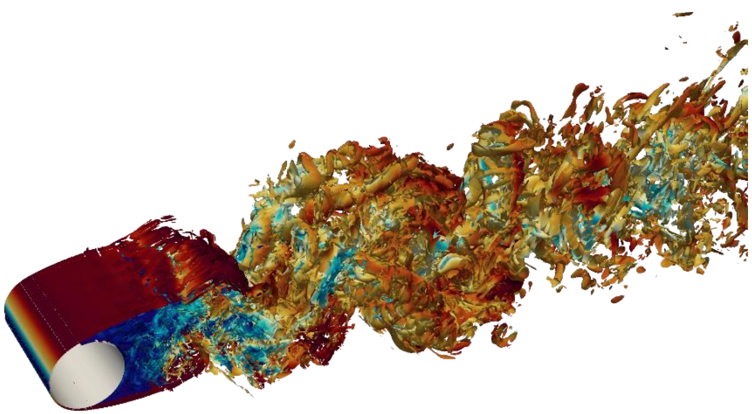
Summary and conclusions of the 4th International Workshop on High Order CFD Methods (11177)

MS910 – 4th Intl. Workshop on High Order CFD Methods
ECCOMAS, Creta, June 9th 2016



K. Hillewaert (Cenaero) in collaboration with
R. Hartmann & T. Leicht (DLR), V. Couaillier (Onera)
ZJ Wang (Ukansas), JS Cagnone (Cenaero)
Contact: koen.hillewaert@cenaero.be

Doc. ref.: CMSD-NS-0XX-00

Organisation

- **Rationale**
  - *"an open and impartial forum for evaluating the status of high-order methods for solving a wide range of flow problems in aeronautics;*
  - *to assess the performance of high-order methods through comparison to production CFD codes well defined metrics;*
  - *to identify pacing items for industrial / large scale deployment."*

- ***ECCOMAS CFD 4-5 june 2016, FORTH Heraklion***
  - *how4.cenaero.be / info@hiocfd4.cenaero.be*

- **Previous editions**
  - *May 27 - 28, 2013, Cologne (Germany)*
  - *AIAA SciTech 2016, Kissimee (FL), 3-4 January 2016*
  - *Z.-J. Wang et al. IJNMF 72(8):811-845, 2013.*

- **Next edition :** AIAA Aerospace Sciences Meeting (Jan 2018)

Basic motivation: push HiOCFD methods forward
Reorganisation in function of aim rather than complexity

- ***Baseline test cases*** **: help the development of new methods and codes**
  - ***Verification / sanity check***
  - ***Stringent convergence criteria with reference solutions***
  - ***Very simple set up / provision of meshes***
  - ***Still challenging cases due to stringent convergence criteria !***
  - ***Permanent database and support by test case leaders***
- ***Advanced test cases: gauge performance of state of the art HiOCFD***
  - ***Challenging cases in terms of (grid) convergence***
  - ***Setup fully mastered: good meshes are available, conditions well defined***
  - ***Competition with***
    - *Standard CFD codes*
    - *Amongst high order methods*
- ***Complex cases: test the full computational chain***
  - ***mesh generation – solver – post-processing***
  - ***Comparable to state of the art in CFD in general***

Baseline test cases

- BI1 – inviscid vortex transport
- Bi2 – Inviscid flow over a bump
- BI3 – Inviscid bow shock

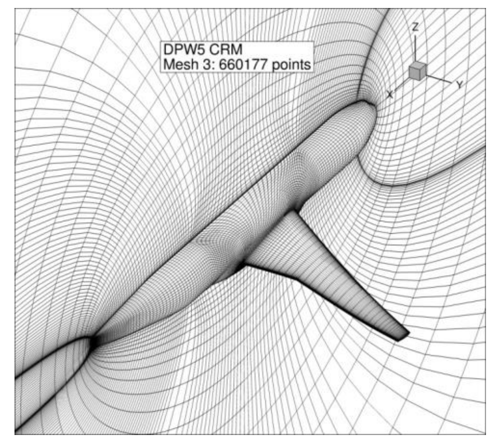
- BL1 – Laminar Joukowski Airfoil Re=1000
- BL2 – Laminar shock wave boundary layer interaction
- BL3 – Pitching and Heaving airfoil

- BR1 – RANS Joukowski airfoil Re=1000000

- BS1 – DNS of Taylor-Green vortex Re=1600
- BS2 – LES of the channel flow Re_tau=590

AR1 – RANS of the CRM wing body
Ralf Hartmann / DLR

- **wing-body configuration**
- **cruise conditions (transonic)**
- **References**
  - **experimental data**
  - **AIAA Drag Prediction Workshops 4 and 5 (55 contributions from 22 groups in DPW-5)**



- **References**
  - **http://commonresearchmodel.larc.nasa.gov**
  - **http://aaac.larc.nasa.gov/tsab/cfdlarc/aiaa-dpw**

(http://aaac.larc.nasa.gov/tsab/cfdlarc/aiaa-dpw/Workshop5/presentations/DPW5_Presentation_Files/14_DPW5%20Summary-Draft_V7.pdf

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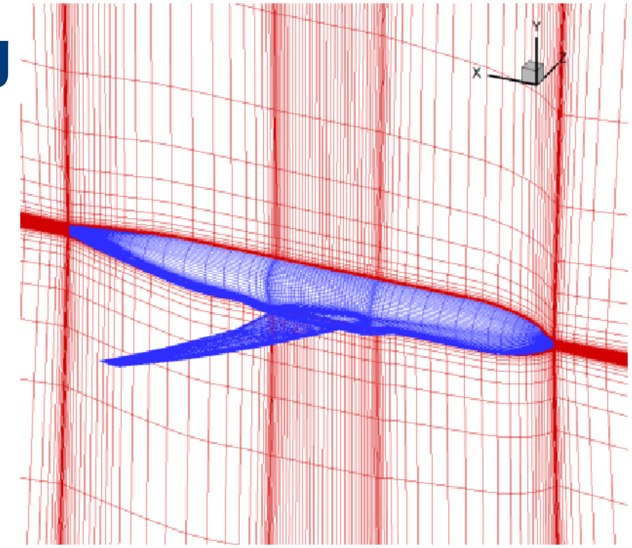
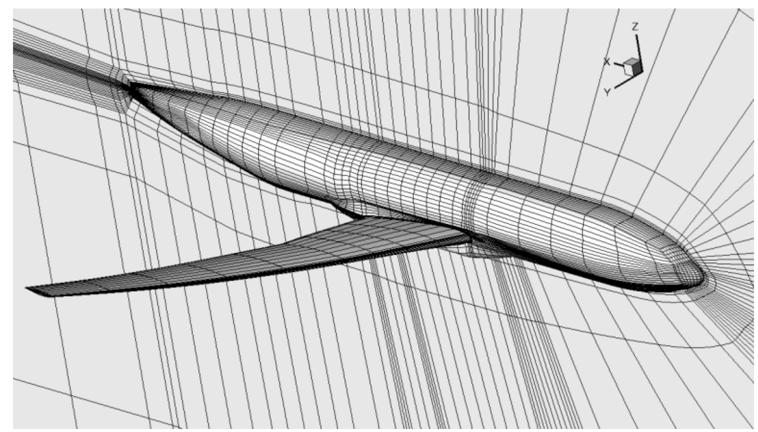
AR1 – RANS of the CRM wing body
Contributions

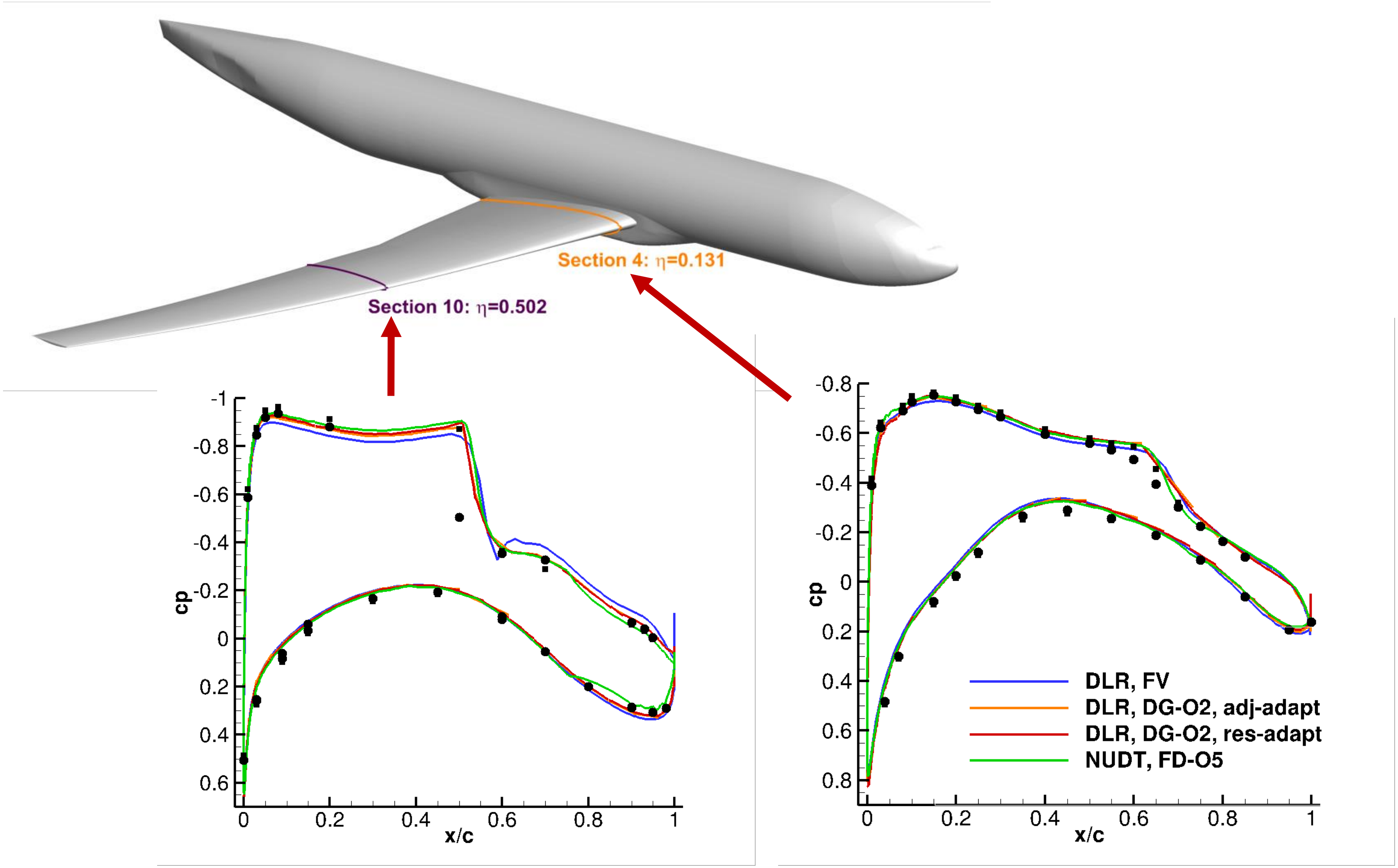
- **S. Wang, Y. Chen, G. Wang, W. Liu, X. Deng**
  NUDT & Sun Yat-sen University, China
  - **FD, 5th-order (WCNS-E5),**
  - **Menter-SST**
  - **on grid family of own ijk-meshes**



- **R. Hartmann DLR**
  - **DG, p=1 (2nd-order),**
  - **Wilcox-kω**
  - **mesh adaptive results driven by**
    - residual indicators
    - adjoint-based indicators for lift
  - **starting from the HioCFD mesh of University of Michigan**



AR1 – RANS of the CRM wing body
Cp distributions



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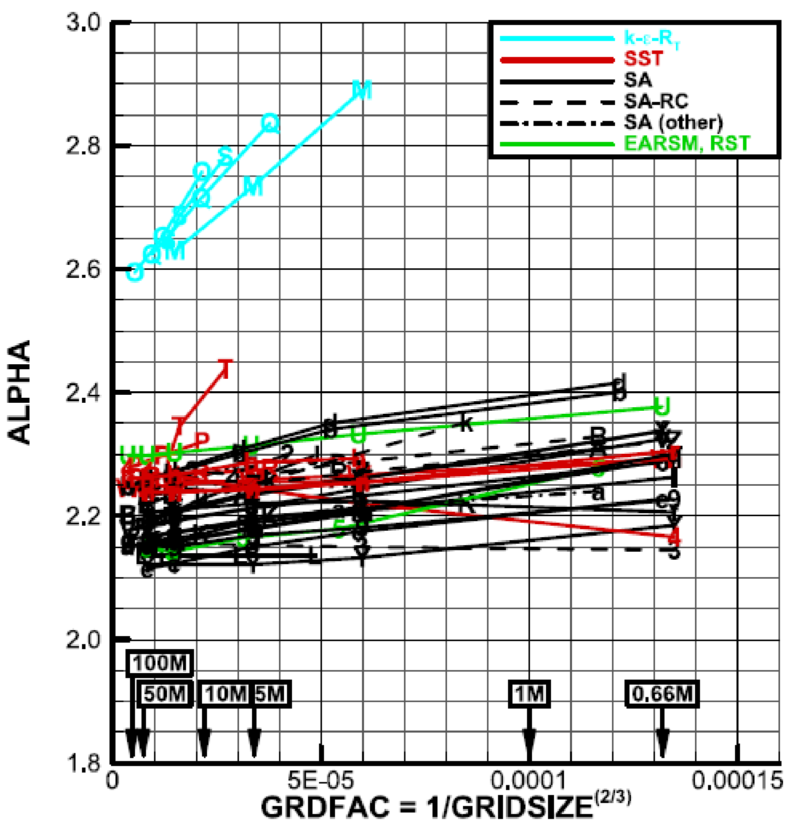
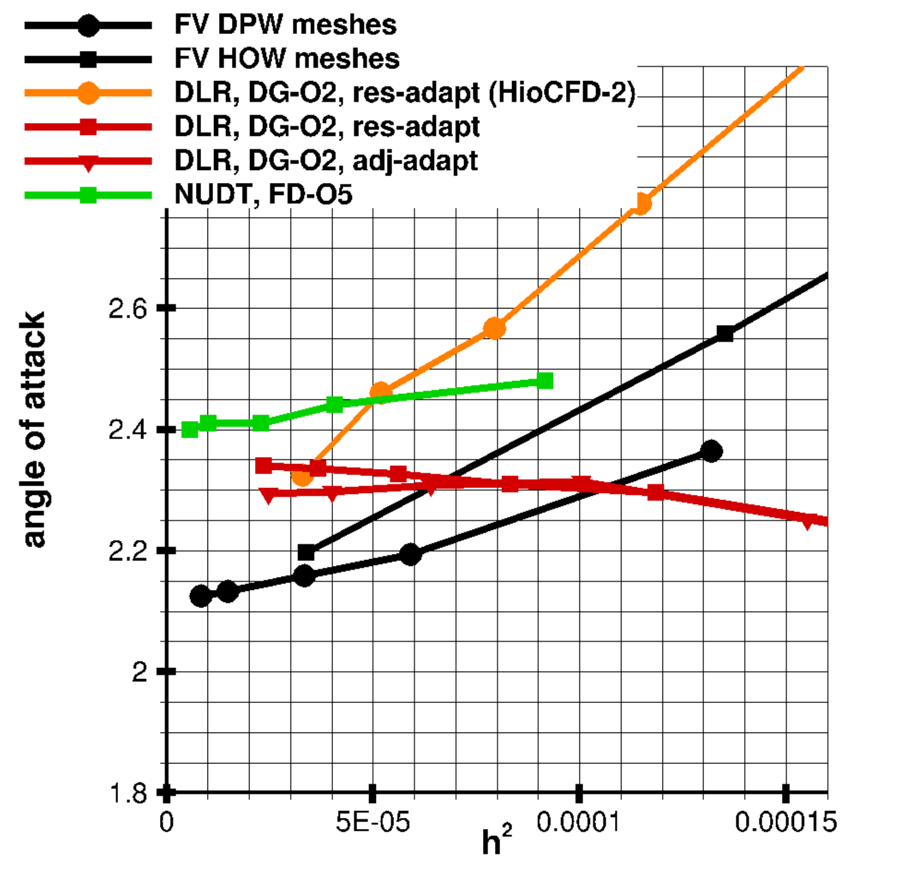
AR1 – RANS of the CRM wing body
Trim angle convergence





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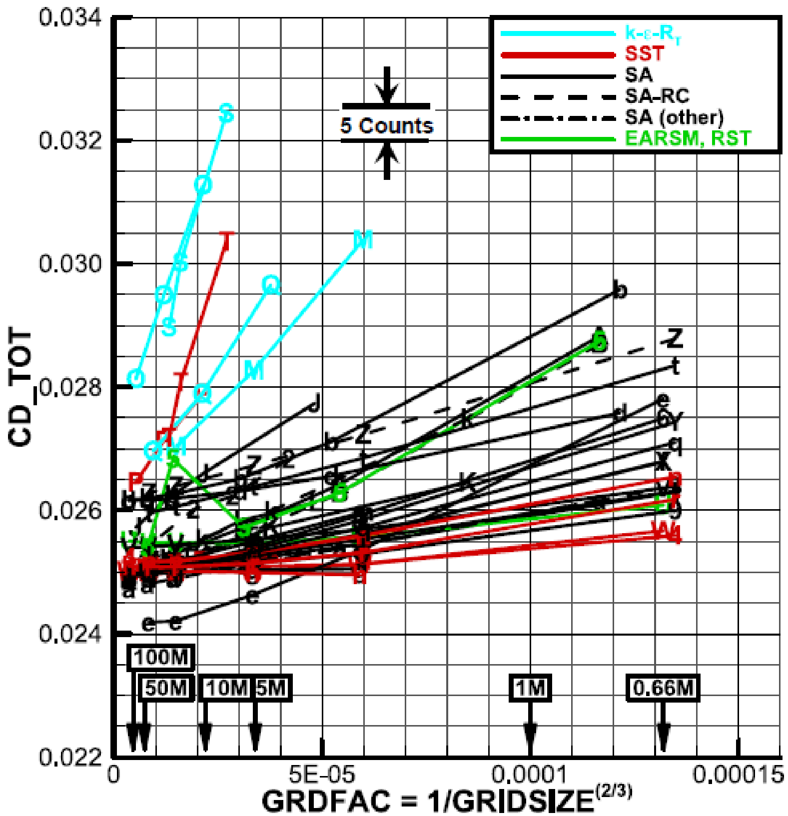
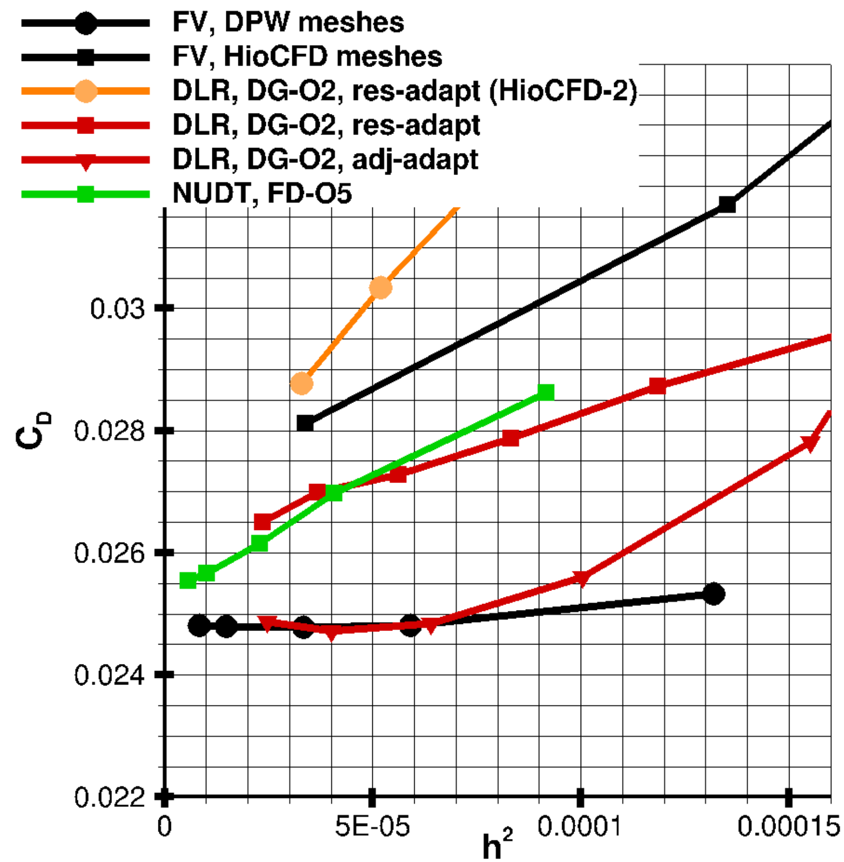
AR1 – RANS of the CRM wing body

Drag convergence





Reference finite volume computations

- DPW mesh results shows surprisingly little variation
  - mainly an effect of underlying mesh sequence.
  - error cancellation for pressure and friction drag (HioCFD-3).

Comparison on HiOCFD meshes:

- Much higher error for FV
- DG with res-adapt and adj-adapt outperformes FV on mesh sequence
- DG with adj-adapt more effective than with res-adapt.

NUDT:

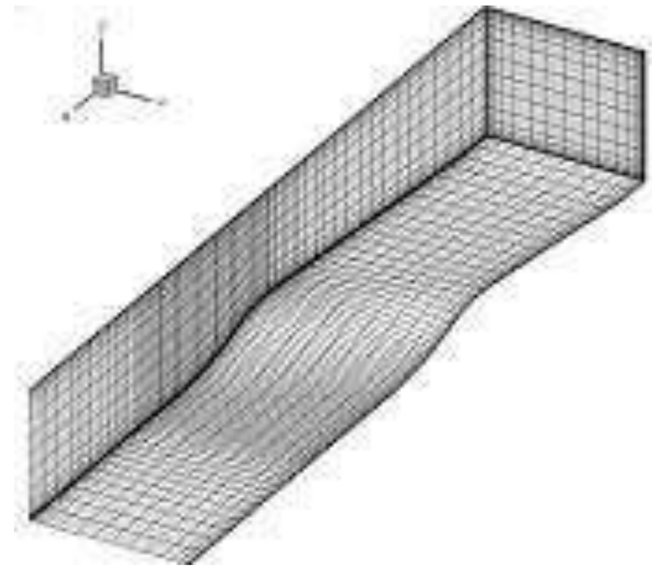
- FD-O5 in range of expectation with C_M and alpha slightly too high.
- Hard to compare since other mesh sequence used

Importance of mesh sequence when comparing !

AR2 – supersonic bump

V. Couaillier and F. Renac (Onera)

- **3D shock wave / turbulent boundary layer using RANS**
  - BL interactions taking place with 4 walls
  - several separations



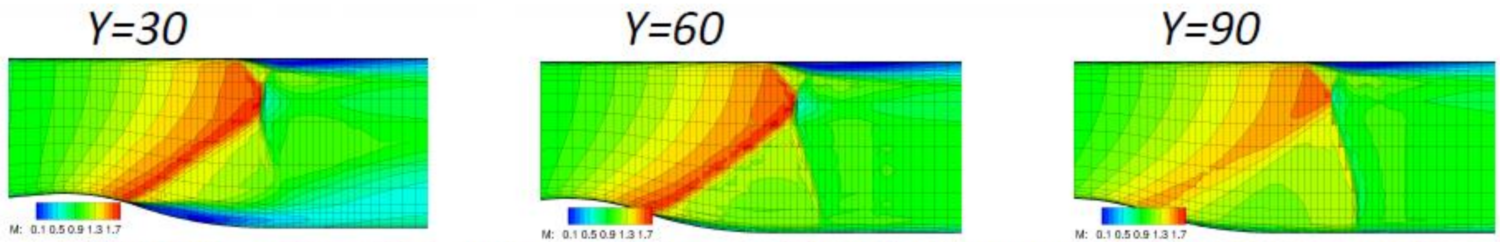
- **Reference**
  - Experiments at Onera by Délery team
  - FV computations with RANS/2 eq.turbulence
- **Quantities of interest**
  - static pressure distribution on the walls
  - turbulent kinetic energy profiles
  - mean stream-wise velocity profiles in longitudinal planes.
- **Governing equations**
  - Sutherland law
  - RANS - turbulence model open (SA, Wilcox k-ω, k-ω SST)

AR2 – supersonic bump
Participants

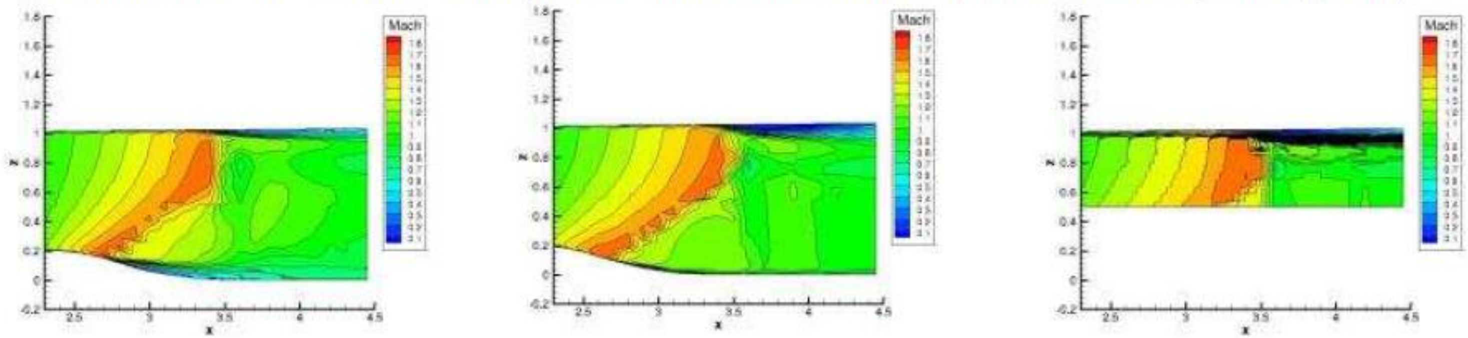
- Aghora solver : Discontinuous Galerkin method
  - Modal/Cartesian DGM with LLF and BR2
  - Shock capturing technique based on entropy production
  - Quadratic meshes 72,950 nodes with flow separation (before separation for p=2) and 540,000 nodes
  - SA model

- University of Bergamo / Migale
  - DGM (p=2)
  - k-ω and XLES

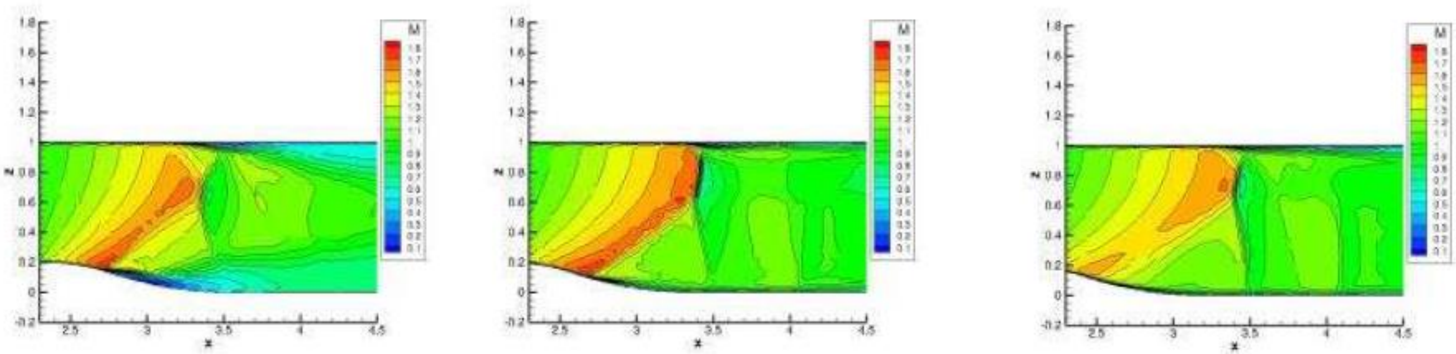
AR2 – supersonic bump
Comparison of flow fields



MIGALE results with Low Reynolds kω model with P2 approximation (U. Bergamo)



Experimental result (ONERA)



Aghora results with S.A. model with P3 approximation (ONERA)

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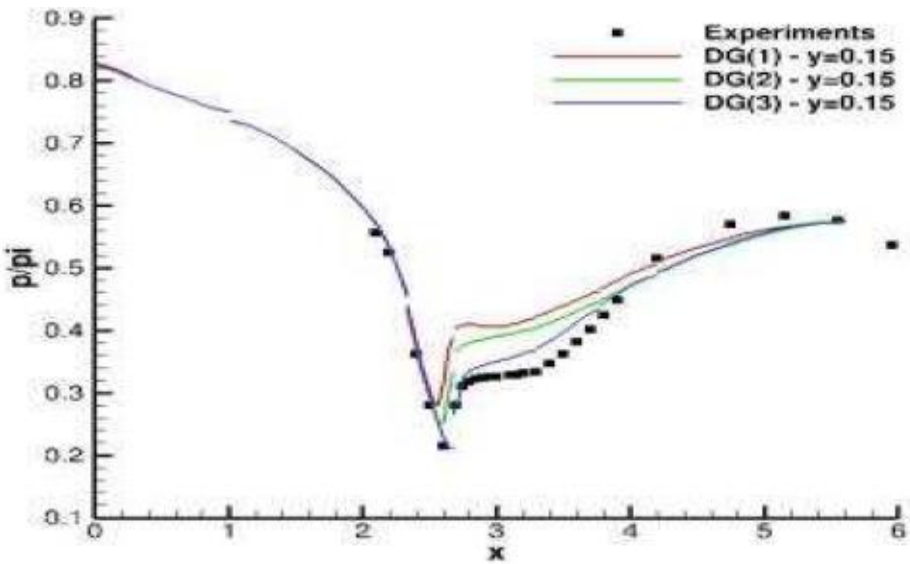
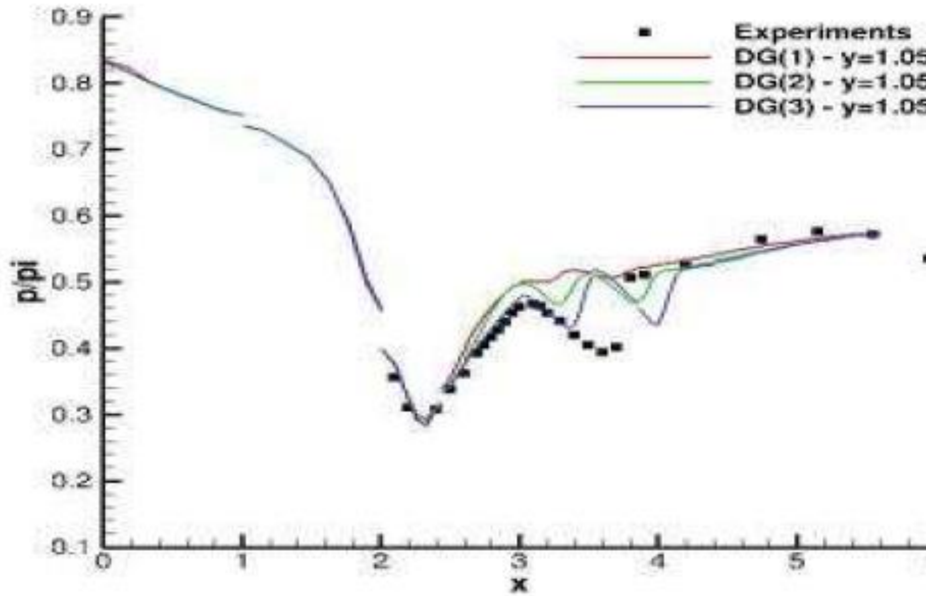
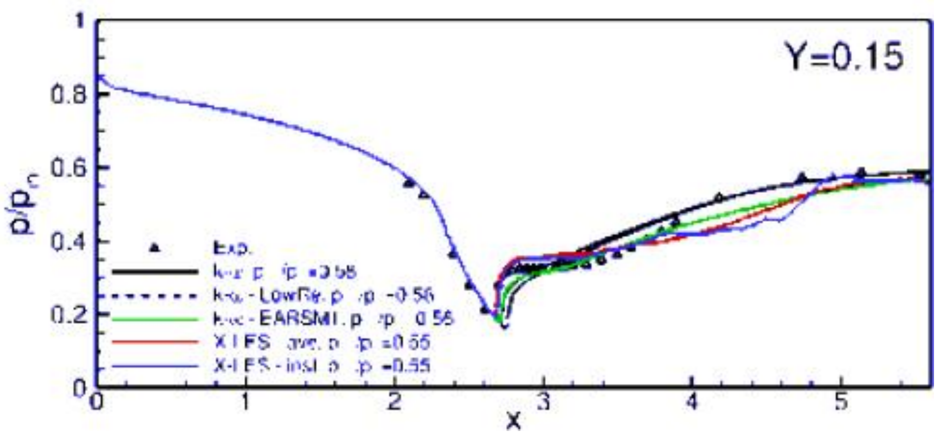
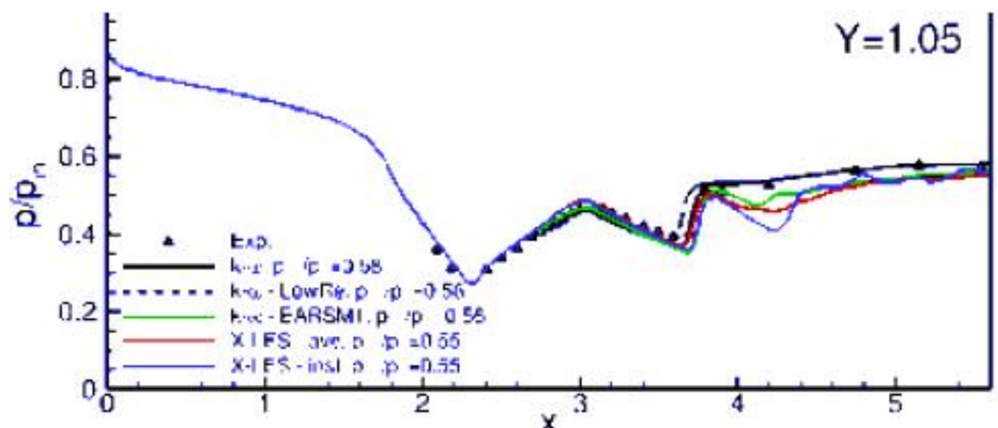
AR2 – supersonic bump
Pressure distribution cuts









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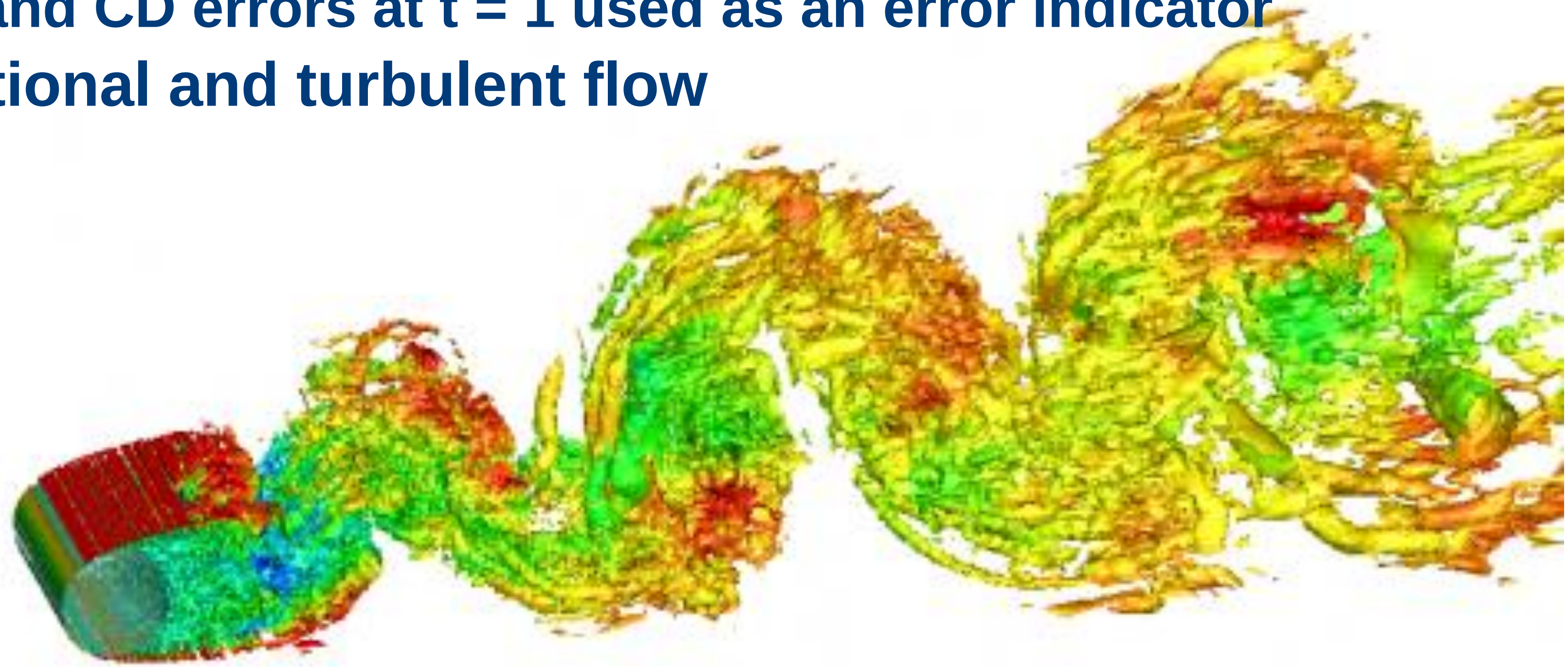
AR2 – supersonic bump
Concluding remarks

- Assessment
  - Demonstration of convergence
  - Extremely difficult case
- Current case could be improved
  - Difficulty to tune exit conditions to get shock location
  - Solution is highly dependent on turbulence model
  - Comparison to profiles and flow fields is more appropriate to judge capture of the physics rather than convergence
- Suggestions
  - Modify the geometry to include a second throat
  - Impose the turbulence model
  - Grid converge the computation to provide the reference
  - Define a quantitative error measure

AS1 – LES of a cylinder at Re=3900

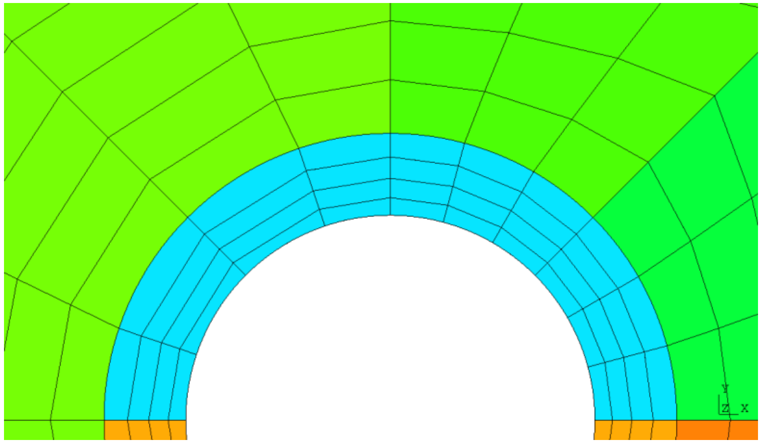
ZJ Wang (Ukansas)

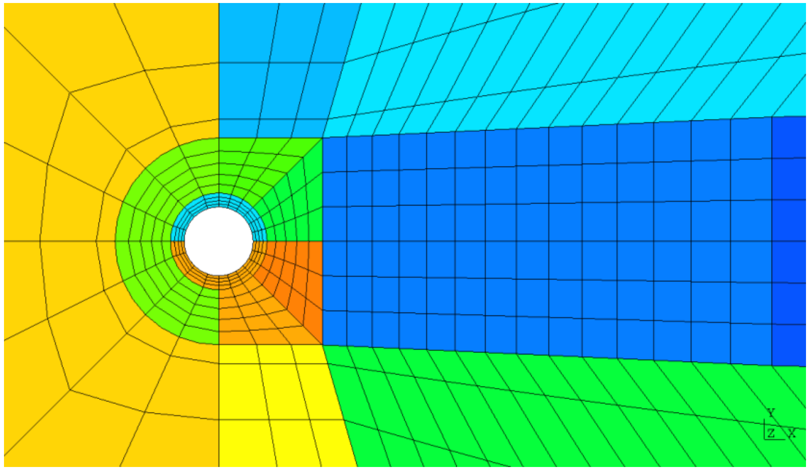
- **Infinitely smooth geometry and initial conditions**
- **Preliminary step**
  - **Non-symmetric initial conditions in the spanwise and circumferential directions so that the path to non-symmetric flow pattern is not due to round-off error**
  - **CL and CD errors at t = 1 used as an error indicator**
- **Transitional and turbulent flow**

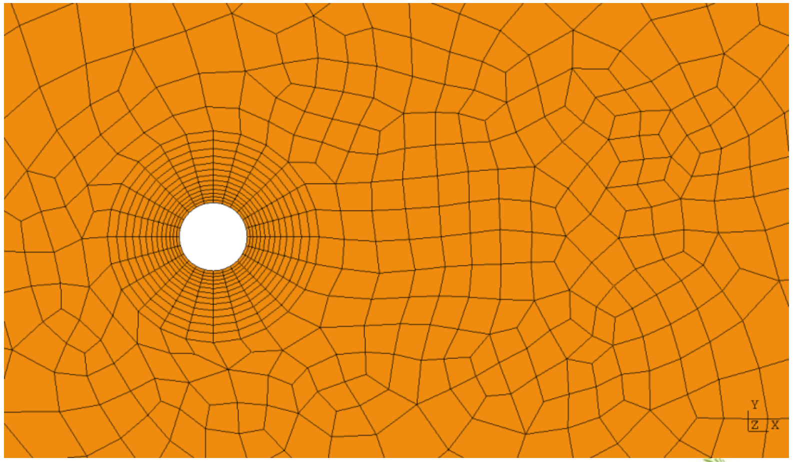


AS1 – LES of a cylinder at Re=3900
Contributions

- **ZJ Wang (UKansas) - SDM**
- **B. Vermeire (ICL) - FR**
- **A. Beck (Ustuttgart) - DGSEM**
- **M. Rasquin (Cenaero) - DGM**

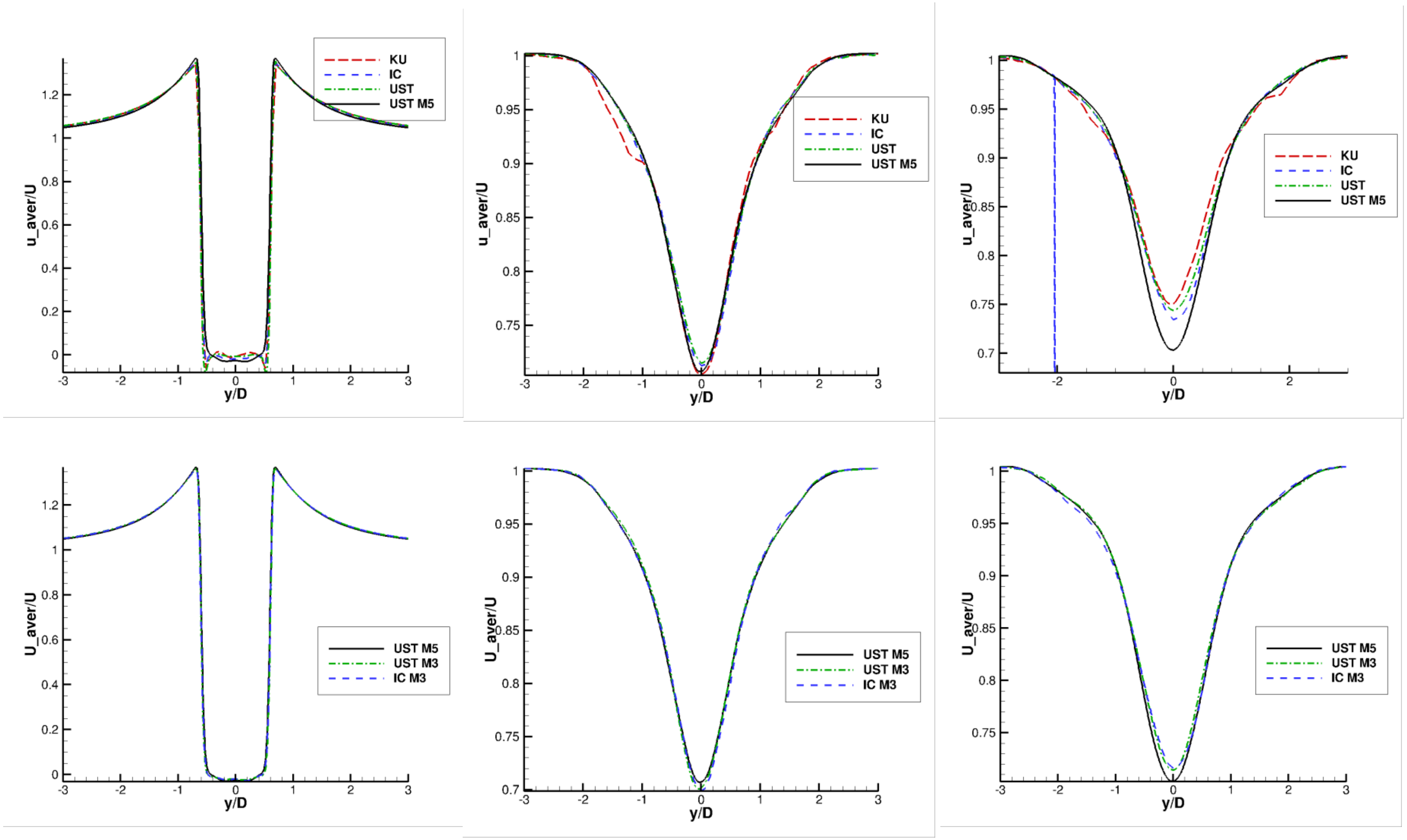






AS1 – LES of a cylinder at Re=3900

Comparison of wake development



X:0.58D

X:6D

X:10D

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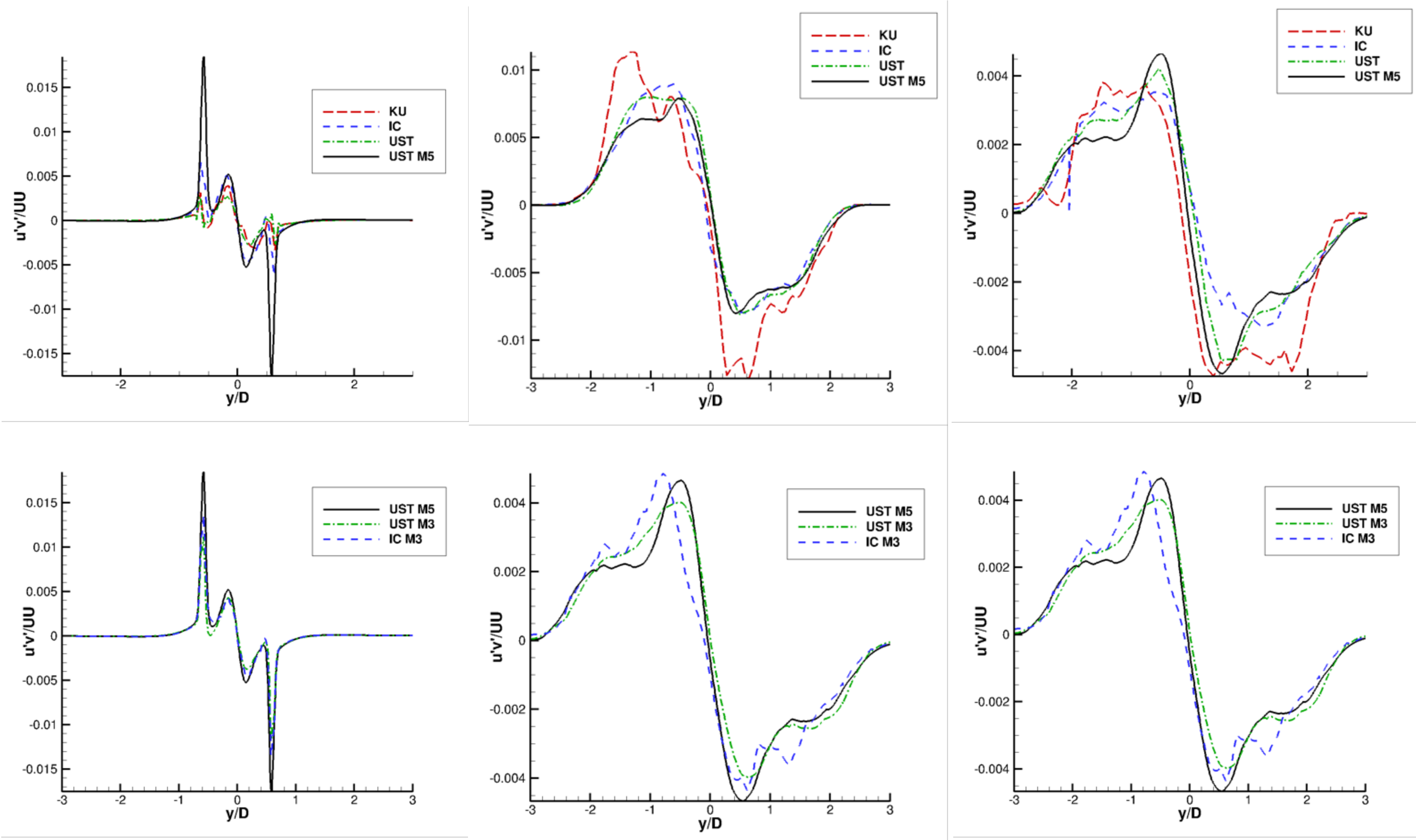
AS1 – LES of a cylinder at Re=3900

Comparison of wake development



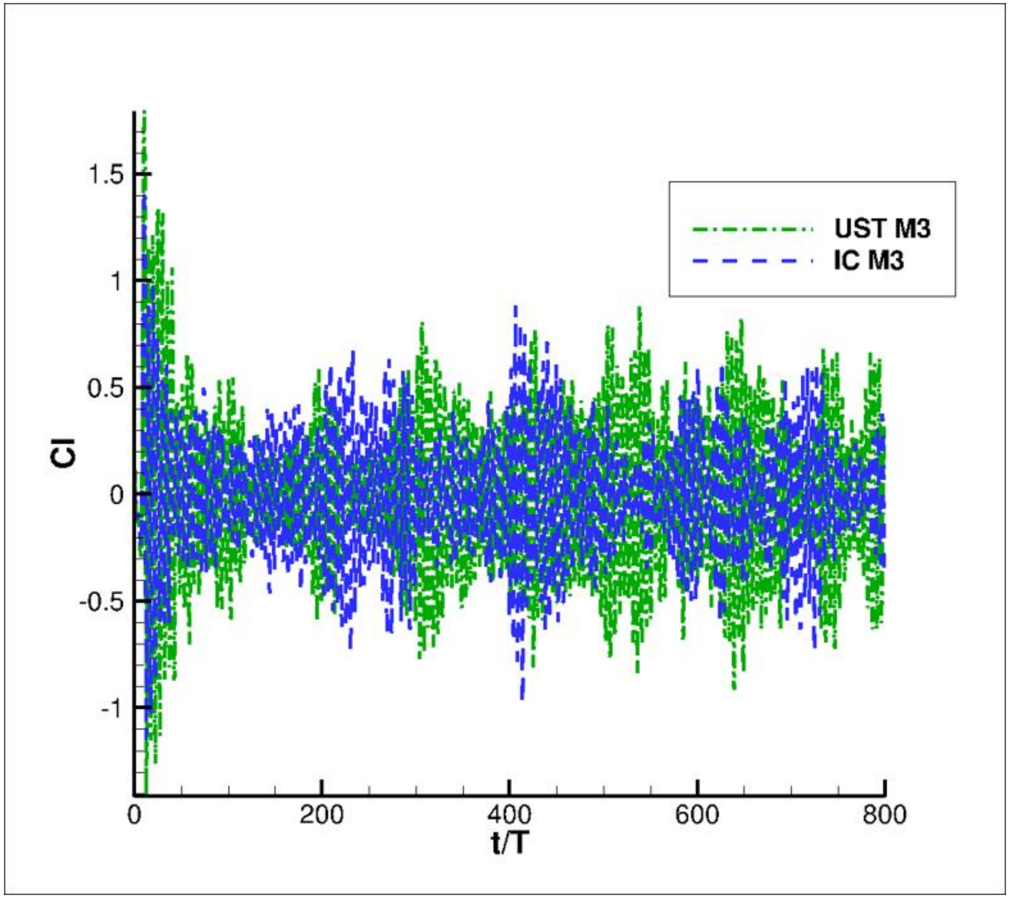
X:0.58D

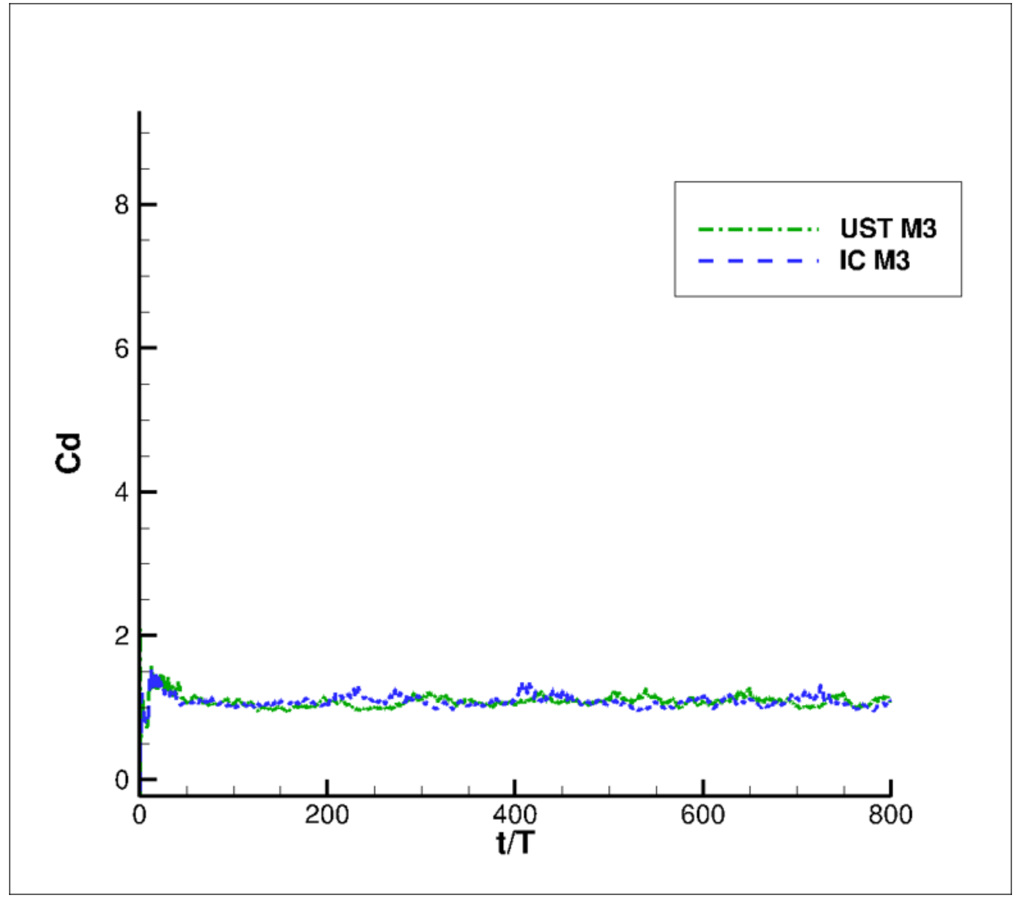
X:6D

X:10D

AS1 – LES of a cylinder at Re=3900

Force evolution in time – low frequency content ?





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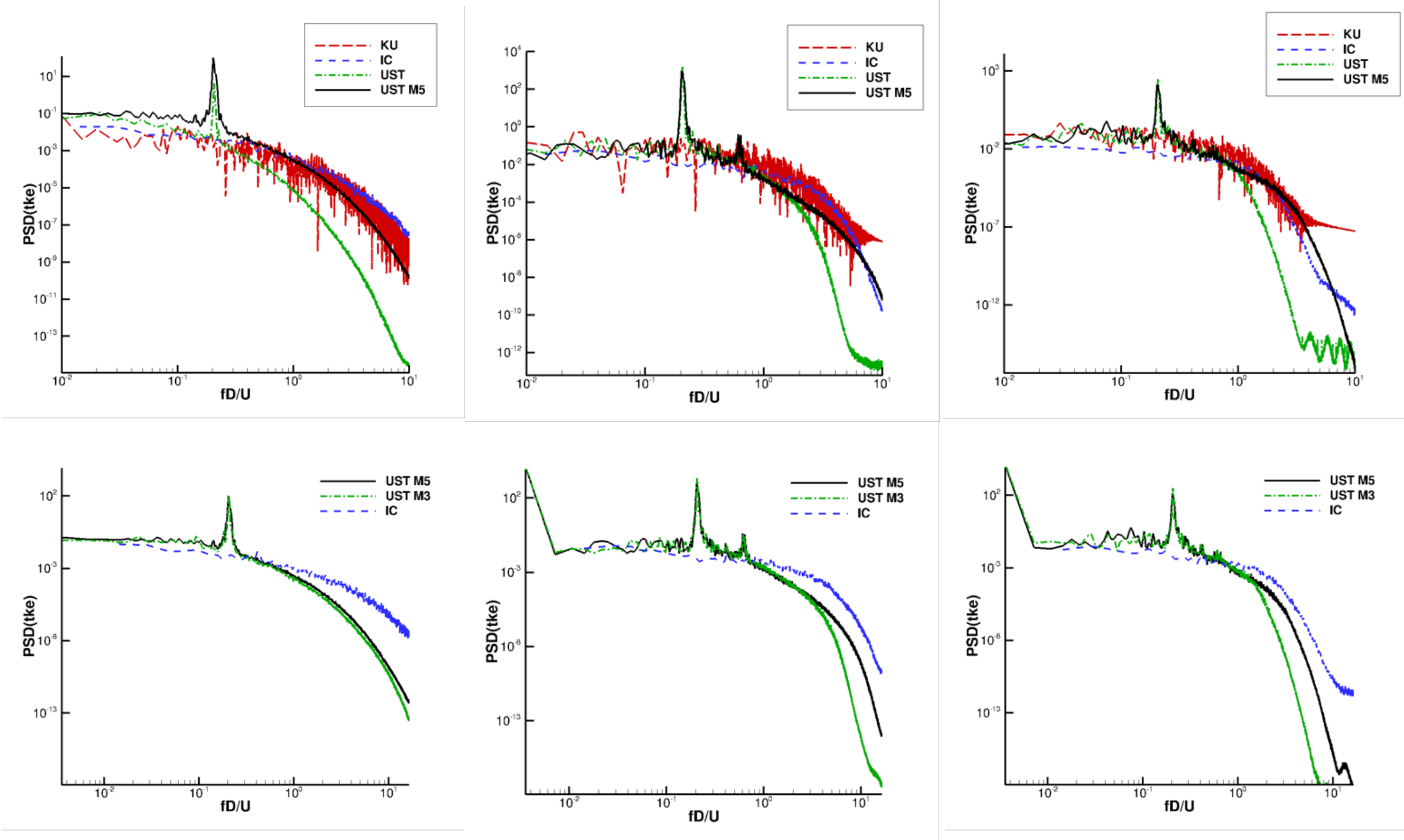
AS1 – LES of a cylinder at Re=3900

Comparison of wake development



X:0.58D

X:6D

X:10D

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AS1 – LES of a cylinder at Re=3900

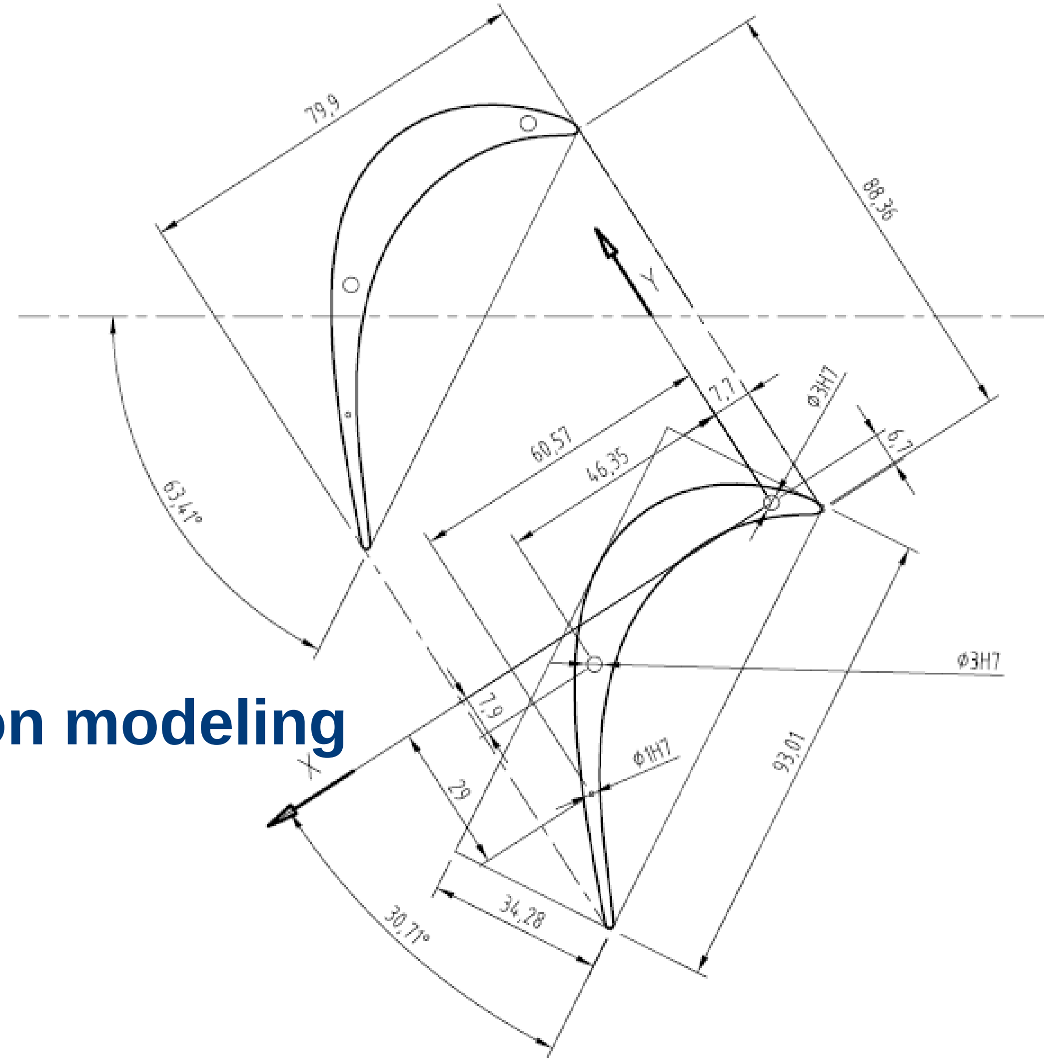
Comparison of wake development

- **Preliminary convergence study Cl, Cd at t=1**
  - **Method/grid converged**
  - **Not directly extendible to turbulent simulations !**
- **Studies on fully turbulent flows**
  - **Decent agreement already obtained for velocity**
  - **Higher order statistics not converged**
  - **block structured mesh can be improved**
- **Improve computational setup**
  - **Clean-up block structured mesh**
  - **statistical processing tools**
    - Clear description of how to compute spectra etc.
    - Include windowing technique
    - Provision of scripts online
  - **span averaging to be imposed ?**

AS2 – DNS and LES of LP Turbine

J.-S. Cagnone (Cenaero)

- **T106C**
  - **Re=80k, M=0.65**
  - **Pitch/Chord = 0.95**
  - **Span/Chord = 10%**
- **T106A**
  - **Re=60K, M=0.4**
  - **Pitch/Chord = 0.798**
  - **span/Chord = 10%**



- **Aim: reference for transition modeling**
  - **Grid convergence**
  - **« Method » convergence**

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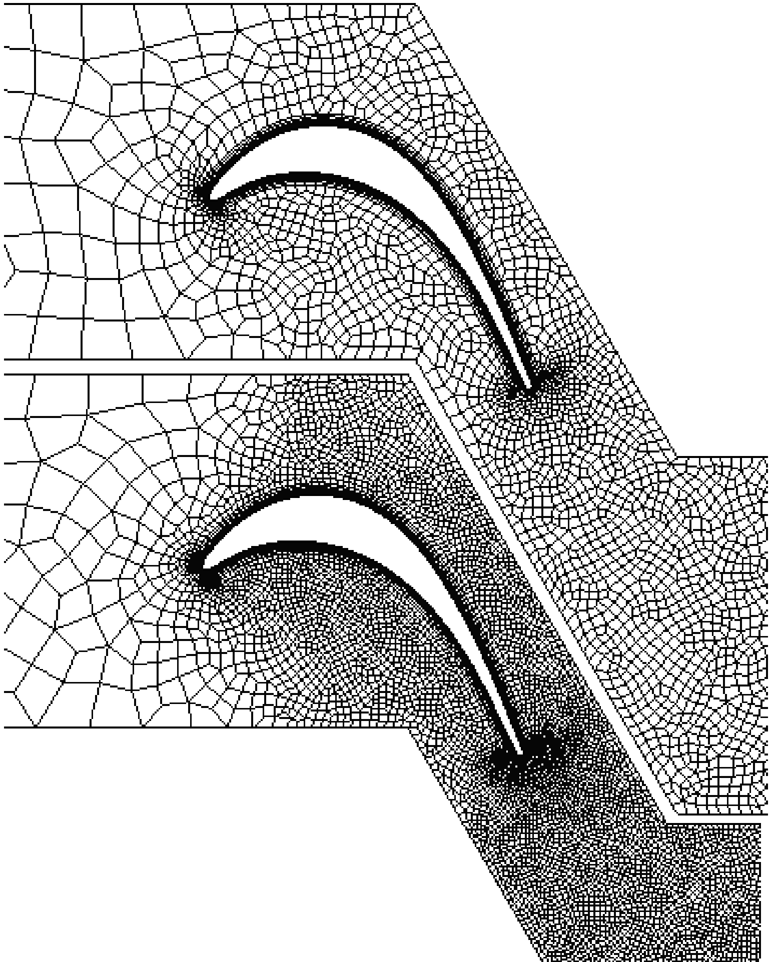
- Onera
  - DGM, LLF, SIP, modal Cartesian, Explicit time integration
  - T106C - Coarse (p=4,5), Baseline (p=3,4,5)
- IAG
  - DGSEM, Roe, BR1, Explicit time integration
  - T106C - Coarse p=6,7 – own meshes
  - T106A – Coarse p=7
- MIT
  - hDG (IEDG), Implicit time integration
  - T106A - Baseline p=2
- Cenaero
  - DGM, Roe, SIP, nodal parametric, Implicit time integration
  - T106A - Coarse p=4,5
  - T106C – Baseline p=4

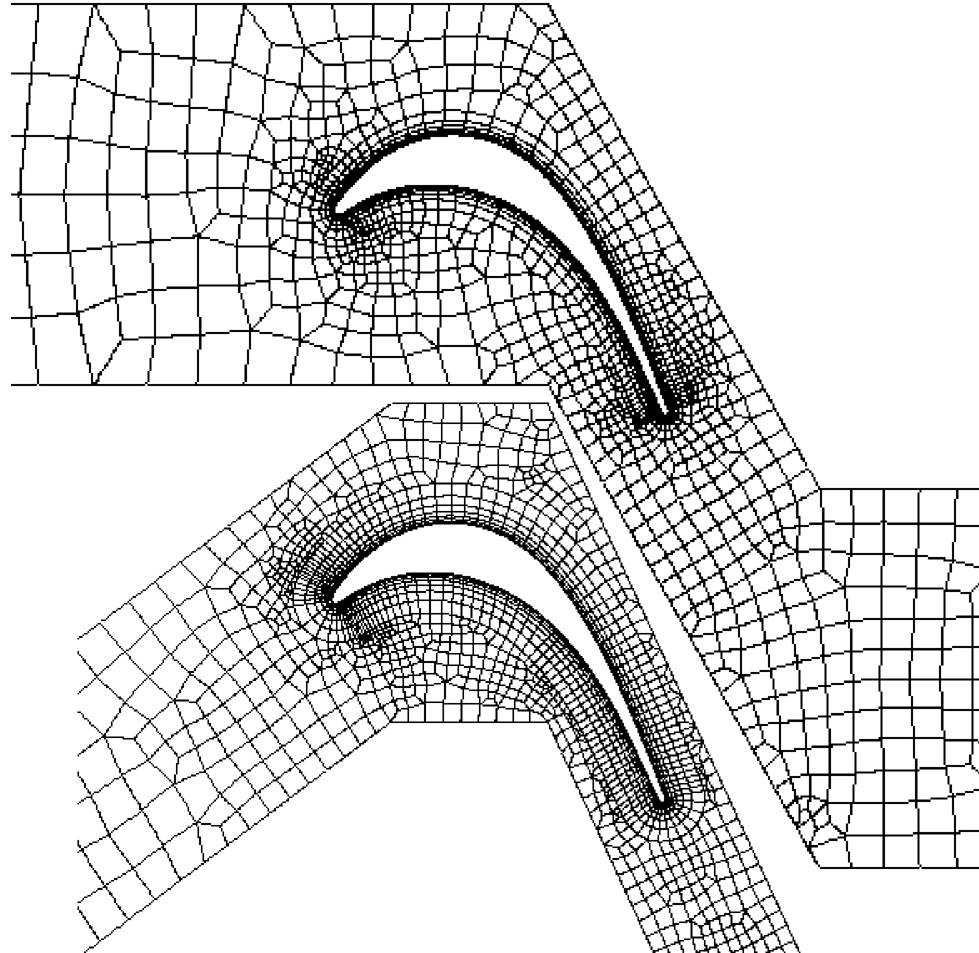
AS2 – DNS and LES of LP Turbine

Mesh configurations



Workshop meshes

Gmsh script tailored to order

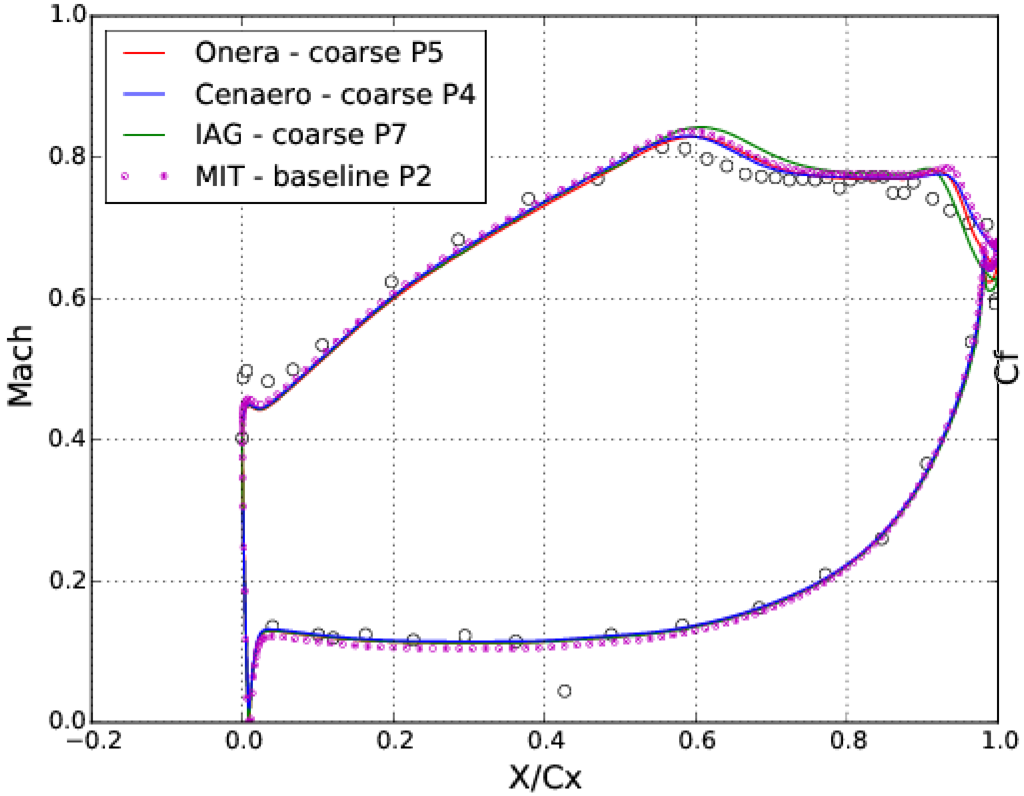


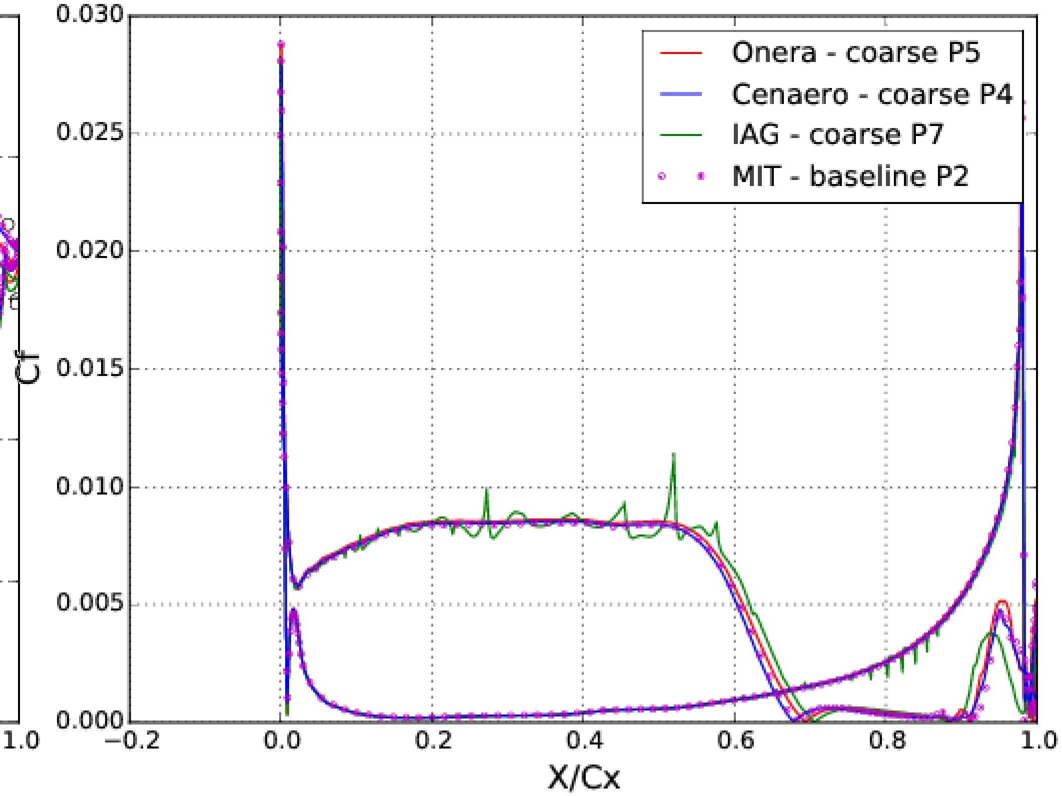
IAG meshes

Derefined near LE/TE

Not refined in the wake

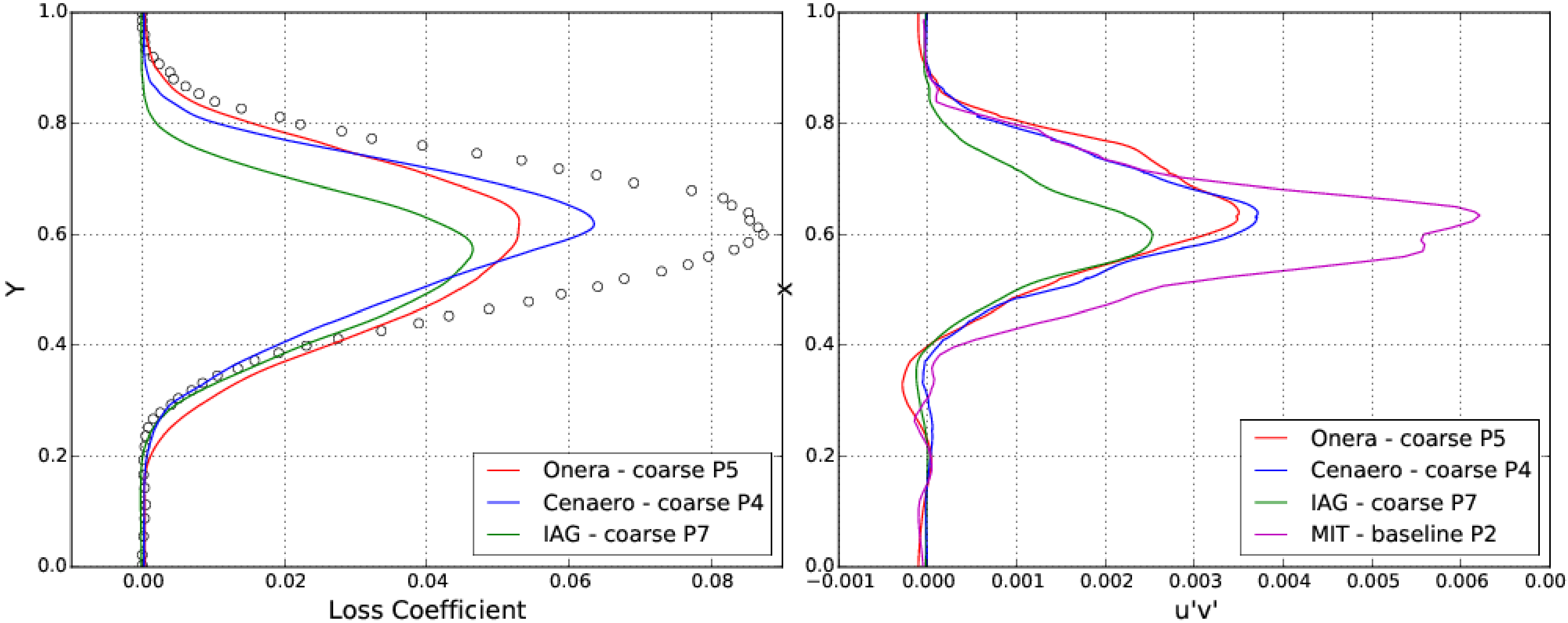
AS2 – DNS and LES of LP Turbine
T106C – blade force distributions





AS2 – DNS and LES of LP Turbine

T106C – blade force distributions



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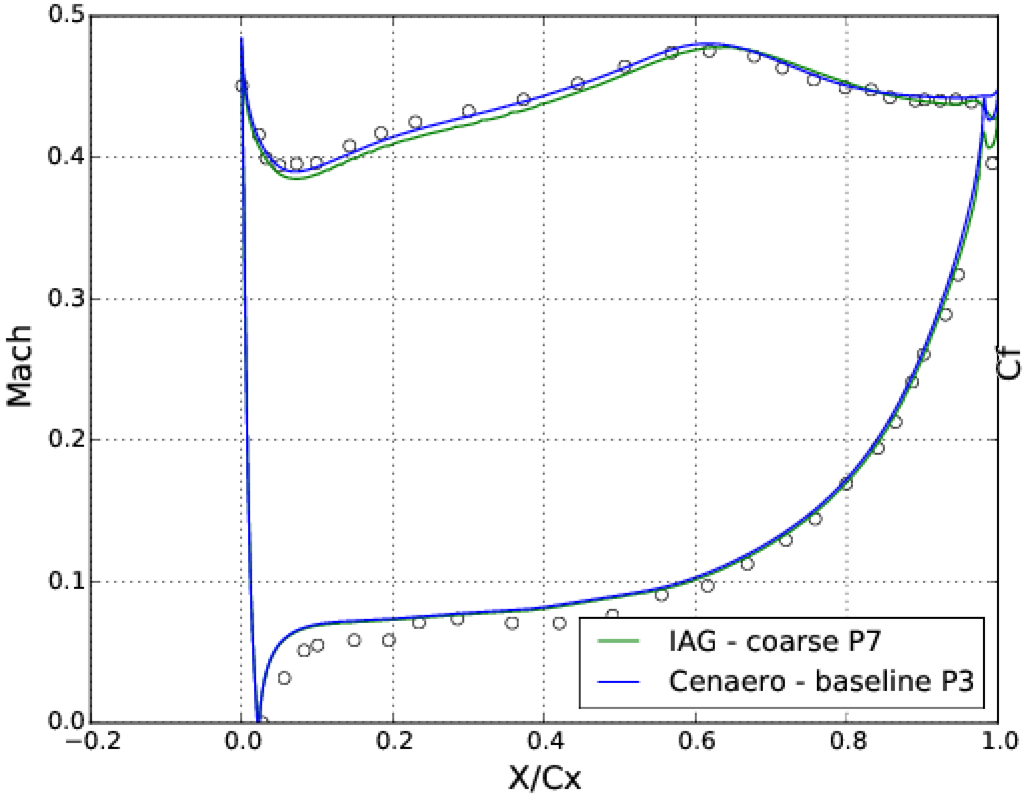
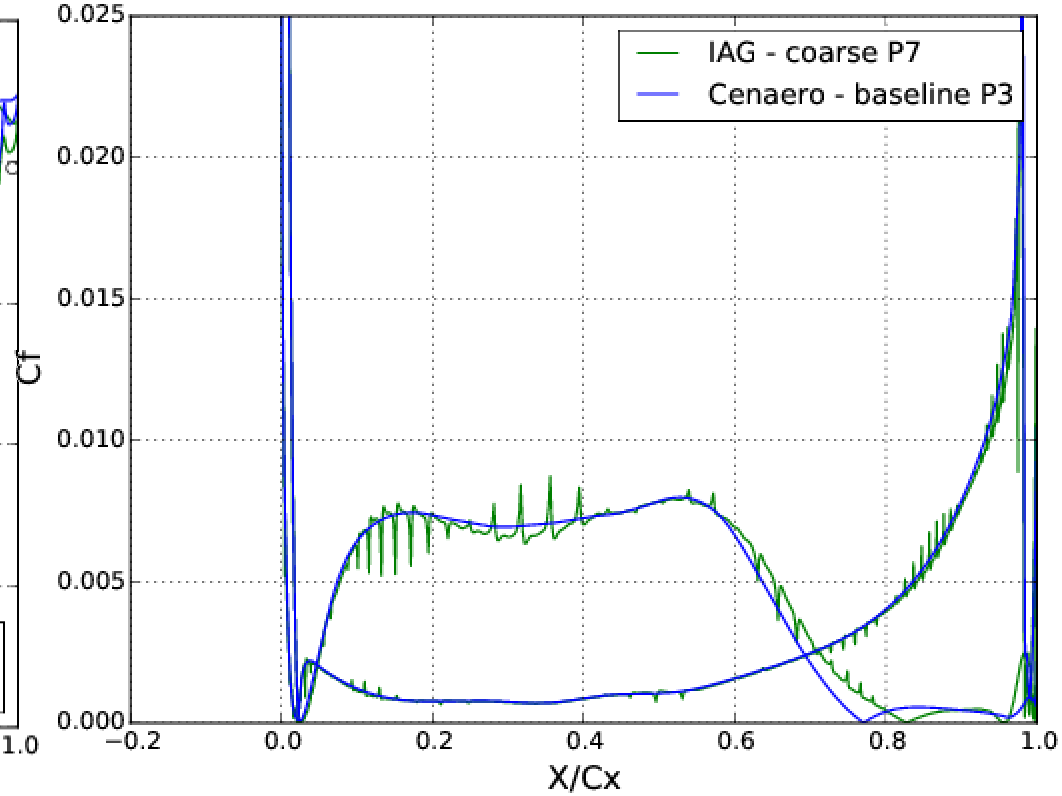
AS2 – DNS and LES of LP Turbine

T106A – blade force distributions





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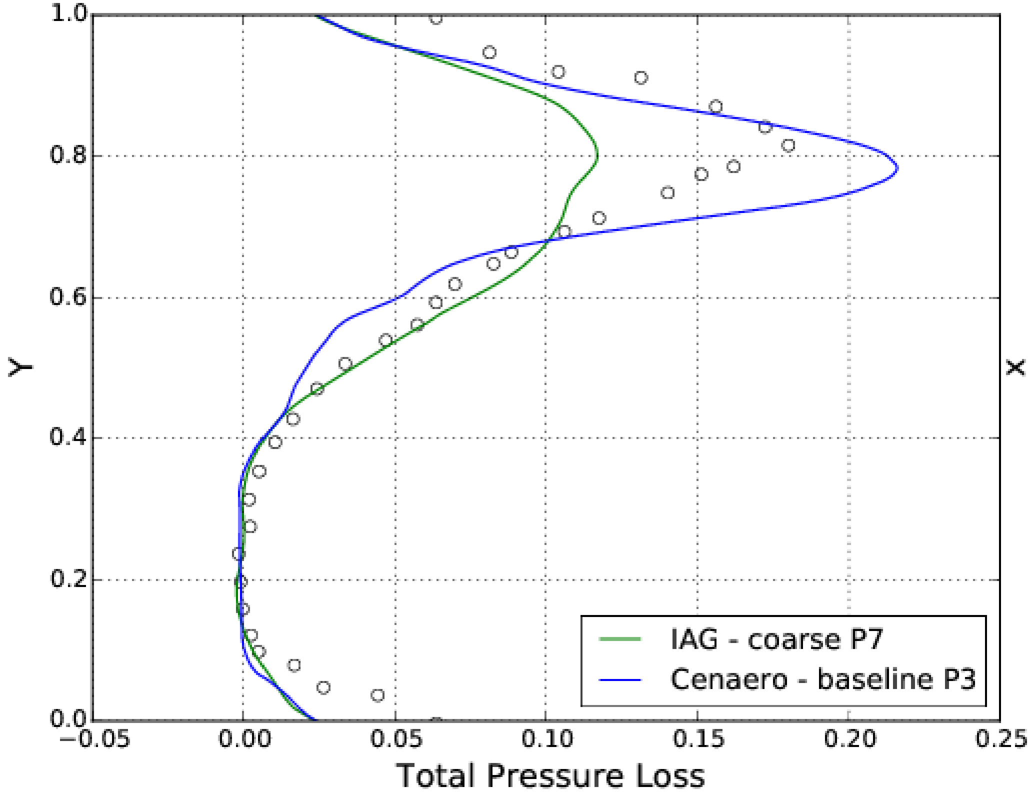
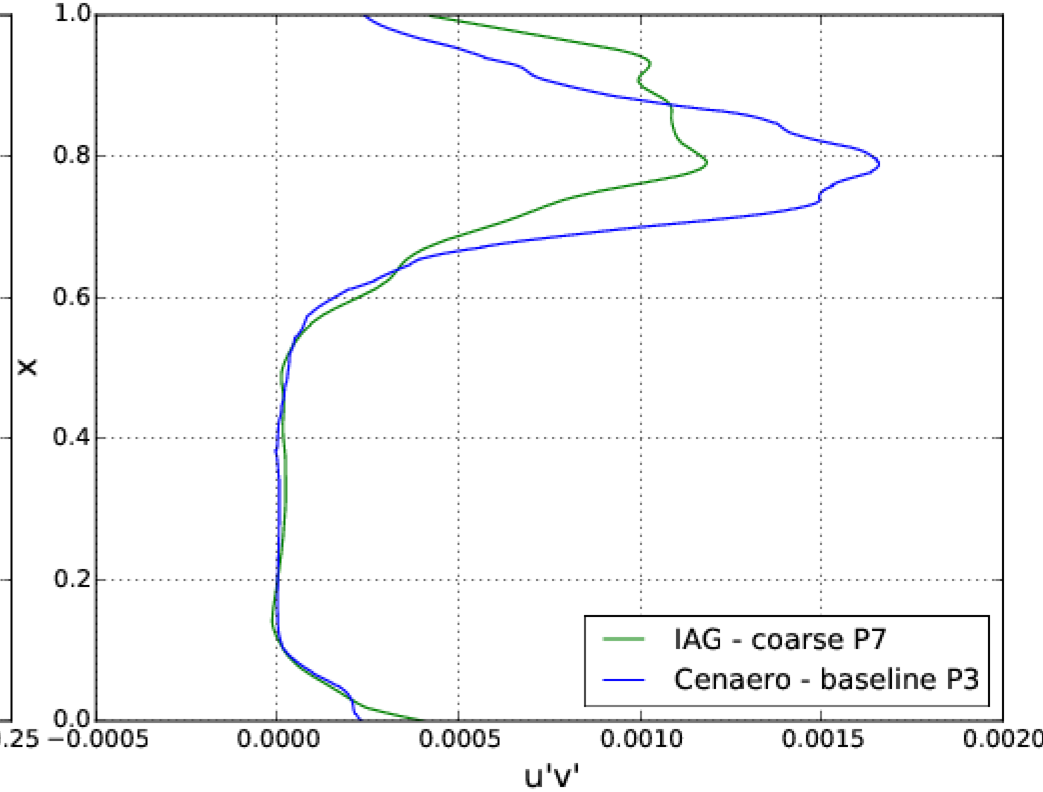
AS2 – DNS and LES of LP Turbine
T106A – blade force distributions





AS2 – DNS and LES of LP Turbine
Contributions

	Method	Resolution	DOF	Avg. CT	Ite/CT
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	30	64479
		P5 coarse	1.7M	30	135406
		P3 baseline	2.9M	30	27633
		P4 baseline	5.1M	30	56419
		P5 baseline	8.2M	30	123096
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	40	4838
		P7 coarse	2.7M	40	5908
MIT	IEDG [1]	P2 baseline	3.2M[2]	7.7	270
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	20	451
		P4 baseline	14.8M	18	902

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AS2 – DNS and LES of LP Turbine

Contributions

	Method	Resolution	DOF	Ite/CT	WU/CT	WU/DOF/CT
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	64479	0.31M	0.292
		P5 coarse	1.7M	135406	1.23M	0.716
		P3 baseline	2.9M	27633	0.45M	0.141
		P4 baseline	5.1M	56419	1.70M	0.332
		P5 baseline	8.2M	123096	4.64M	0.566
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	4838	0.10M	0.069
		P7 coarse	2.7M	5908	0.15M	0.068
MIT	IEDG	P2 baseline	3.2M	270	0.04M	0.013
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	451	0.29M	0.110
		P4 baseline	14.8M	902	4.38M	0.295

AS2 – DNS and LES of LP Turbine
Contributions

	Method	Resolution	DOF	Ite/CT	WU/CT	WU/DOF/RES
Onera	LLF/SIP Pascal basis	P4 coarse	1.1M	64479	0.31M	1.13μ
		P5 coarse	1.7M	135406	1.23M	1.32μ
		P3 baseline	2.9M	27633	0.45M	1.27μ
		P4 baseline	5.1M	56419	1.70M	1.47μ
		P5 baseline	8.2M	123096	4.64M	1.15μ
IAG	Roe/BR1 Tensor basis	P6 coarse	1.5M	4838	0.10M	2.87μ
		P7 coarse	2.7M	5908	0.15M	2.31μ
MIT	IEDG	P2 baseline	3.2M	270	0.04M	0.17μ
Cenaero	Roe/SIP Tensor basis	P4 coarse	2.6M	451	0.29M	2.68μ
		P4 baseline	14.8M	902	4.38M	3.63μ

AS2 – DNS and LES of LP Turbine
Conclusions

- **Results**
  - **Onera/Cenaero: convergence of results**
  - **IAG: inadequate mesh (normals, wake resolution)**
- **Timings**
  - **Cost per dof and residual is similar for all 3 DG (x2 between tensor product and Pascal space)**
  - **Large dependence on time stepping scheme (and mesh)**
  - **MIT: EIDG very economical**
- **Experimental match**
  - **Confirmed disagreement identied during HOW2 for T106C**
  - **Marginally better agreement for T106A**
- **Further work ?**
  - **IAG : use workshop meshes / meshing script**
  - **MIT: use correct conditions**
  - **Complete grid/order convergence studies ?**

C1 - The DLR F11 high lift configuration

Compilation by Ralf Hartmann (DLR)

- **Part of the 2nd AIAA High Lift Prediction workshop (HiLiftPW-2, Case 2b).**
- **Config 4: with slat tracks and flap track fairings**
- **Flow conditions**
  - **Ma= 0.175**
  - **Re=15.1e6 (high Re-No.)**
  - **alpha = 7°, 16°, 18.5°**
  - **run fully turbulent**
- **Available data:**
  - http://hiliftpw.larc.nasa.gov/index-workshop2.html
  - Rudnik, R., Huber, K., and Melber-Wilkending, S., EUROLIFT Test Case Description for the 2nd High Lift Prediction Workshop, AIAA Paper 2012-2924, June 2012.
  - Rumsey, C. L., Slotnick, J. P., Overview and summary of the Second AIAA High Lift Prediction Workshop. AIAA Paper 2016-0747, Jan. 2016.

C1 - The DLR F11 high lift configuration (R. Hartmann/DLR)

Contributions to meshing and solution challenge

R. Hartmann (DLR), H. McMorris (CentaurSoft), T. Leicht (DLR)

- Quadratic (3rd-order) curved hybrid mesh (CENTAUR) for Config 4
- RANS Wilcox k-ω
- 3rd-order Discontinuous Galerkin (DG) for Config 4 (alpha=7°)
- 35.2e6 DoFs/eqn.

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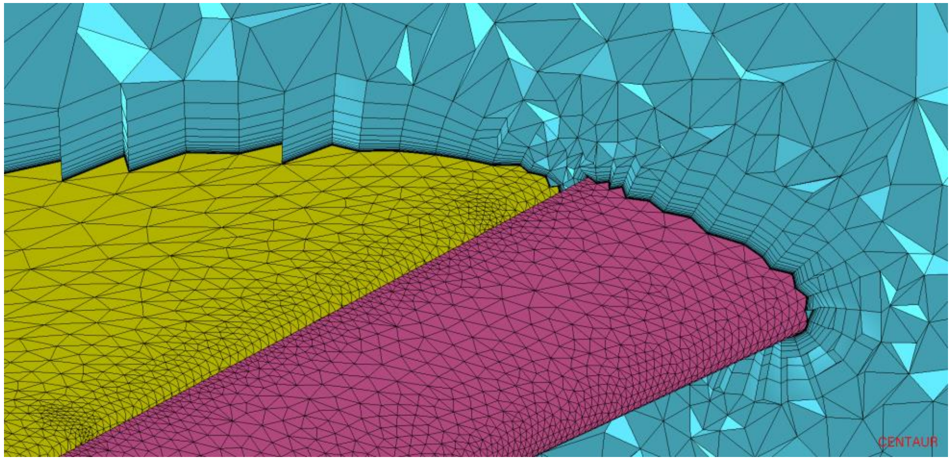
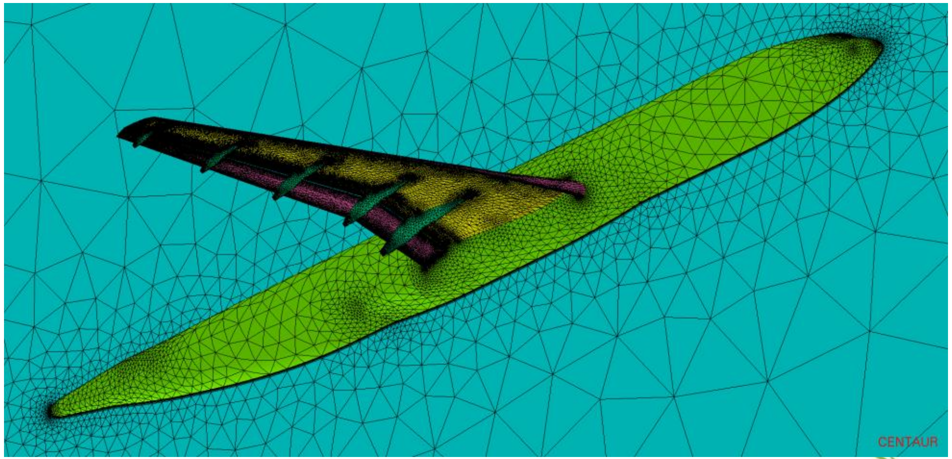
- Linear block-ijk (ICEM): family (Config 2), single mesh (Config 4)
- RANS Menter-SST
- 5th-order Finite Difference (FD) for Config 2 (alpha=7°, 16°, 18.5°)
- 9.8e6, 32.0e6, 100.6e6 DoFs/eqn

C1 - The DLR F11 high lift configuration
DLR & CentaurSoft

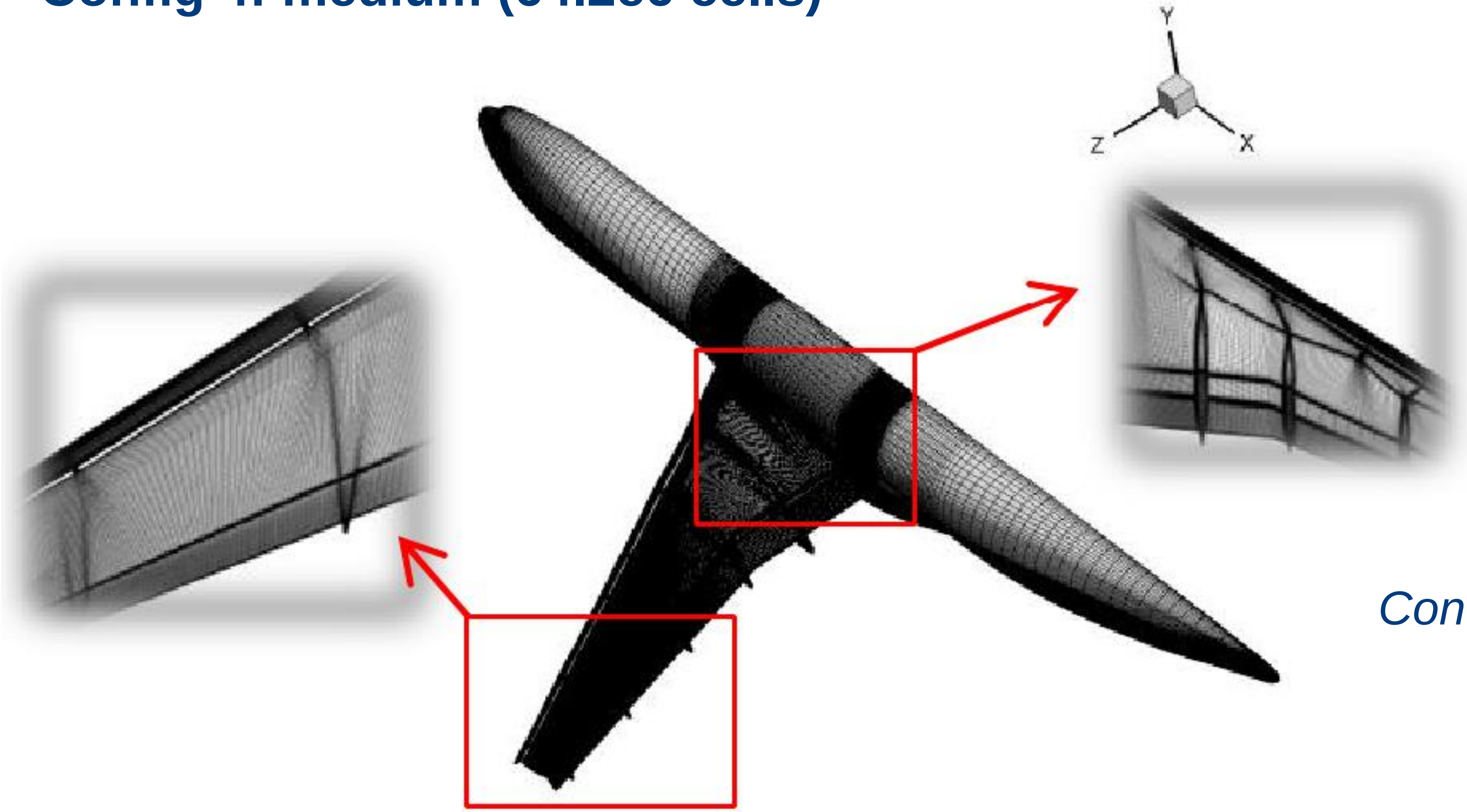
- **Quadratic curved hybrid mesh**
- **3.5e6 elements (prisms, pyramids and tetrahedra), 1.4e6 vertices, 11.2e6 nodes**
- **Not fully regular**
  - **Positive Jacobians in all quadrature points for DG(2)**
  - **Negative Jacobians for few quadrature points of DG(3)**
- **Is available in Gmsh and CGNS format and can be provided upon request (Ralf.Hartmann@dlr.de)**



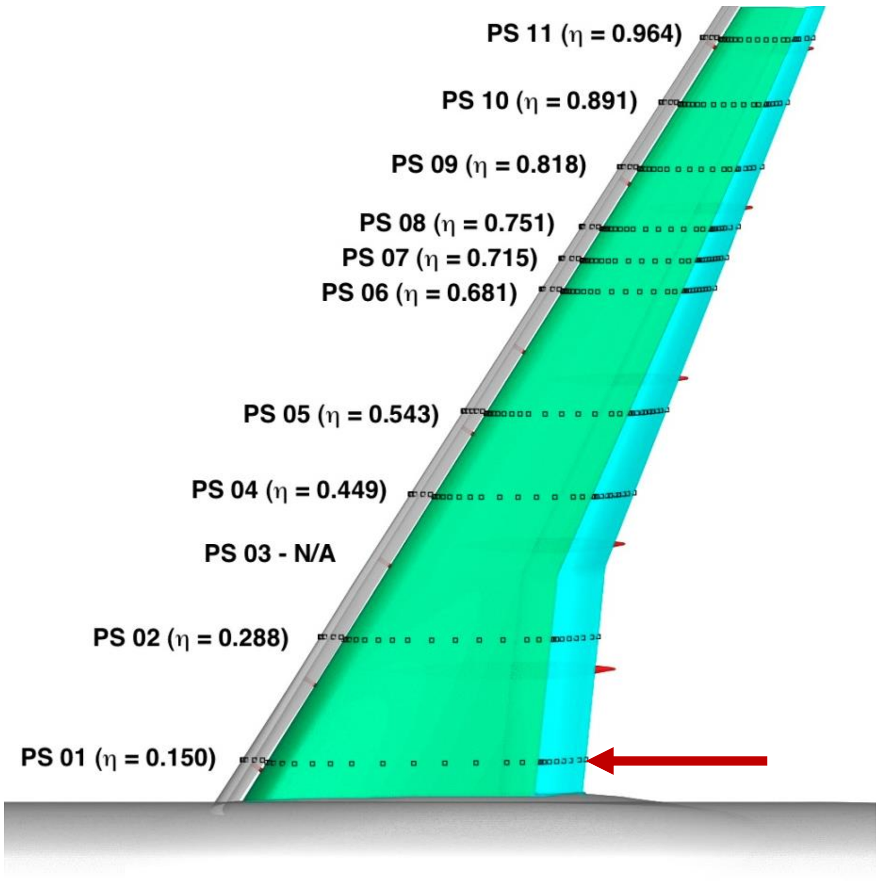


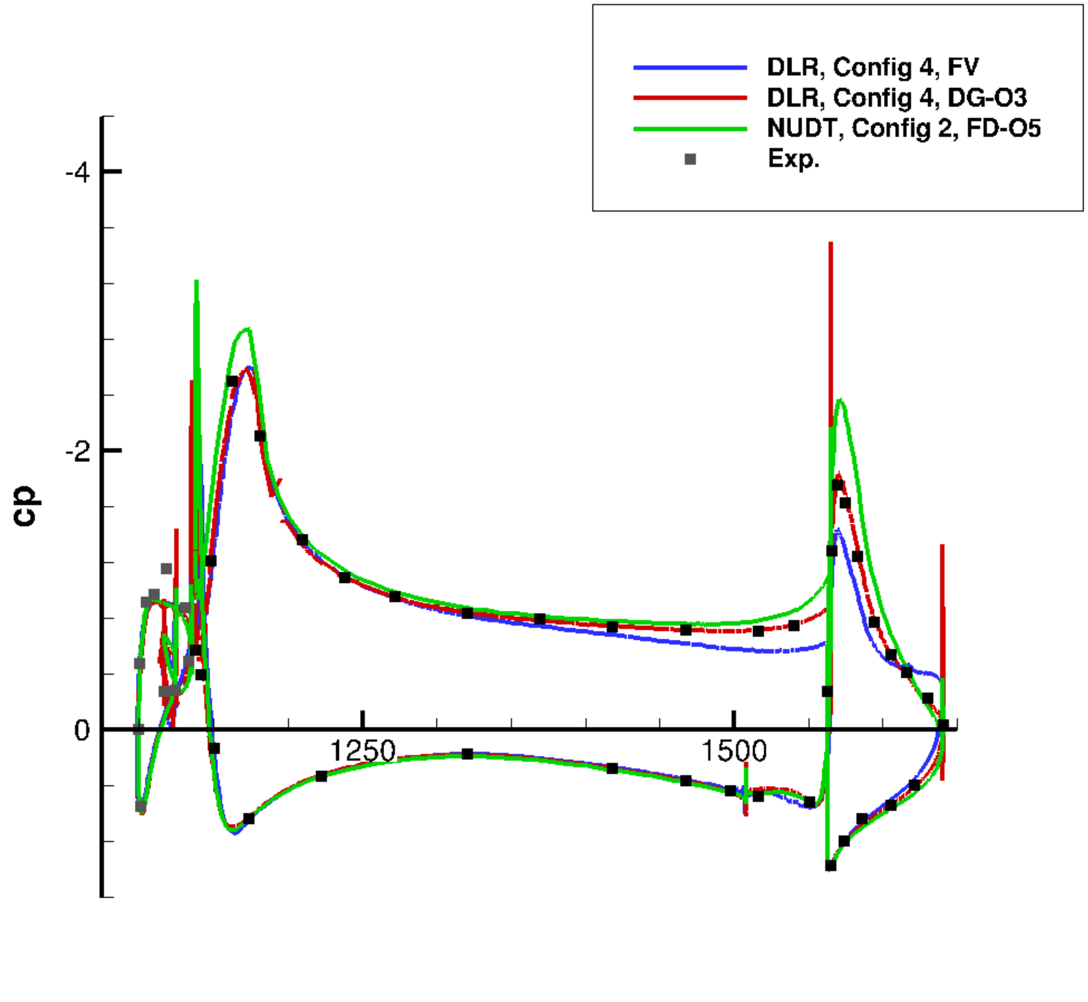
C1 - The DLR F11 high lift configuration

- **Linear block-structured meshes (ICEM):**
  - **Config 2: coarse (9.8e6), medium (32.0e6), fine (100.6e6 cells)**
  - **Config 4: medium (64.2e6 cells)**



Config 4


PS 11 (η = 0.964)
PS 10 (η = 0.891)
PS 09 (η = 0.818)
PS 08 (η = 0.751)
PS 07 (η = 0.715)
PS 06 (η = 0.681)
PS 05 (η = 0.543)
PS 04 (η = 0.449)
PS 03 - N/A
PS 02 (η = 0.288)
PS 01 (η = 0.150)


DLR, Config 4, FV
DLR, Config 4, DG-O3
NUDT, Config 2, FD-O5
Exp.
cp
-4
-2
0
1250
1500

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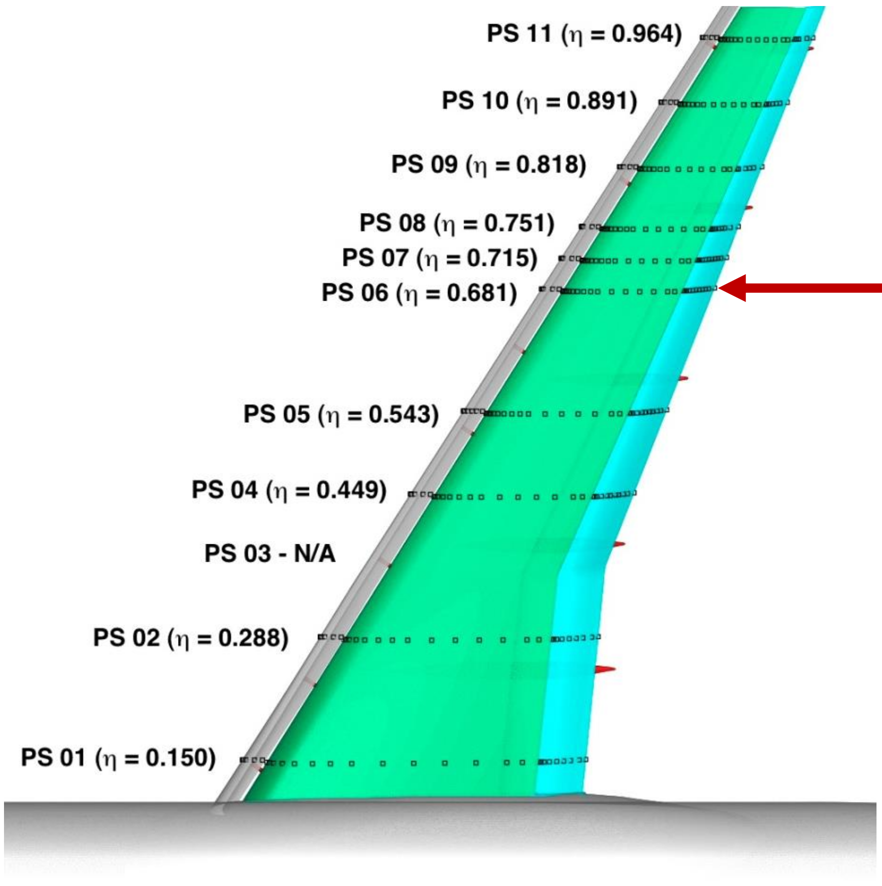
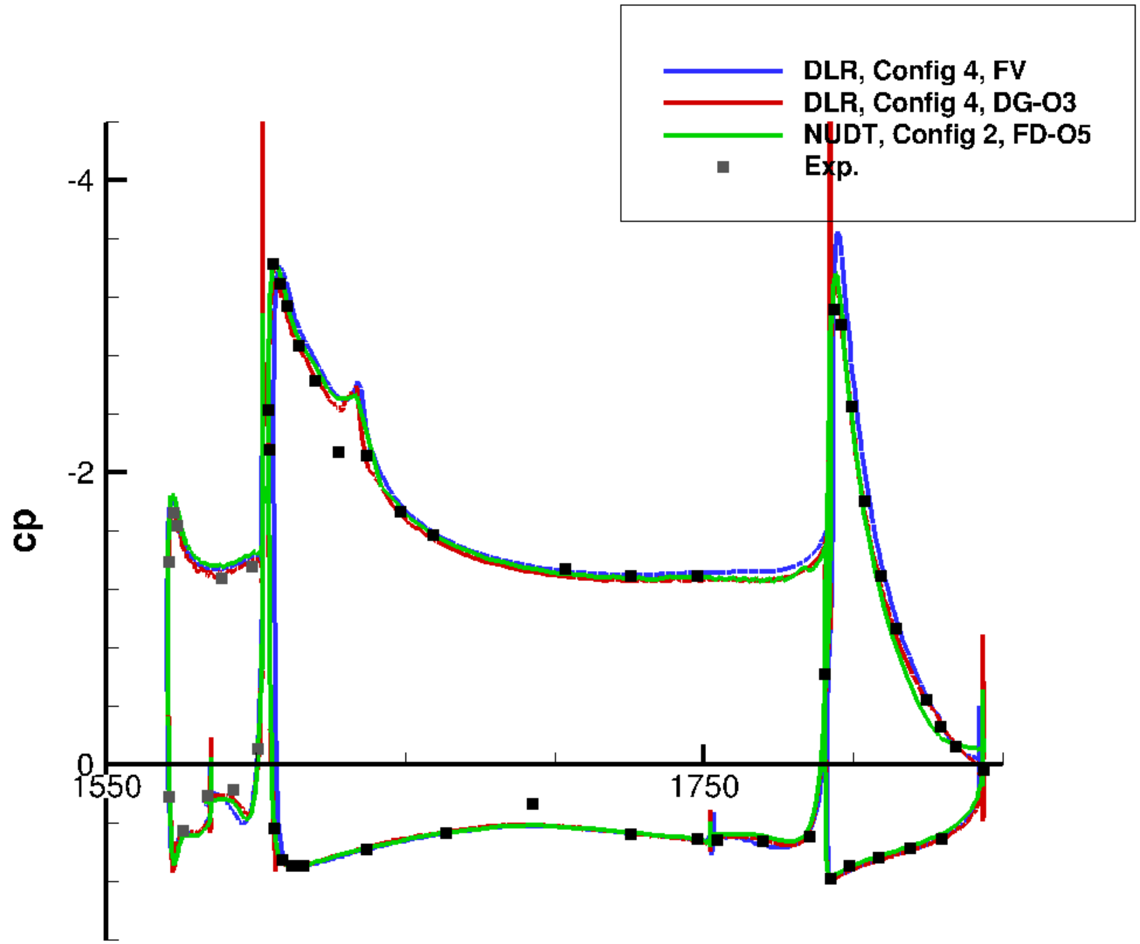
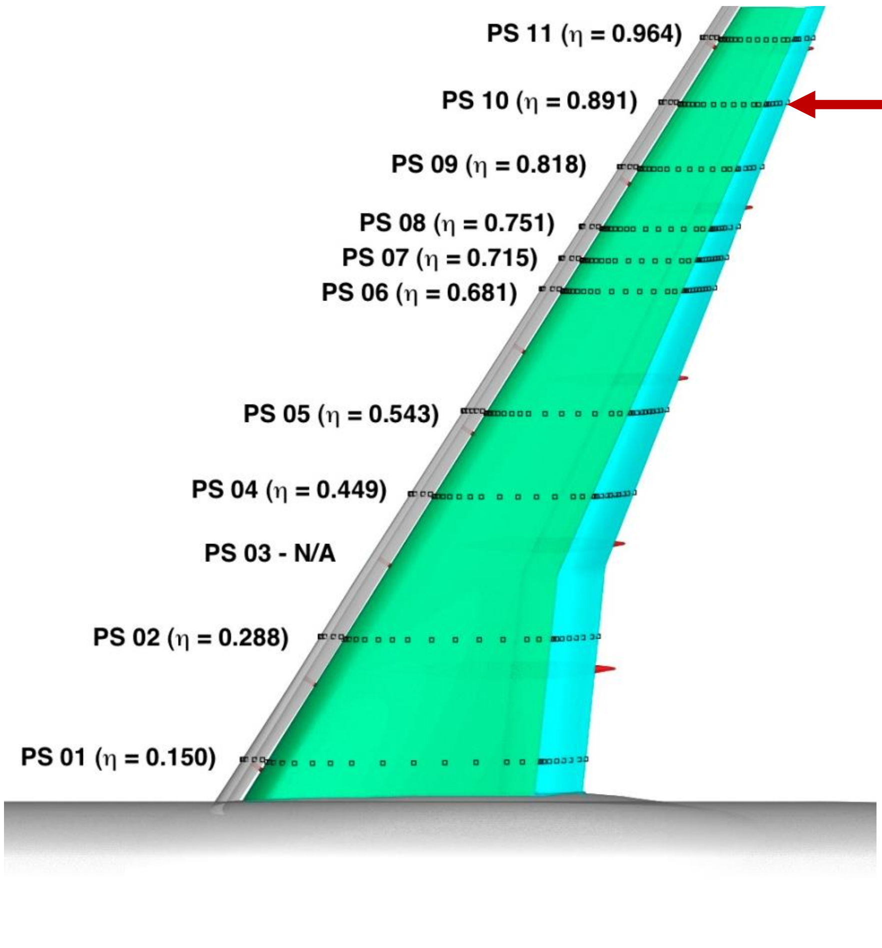

PS 11 (η = 0.964)
PS 10 (η = 0.891)
PS 09 (η = 0.818)
PS 08 (η = 0.751)
PS 07 (η = 0.715)
PS 06 (η = 0.681)
PS 05 (η = 0.543)
PS 04 (η = 0.449)
PS 03 - N/A
PS 02 (η = 0.288)
PS 01 (η = 0.150)


DLR, Config 4, FV
DLR, Config 4, DG-O3
NUDT, Config 2, FD-O5
Exp.
cp
-4
-2
0
1550
1750


PS 11 (η = 0.964)
PS 10 (η = 0.891)
PS 09 (η = 0.818)
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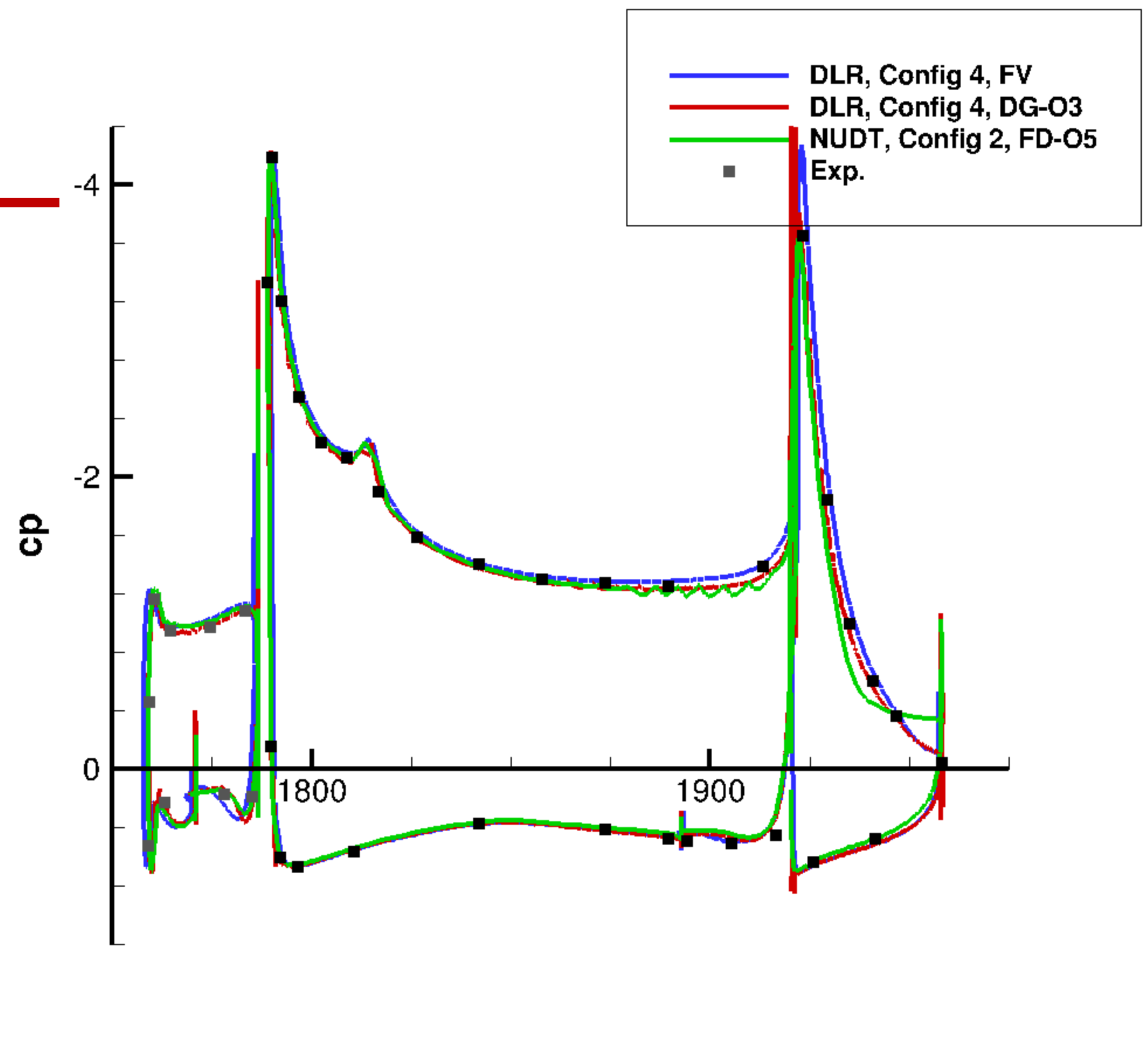
PS 06 (η = 0.681)
PS 05 (η = 0.543)
PS 04 (η = 0.449)
PS 03 - N/A
PS 02 (η = 0.288)
PS 01 (η = 0.150)


DLR, Config 4, FV
DLR, Config 4, DG-O3
NUDT, Config 2, FD-O5
Exp.
cp
-4
-2
0
1800
1900

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C1 – DLR High Lift F11 Configuration
Conclusions

- **Meshing**
  - (Linear ijk meshes for FD)
  - High order mesh generation by specialist at CentaurSoft
  - Only third order (quadratic)
  - Stricter quality control to be integrated in GG
  - Still quite time-consuming iterative task

- **Computations:**
  - Force coefficients are in the range of HiLiftPW-2 results
  - Very good correspondence for Cp distribution,
  - DG better comparison to experiments than reference computation

Concluding remarks
Evolution of the workshop

- **Aim : progressing high order methods in to the realm of practical applications**
  - **Test codes on actual challenging cases**
    - **Advanced** test cases which only test solvers
    - **Challenge** test cases which test the full chain
  - **Help development of new methods/codes / functionalities through a more extensive baseline database**
- **Proposal**
  - **Baseline = continuous effort, very detailed and explicit database**
  - **Workshop : only advanced and complex cases, if possible sponsored by industry**
  - **Strict quality control on conditions and detailed description including meshes and post-processing routines**
  - **Baseline cases as a prerequisite for the A and C cases**
  - **Migration C -> A -> B**

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- All of the participants !

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