Towards Industrial LES/DNS in Aeronautics
Paving the Way for Future Accurate CFD

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Outline

- Short description of TILDA project
- Results overview of TILDA project partners at mid-term
- Highlight of some results regarding DG methods for turbulent flow computation

Objectives TILDA

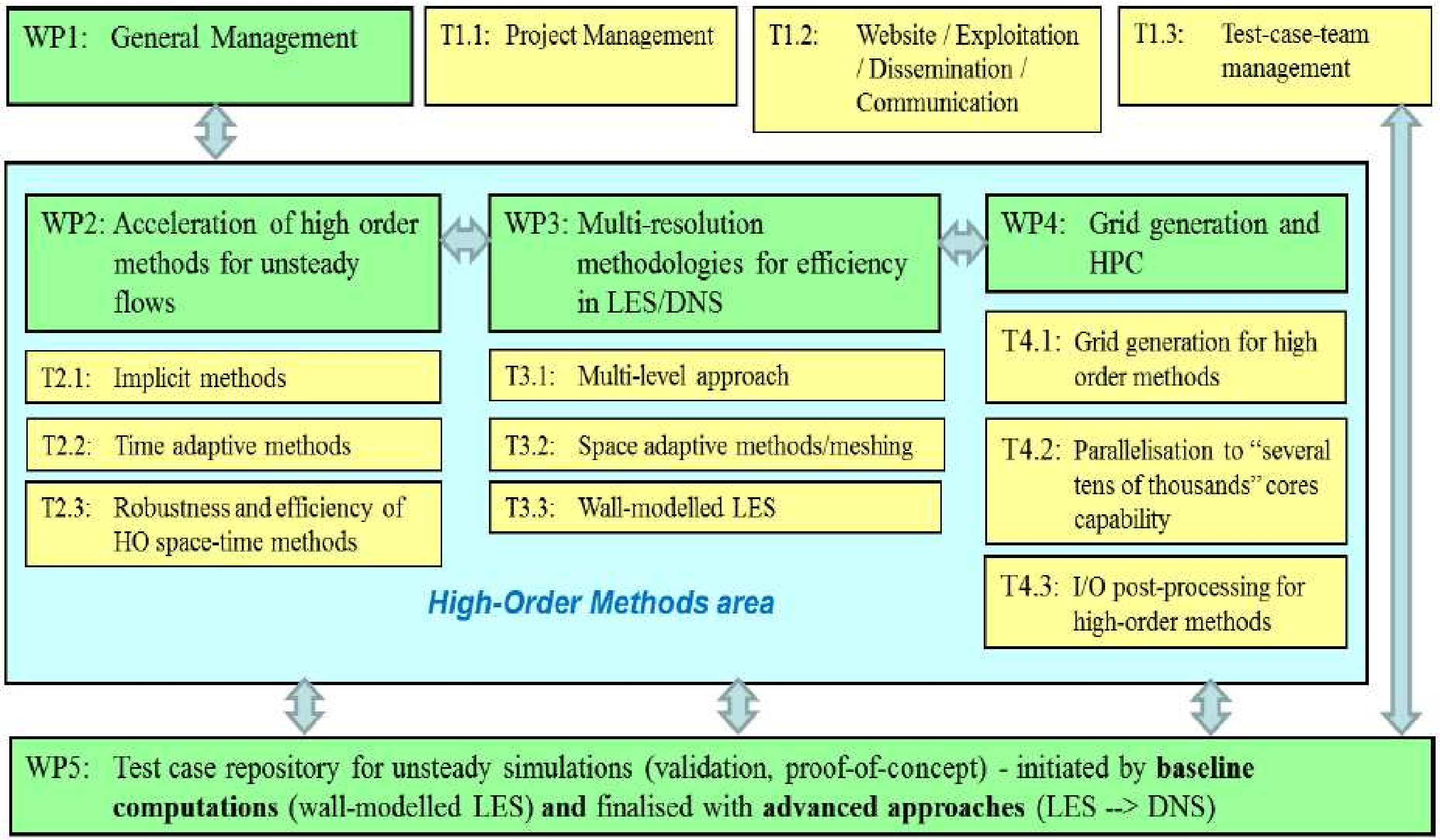
- The main goal of the TILDA project is
  - to combine efficient high-order numerical schemes (HOMs) and innovative LES and DNS techniques in order to solve complex flow configurations at industrial operational conditions.
  - Obtaining high resolution LES/DNS at the industrial levels (TRL 5-6), reducing the need for experiments and increasing further the predictive capacity of CFD simulations in the full design envelope

- The project aims at performing high-order computations of complex LES/DNS cases:
  - Fully exploiting HPC advancements running on many tens of thousands of processors in a turn-around times of a 1-2 days.
  - Exploiting HOM to reach billions of degrees-of-freedom (DOF) on reasonable grids sizes.

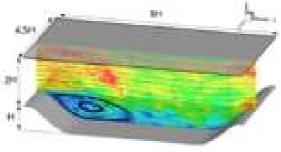
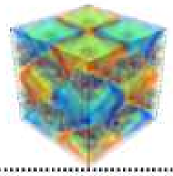
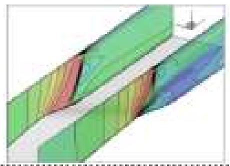
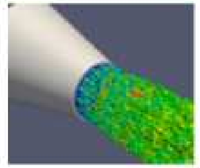
List of Partners

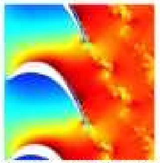
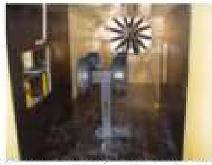
No	Name	Short Name	Country
1	NUMERICAL MECHANICS APPLICATIONS INTERNATIONAL SA	NUMECA	Belgium
2	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	DLR	Germany
3	OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES	ONERA	France
4	DASSAULT AVIATION SA	DASSAV	France
5	SAFRAN	SAFRAN	France
6	CENTRE EUROPEEN DE RECHERCHE ET DE FORMATION AVANCEE EN CALCUL SCIENTIFIQUE	CERFACS	France
7	CENTRE DE RECHERCHEEN AERONAUTIQUE ASBL - CENAERO	CENAERO	Belgium
8	UNIVERSITE CATHOLIQUE DE LOUVAIN	UCL	Belgium
9	UNIVERSITA' DEGLI STUDI DI BERGAMO	UNIBG	Italy
10	IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE	ICL	United Kingdom
11	FEDERAL STATE UNITARY ENTERPRISE THE CENTRAL AEROHYDRODYNAMIC INSTITUTE NAMED AFTER PROF. N.E. ZHUKOVSKY	TsAGI	Russian Federation

Work Packages Overview



TILDA Kick-Off meeting *Brussels* *June 2015* *7*

Validation/verification = fundamental/basic test cases			Proof-of-concept TC
			
TC-F1: Periodic Hill Re_H=10600 LES 13x10^6 points Re_H=10600/19000/37000 (Exp.)	**TC-F2: Taylor-Green vortex** Re=1600 (DNS) Re=5000 (LES)	**TC-F3: Shock boundary layer interaction on swept bump** Ma=0.75 Re=1.13 10^6	**TC-P1: Jet with/without micro-jets – fluidic injection** Ma=0.9 Re=10^6
Justification for Test Case: RANS isn't able to deliver decent results	**Justification for Test Case:** Detailed grid convergence assessment of LES and DNS for transition on unstructured meshes	**Justification for Test Case:** Fundamental geometry but complex physics due to shock stability/position	**Justification for Test Case:** RANS can't compute turbulence effects at all
Quantifiable Objective[2]: **1** day on e.g. 50,000 cores	**Quantifiable Objective[2]:** **0.025/0.75** day on e.g. 50,000 cores – depending on Re	**Quantifiable Objective[2]:** **2-3** days on e.g. 50,000 cores	**Quantifiable Objective[2]:** **2-3** days on e.g. 50,000 cores
Area of Impact: External aerodynamics	**Area of Impact:** General aerodynamics	**Area of Impact:** Wing / turbomachinery	**Area of Impact:** Aero-acoustics
Test-case Team[1]: **CENAERO**, DLR, UCL, ONERA, CERFACS, TsAGI, UNIBG, SAFRAN	**Test-case Team[1]:** **DLR**, CENAERO, ONERA, CERFACS, UCL, TsAGI, UNIBG, NUMECA, DASSAV	**Test-case Team[1]:** **ONERA**, CERFACS, UCL, CENAERO, TsAGI, UNIBG, NUMECA	**Test-case Team[1]:** **CERFACS**, UCL, NUMECA, CENAERO

Proof-of-concept = industrial demonstrator test cases, cont.				
				
TC-P2: Generic Falcon business jet in landing configuration M=0.20 α=5.0° z=0 ft	**TC-P3: T106C high-lift Cascade** Ma-in=0.28 Ma-out= 0.59 Outflow: Re= 80,000 – 150,000	**TC-P4: Noise suppressing nozzle with chevrons** Npr=2.8; Schlieren & Laser sheet; PIV: Velocity & fluctuations; Noise: 1/3 octavo meas.	**TC-P5: Boeing Rudimentary Landing Gear[3]** U=40m/s (M≈0.12) $Re=UD/\nu \approx 10^6$	**TC-P6: NASA Rotor 37** 36 multiple-circular-arc blade Tip Speed= 1500ft/sec Pressure ratio =2.106
Justification for TC: Application challenge full aircraft	**Justification for TC:** DNS and LES of natural and bypass transition in flight condition	**Justification for TC:** Environmental aspect, noise suppressing nozzle	**Justification for TC:** Landing Gear is a major noise source	**Justification for TC:** Difficult to predict near-stall performance
Quantifiable Objective[2]: **2-3** days on e.g. 50,000 cores	**Quantifiable Objective[2]:** **0.5** day on e.g. 50,000 cores	**Quantifiable Objective[2]:** **1** day on e.g. 50,000 cores	**Quantifiable Objective[2]:** **2-3** days on e.g. 50,000 cores	**Quantifiable Objective[2]:** **2-3** days on e.g. 50,000 cores
Area of Impact: Aeroacoustics, external aerodynamics	**Area of Impact:** Jet engines, turbo-machinery	**Area of Impact:** Aeroacoustics; nozzle/jet flow	**Area of Impact:** Aeroacoustics; external aerodynamics	**Area of Impact:** Turbomachinery; internal aerodynamics
Test-case Team[1]: **DASSAV**, UCL, NUMECA	**Test-case Team[1]:** **CENAERO**, UCL, ICL, ONERA, SAFRAN, NUMECA	**Test-case Team[1]:** **TsAGI**, ICL, UCL	**Test-case Team[1]:** **DLR**, ONERA, ICL, UNIBG, UCL, DASSAV	**Test-case Team[1]:** **NUMECA**, CENAERO, ONERA, UNIBG, SAFRAN

TILDA approach for numerical methods

Various HO finite element type methods

- Discontinuous Galerkin methods : U. Bergamo, ONERA, DLR, TsAGI, CENAERO, U. C. Louvain, SAFRAN
- Spectral Difference methods : CERFACS
- Flux Reconstruction schemes : IMPERIAL COLLEGE, NUMECA
- Continuous Finite Element methods : DASSAULT Aviation

All these methods use unstructured meshes, either purely tetrahedral meshes or hybrid element types

Comparison with reference FV methods (2^{nd} order but also HO FV methods) are made within the context of the HO CFD workshop and with classical codes used for current applications

Under the TILDA framework, NUMECA is working on the development of an unstructured high-order solver based on Flux Reconstruction (FR) schemes, within the software FINE/Open™. The state-of-the-art is an explicit Navier-Stokes solver on unstructured grids composed of every cell shapes (Hexas, Tetras, Prims, Pyrams).

1. **Work Package 2.1:** Various efforts have been undertaken to improve the efficiency of the explicit FR solver,

- BLAS libraries are used in order to boost efficiency in mat-mat operations present in the solver.
- The data structure of solver has been enhanced in order to reduce memory footprint.
  - ➢ On average a 30% reduction of memory is observed for all polynomial orders “p”.
- A Tensor product FR formulation has been developed, more efficient and available on Hexa cells.

Ratio time optim.	FineFR_p1	FineFR_p3	FineFR_p5
FR-BLAS solver	x1.09	x1.47	x1.72
FR-Tensor solver	x1.02	x1.85	x4.35

Results on time performance of the Navier-Stokes FR solver: Ratio of times per iteration, of the optimised versions of the solver with respect to the old version prior to optimisation work. Results are obtained in a mesh of 48x48x48 cells.

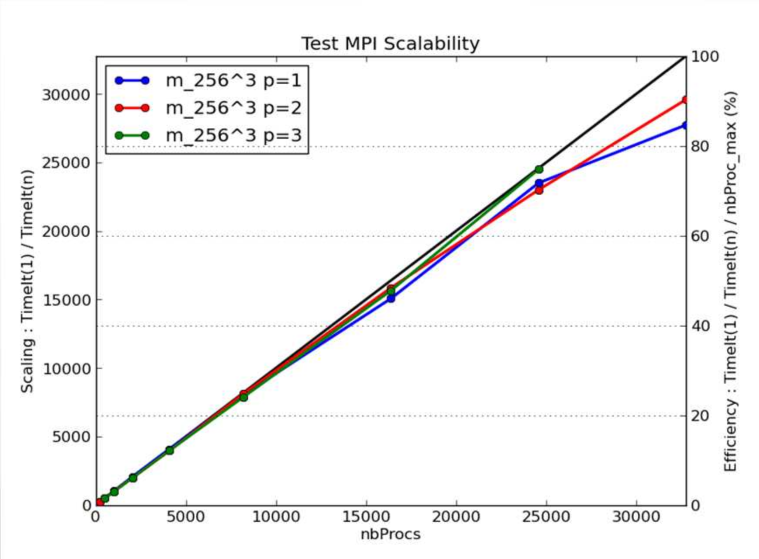
2. **Work Package 3.1:** The extension of the FR solver to handle non-conforming meshes, both in h- and p- senses, is ongoing. This is the first step of an implementation of a MultiLevel approach for under-resolved computations.

- The approach chosen to handle the coupling of non-conforming elements is the so-called “Mortar Element”, proposed by Kopriva and Kolias in (Kopriva & Kolias, 1996), (Kopriva, 1996).

3. **Work Package 4.2:** The parallel scalability of the FR solver has been enhanced.
- Thanks to the design of MPI communicators tailored for high-order methods.

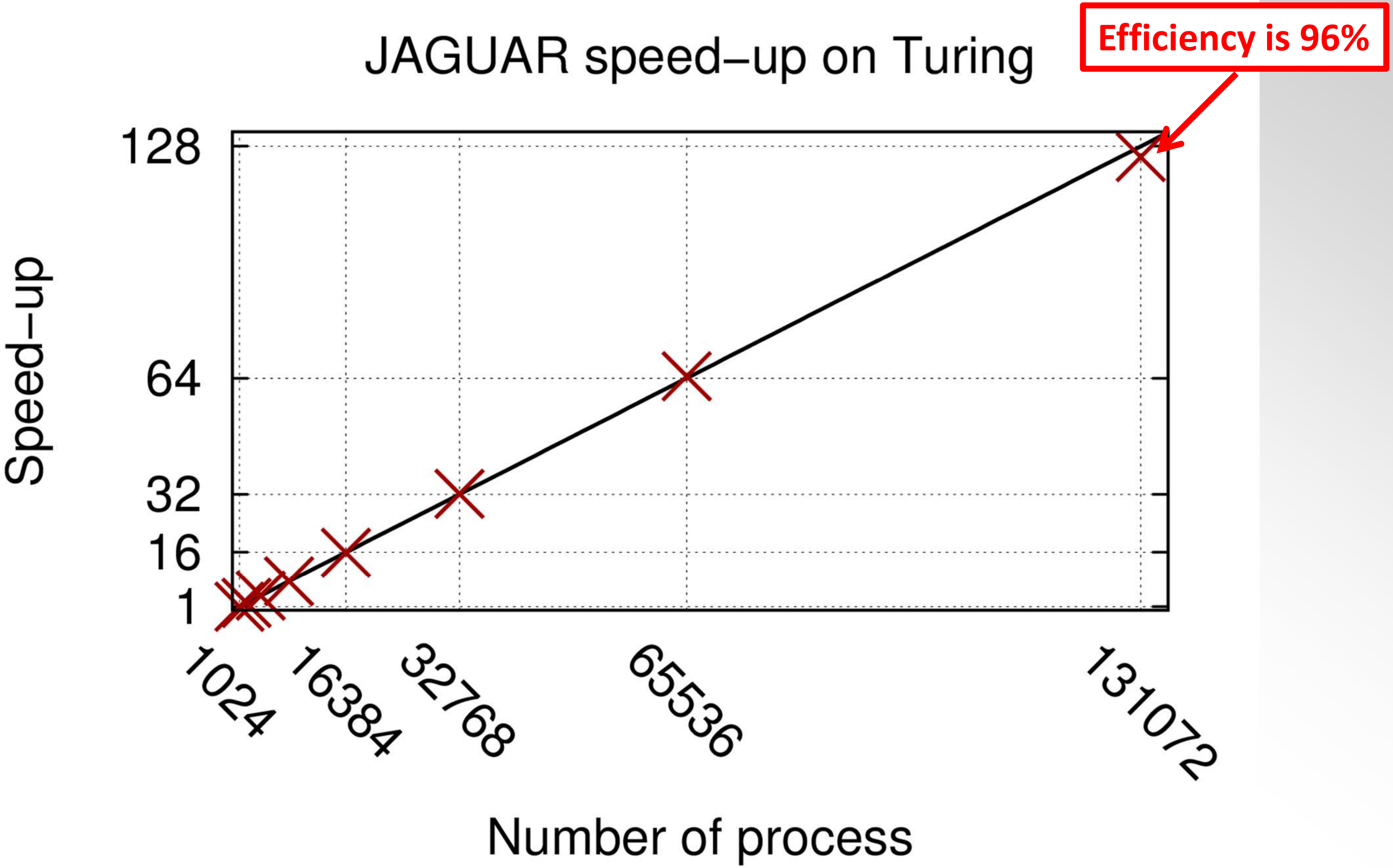
Parallel scalability tests of the FR solver on massive platforms have been conducted. Some specifications are:
- Computation domain is a cube of 256x256x256 cells.
- Only kernels of the “raw” algorithm of the FR solver are measured. Other kernels for pre- or post-processing (solution output, monitor of residuals, …) are not accounted for.
- Test conducted in the supercomputer Titan.

- Main conclusion: optimal parallel scalability of the FR solver is observed up to ~36000 cores. The next step is the optimisation of kernels for solution output with the aid of parallel I/O libraries.



Results on parallel scalability of the laminar FR solver, up to polynomial order p=3 and nbcores =~36000 cores.

- CERFACS aims to use its Spectral Difference solver JAGUAR for ***massively parallel computations*** with focus on ***aeroacoustics*** with:
  - *h/p* adaptation (space and polynomial degree)
  - dedicated boundary conditions
  - co-treatment for processing data on the fly
- HPC capability still drives the developments of the Kernel: MPI, OpenMP, Hybrid MPI/OpenMP
- Current efficiency shown on the IBM BlueGene/Q at IDRIS
  - Reference test case: 2 097 152 cells, p=4, 262 144 000 DoF
  - flat MPI, 2 threads/processor
  - Reference for 1024 process

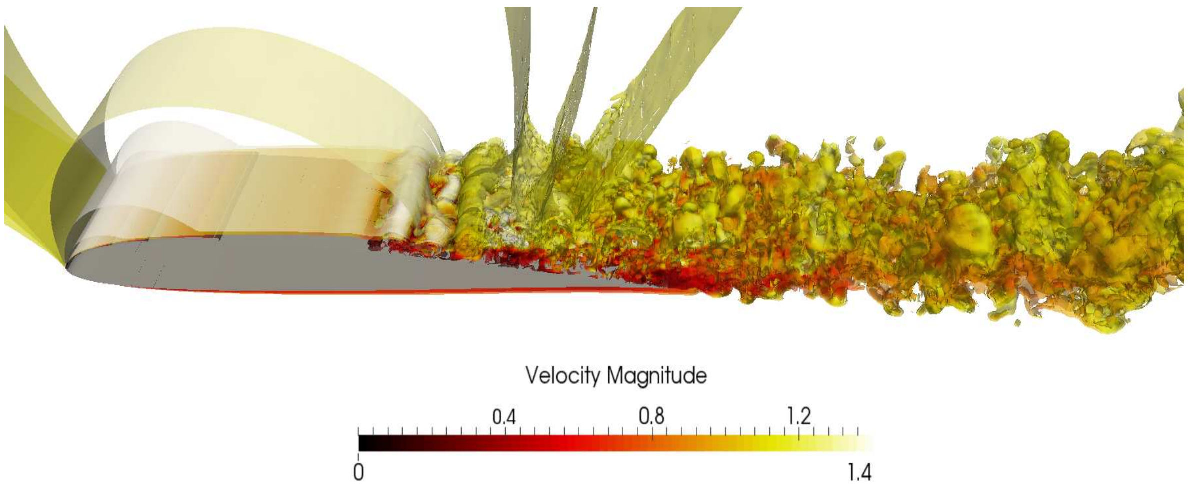

JAGUAR speed–up on Turing
Efficiency is 96%
Speed–up
128
64
32
16
1
1024
16384
32768
65536
131072
Number of process

Development and testing of PyFR (under Task 4.2):

- Cross-platform peta-scale CFD with just 8000 lines of Python!
- Arbitrary order of accuracy in space on mixed element unstructured grids via Flux Reconstruction approach
- Open-source BSD license
- Recent simulations with PyFR on Titan and Piz Daint shortlisted for 2016 Gordon Bell Prize
- Checkout www.pyfr.org

Controlling aliasing driven instabilities (under Task 3.2):

- Aliasing driven instabilities in Flux Reconstruction resulting from, for example, point-wise projection of a non-polynomial flux into a polynomial space, can lead to instabilities
- Investigating de-aliasing strategies to suppress such instabilities
- These include use of new Flux Reconstruction correction functions that are provably stable for 1D linear problems
- Also investigating role of temporal discretisation errors

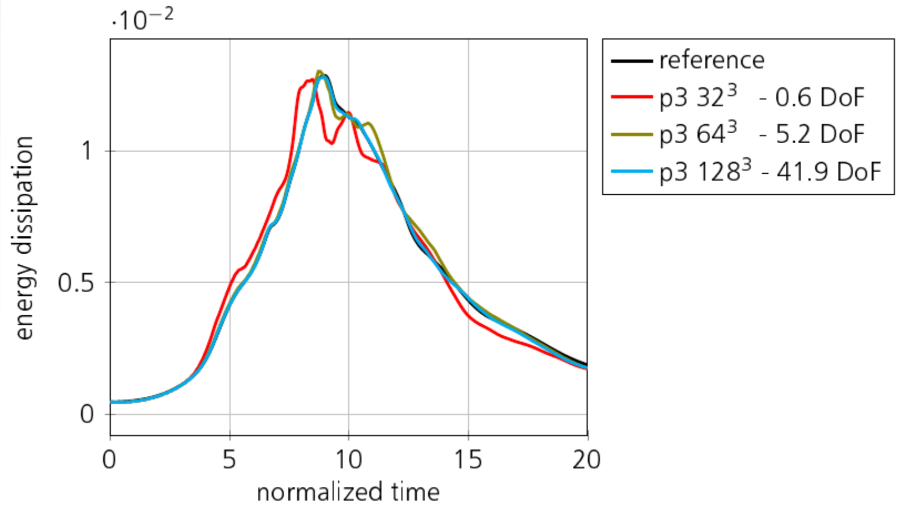


DLR: Proposed work within TILDA

- Work on efficiency / cost reduction for Scale-resolving simulations
  - Temporal discretization
    - Implicit time integration schemes (WP 2.1)
  - Spatial discretization
    - adaptive mesh refinement with hanging nodes near solid walls for wall-resolved LES (WP 3.2)
    - wall functions for wall-modelled LES (WP 3.3)
  - Parallelization (WP 4.2)

- Management of test cases and tasks
  - TC-F2 (Taylor Green vortex)
  - TC-P5 (Boeing Rudimantary Landing Gear)
  - WP 2.1 (Implicit Methods)
  - WP 3.2 (Space adaptive methods/meshing)

DLR: Implicit time integration schemes (WP 2.1)



Taylor Green Vortex

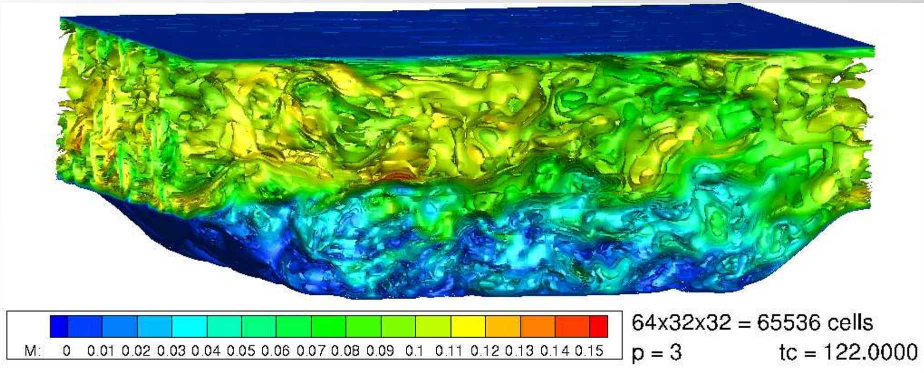
Taylor Green Vortex at Re=1600
DG, p=3 on 64^3 mesh

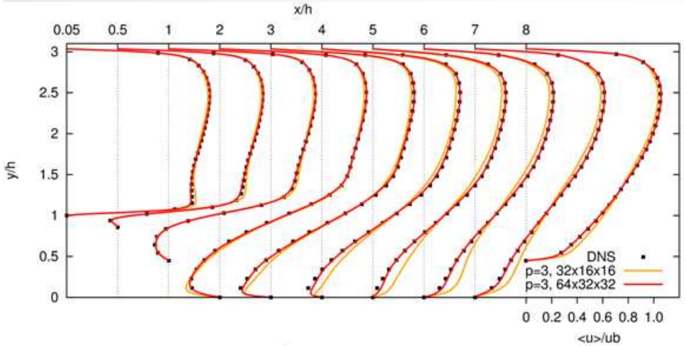
Scheme	Time step size	Run time	Note
ERK4	0.001	**1.0**	reference
SDIRK-4	0.1	20.1	Baseline
		0.4	freeze for Jacobian for 2 time steps, nonlinear tolerance 10^{-4}

DLR: Near-wall local mesh refinement (WP 3.2)

Periodic Hill test case (Re=2800)

DG discretization
Global p-adaptation
Quadratic mesh (64x32x32 elem.)

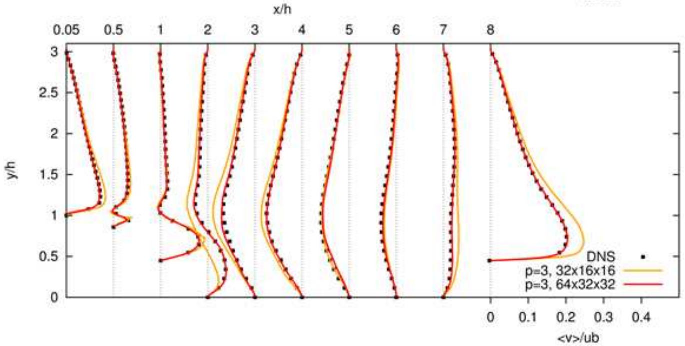




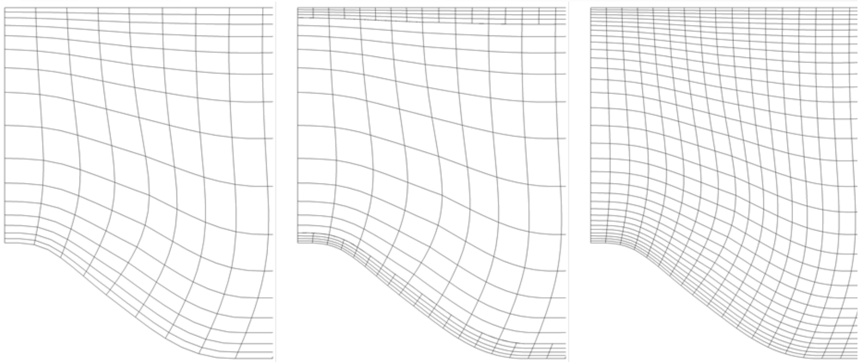
p=3 (4th order)

	# cells	DoFs/eqn
coarse	32x16x16	1.64e5
fine	64x32x32	1.31e6

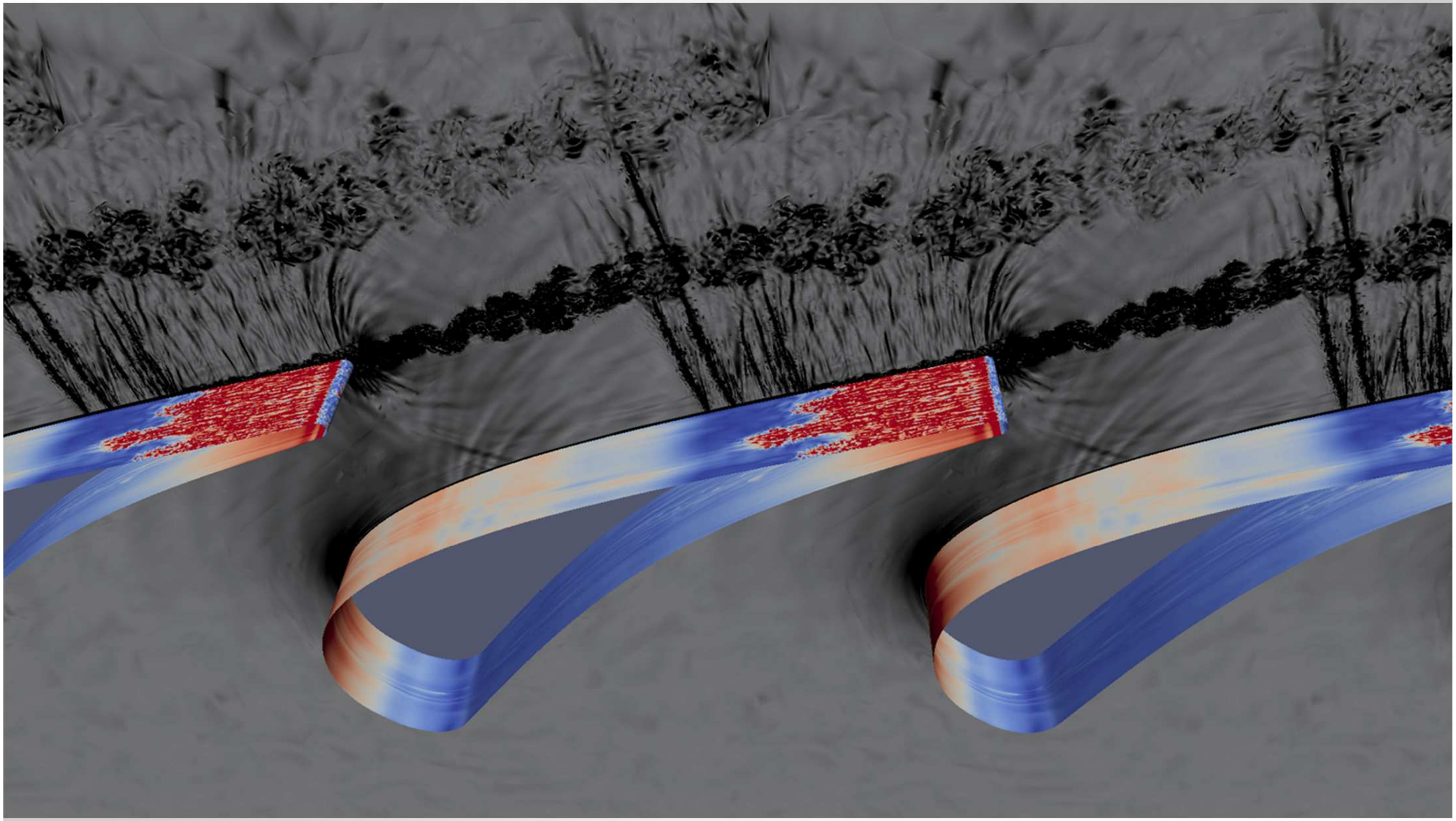
Ongoing work:
Comparison of solutions
- on globally refined meshes, and
- on near-wall locally refined meshes



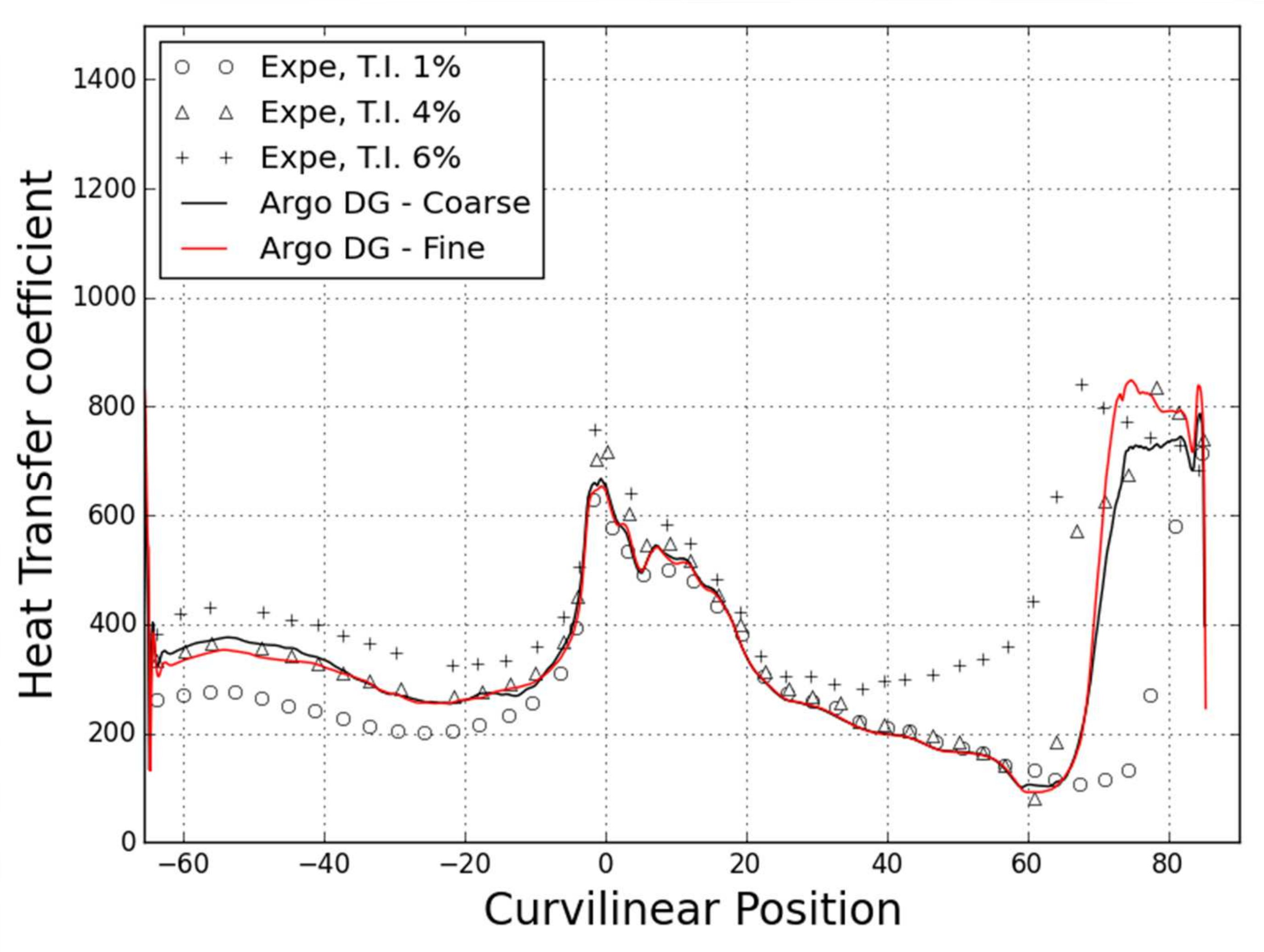
Velocities averaged over the convective time units:
tc = 102 – 122
(mass-weighted averages)



Validation ILES on LS89



Validation DGM/ILES on LS89

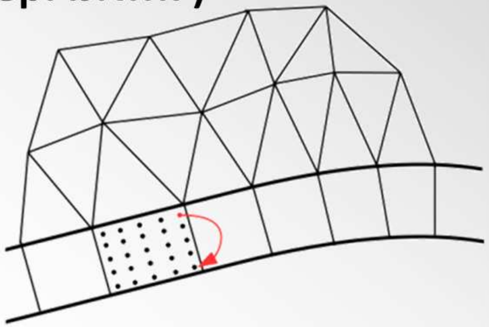


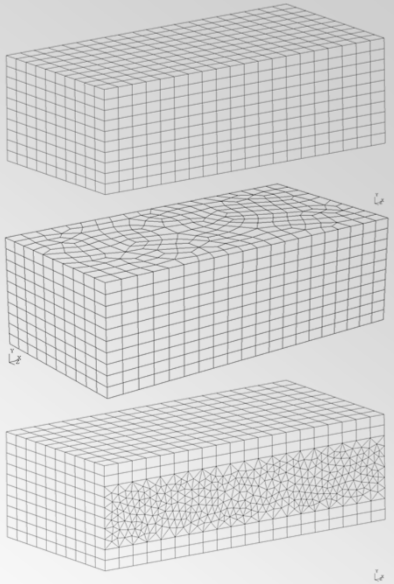
DGM/Wall Modeled ILES – calibration/validation

Apples project / PhD A. Frère

Calibration channel flow Re_τ=5.200, 50.000 (prep. IJNMF)

- parametric and physical location of intercept
- order dependence
- normal aspect ratio
- tangential aspect ratio
- grid type



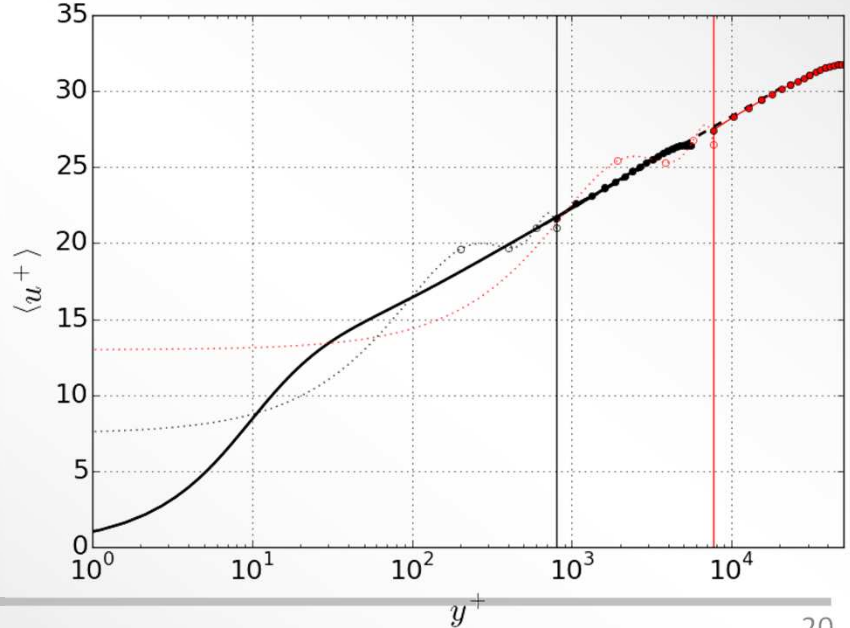


Technical constraints

- local / instantaneous (convergence, homogeneity)
- 'lower' orders of interpolation 3 -> 5
- elements on processor - parallel scaling

Conclusions

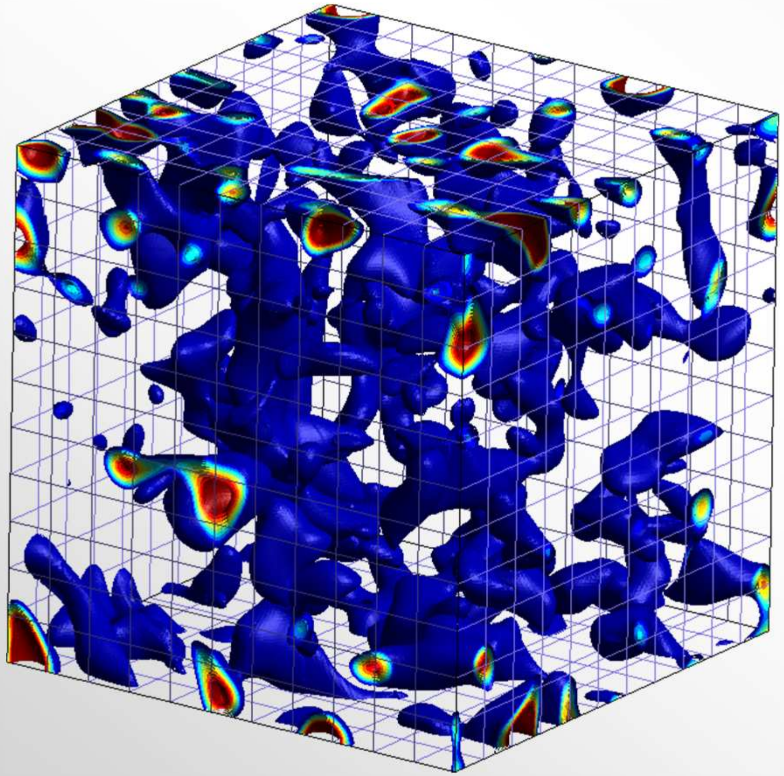
- high order P >= 4 required near wall
- grid type / tangential wall aspect ratio insensitive
- log layer intercept required
- erratic behavior in first cell …
- … but very good correspondence later on
- instantaneous and local (<-> averaging) sufficient

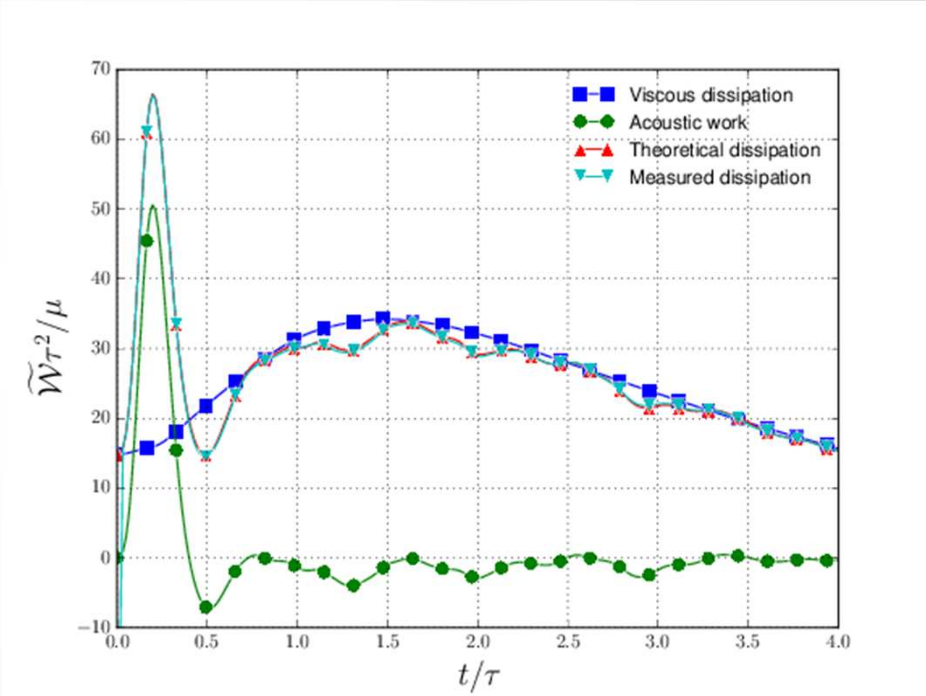


Future work

- non-equilibrium models (1D RANS normal to the wall)
- transition criteria

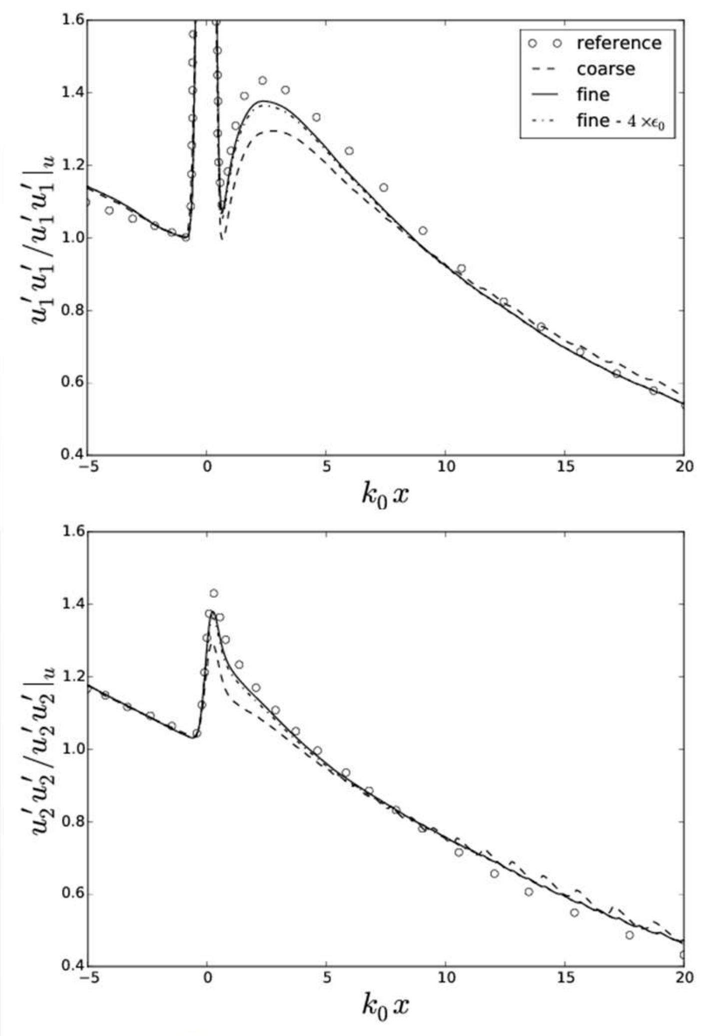
DGM/ILES transonic HIT – Energy balance (CTR)

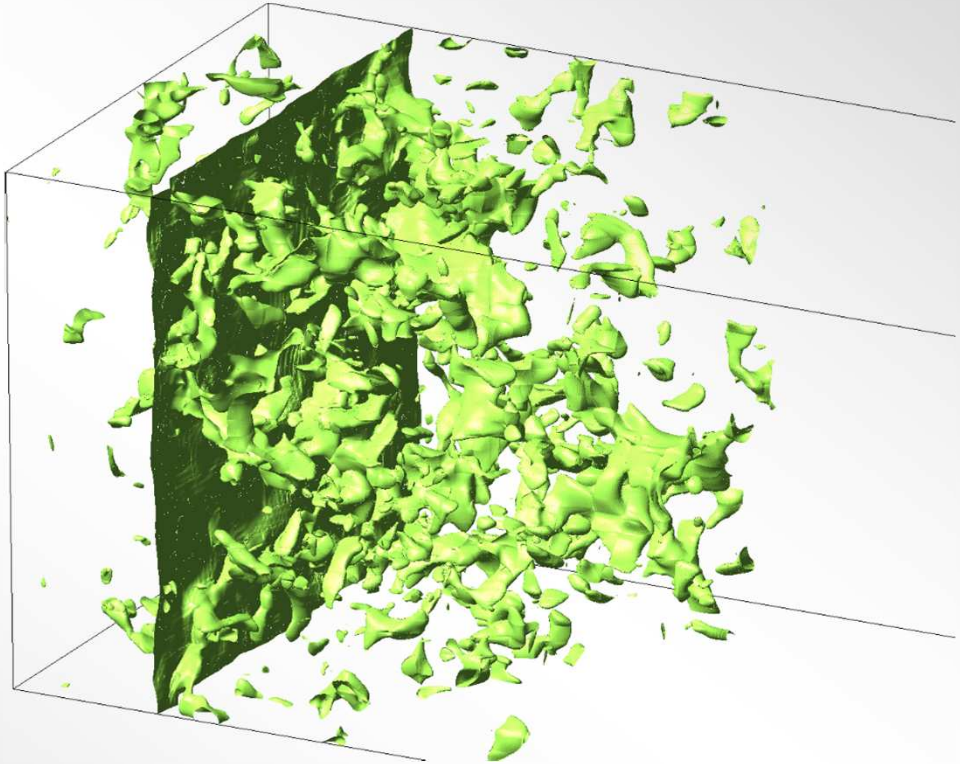




M_t=0.6, Re_λ=100, 64^3

DGM/ILES of shock-turbulence interaction (CTR)



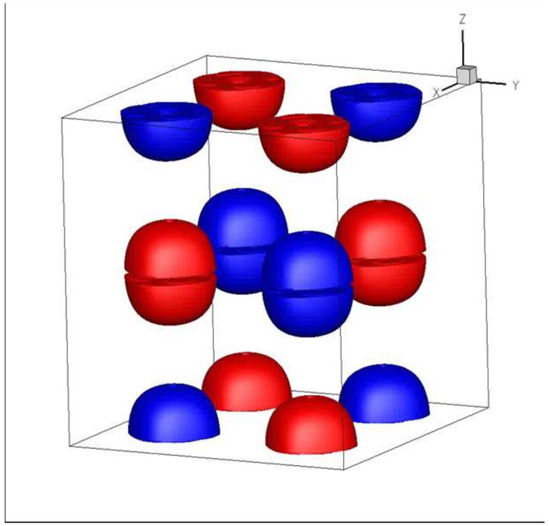


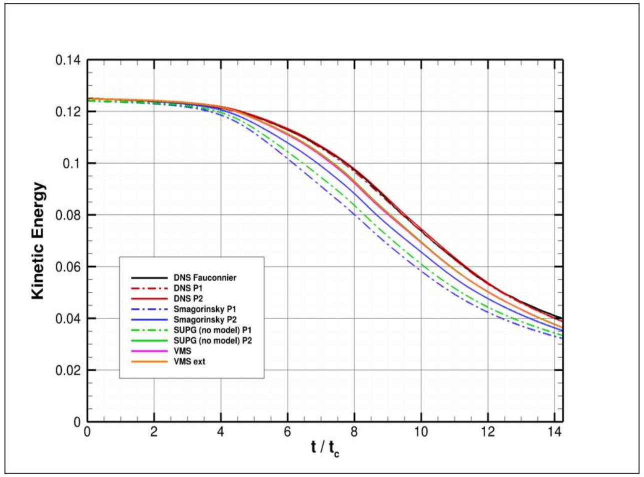
M=1.5, M_t=0.22, Re_λ=100, 64^2

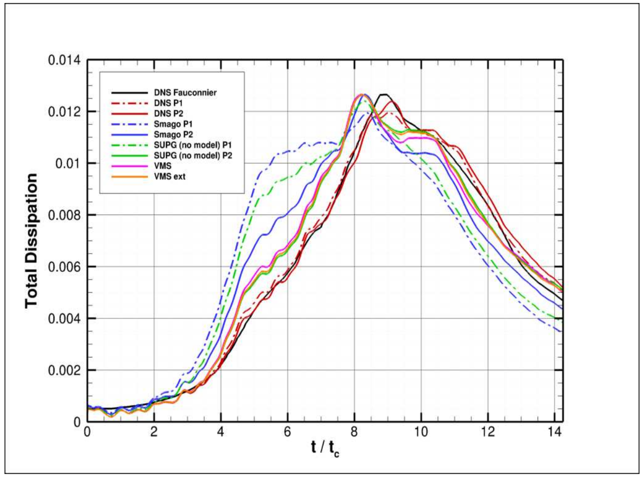
Description of Dassault Aviation CFD code AeTher

- **in-house compressible Navier-Stokes solver**
  - stabilized *continuous* Finite Elements formulation
    - SUPG: Streamline-upwind Petrov Galerkin
  - symmetric form of the equations written in terms of entropy variables
  - up to 4th-order with P3 tetrahedra
  - fully implicit time integration
  - highly scalable: strong scalability demonstrated up to 16,384 MPI processes

TC-F2: Taylor-Green vortex





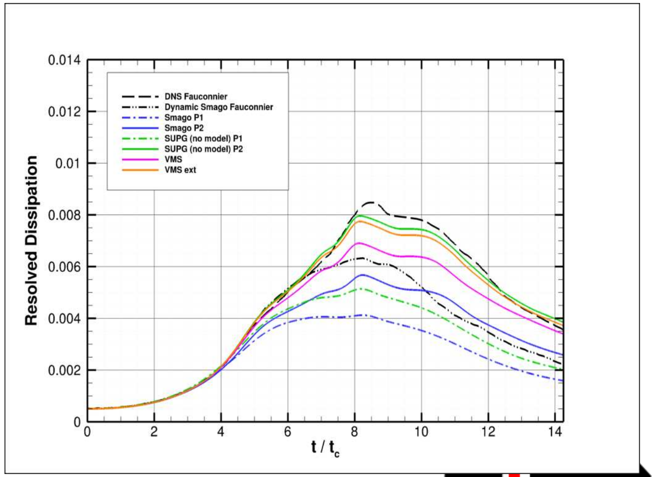


- **DNS: 256^3, Re=1500**
- **LES: 64^3 (64x coarser)**

D. Fauconnier

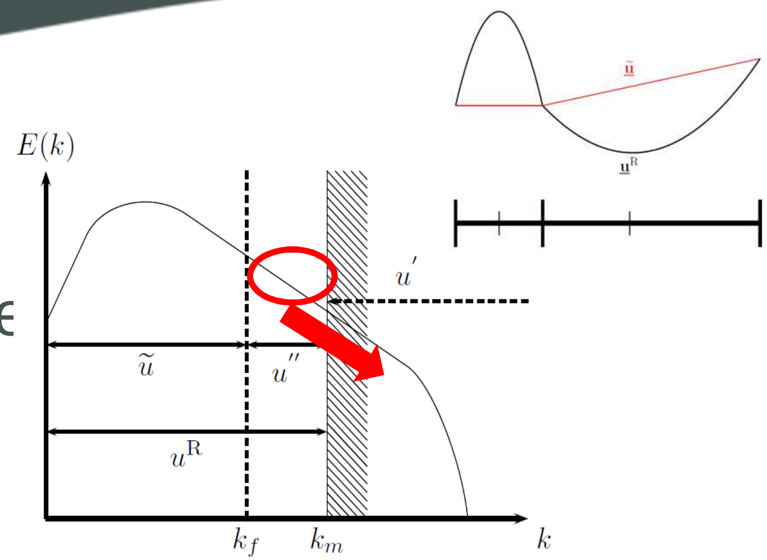
Development of a Dynamic Finite Difference Method for Large-Eddy Simulation

Ph.D. Thesis, Universiteit Gent, 2008

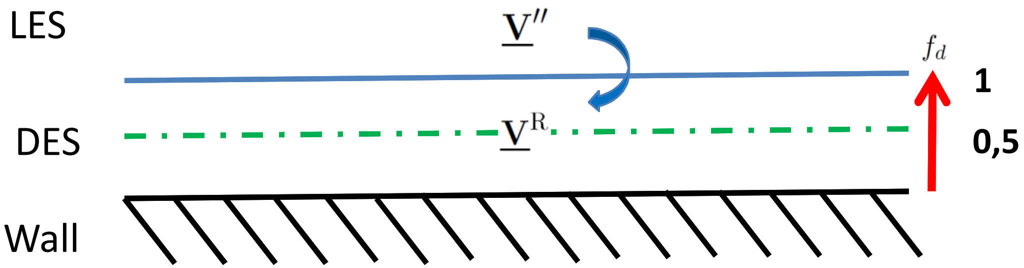


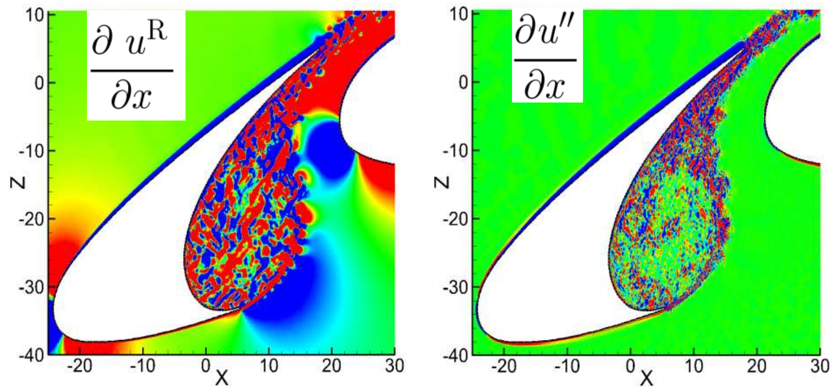
Higher-order LES

- **Multi-level approach**
  - VMS with explicit filtering at the element level
- **Wall-modeled LES**
  - hybrid approach: VMS-based DES



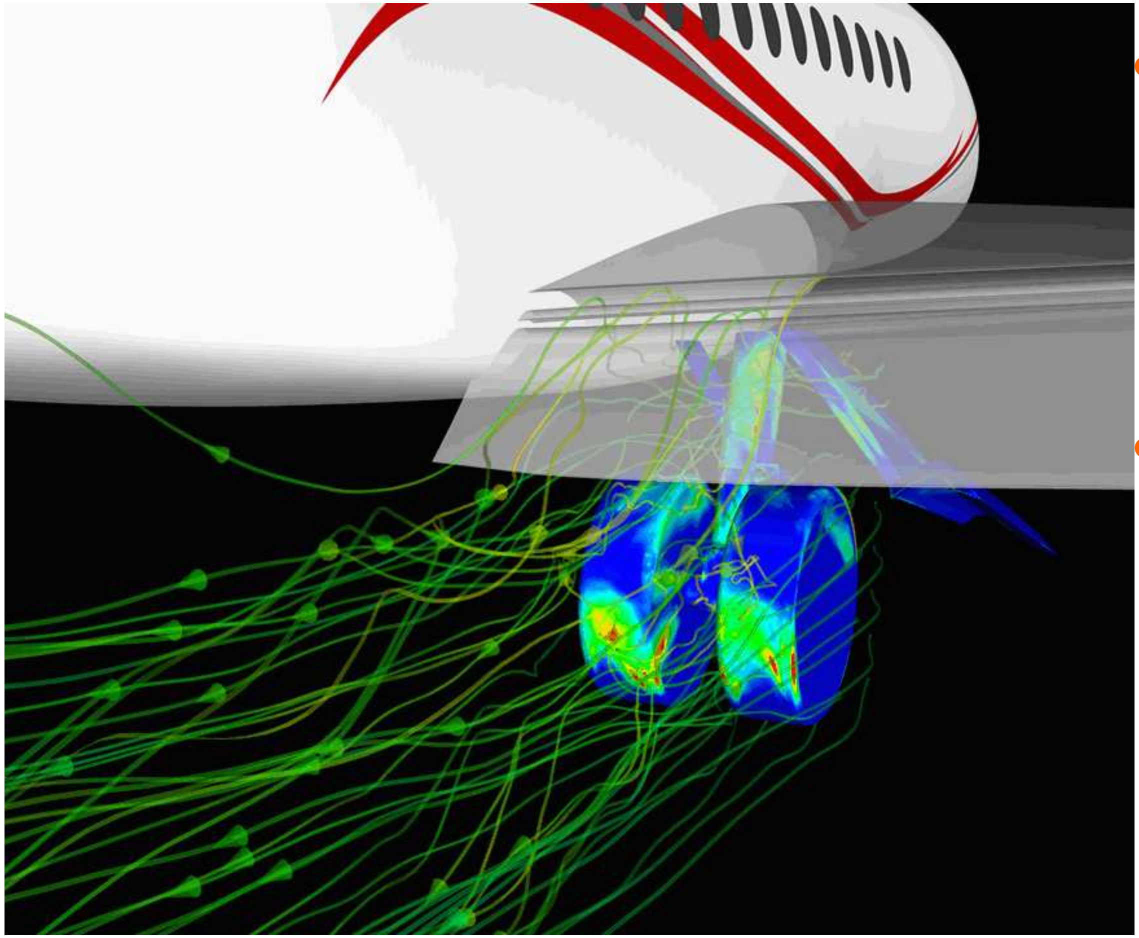
efficient separation of scales





Future work: TC-P2

Generic Falcon business jet in landing configuration



- **complete Falcon**
  - high-lift devices
  - landing gear
- **expected turn-around time**
  - 2-3 days on 50,000 cores

University of Bergamo

UNIBG's main tasks within TILDA

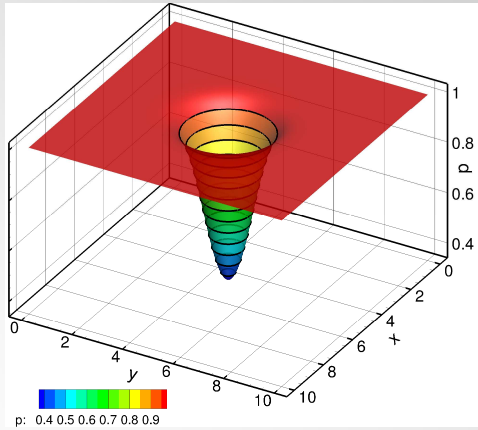
- To apply implicit time integrators to the under-resolved simulation of turbulence
- To take advantage of *h/p*-adaptation and modern parallel computer architectures

To date Several high-order temporal schemes are implemented

- Modified Extended BDF
- Two Implicit Advanced Step-point (TIAS)
- Explicit Singly Diagonally Implicit R-K (ESDIRK)
- linearly implicit Rosenbrock method

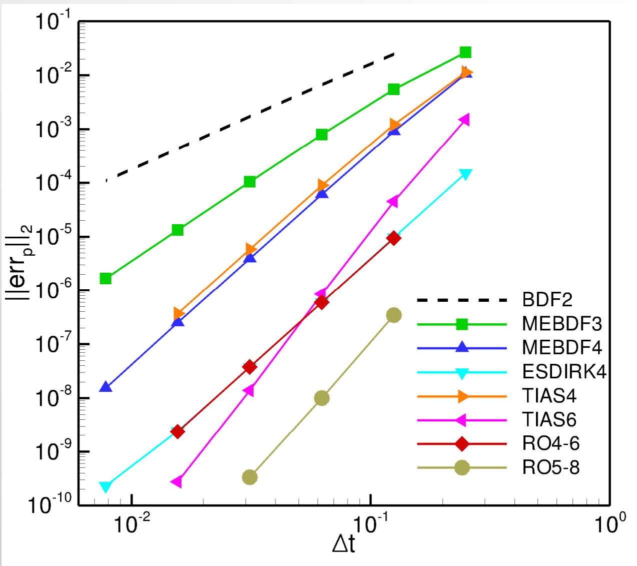
} *non-linear systems solution*

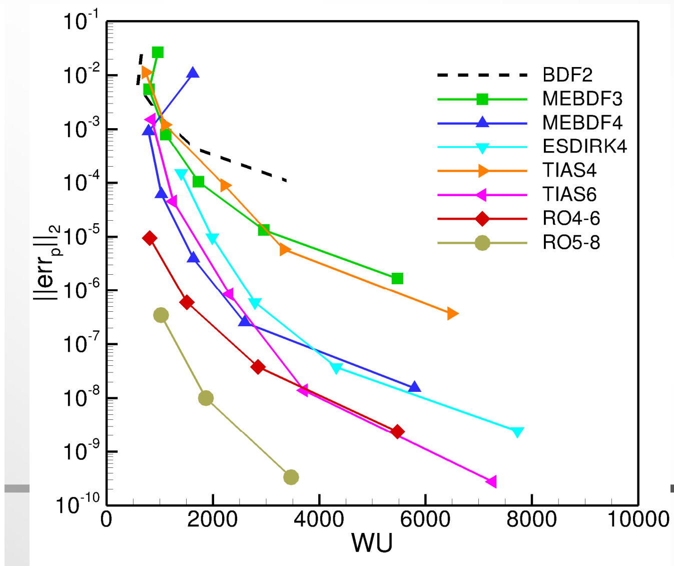
linear systems solution (here via GMRES)



i) Hi-O schemes are more efficient than Lo-O ones for high required accuracy

ii) Rosenbrock-type schemes are appealing both for accuracy and efficiency

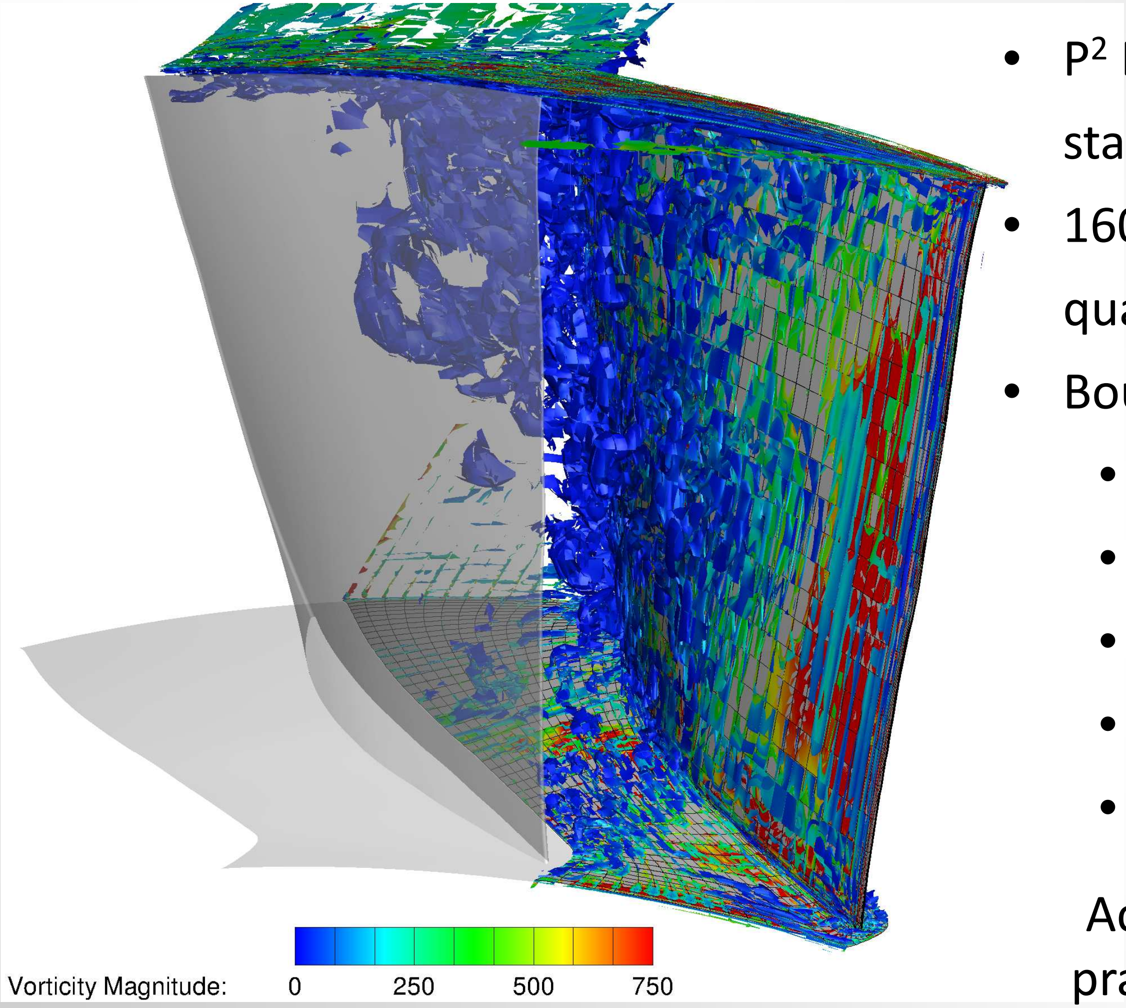




Convection of an isentropic vortex P^6 solution on 50x50 el.

UNIVERSITÀ DEGLI STUDI DI BERGAMO

X-LES (hybrid RANS\LES) of the transonic flow in the NASA Rotor 37



iso-surface of Q-criterion

- P^2 DG computation using a 3rd order 3 stages Rosenbrock scheme (ROS3P)
- 160512 hexahedral elements with quadratic edges
- Boundary conditions
  - p_{01} = 101325Pa
  - T_{01} = 288K
  - ω = 1800rad/s
  - Tu_1 = 3%
  - α_1 = 0°

According to our experience, for a practical usage of X-LES, initializing with RANS seems mandatory

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28

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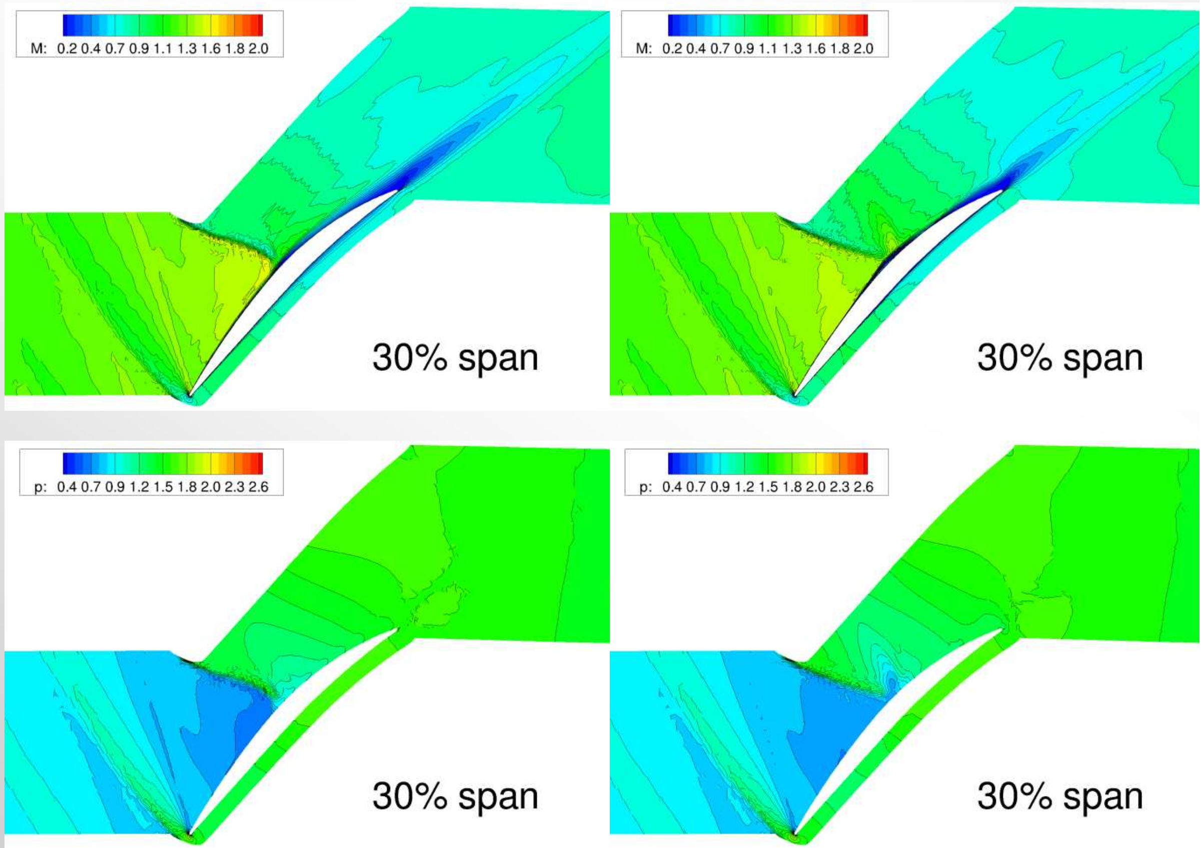
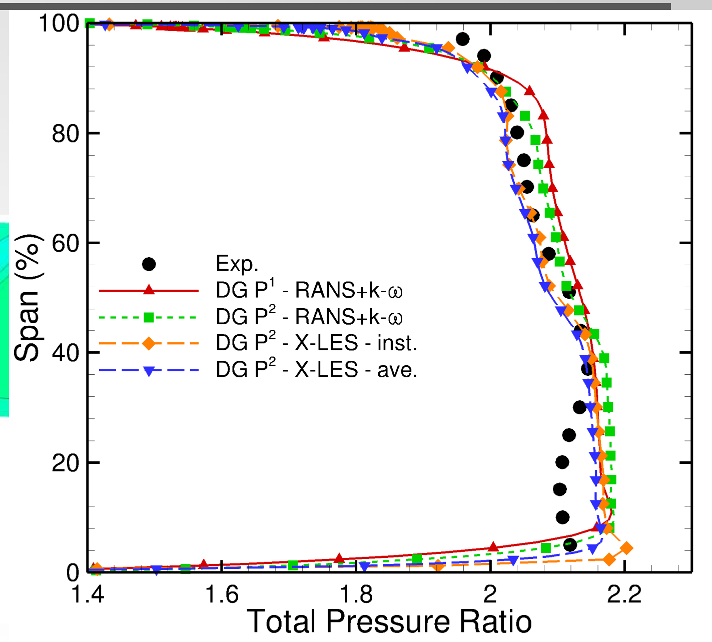
X-LES of the NASA Rotor 37

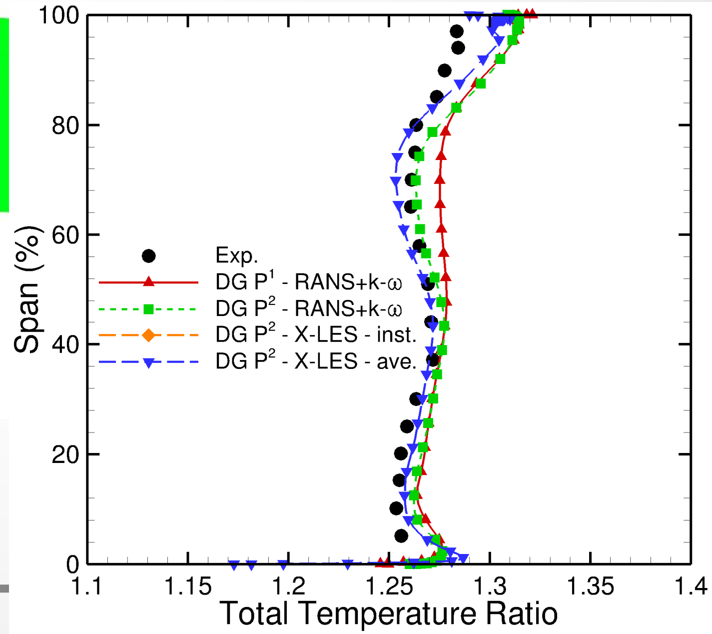
Spanwise section contours and distributions



RANS

X-LES
(time averaged)





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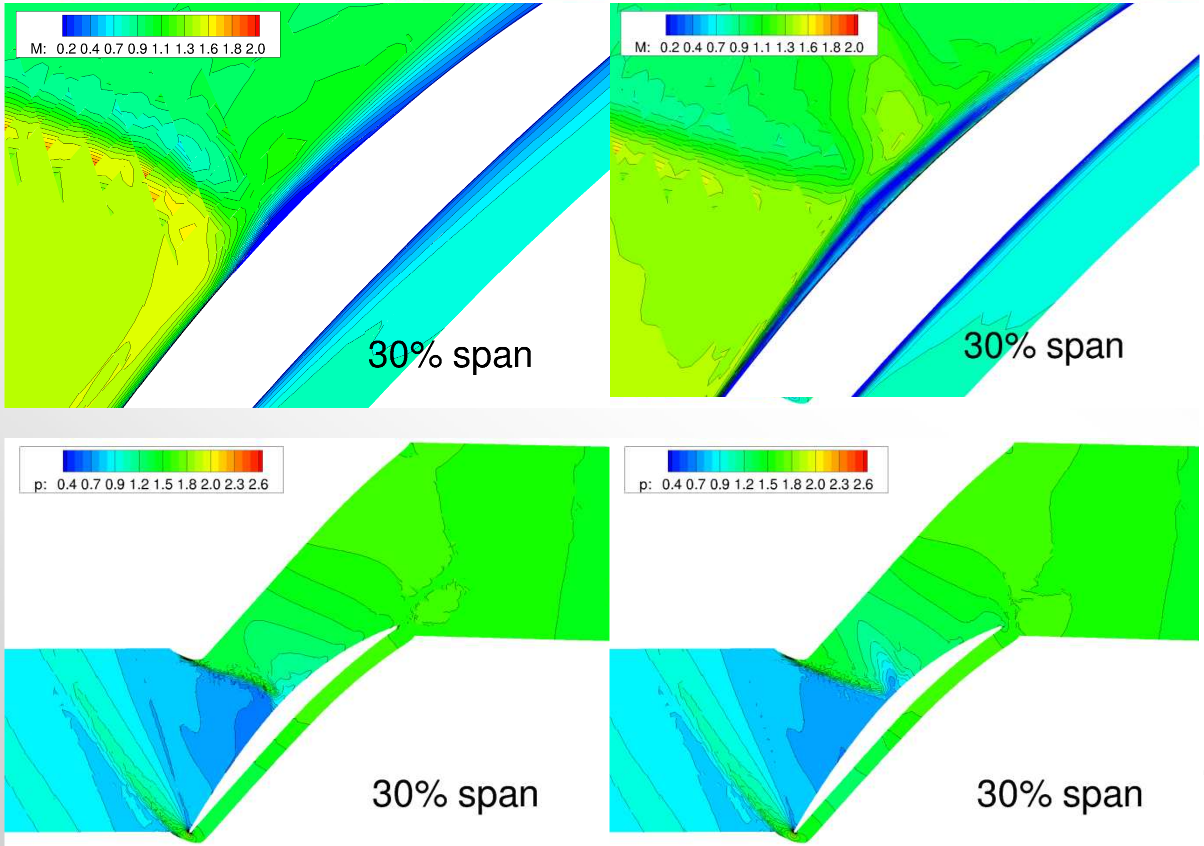
X-LES of the NASA Rotor 37

Spanwise section contours and distributions

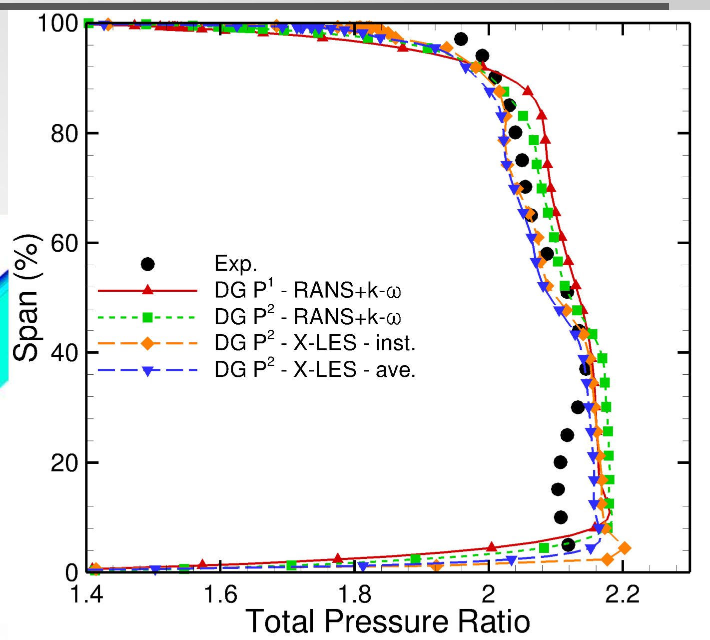
shock-boundary layer interaction detail

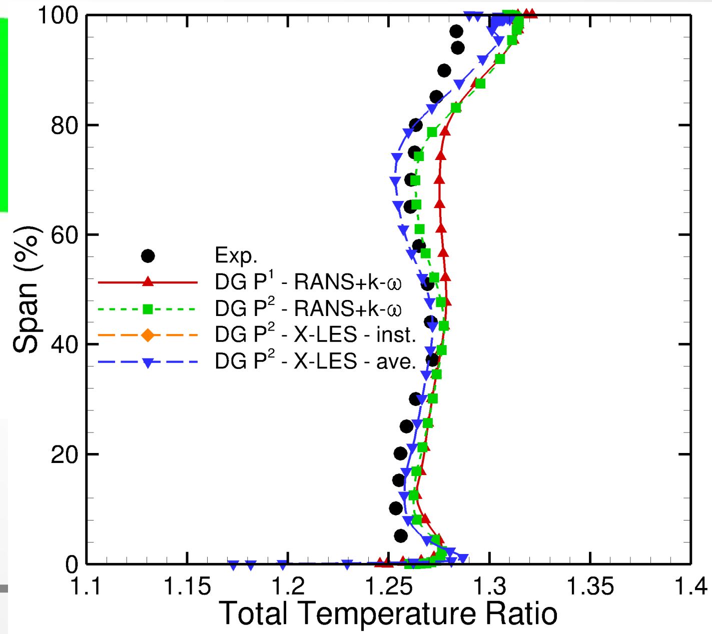


RANS

X-LES

(time averaged)





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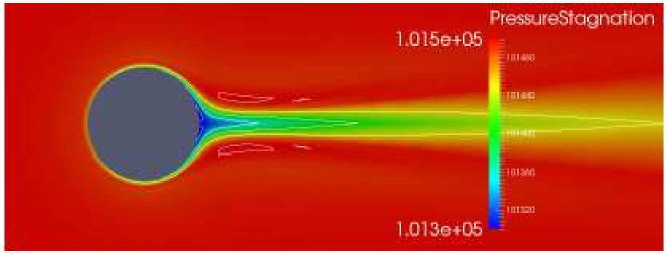
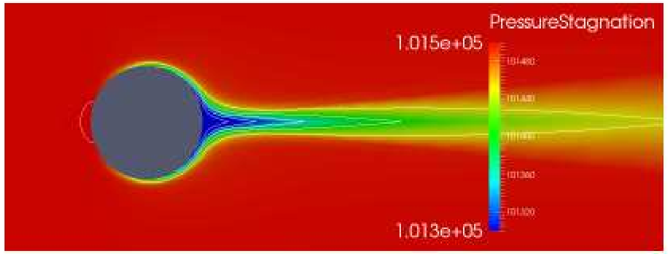
Cylinder. Total pressure flowfield

Grid 128x32x1

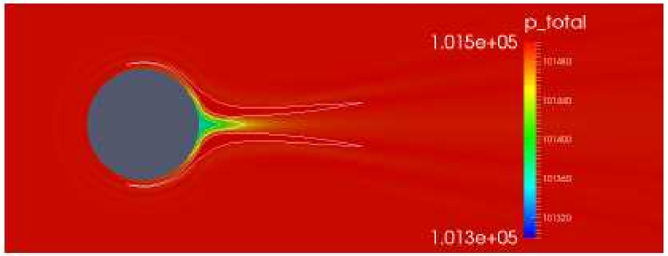
FV, Central



DG, K=1



FV, WENO5



DG, K=3, curvature

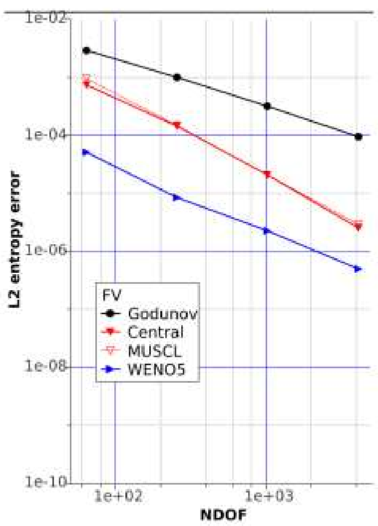
TsAGI

Cylinder. Error of entropy in the L2 norm

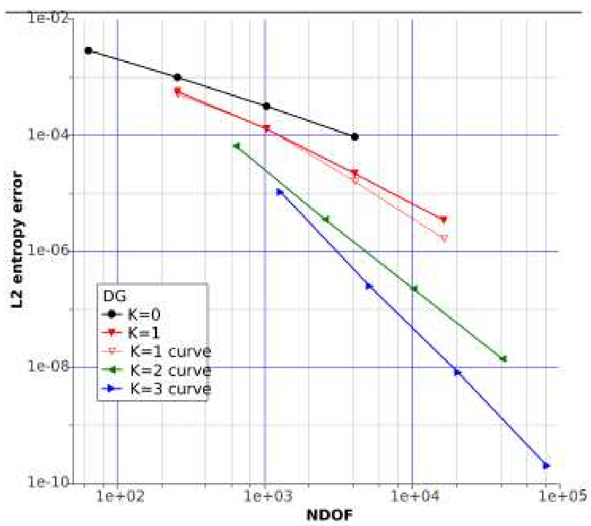
$$e_{entropy} = \left(\frac{p}{p_\infty}\right) \Big/ \left(\frac{\rho}{\rho_\infty}\right)^{\kappa} - 1, \qquad Order = 2\,\frac{\log\left(e_{i-1}\;/\;e_i\right)}{\log\left(NDOF_i\;/\;NDOF_{i-1}\right)}.$$

$NDOF$ = the product of the mesh size and the number of degrees of freedom.

FV



DG



The same result for the drag

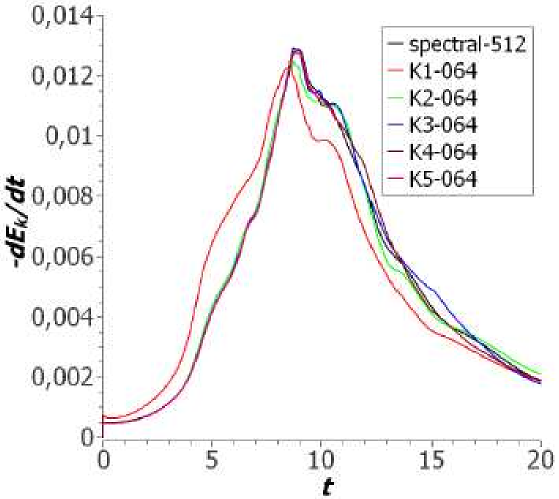
TsAGI

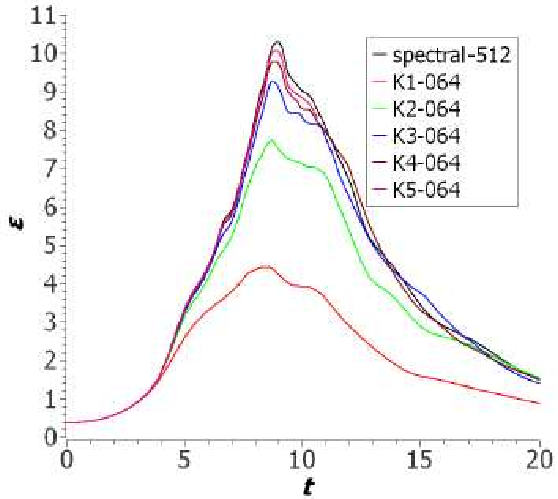
Taylor-Green Vortex. Base TILDA testcase

TsAGI

Mandatory results:

$$E_k = \frac{1}{\rho_0 \Omega} \int_\Omega \rho \frac{v \cdot v}{2} d\Omega \qquad \epsilon = \frac{1}{\rho_0 \Omega} \int_\Omega \rho \frac{\omega \cdot \omega}{2} d\Omega$$



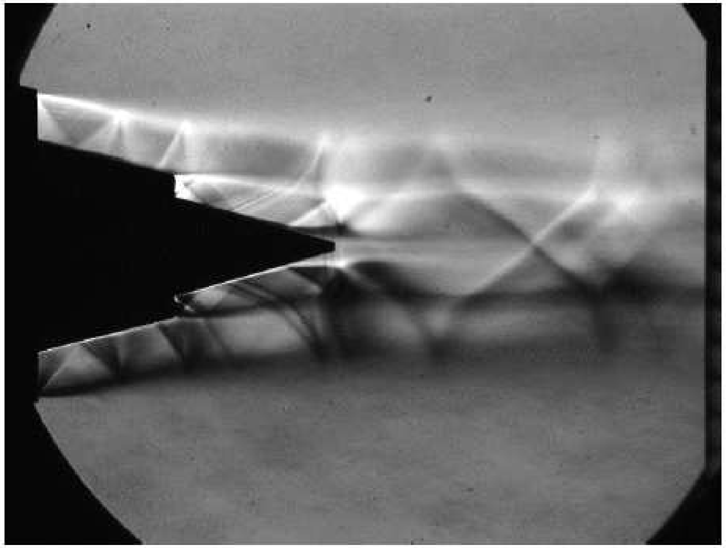


Comparison with spectral method at fine mesh

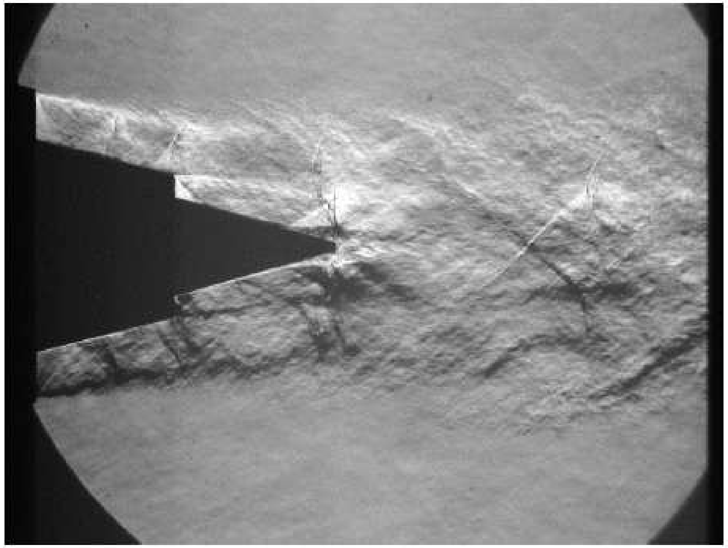
W.M. van Rees, A. Leonard, D.I.Pullin and P. Koumoutsakos, A comparison of vortex and pseudo-spectral methods for the simulation of periodic vortical flows at high Reynolds number, J.Comput.Phys., 230(2011), 2794-2805

Shlieren-visualization of dual-stream jet. Supersonic uderexpanded jet on inner (1) and outer (2) stream jet

Flow regime - Npr1= 5.0, Npr2=2.8



Exposure equal 0.01 sec



Exposure equal 3 microsec

TsAGI

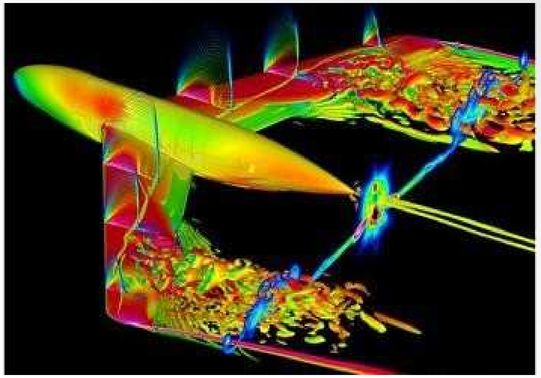
Stakes and prospects in CFD 2020/2030

Progress: 2nd-order CFD based on RANS models mature but ...

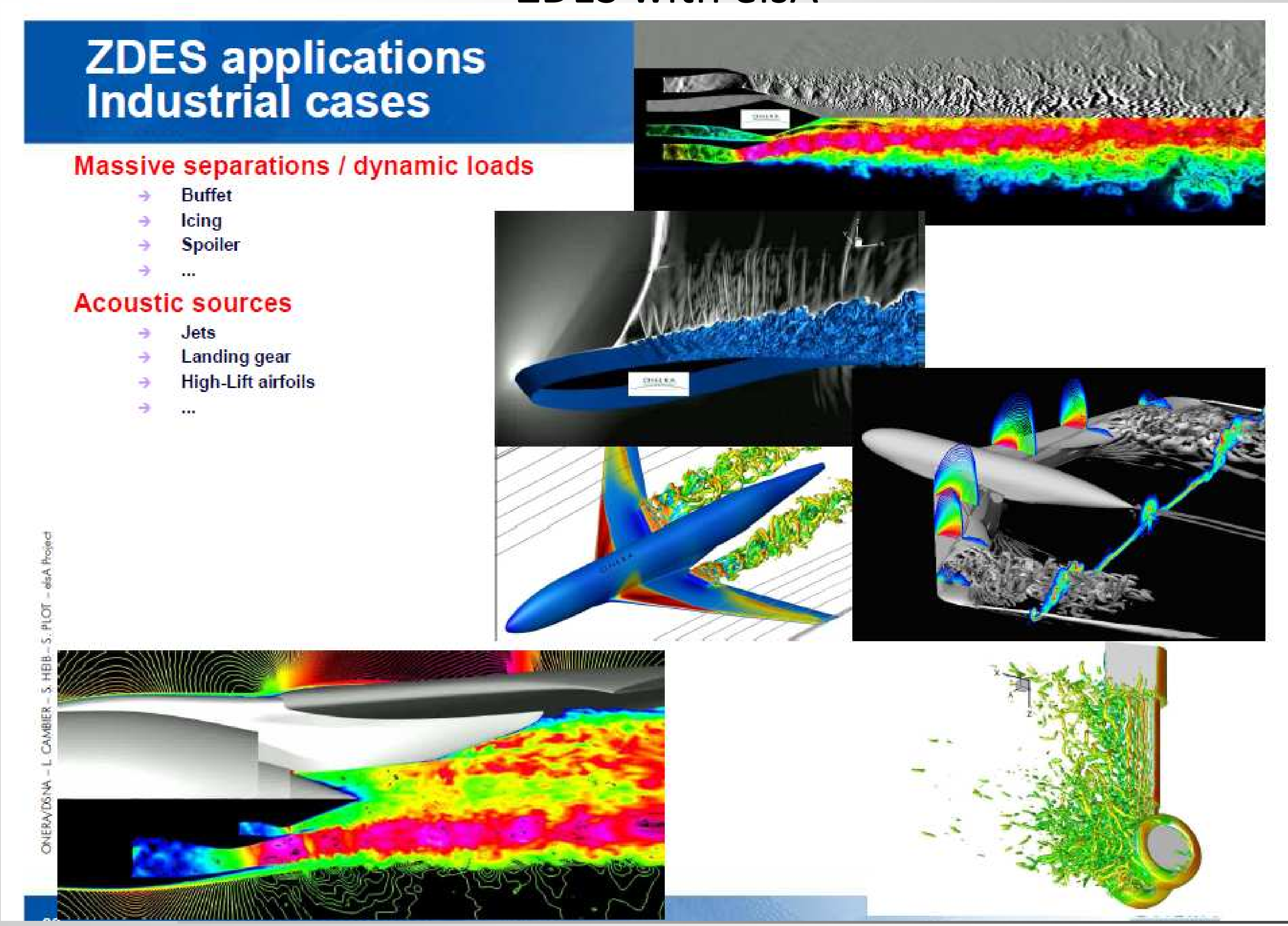
- RANS models limited to “nominal” flow configurations
- Mesh convergence analysis show the limitations of classical 2nd-order methods (regularity, resolution, etc.) → improve by means of *hp*-adaptation
- Accurate imposition of boundary conditions still a problem for sensitive configurations
- Unsteady (LES) computations required for configurations of practical interest

Challenges:

- High-fidelity CFD methods require firstly accuracy
- Level of modeling : Hybrid RANS/LES, LES, DNS
- Accuracy of space-time discretization
- HPC parallelization
- *hpm*-adaptation for accuracy and efficiency
    - *h* : mesh refinement
    - *p* : order of accuracy (polynomial degree)
    - *m* : physical model
- Huge data management for pre-, co-, and post-processing


DES computation using elsA

ZDES with elsA



Why high-order DG ?

- Arbitrarily high-order of accuracy on unstructured grids
- Low dissipation, dispersion
- Boundary conditions:
  - The order of accuracy of the numerical scheme is conserved at the boundary
  - Possibility to enforce boundary conditions weakly (Collis, 2002)
- Provide local information in physical and spectral space (hp-adaptivity)
- Orthogonal hierarchical basis that supports multiscale turbulence modelling
- Compact schemes $\rightarrow$ ideal for HPC

Cons of high-order DG

- Robustness issues (Runge phenomena at discontinuities)
- Time explicit discretization: (linear scalar advection: Chavent Cockburn '89, Cockburn Shu '91 '01)

$$CFL \leq \frac{1}{2p+1}$$

- High computational cost (volume integral, numerical quadratures, etc.)
- Large memory requirements (large number of DOFs / element)

Aghora : The current status (1/2)

- The full set of compressible Navier-Stokes equations can be solved in 3D
- Modal approach: the degrees of freedom (DoFs) are the coefficients of the polynomial expansion :

$$\mathbf{u}_h(\mathbf{x}, t) = \sum_{k=1}^{N_p} \phi^k(\mathbf{x}) \mathbf{U}_j^k$$

→ natural implementation of multiscale turbulence models and p-adaptation.

- Nodal approach (recently implemented, PhD thesis Raphaël Blanchard) → gain in CPU cost
- Multi-element meshes (hexahedra, tetrahedra, prisms)
- Convective fluxes : Lax-Friedrichs, Roe, etc. numerical fluxes across the interfaces.
- Viscous fluxes : Bassi-Rebay 2 (BR2, JCP 1997) scheme or Symmetric Interior Penalty method (SIP)
- Order of the spatial scheme given by the specified polynomial degree
- Shock capturing technique based on entropy production (Guermond et al., 2011)
- Explicit time integration : up to 4th-order Runge-Kutta schemes
- Implicit time integration : several time-integration strategies (Renac *et al*, JCP 2013)
    - Inexact Newton method : solution of linear system by GMRES + ILU0 preconditioning (with mixed precision algorithms)
    - ESDIRK (Explicit Singly Diagonal Implicit Runge-Kutta)
- CFL evolution from pseudo-transient continuation technique
- Dual-Time stepping technique

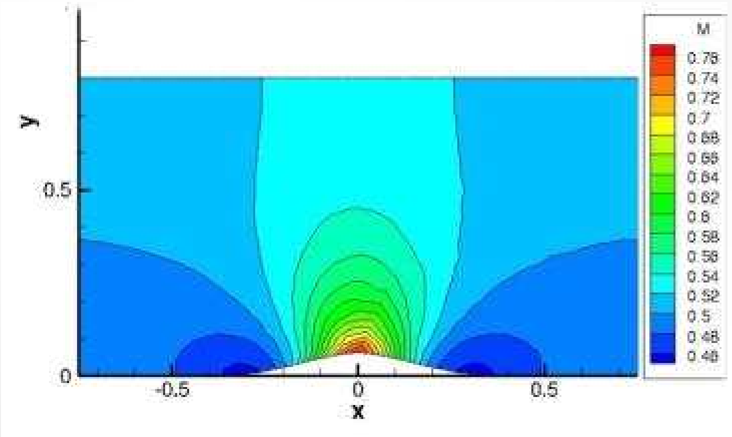
Aghora : The current status (2/2)

- Economical quadrature rules[3] (use element symmetries to reduce number of integration points)
- Shock capturing methods (Hartmann & Houston 2002, Hartmann 2013, Guermond et al. 2011) ppp
- General thermodynamics : p = p(ρ, ρe) (e.g. stiffened gas, wan der Waals EOS)

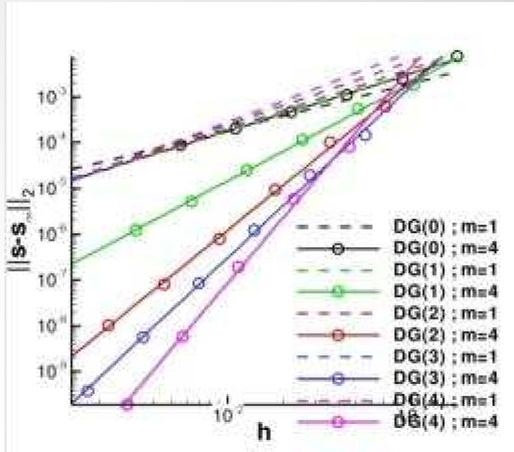
Turbulence modelling:

- RANS Wilcox $\kappa - \omega$ model (Wilcox 1993): $\kappa - \omega$ and $\kappa - log\,(\omega)$ formulations (Bassi et. al 2005, 2009, Hartmann 2012). Spalart-Allmaras model.
- DNS simulations (TGV at Re = 1600, dipole-wall collision problem at Re = 1000, incompressible and 2D periodic hill at Re_b = 2800)
- LES simulations : Variational Multiscale Simulation, VMS, and residual-based VMS, RBVMS, (HIT, TGV, channel flow)
- ZDES simulations
- Turbulent injection conditions : SEM (Synthetic Eddy Method)

Aghora / DG – Verification of method accuracy : scheme / geometry

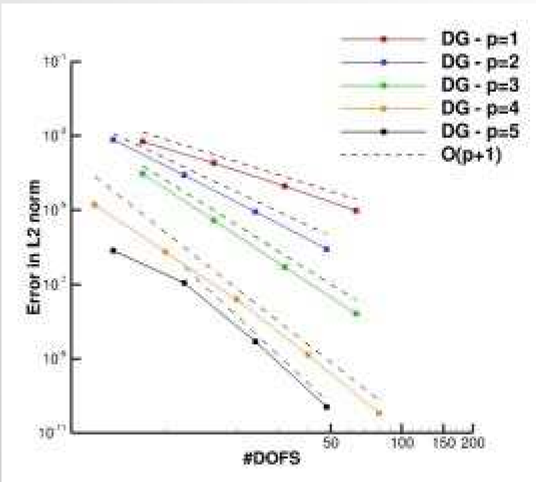


Subsonic Euler flow

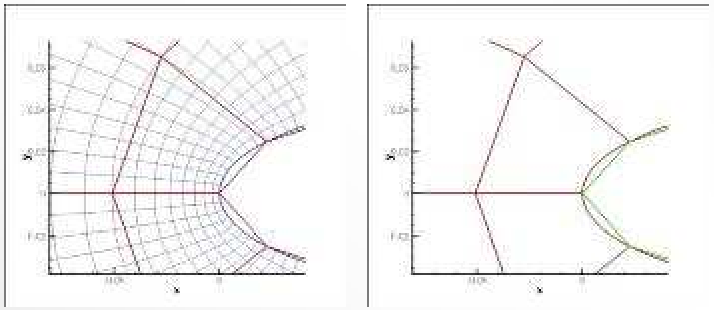


Entropy error vs. Mesh refinement

High-order scheme/geometry for accuracy of HO spectral type schemes (Aghora – HOCFD 2012)

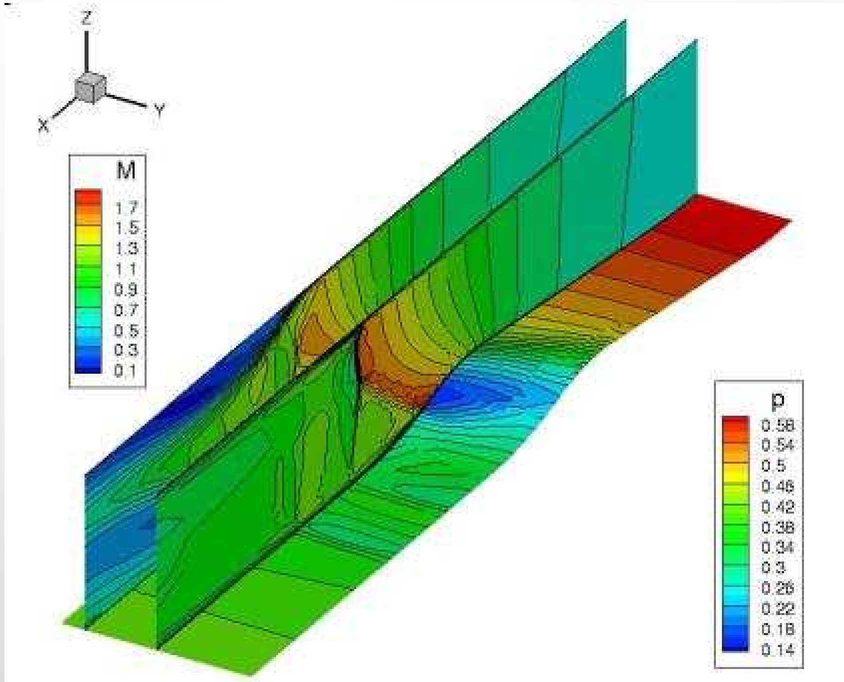


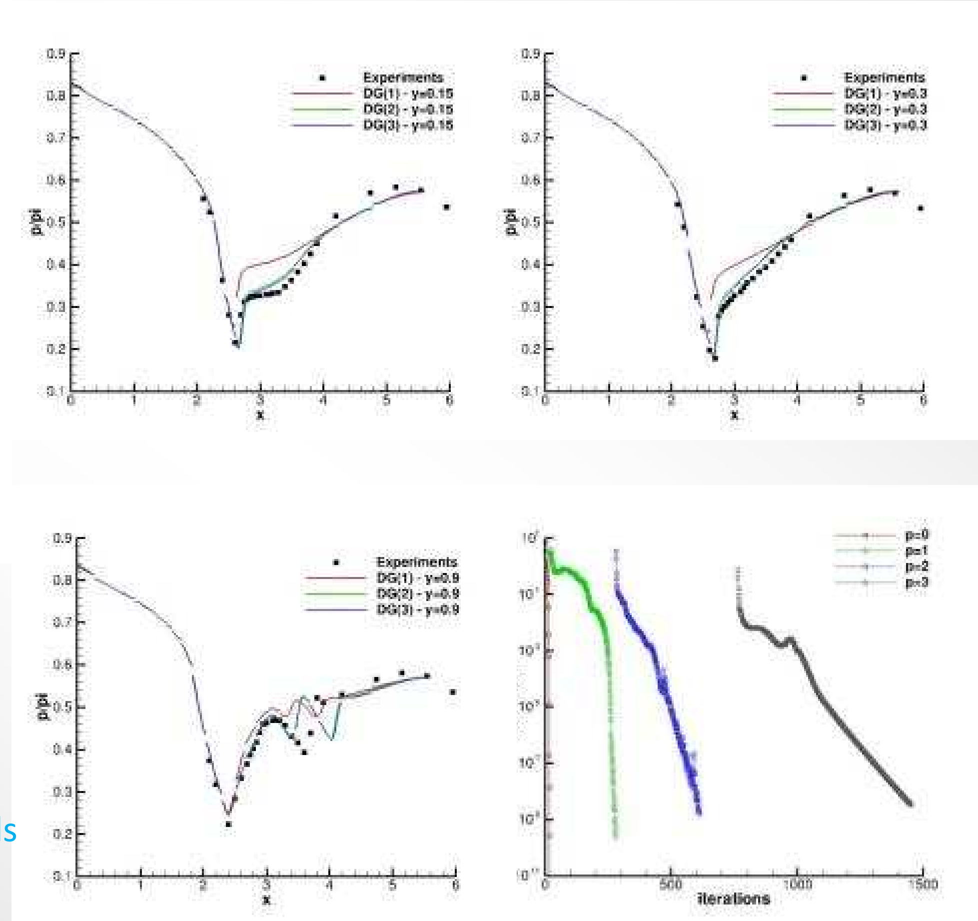
Strong demand on of High-Order meshes



Aghora – Bosse 3D Onera / Calculs DG avec modèle RANS/SA

ONERA
THE FRENCH AEROSPACE LAB





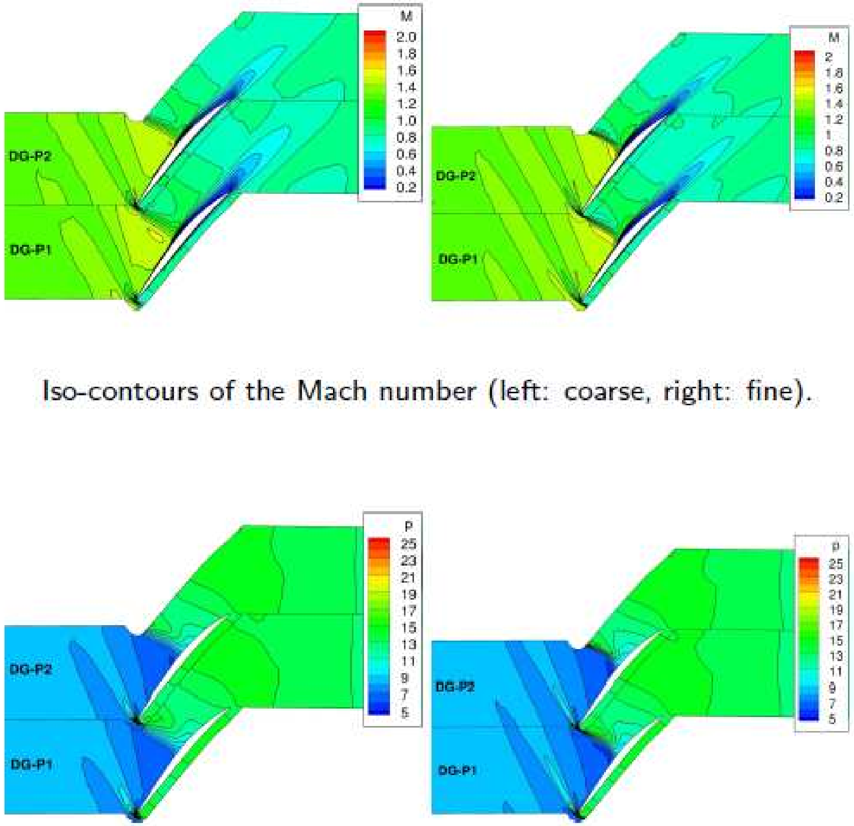
Implicit method with shock-capturing technique
Accuracy, effiiceny, robustness with HO DG
French GENCI projects 2015-2016
2400 cores using OCCIGEN
F. Renac, Intern. Workshop on High-Order CFD methods
AIAA 2015, ECCOMAS 2016

Aghora.

Aghora : NASA ROTOR 37 – DG computations with RANS/SA model

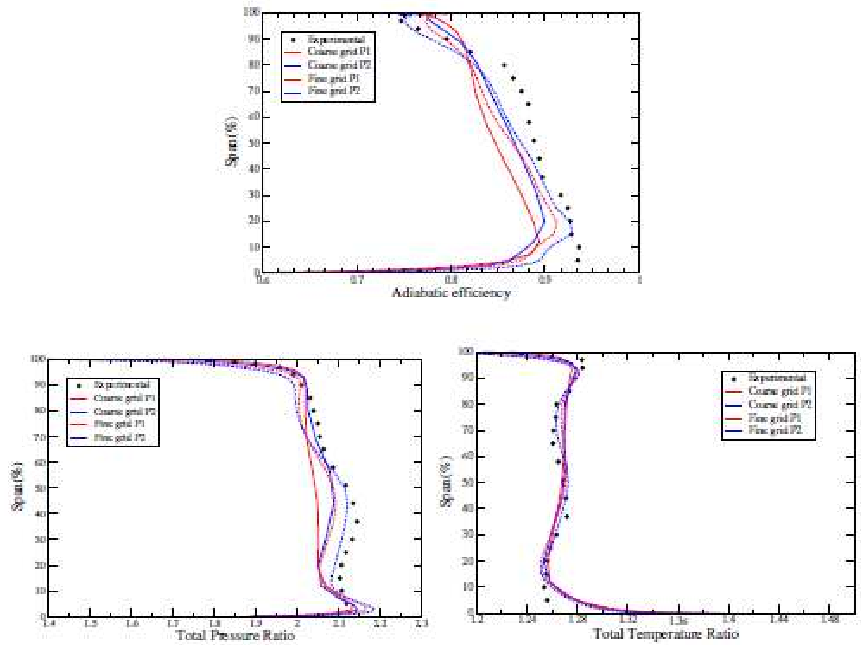
The NASA rotor 37 : DG-p1/p2 simulations on hexahedral meshes

Coarse mesh with 87,769 points, fine mesh with 672,896 points.



Iso-contours of the Mach number (left: coarse, right: fine).

Iso-contours of the static pressure (left: coarse, right: fine).

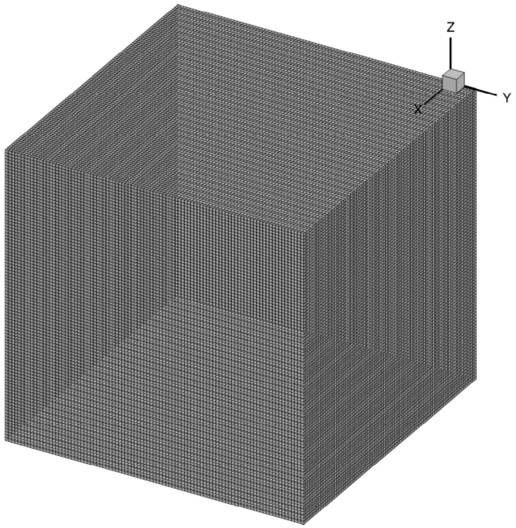


Spanwise profiles of adiabatic efficiency, total pressure ratio and total temperature ratio.

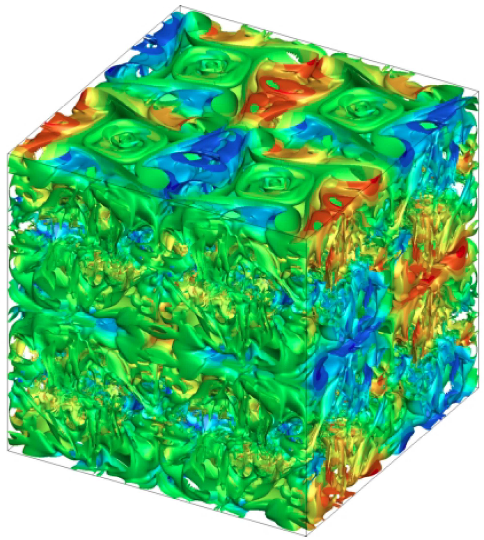
Strong scalability tests

Numerical experiments using the Taylor-Green vortex

- 3D compressible Navier-Stokes equations:
  - DNS of a periodic and transitional flow
  - $M_\infty = 0.1, \; Re = 1600$
  - IC: analytical velocity profile
- Numerics:
  - Explicit time discretization (SSP RK4)



(a) Mesh 96 elements



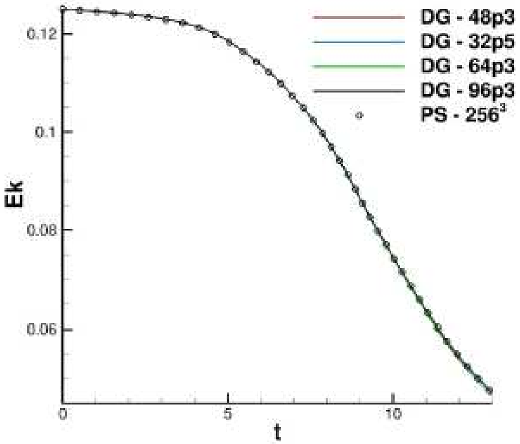
(b) Iso-surfaces of vorticity ($t = 14, \; p = 3$)

Aghora.

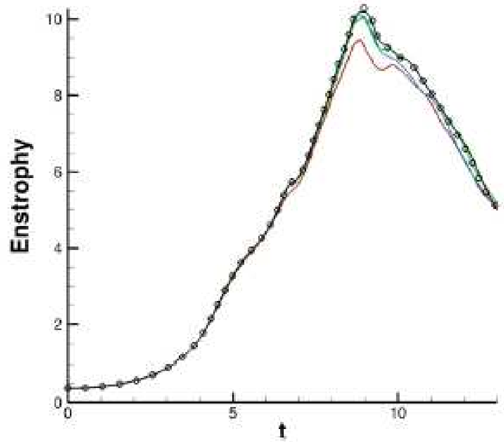
Taylor-Green Vortex – DNS computations – hp analysis

Decaying turbulence in a periodic box

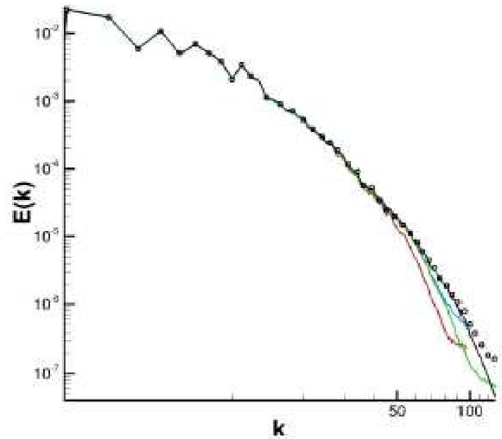
DG Comp.	DG 48p3	DG 64p3	DG 96p3	DG 32p5
Order (p+1)	4	4	4	6
#DoFs / Elements	192^3 / 48^3	256^3/ 64^3	384^3 / 96^3	192^3 / 32^3



Turbulent kinetic energy



Enstrophy



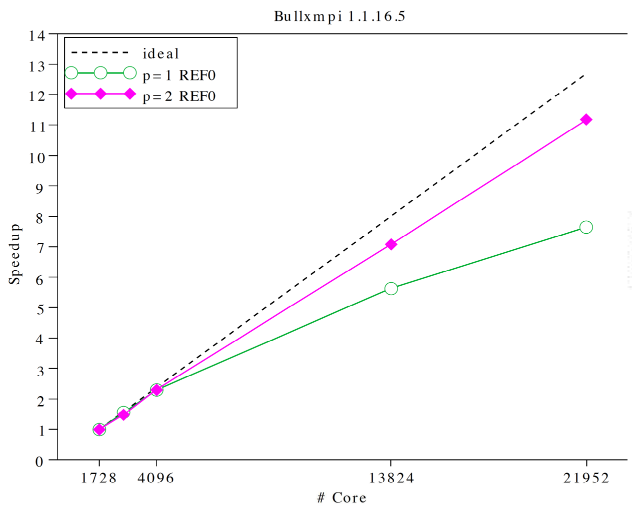
Energy spectra at peak

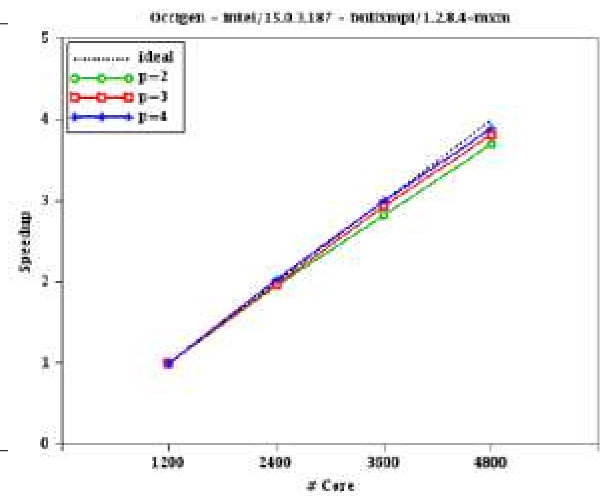
o Reference computation : Fourier pseudo-spectral code developed by S. Cant (Cambridge Univ.)

Strong scalability tests

Numerical experiments using the Taylor-Green vortex

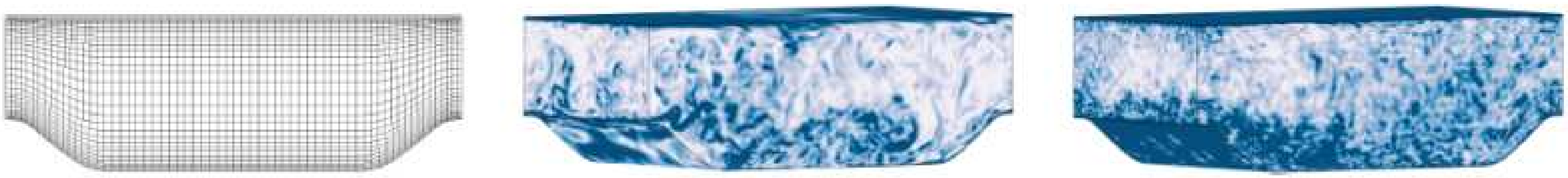
- Sensitivity of the polynomial degree p on the speedup with REF0 version on *Curie*
  - Strong scalability analysis on a mesh with 336 elements
    - Ratio elts/ghosts per domain $\sim$ 4 at the largest scale
  - Receive-send message frequency (measured with 13 824 cores)
    - $p = 1$, $\sim$ 41 messages/s
    - $p = 2$, $\sim$ 15 messages/s
    - $p = 4$, $\sim$ 02 messages/s
  - On 21 952 cores with $p = 2$, efficiency of the speedup $\sim$ 88%





Strong scalability analysis

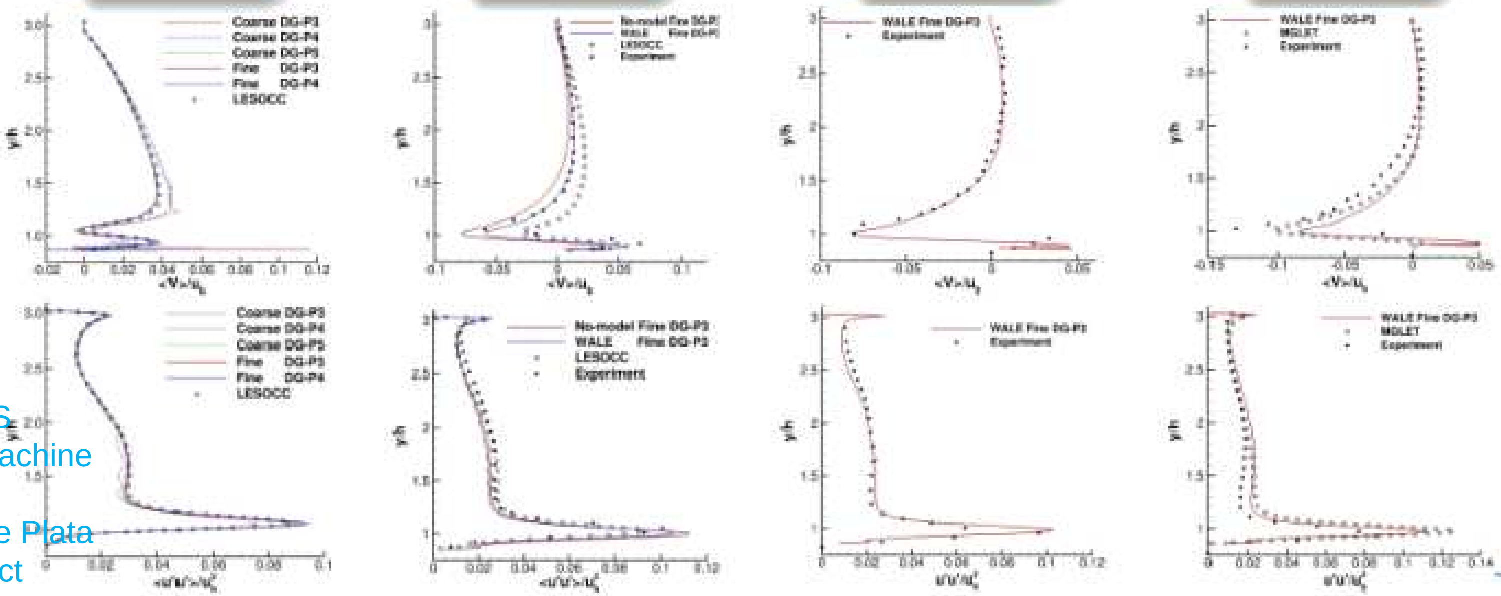
2D periodic hill at $Re_b = 2800$ up to $37\,000$: DNS & LES based on WALE approach
DG-P3 to DG-P5 on two levels of mesh refinement (0.5 to 4.2 MDOFs)



Fine 4th-order mesh $64 \times 32 \times 32$ | Vorticity magnitude $Re_b = 2\,800$ | Vorticity magnitude $Re_b = 10\,595$

Profiles of mean vertical velocity $\langle V \rangle$ and Reynolds stresses $\langle u'u' \rangle$ at station x=0.5h

$Re_b = 2\,800$ | $Re_b = 10\,595$ | $Re_b = 19\,000$ | $Re_b = 37\,000$



DNS and LES
OCCIGEN machine
2400 **cores**
M. de la Llave Plata
GENCI Project

Computation synthesis on Periodic hill computations

- **DNS at Re_b = 2800** :

  •*h* and *p* convergence analyses highlight the benefit of increasing *p* rather than reducing *h*
  •DG-p5 on coarse mesh (1.77M dofs) in good agreement with reference DNS (13.1M dofs)
  •Loss of resolution in vicinity of separation point for DG-p3 and DG-p4 coarse mesh simulations → local hp-adaption highly beneficial in marginally resolved areas

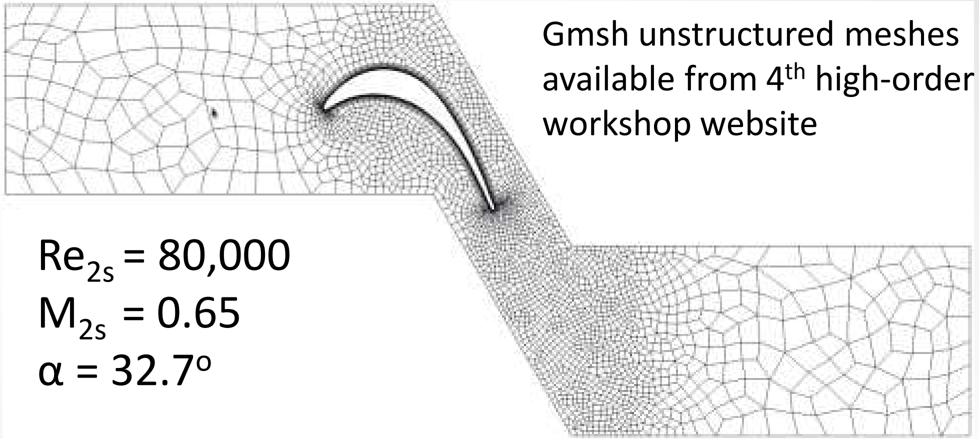
- **LES at Re_b = 10,595** :

  •Solutions from the no-model and the WALE approaches not fundamentally different.
  •WALE approach → slightly better results near separation point and in recirculation area.
  → smoothing effect on the interface jumps (in particular for <u'u'>)

- **WALE-based LES at Re_b = 19,000 and Re_b = 37,000** :

  •No-model approach does not provide stable simulations at this higher Reynolds number.
  •Overall good agreement with reference data, main discrepancies near separation point.

AS2 - Transitional flow in the T106C LPT



Gmsh unstructured meshes available from 4th high-order workshop website

Re_{2s} = 80,000
M_{2s} = 0.65
α = 32.7°

Simulation	# Elements	Order	# MDOFs
DG-P4 Coarse	30,768	5	1.1
DG-P5 Coarse	30,768	6	1.7
DG-P3 Baseline	146,426	4	2.9
DG-P4 Baseline	146,426	5	5.1
DG-P5 Baseline	146,426	6	8.2

DNS and LES
OCCIGEN machine
2400 **cores**
M. de la Llave Plata
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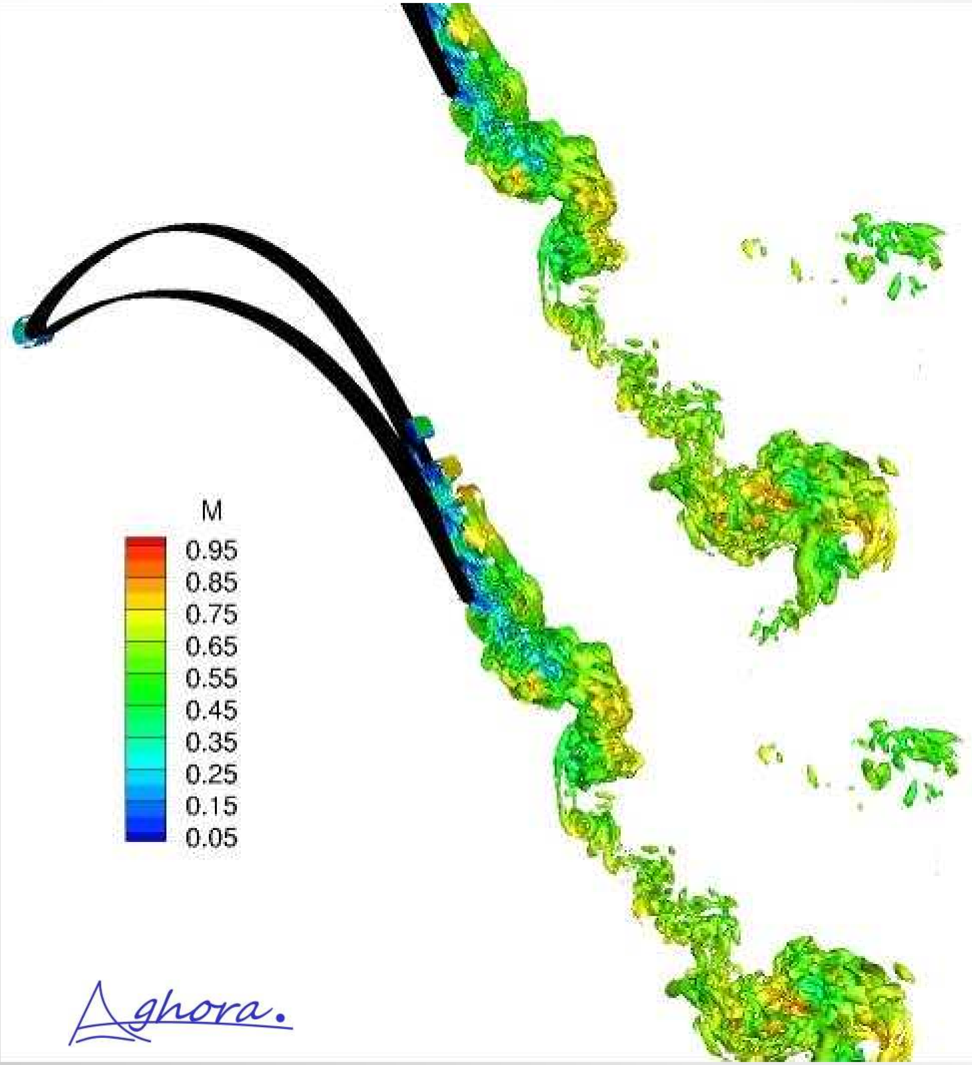
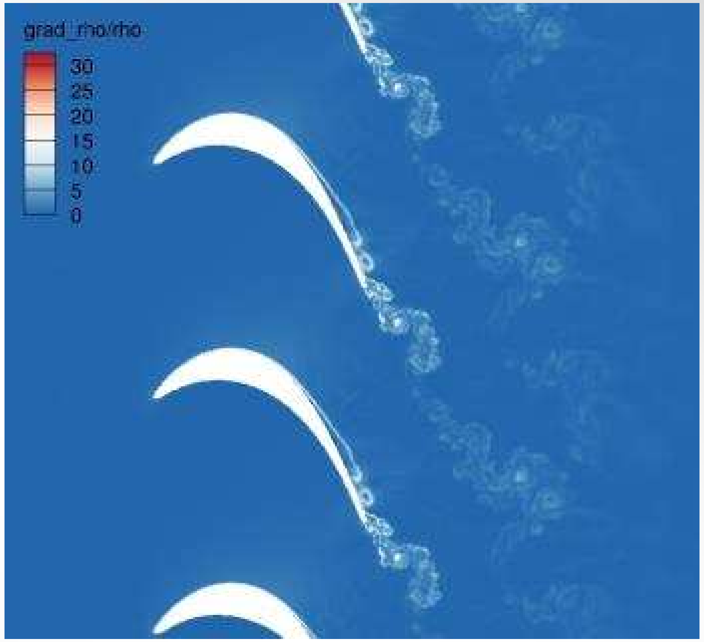
Additional DG-P3 on baseline resolution to study effect of injection angle

AS2 - Transitional flow in the T106C LPT



DG-P3 simulation on baseline grid
2.9 MDOFs



Contours of grad (ρ)/ρ

AS2 - Transitional flow in the T106C LPT

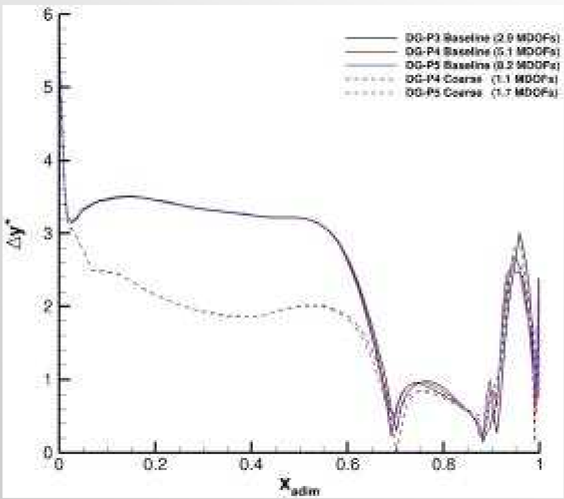
Under-resolved DNS simulations & de-aliasing through over-integration

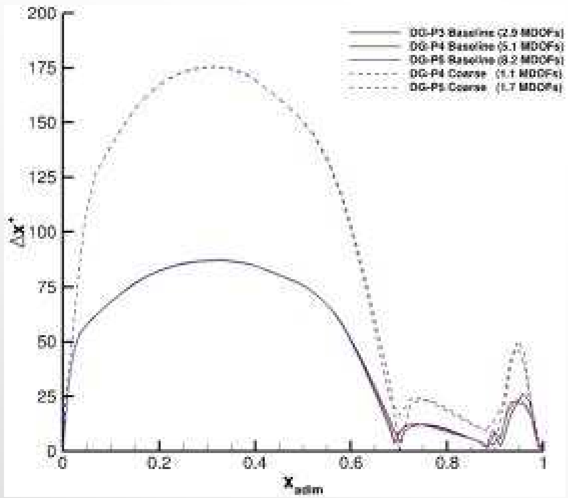
p+2 integration points (except for DG-P5 baseline simulation, p+1)

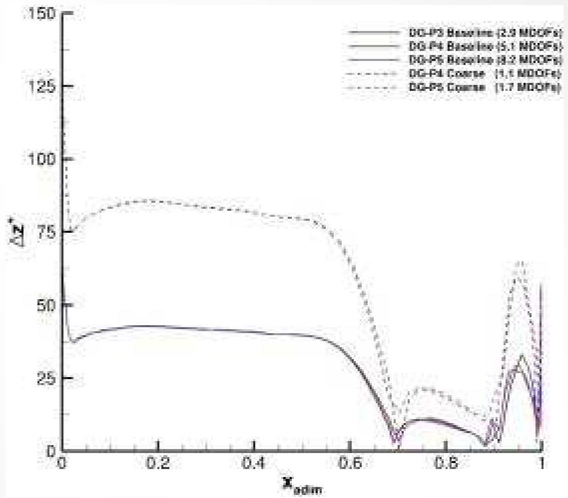
Grid resolution

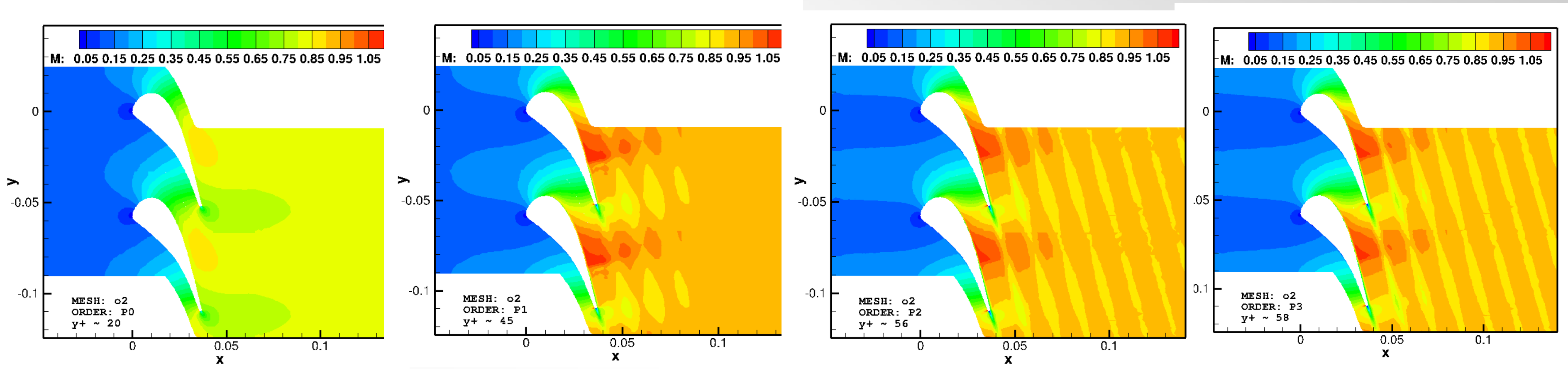
$\Delta y^+_{DG} \approx \Delta y^+/(p+1)$
$\Delta x^+_{DG} \approx \Delta x^+/(p+1)$
$\Delta z^+_{DG} \approx \Delta z^+/(p+1)$

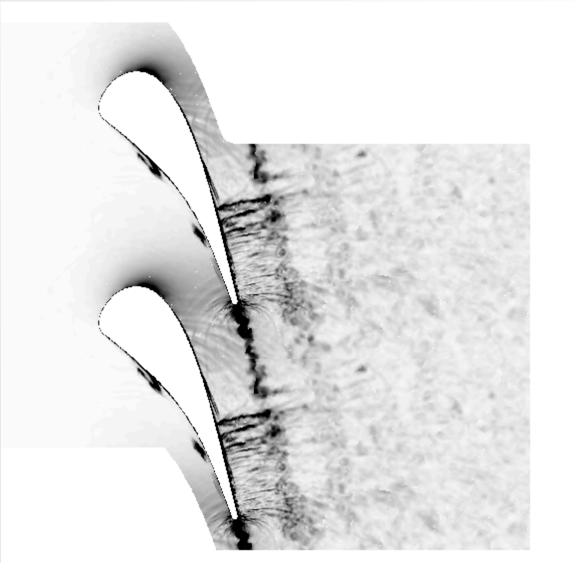
Simulation	Δy^+_{DG}	Δx^+_{DG}	Δz^+_{DG}
DG-P4 Coarse	0.6	35	16
DG-P5 Coarse	0.5	29	13
DG-P3 Baseline	0.9	20	10
DG-P4 Baseline	0.7	16	8
DG-P5 Baseline	0.6	13	7

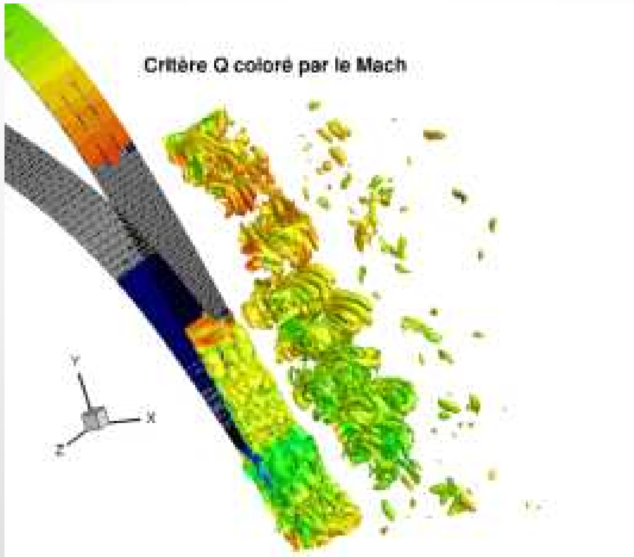


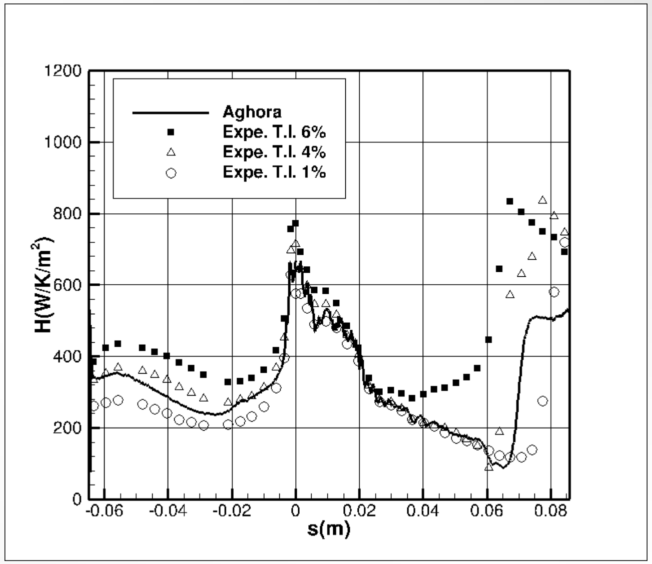





M: 0.05 0.15 0.25 0.35 0.45 0.55 0.65 0.75 0.85 0.95 1.05
MESH: o2
ORDER: P0
y+ ~ 20
MESH: o2
ORDER: P1
y+ ~ 45
MESH: o2
ORDER: P2
y+ ~ 56
MESH: o2
ORDER: P3
y+ ~ 58
x
y




Critère Q coloré par le Mach

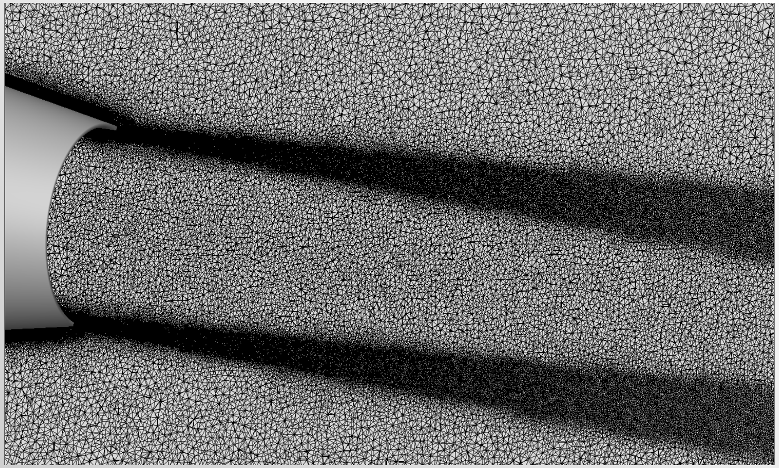

Aghora
Expe. T.I. 6%
Expe. T.I. 4%
Expe. T.I. 1%
H(W/K/m²)
s(m)

❑ Comparison with a reference Finite Volume (FV) solution

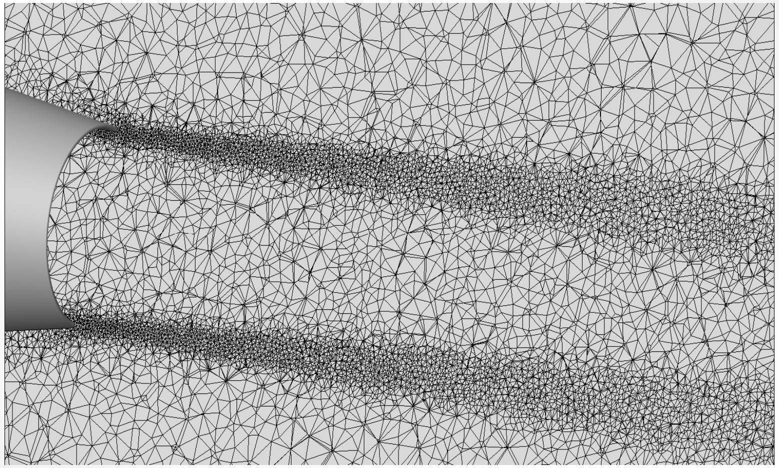
- With mesh grids made from the **same mesh file** but **different resolutions**

Grid	Δ/D_j (%)	n_θ	Cut-off (St)	Nb of cells ($\times 10^6$)	$T.U_j/D_j$
CEDRE FV2	0.38	838	1	165	250
Aghora DGp3	2	157	1	3.9	180

At $x/D_j = 0$ and $r/D_j = 0.5$



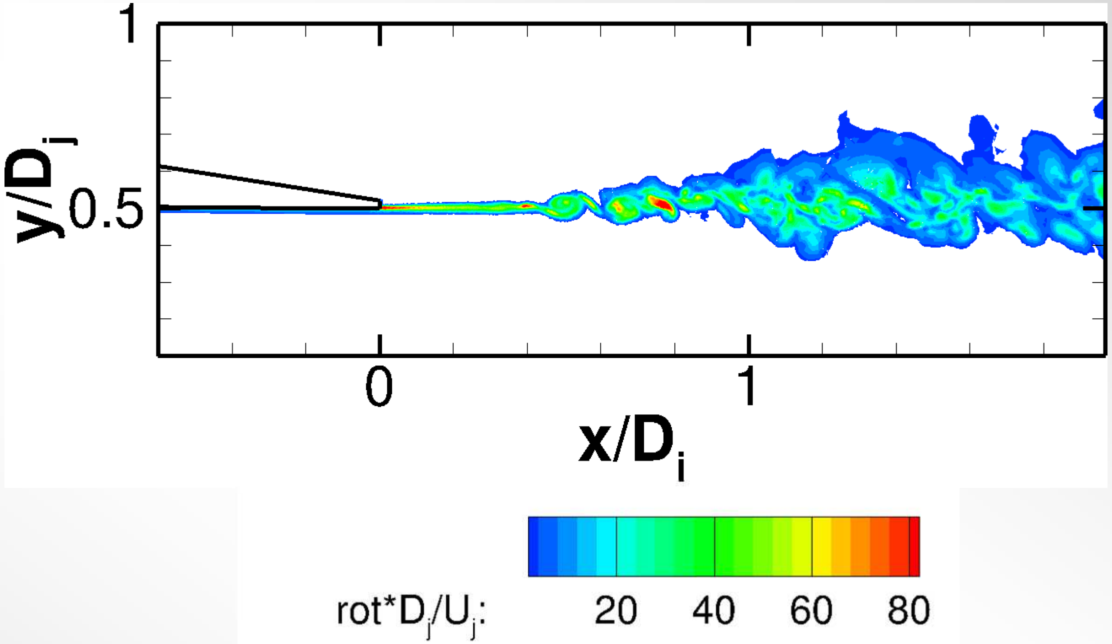
CEDRE FV2



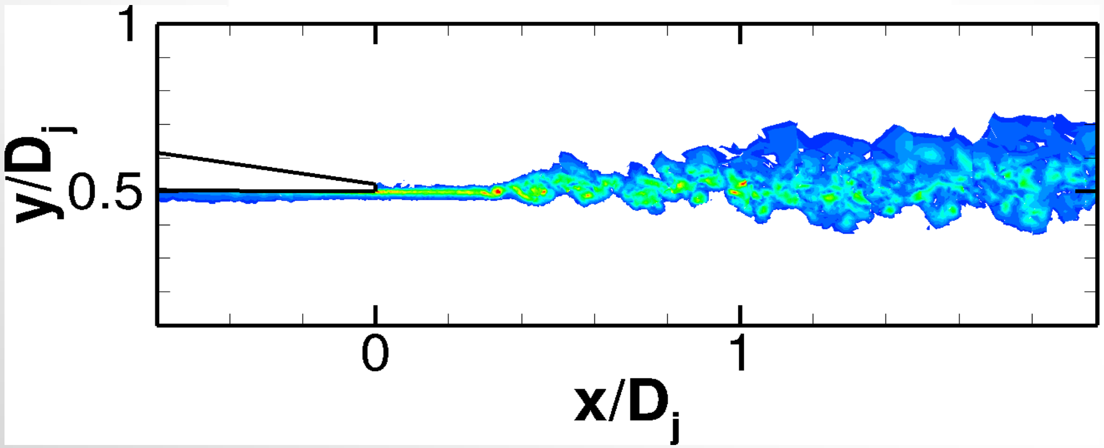
Aghora DGp3

Shear layer development : vorticity norm (x,y)

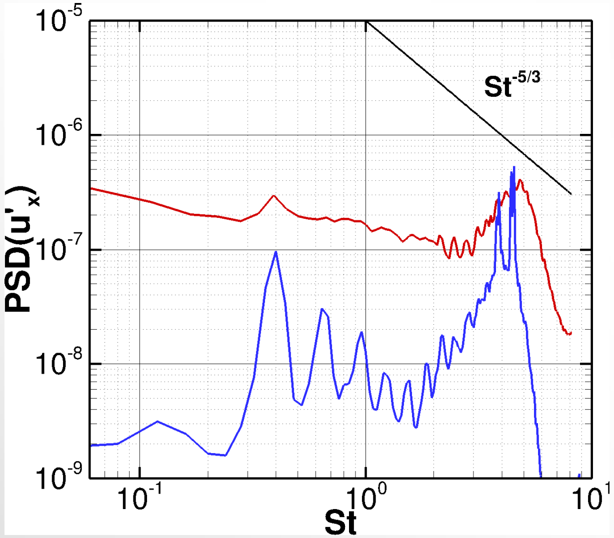
CEDRE FV2 simulation



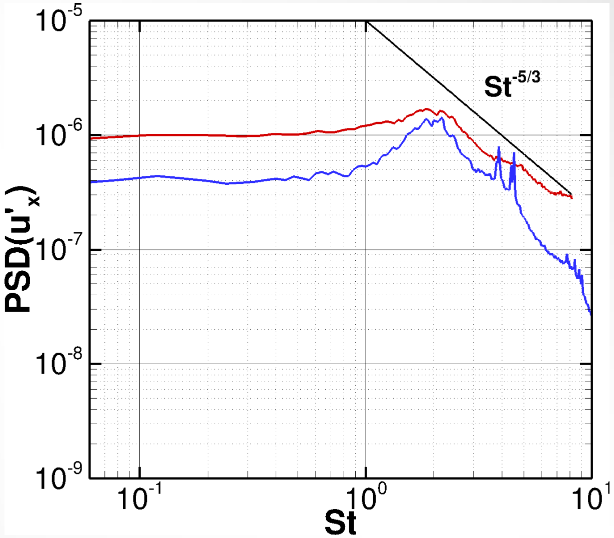
Aghora DGp3 simulation



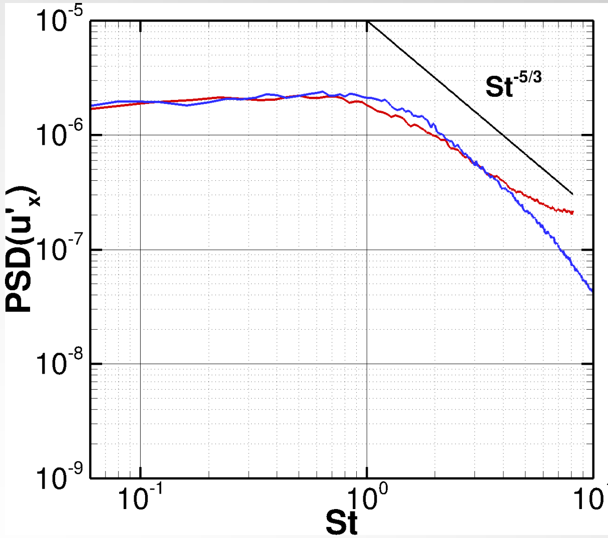
Shear layer development : velocity spectra (PSD) at r/Dj=0.5



$x/D_j = 0.25$



$x/D_j = 0.5$



$x/D_j = 1$

- *Aghora* DGp3 simulation:
  - Marked peaks visible for $x/D_j \leq 0.5$
  - Flat spectra for $x/D_j \geq 1$

=> turbulent state reached sooner than the FV2 one

Aghora simulation
CEDRE simulation

Some concluding remarks :

- All HO finite element methods (DG, CFE, FR, SD) computations are able to reproduce the Reynolds-number dependent features of the flow (length of recirculation region, profiles of wall-shear stress and mean pressure distribution).
- Further LES computations require local *h* and/or *p* refinement with “spectral type” methods
- HO spectral type methods complementary to classical FV methods (2^{nd} order and HO)
- Use of a hybrid openMP/MPI, GPU/heterogeneous strategy necessary to reduce CPU time for configurations using very coarse meshes in combination with high polynomial degrees.
- Need to implement efficient and accurate post-processing technique
  - Efficient parallel co-processing on HPC architectures
  - Accuracy : remove the unphysical high-frequency due to jumps for marginally resolved simulations
- TILDA organize an open HO CFD workshop : 21-23 November 2016 in Toulouse (Cerfacs)

  https://www.eventbrite.co.uk/e/tilda-symposium-workshop-on-industrial-les-dns-registration-19871723861
- HO methods lead to closer research between CFD and CAA communities for High Accuracy fine turbulence prediction
- HO spectral type methods complementary to classical FV methods (2^{nd} order and HO)

Outline