N_h + 1$$

Transforming back to the time domain and using pseudo time gives

$$V\frac{\partial W}{\partial \tau} + \omega V D_t(W_n) + R(W_n) = 0 \qquad 1 \le n \le 2N_h + 1$$

Pseudo time term

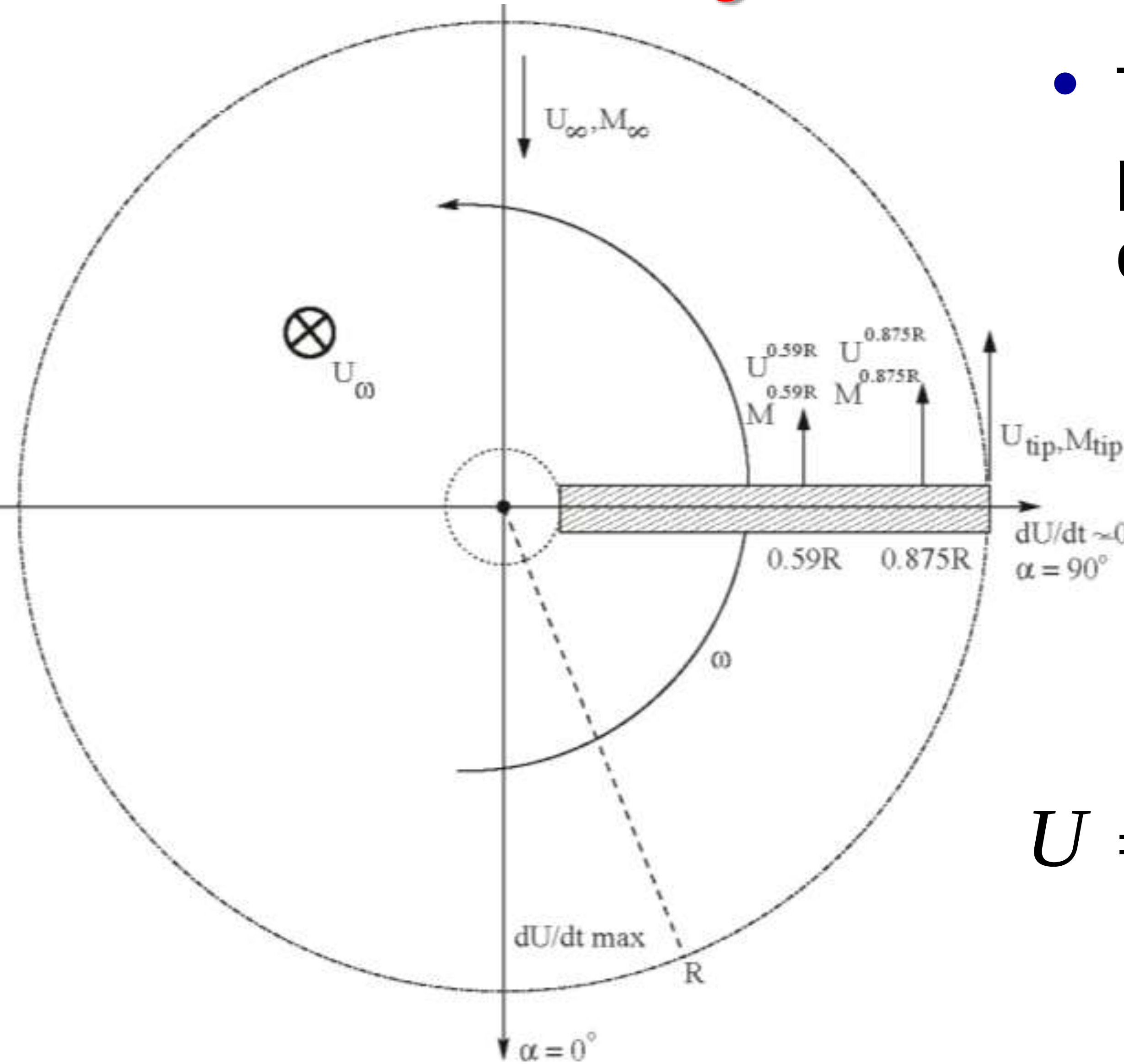
Unsteady source term

Couples all snapshots

Residual evaluation

Very large steady state problem

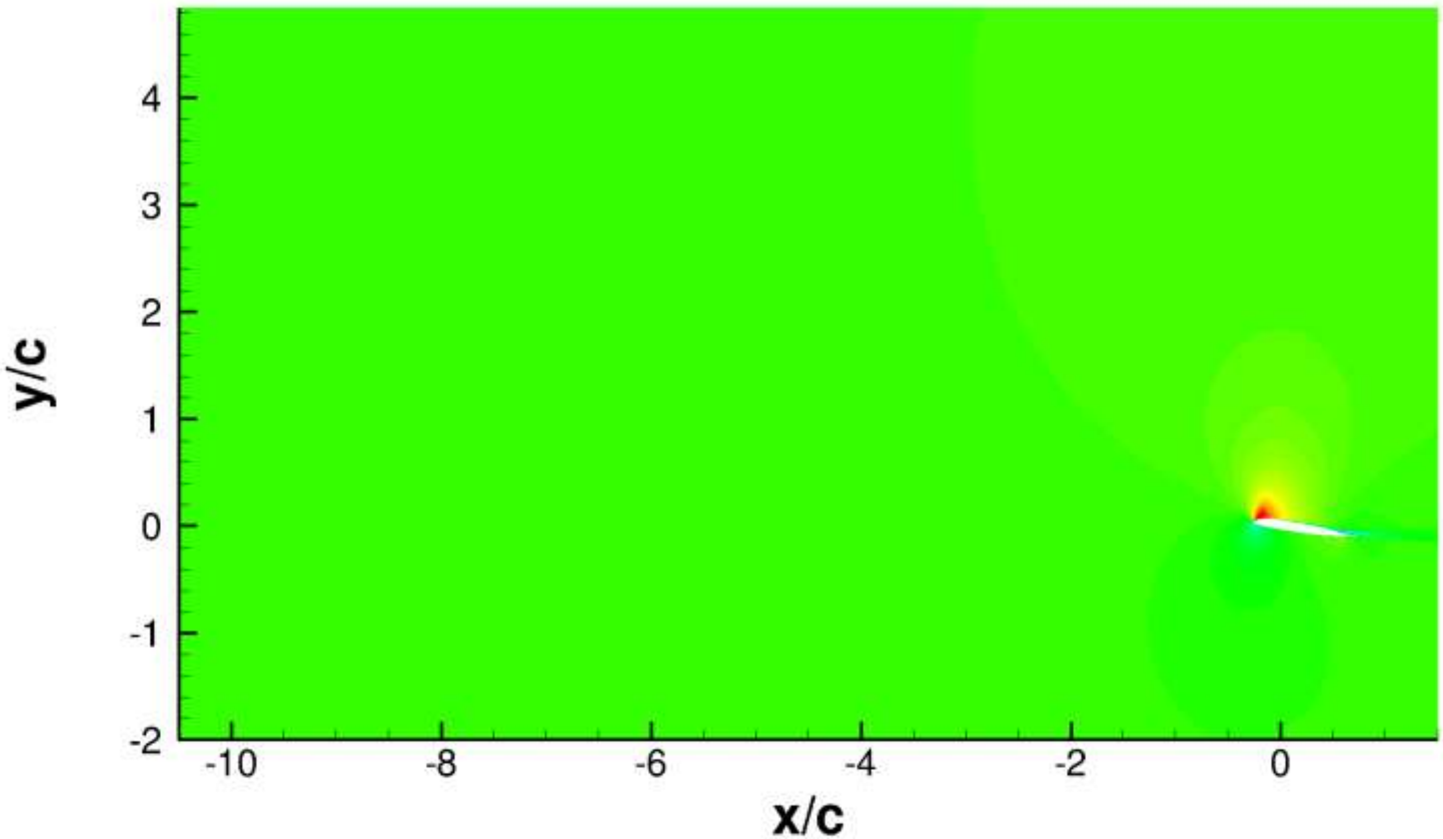
Pitching-Translational motions (dM/dt)

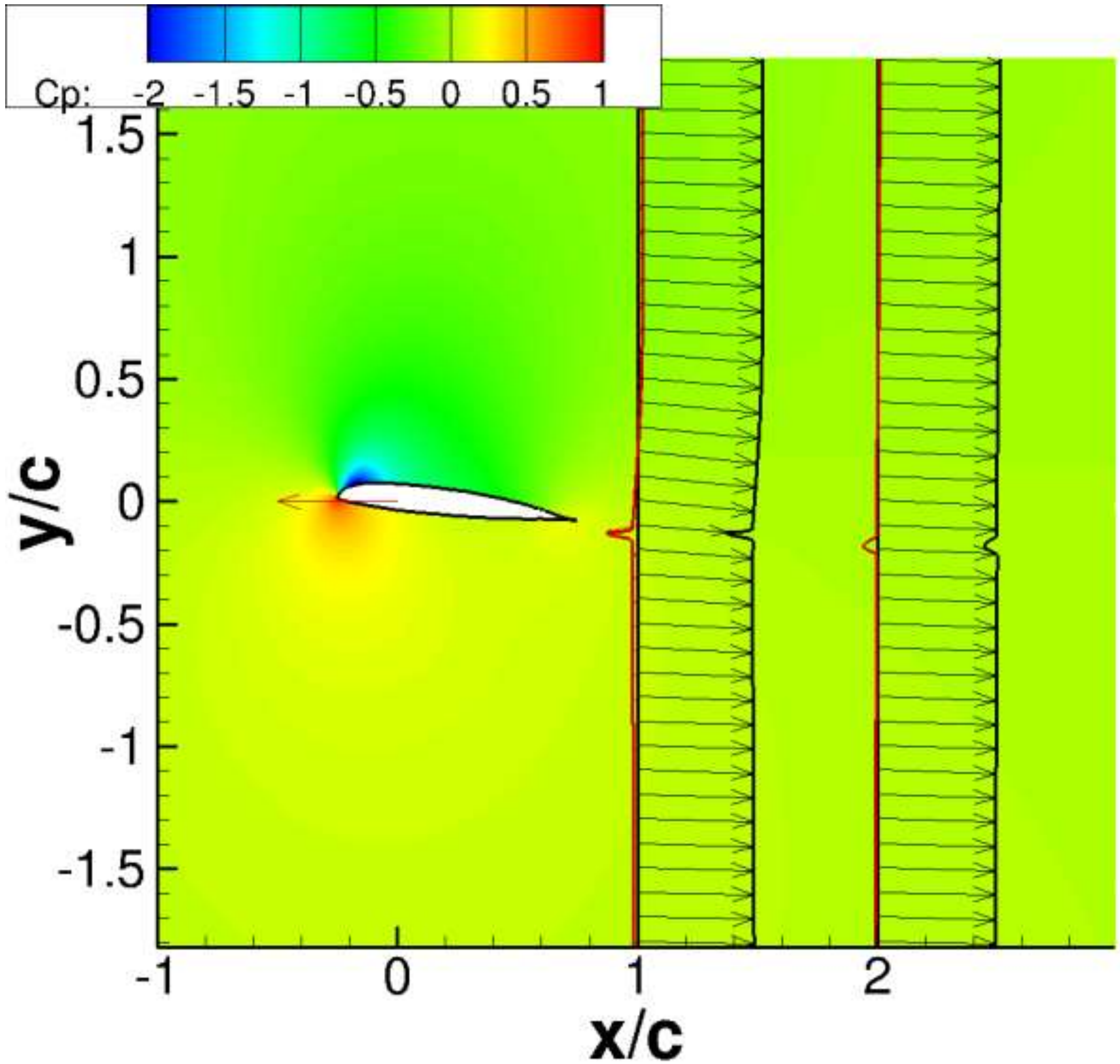


- This combines the pitching and translation of the blade
  - The sections are forced into harmonic pitching motion
  - The centre of rotation carries out a harmonic translational motion

$$U = U_{tip}\frac{r}{R} + U_{\infty}\sin(\omega t)$$

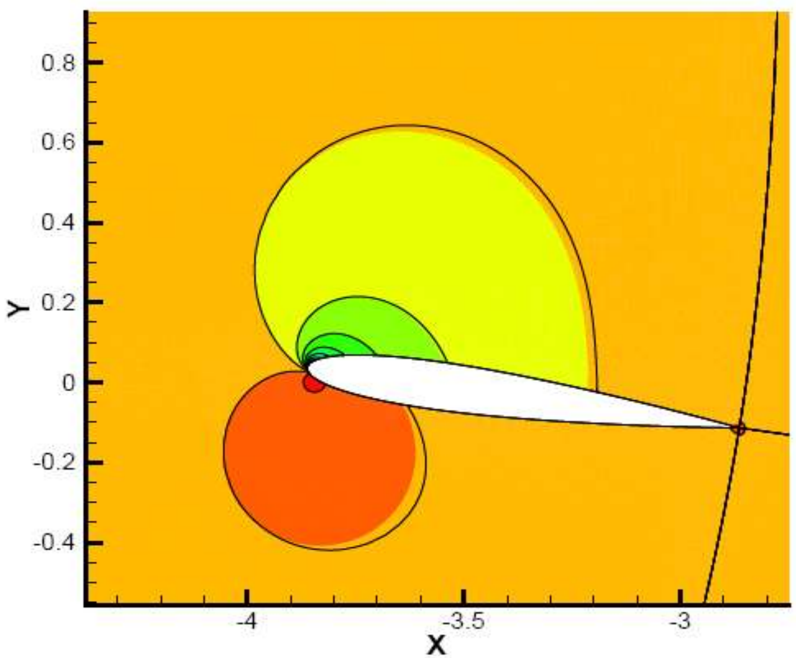
Rotor Blade Section



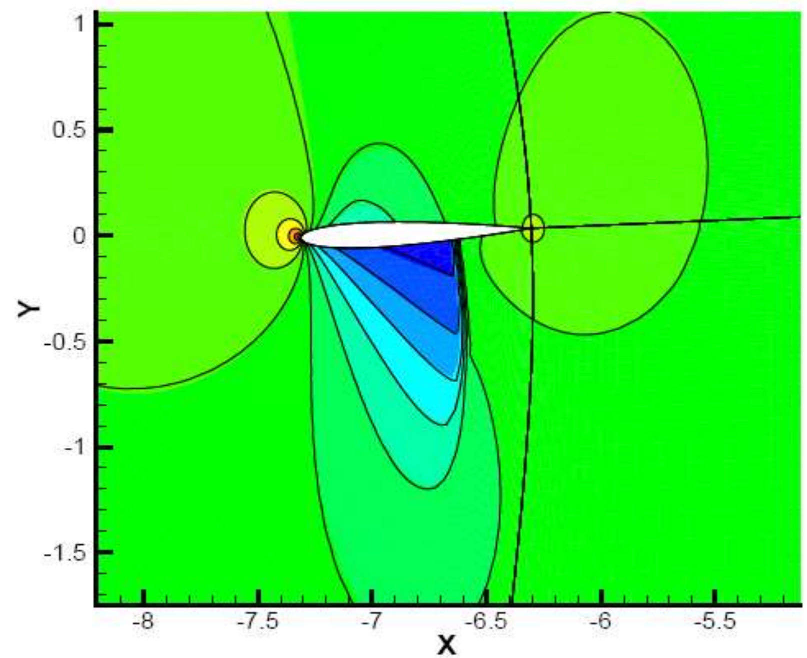

Cp: -2 -1.5 -1 -0.5 0 0.5 1
1.5
1
0.5
y/c
0
-0.5
-1
-1.5
-1 0 1 2
x/c

Harmonic Balance vs Time Marching

- Harmonic balance results using 5 modes for the inviscid dMdt case. The implicit flow solver was used.

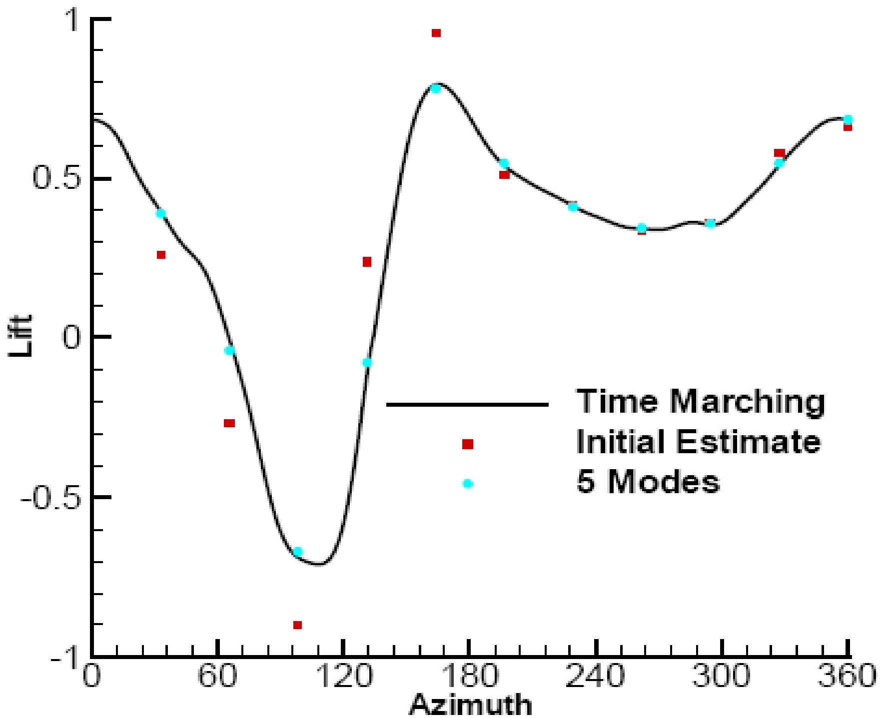


(a) Retreating side 5 modes, 295 degrees of azimuth

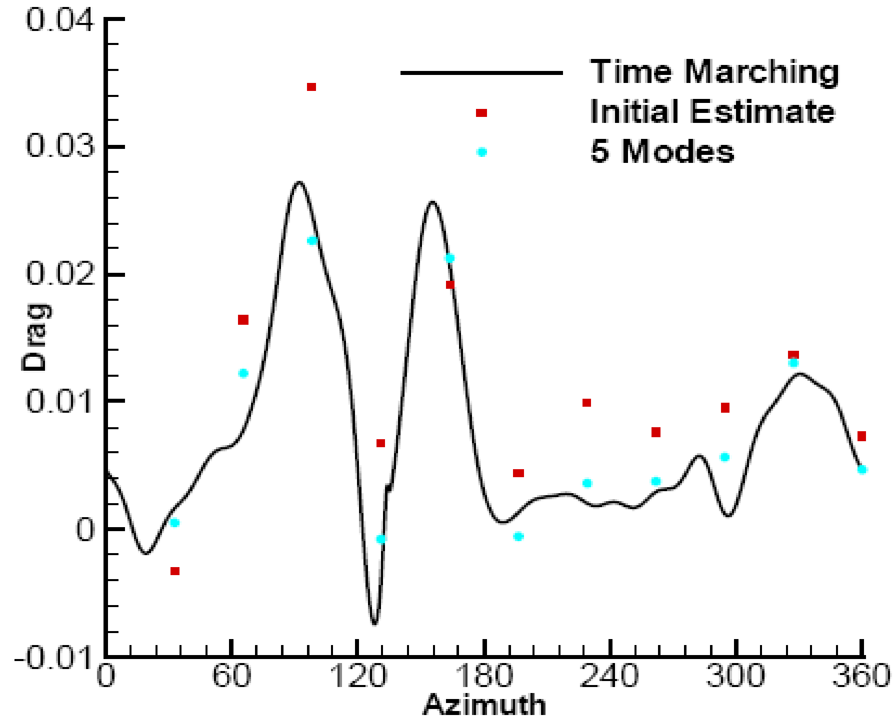


(b) Advancing side 5 modes, 98 degrees of azimuth

dM/dt, 5 modes, turbulent

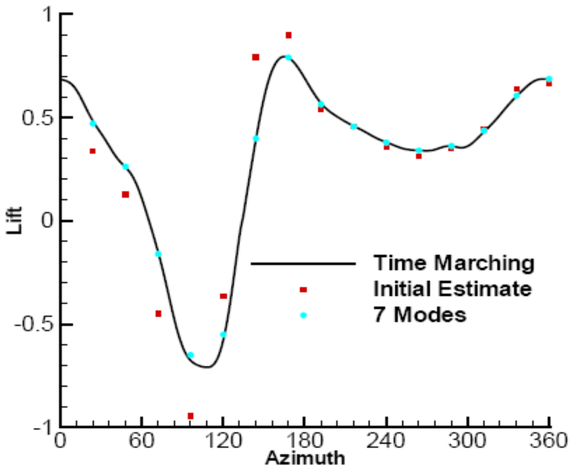


(a) Lift variation against Azimuth

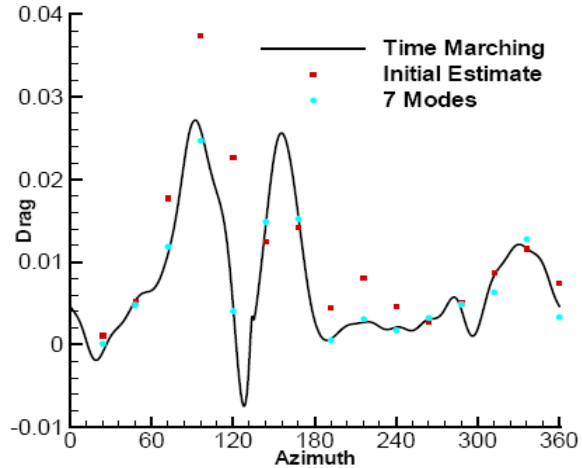


(b) Drag variation against Azimuth

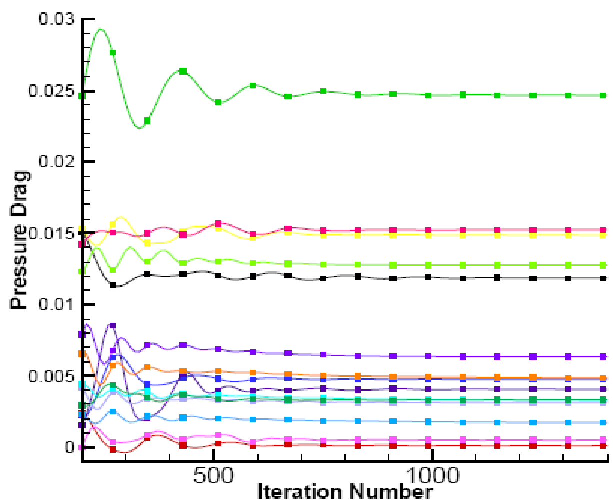
7-modes - turbulent dM/dt



(a) Lift variation against Azimuth



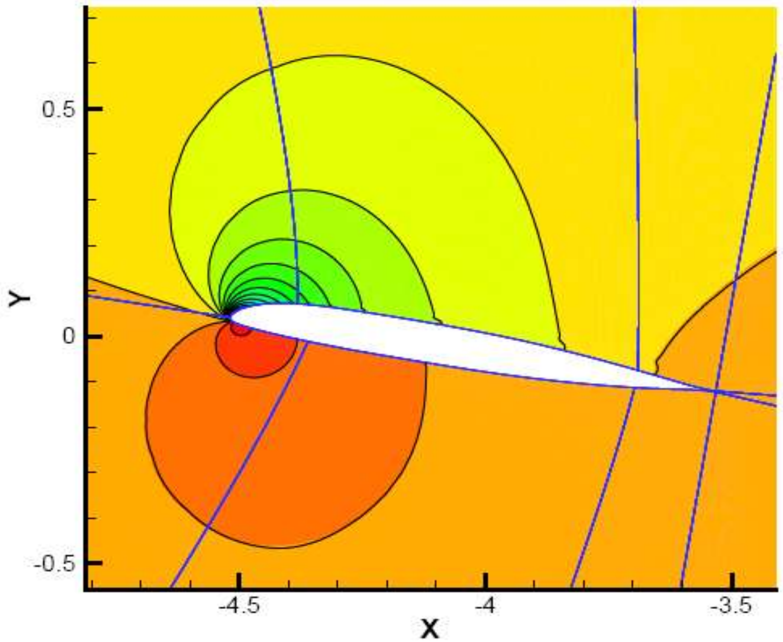
(b) Drag variation against Azimuth



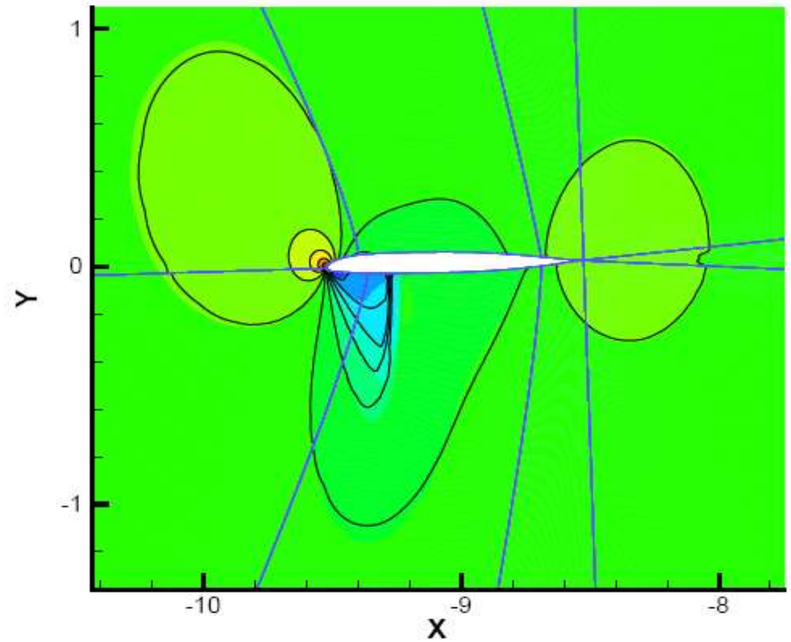
(c) Drag convergence against iteration number

Harmonic Balance vs Time-Marching - Turbulent

- Harmonic balance results using 7 modes

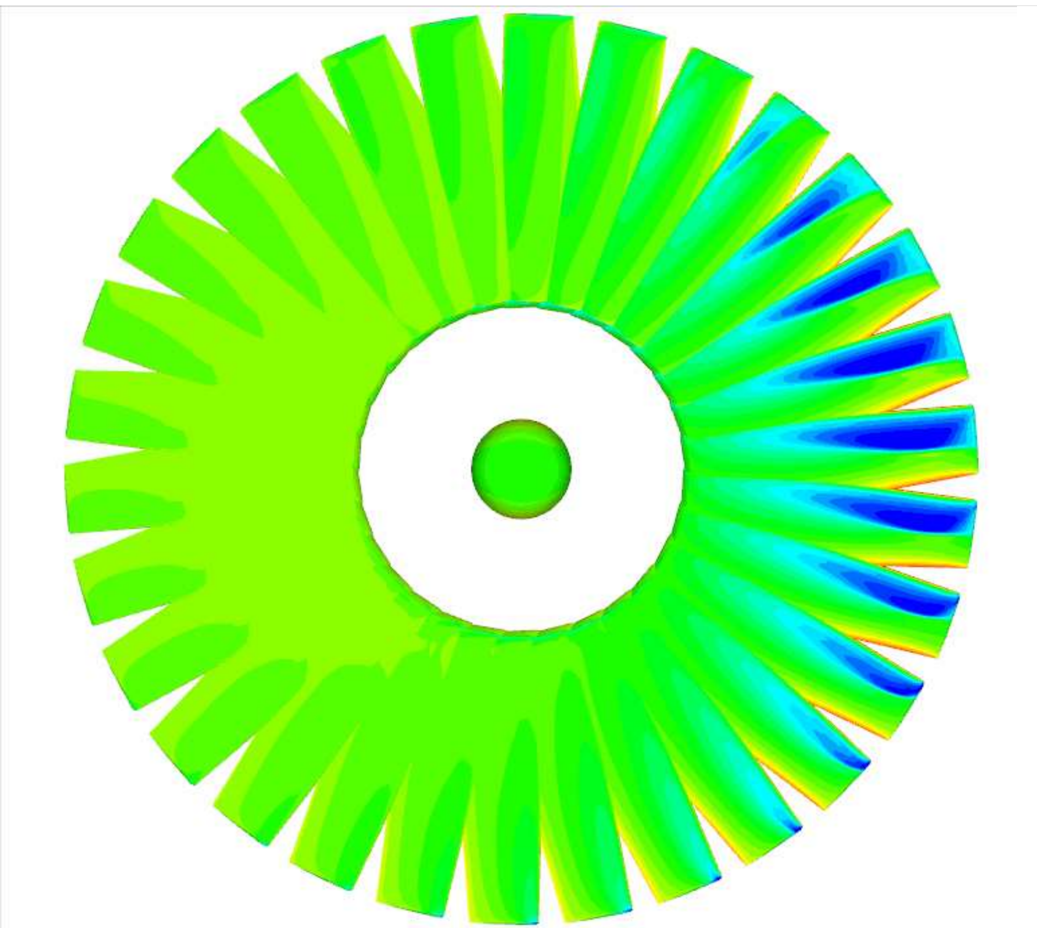


(a) Retreating side 7 modes, 288 degrees of azimuth

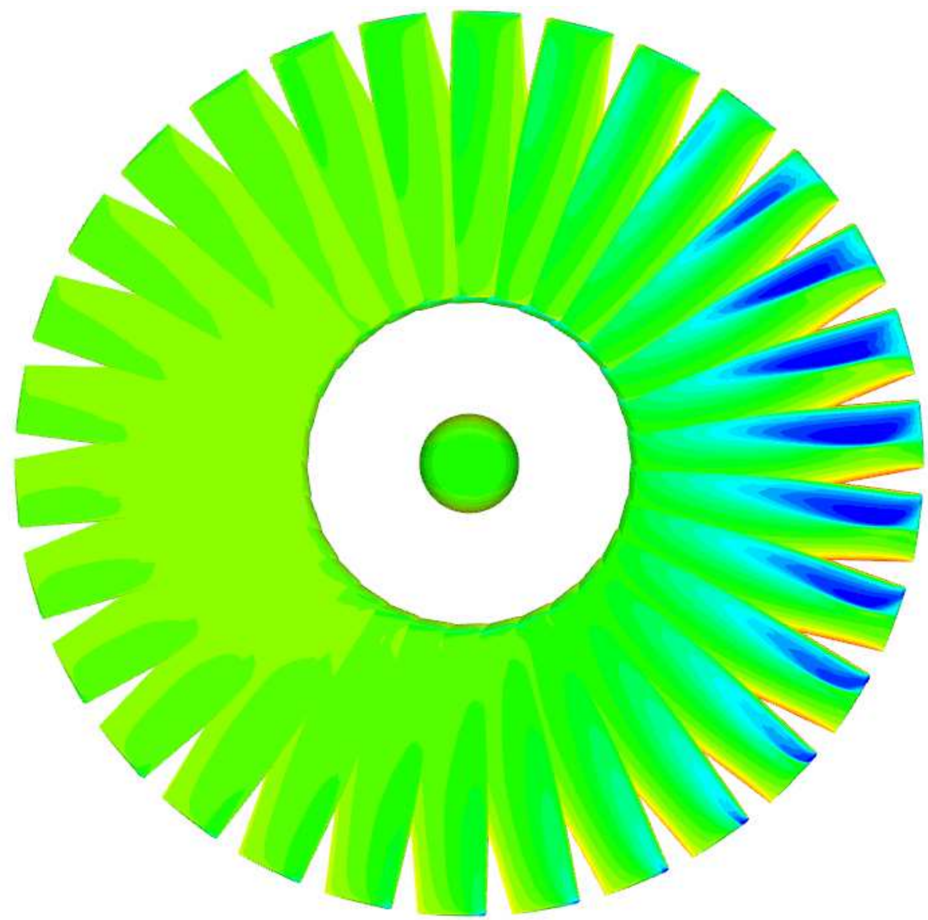


(b) Advancing side 7 modes, 120 degrees of azimuth

ONERA 2-blade Non-lifting Rotor Pressure Disks



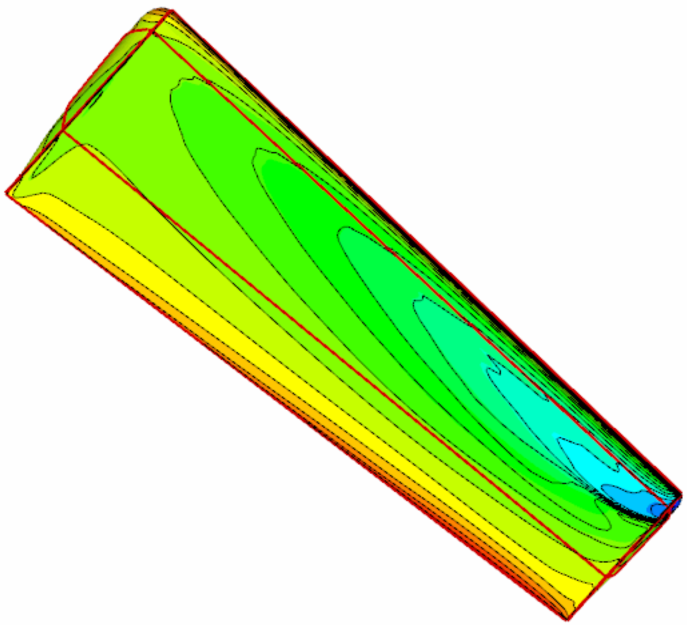
Time Marching



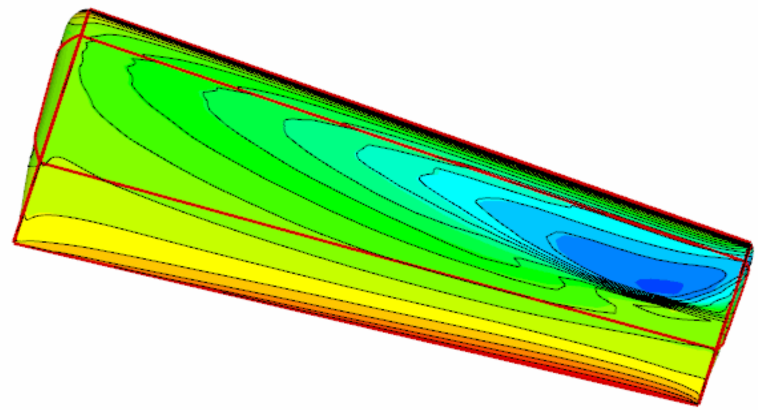
Harmonic Balance
7 Modes

ONERA 2-blade Non-lifting Rotor

Solid lines correspond to the harmonic balance solution
Colour contours correspond to the time-marching



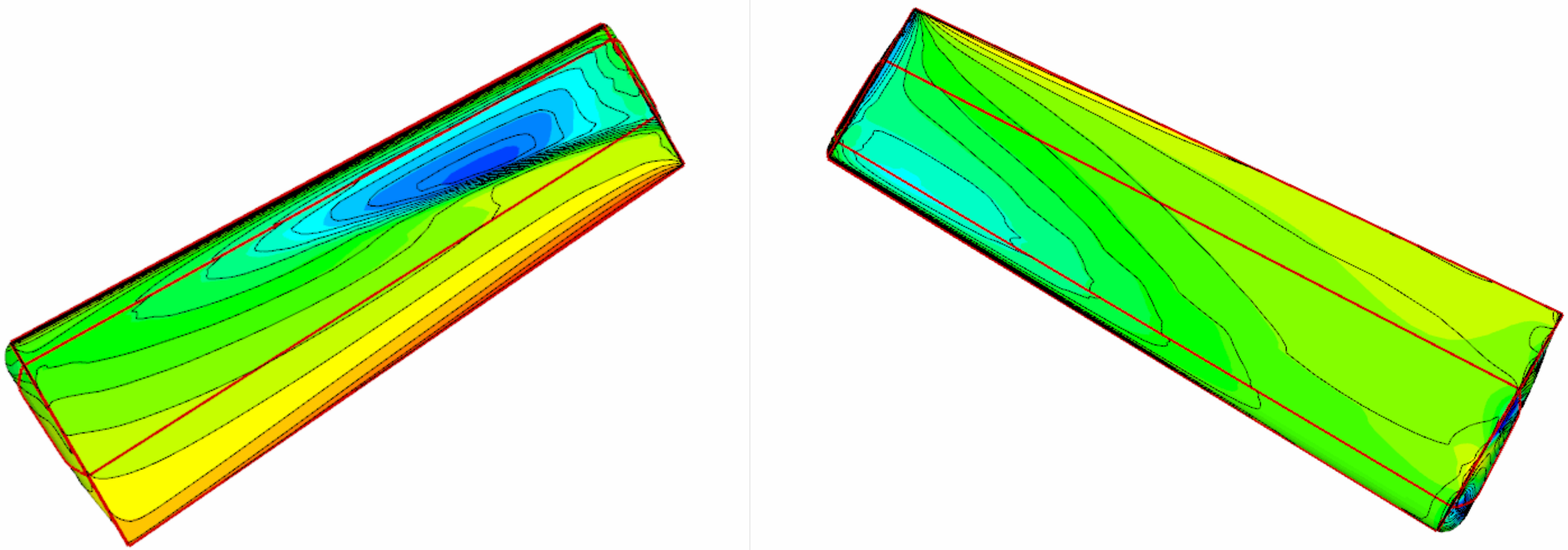
Ψ=48 deg.



Ψ=72 deg.

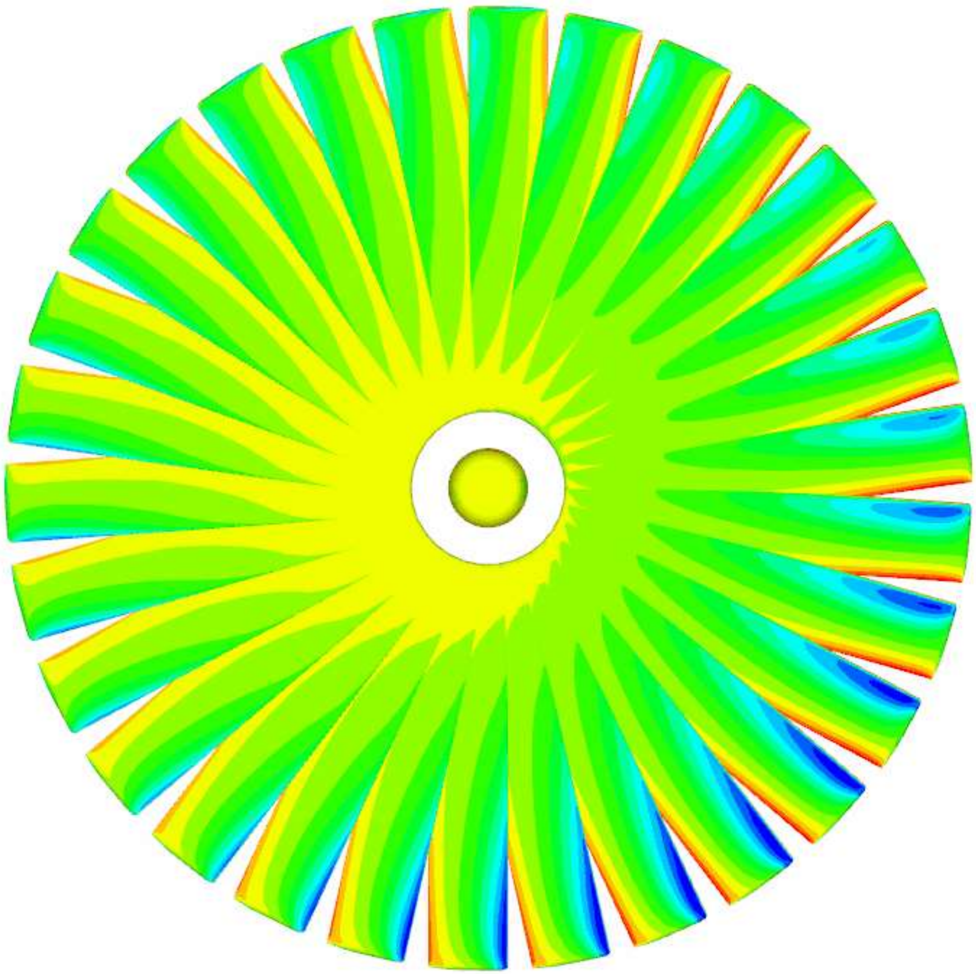
ONERA 2-blade Non-lifting Rotor

Solid lines correspond to the harmonic balance solution
Colour contours correspond to the time-marching

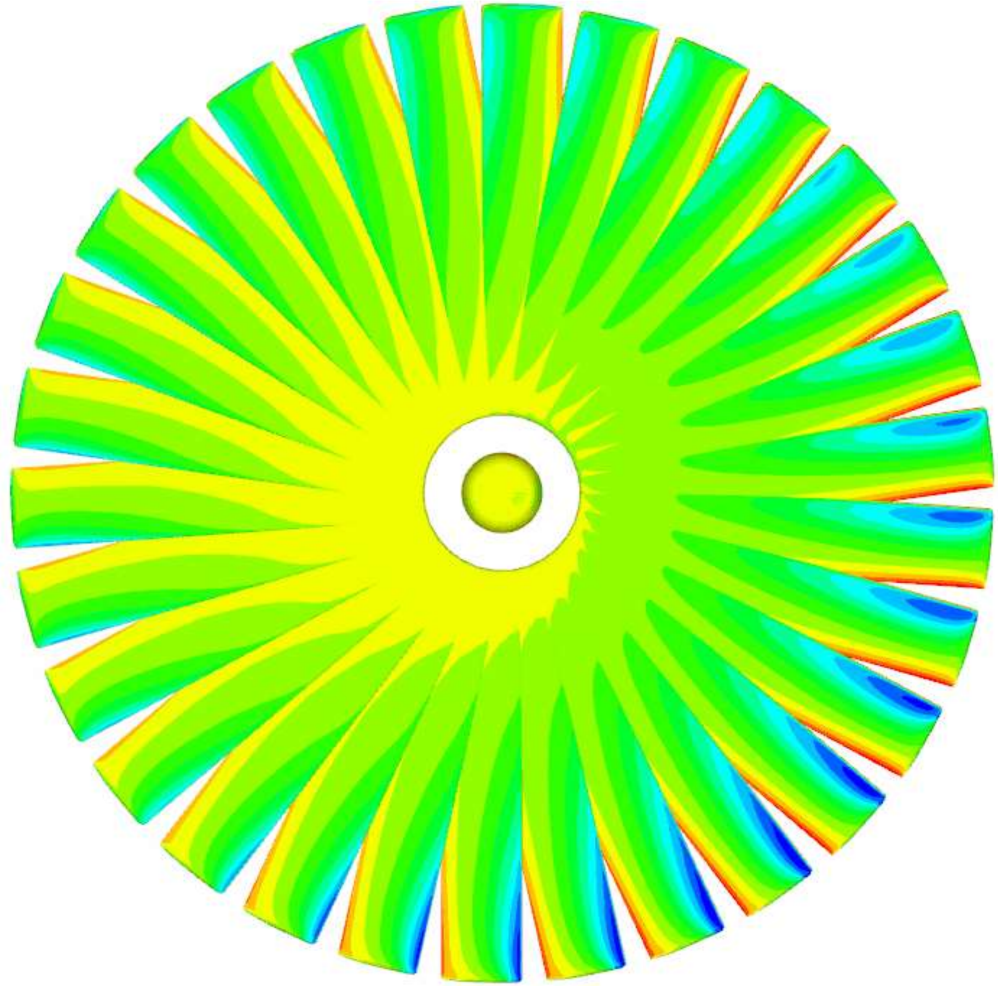


Ψ=120 deg. Ψ=240 deg.

Lifting Rotor Pressure Disks Time Marching vs 7 Modes

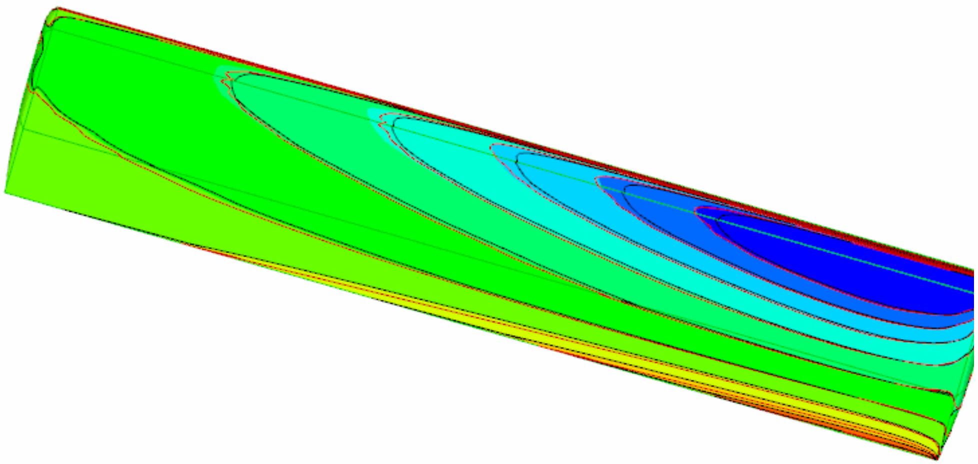


Time Marching

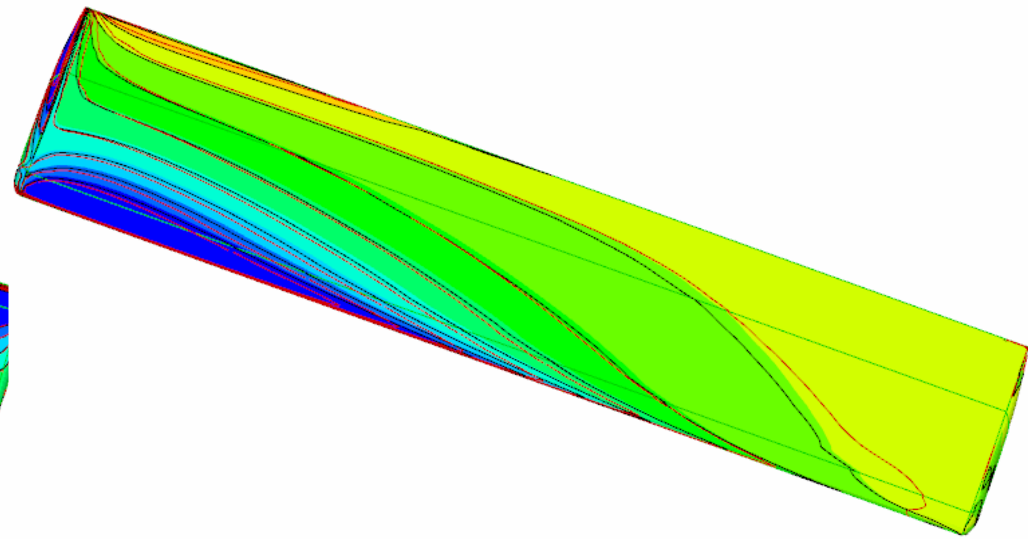


Harmonic Balance

Lifting Rotor Surface Pressure Comparison



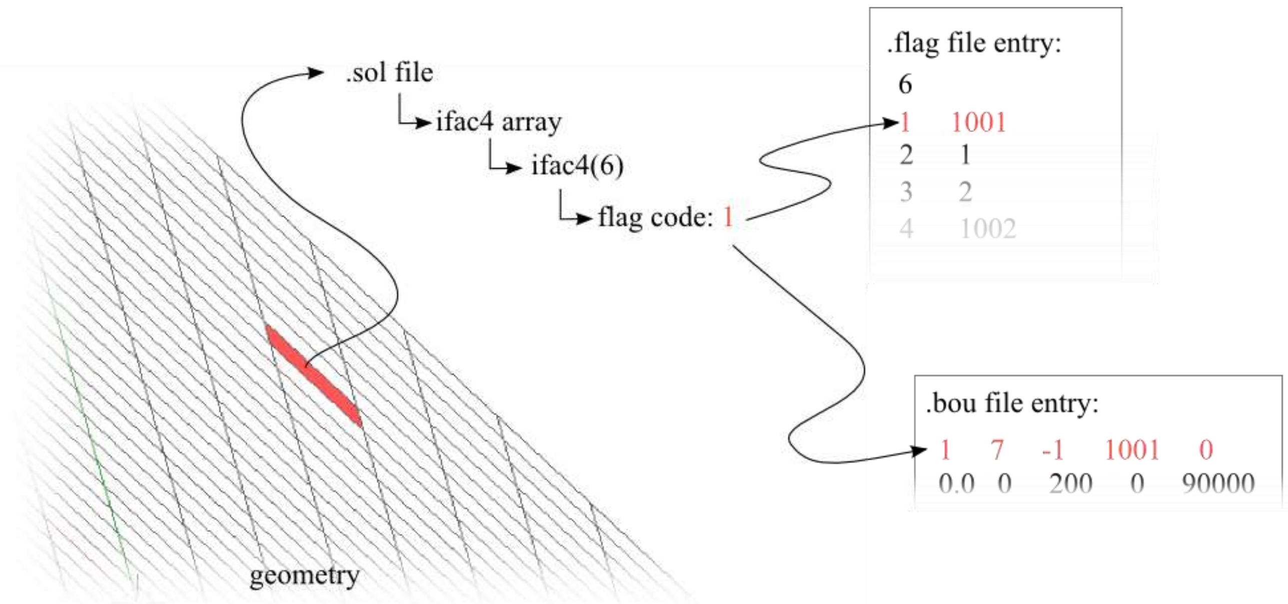
Ψ=72 deg.

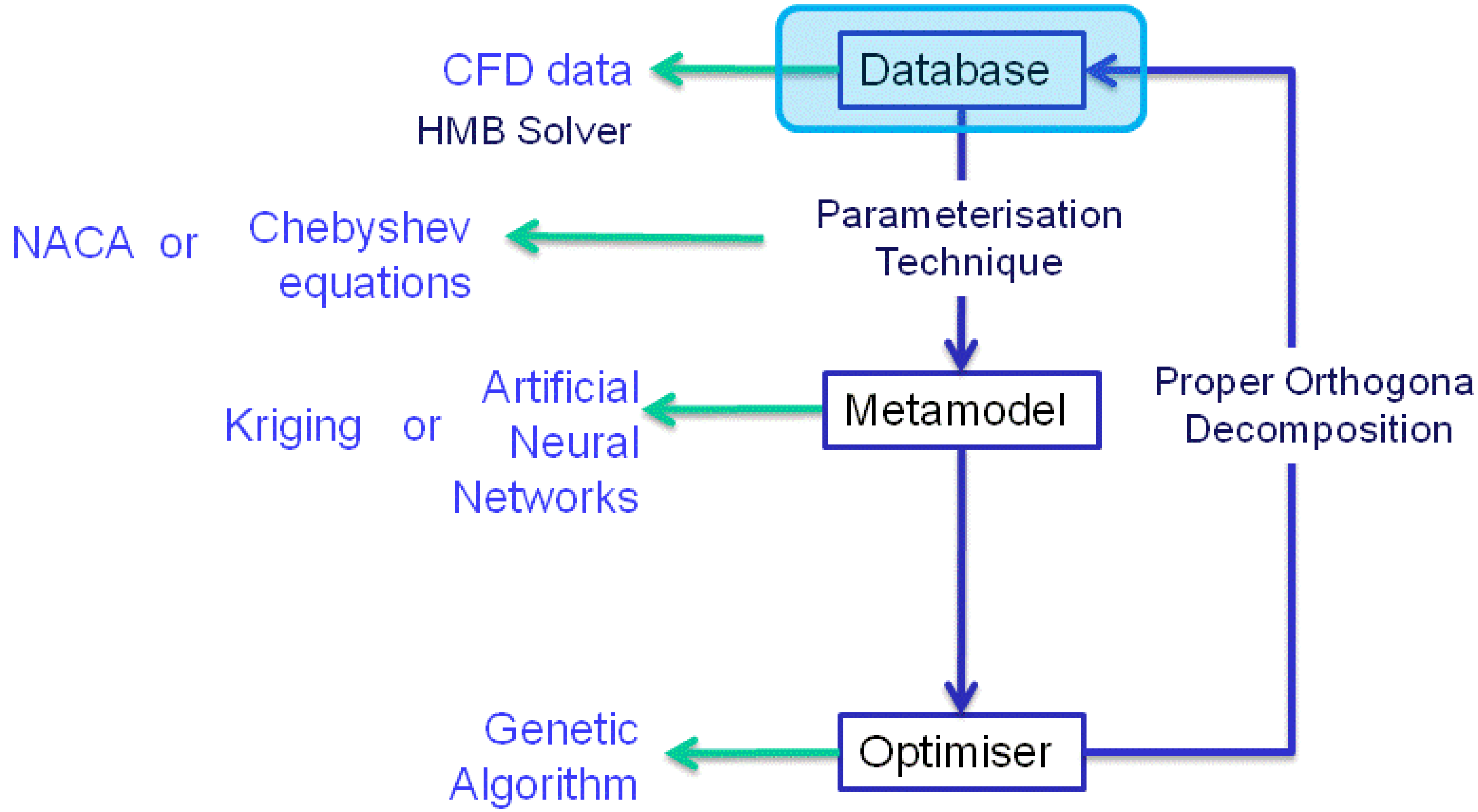


Colour Time-Marching
Black lines Inviscid 7 Modes HB
Red lines Turbulent 2 Modes HB

Ψ=252 deg.

Optimisation and Design

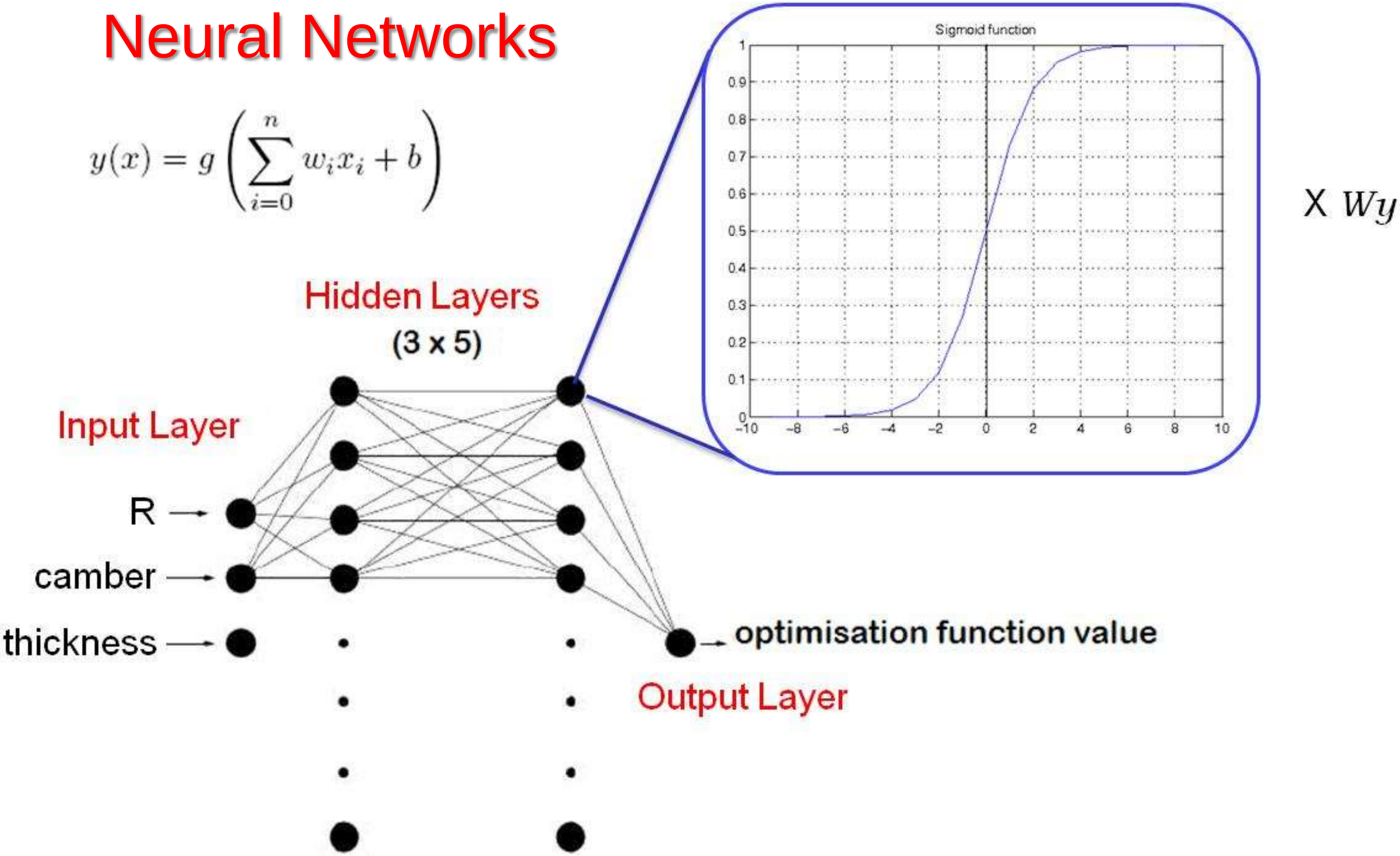




CFD data
HMB Solver
Database
NACA or
Chebyshev equations
Parameterisation Technique
Kriging or
Artificial Neural Networks
Metamodel
Proper Orthogonal Decomposition
Genetic Algorithm
Optimiser

Neural Networks

$$y(x) = g\left(\sum_{i=0}^{n} w_i x_i + b\right)$$



Optimiser – Genetic Algorithm

Population — Database: parameters and performance

↓

Assessment — Combine loads using objective function

↓

Selection — Roulette wheel

↓

Crossover — Swap parameters

↓ (to Mutation, or straight on to Competition)

Mutation — Convert to binary and switch one bit to 1 or 0

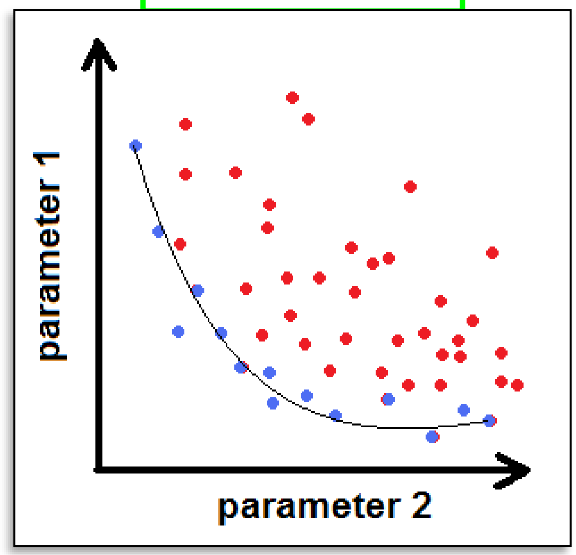
↓

Competition — Metamodel used to find loads

↓

Survival — OFV > threshold to enter next generation

Pareto front

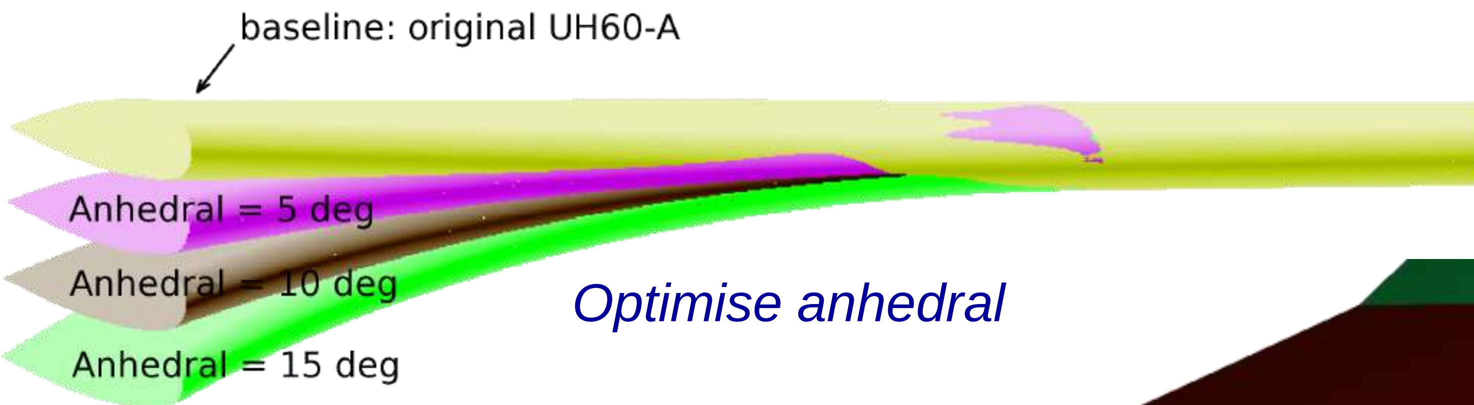


Case 5 - UH60-A Forward Flight

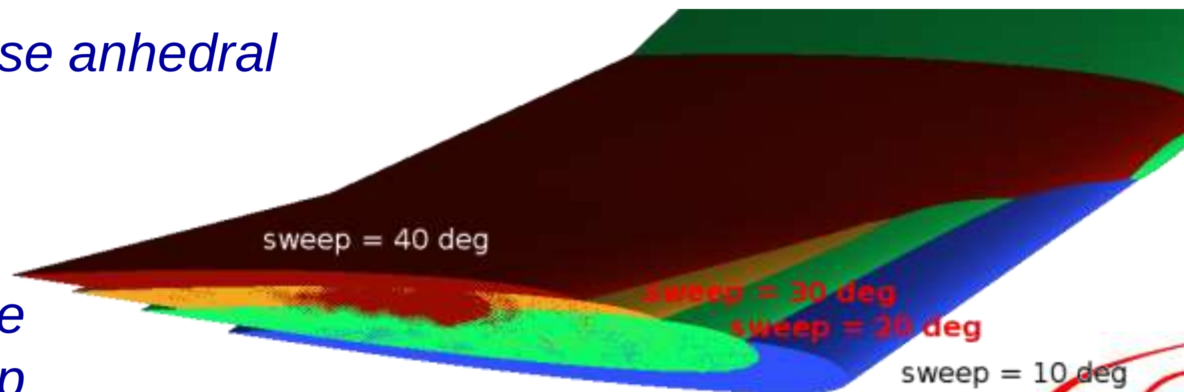
Optimise UH60-A Rotor sweep and anhedral

Objective: Improve pitching moment, reduce stall on retreating side and shock on advancing side

Database: 5 values of sweep (0, 10, 20 30 and 40 deg)
4 values of anhedral (0, 5, 10 and 15 deg)

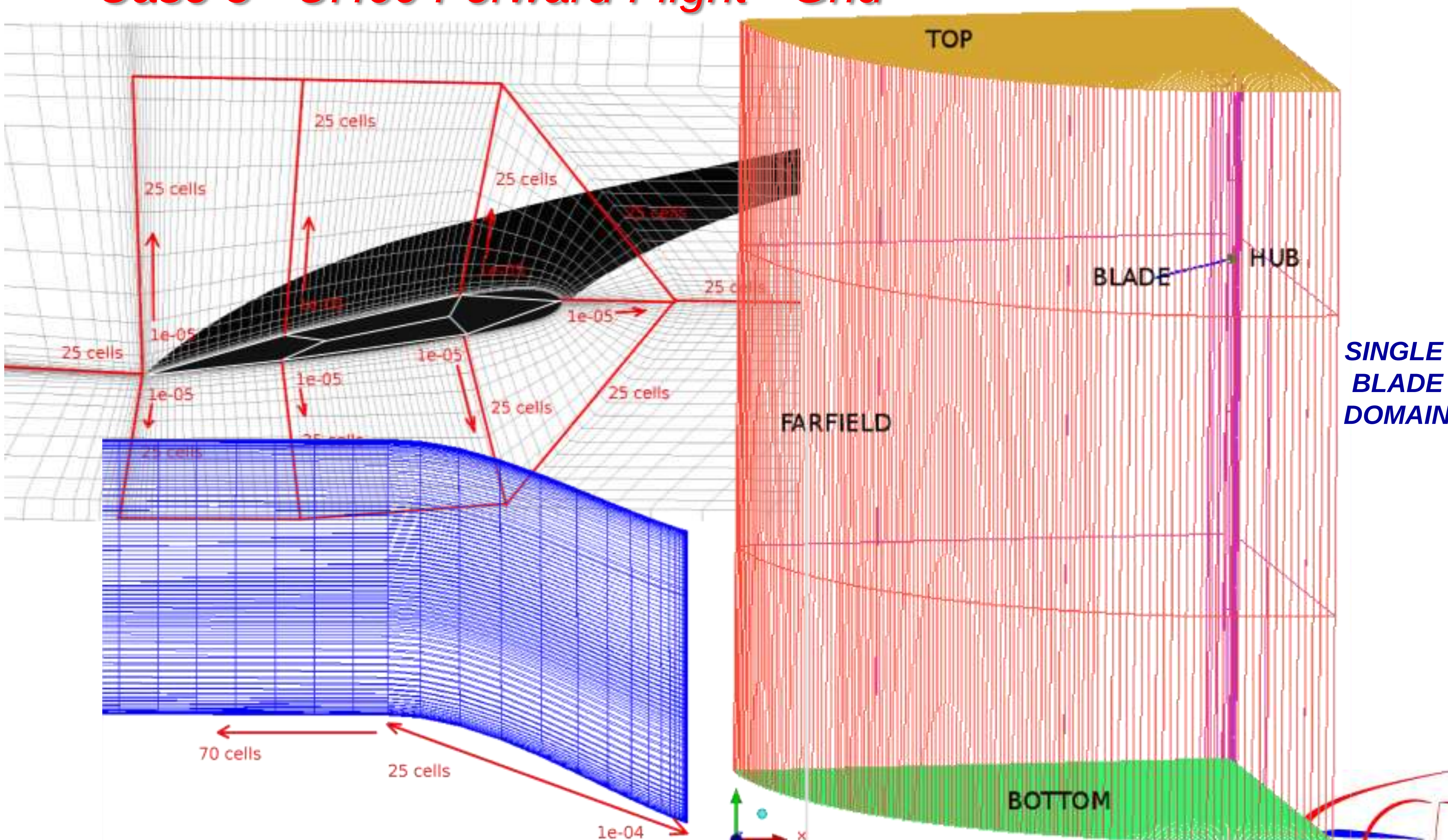


Optimise anhedral



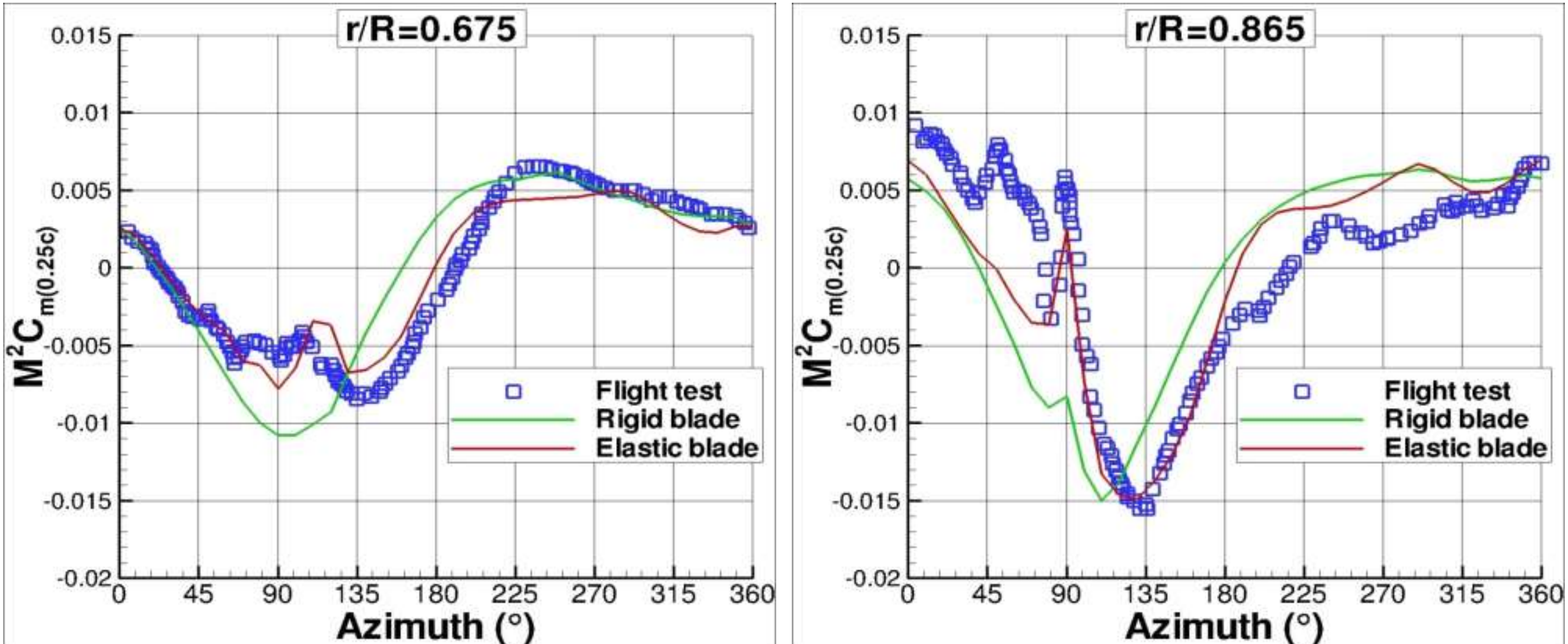
Optimise sweep

Case 5 - UH60 Forward Flight - Grid



Case 5 - UH60 Forward Flight Validation

$M_\infty^2 C_m$:



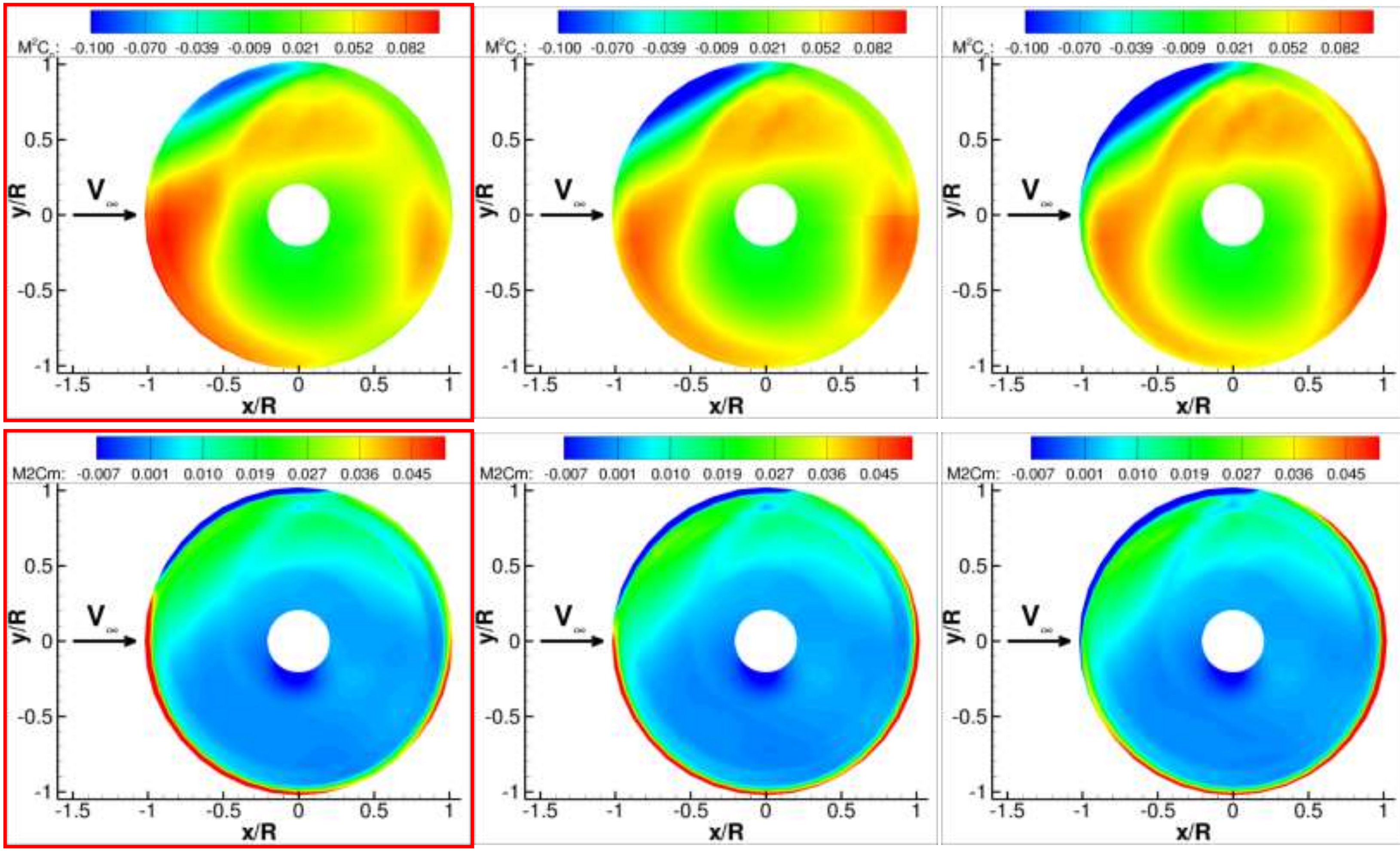
(Mean part removed)

Variation of Tip Anhedral

Sweep maintained at 20 degrees

M^2C_n

M^2C_m

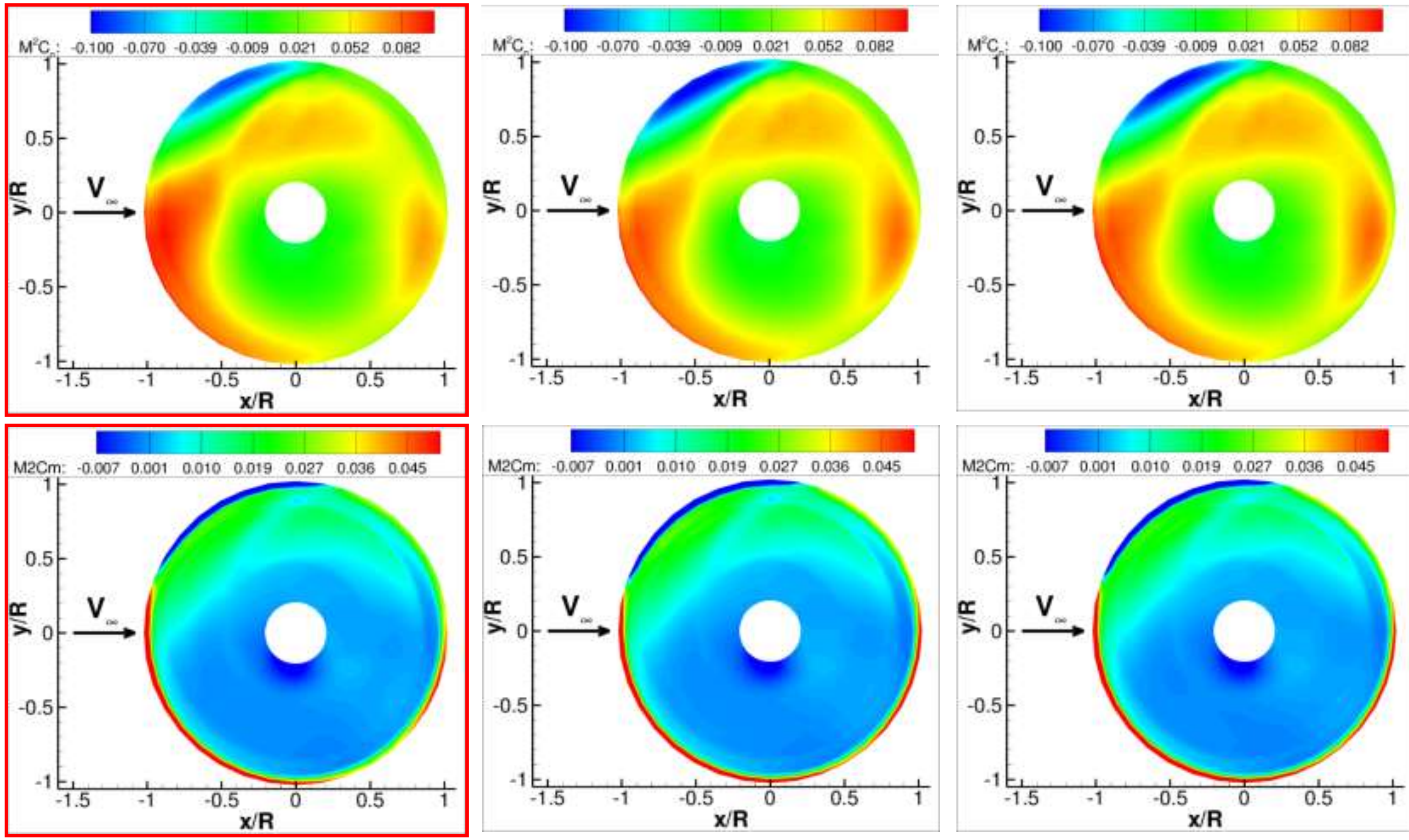


Anhedral = 0 deg   Anhedral = 5 deg   Anhedral = 15 deg

Original rotor in red border

Variation of Tip Sweep

Anhedral maintained at 0 degrees



M^2C_n

M^2C_m

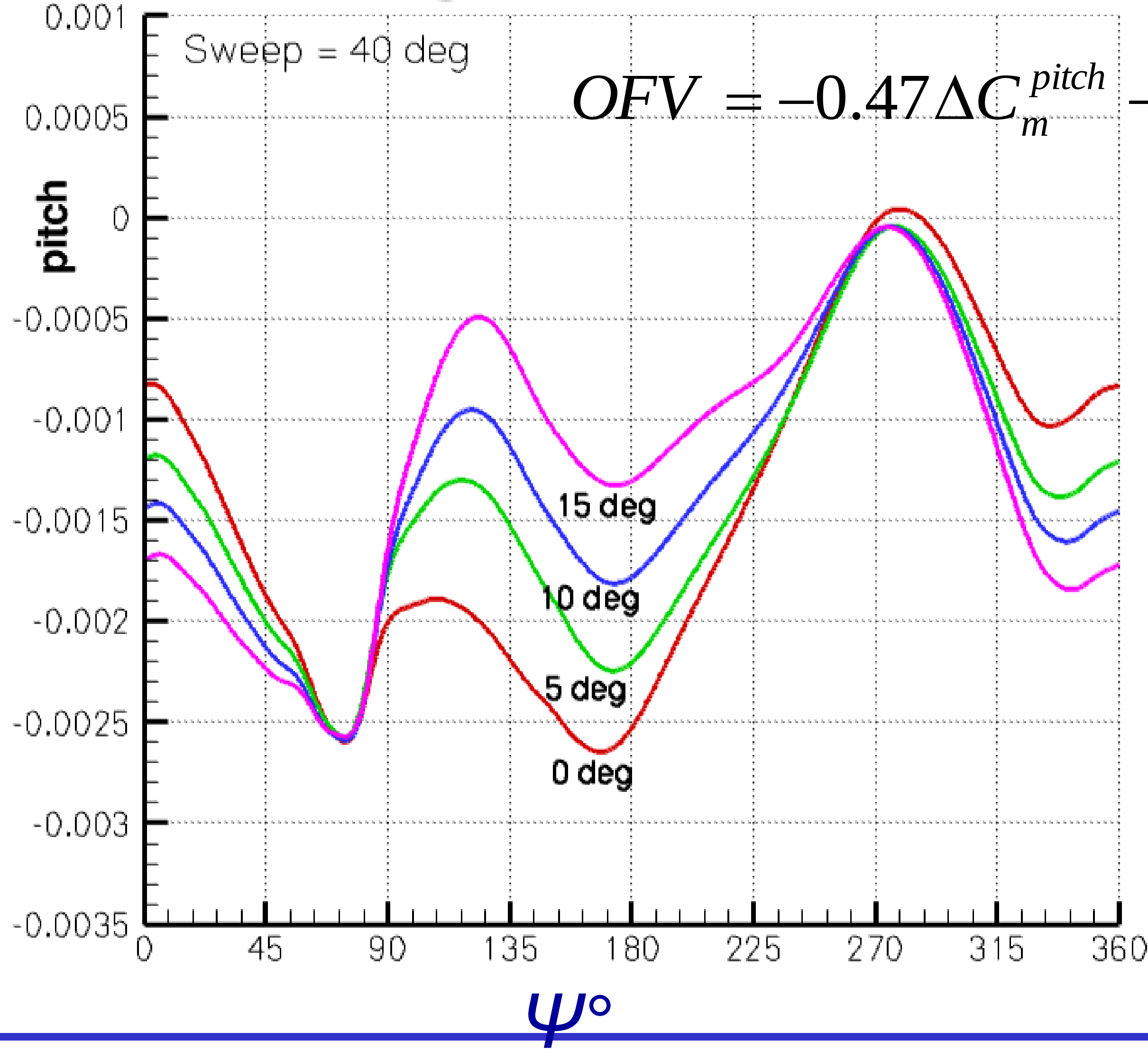
Sweep = 20 deg | *Sweep = 30 deg* | *Sweep = 40 deg*

Original rotor has red border

NOTE: For all cases, the maximum variation in C_T and C_Q < 5%

Case 5 - UH60 Forward Flight – Effects of anhedral and sweep

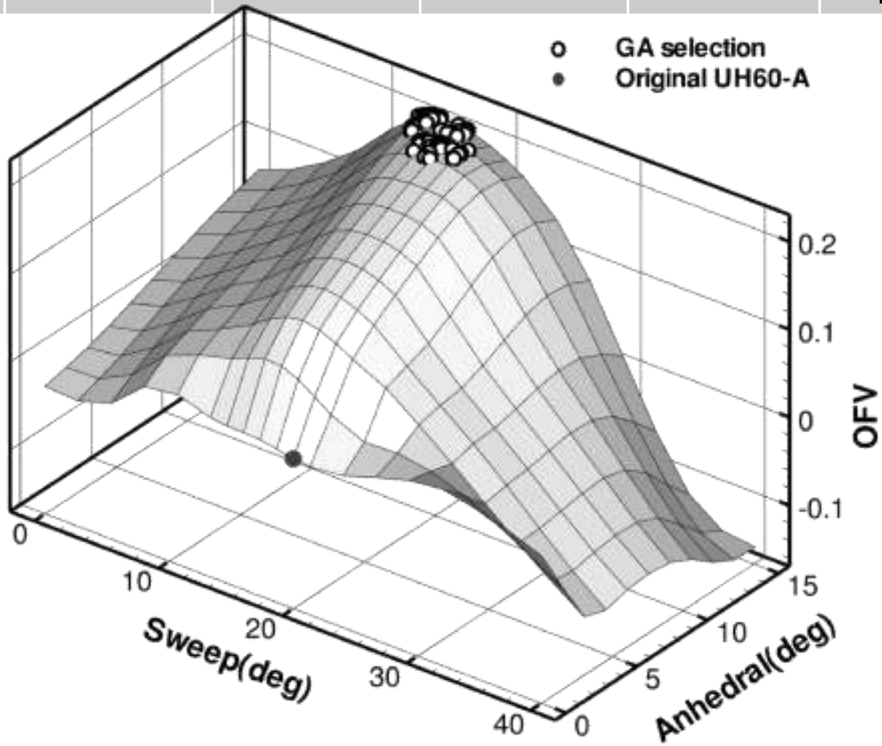
$$OFV = -0.47\Delta C_m^{pitch} - 0.53C_m^{pitch} + 1$$



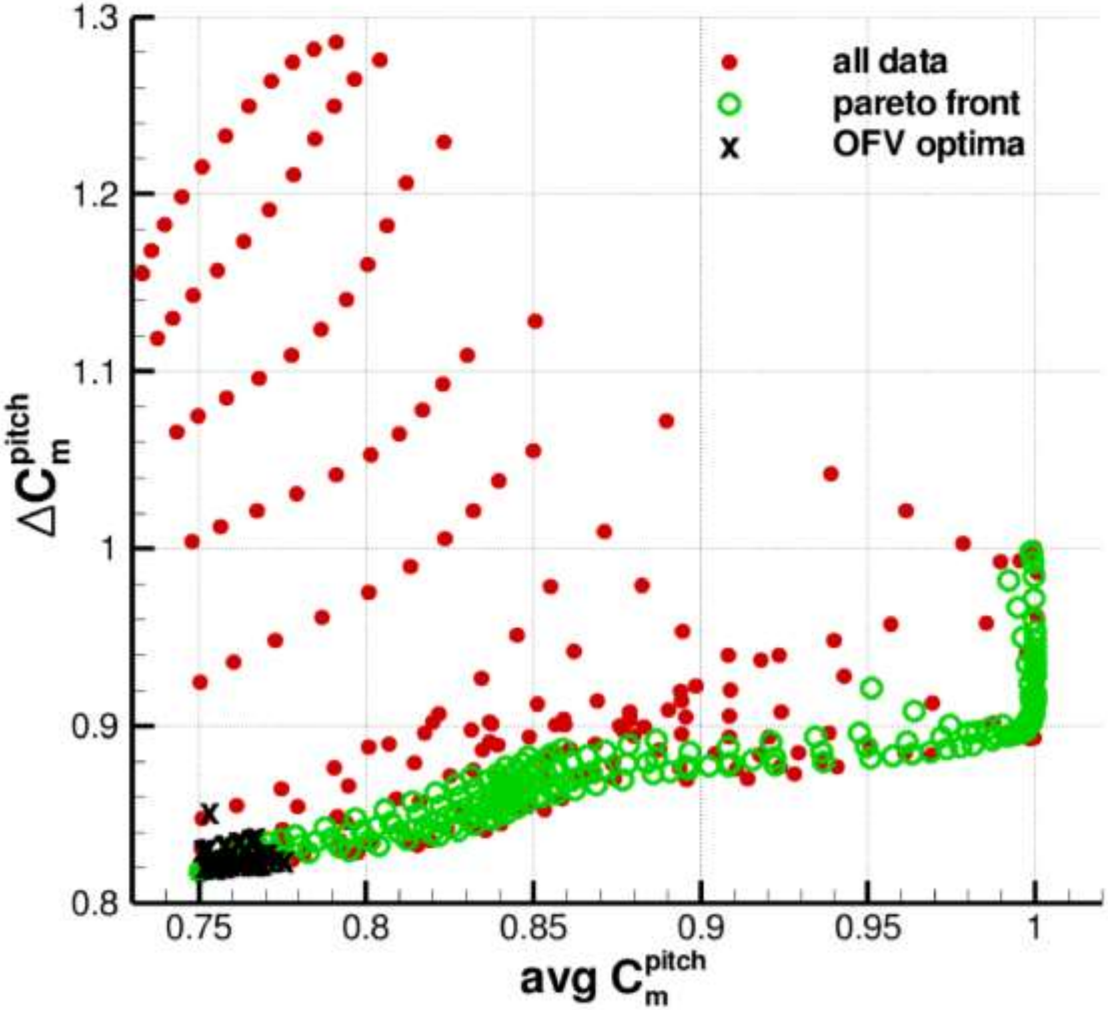
Case 5 - UH60 Forward Flight - Optimum

Sweep	Anhedral	Avg Cm	ΔCm	Cm-vib	CQ	OFV	Remark
20	0	1.000	1.000	1.000	1.000	0.000	Original
20	15	0.748	0.815	1.124	0.906	0.183	Optimum 1
16.7	13.7	0.759	0.824	1.052	0.933	0.209	Optimum 2

NOTE:
All training values are scaled values with the original rotor: Sweep 20, anhedral 0.

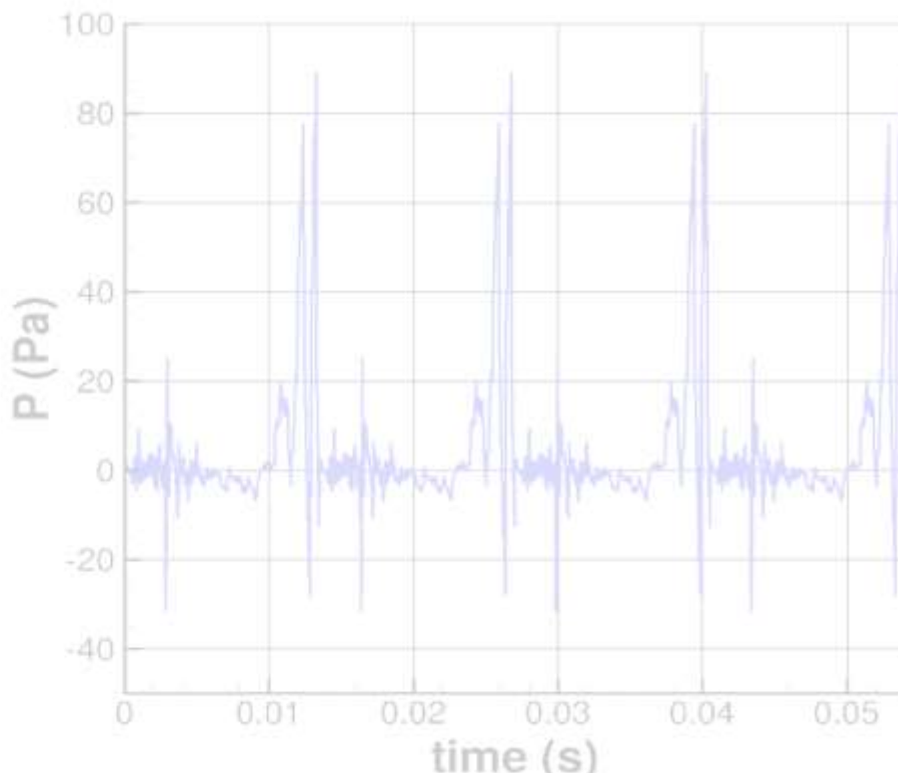


Case 5 - UH60 Forward Flight – Pareto comparison



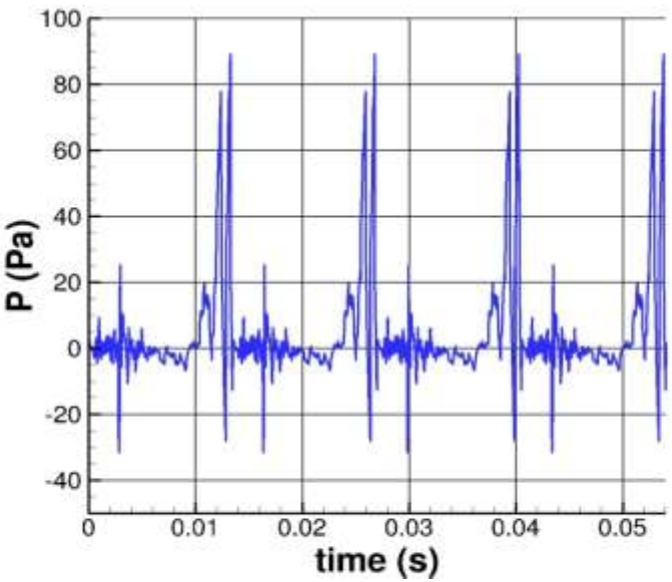
NOTE: All training values are scaled values with the original rotor: Sweep 20, anhedral 0.

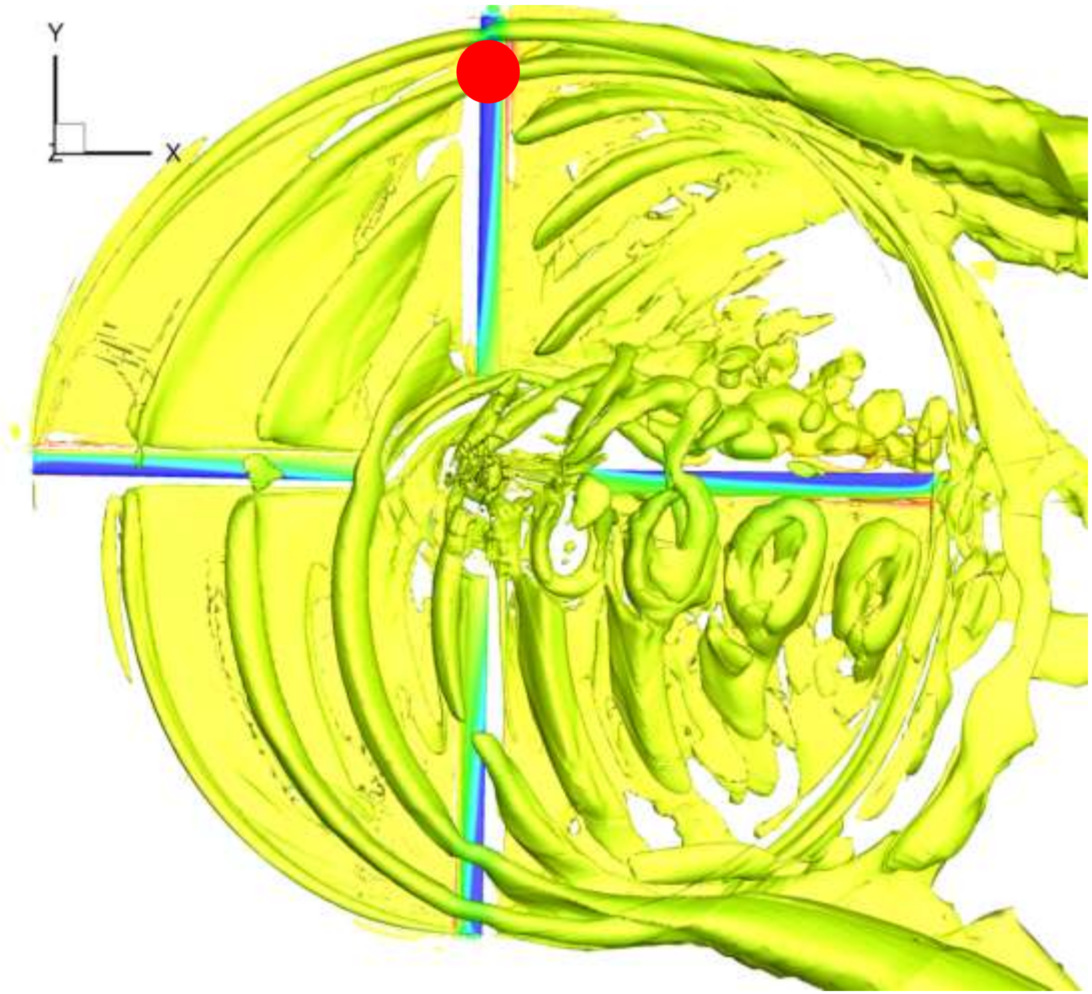
Acoustics



HART-II Rotor in Forward Flight

Isosurfaces of λ_2 criterion





Sound field computed for full-size rotor

Find the real recording!

Simulated flight of a Lynx-size aircraft

Summary & Outlook

CFD for Helicopter Configurations – Summary

- Realistic predictions are possible with current methods and computers.
  - Experiments are now available for validation of the methods.
- High fidelity predictions require attention to many effects (conditions, shape, blade dynamics, trimming, turbulence modelling)
  - Still in the RANS/URANS framework
  - Transition to turbulence
  - DES, simulation of turbulence
- There are also other questions to ask:
  - Do we learn enough from these CFD calculations and how fast can we compute?
  - How can CFD be used in industrial practice?
  - HPC and Frequency Domain methods present an opportunity!
- Need for a low cost facility for rotor testing
  - To support research with data and rapid assessment of ideas

Further Reading

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- A. Spentzos, G.N. Barakos, K. Badcock and B. Richards, Modelling three-dimensional dynamic stall of helicopter blades using computational fluid dynamics and neural networks, Proc. IMechE Vol 220 Part G: J. Aerospace Engineering, pp. 605-618,2006, DOI: 10.1243 / 09544100 JAERO101.

- R. Steijl, G.N. Barakos and K. Badcock, A Framework for CFD Analysis of Helicopter Rotors in Hover and Forward Flight, Int. Journal of Numerical Methods in Fluids, 51, 819-847, 2006, DOI 10.1002/fld.1086.

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- Steijl, R., Barakos, G. and Badcock, K. " A CFD study of advancing side aerodynamics", accepted for publication, AIAA J. Aircraft, September 2007.

Further Reading

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- Woodgate, M. and Barakos, G, Implicit CFD Methods for Fast Analysis of Rotor Flows, AIAA Journal, Vol. 50, Issue 6, pp. 1217-1244, 2012.
- Johnson, C., Woodgate, M. and Barakos, G. ,Optimising Aspects of a BERP-like Rotor using Frequency-Domain Methods, 51st Aerospace Sciences Meeting, Special session on Rotorcraft Computational Methods, 7-10 January 2013,
- Woodgate M., and Barakos, G., Implicit CFD Methods for Fast Analysis of Rotor Flows, Paper No AIAA-2012-421 , 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, Jan. 9-12, 2012.
- Johnson C. , and Barakos, G., Development of a Framework for Optimising Aspects of Helicopter Aerodynamics Paper 93, proceedings of the 37th European Rotorcraft Forum, September 13-15, 2011, MAGA Gallarate (VA) Italy
- Woodgate M. and Barakos, G., Harmonic Balance Solutions for Realistic Rotor Configurations Paper 97, proceedings of the 37th European Rotorcraft Forum, September 13-15, 2011, MAGA Gallarate (VA) Italy.
- Johnson C., and Barakos, G., Development of a Framework for Optimising Rotor Blade Designs, 46th Symposium of Applied Aerodynamics - Aerodynamics of rotating bodies, Orleans, France, March 28-30, 2011, proceedings by 3AF.
- Johnson C., and Barakos, G., Optimising Aspects of Rotor Blades in Forward Flight, AIAA Paper 2011-1194, 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, USA, 4-7 January 2011.


Thank you very much for attending!
Happy to take on any questions you may have.
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