Code MIGALE state-of-the-art

A. Colombo

HiOCFD4

4th International Workshop on High-Order CFD Method

Foundation for Research and Technology Hellas (FORTH), Heraklion (Crete)

4th June 2016

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…with the contribution of

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TILDA

Towards Industrial LES/DNS in Aeronautics
Paving the Way for Future Accurate CFD
grant agreement No.635962

Brief code summary

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- Discontinuous Galerkin (DG) method on hybrid grids
- Physical frame orthonormal basis functions
- 2D/3D steady and unsteady compressible and incompressible flows
- Explicit and implicit time accurate integration
- Fixed or rotating frame of reference

- Euler
- Navier–Stokes
- RANS coupled with the k-ω (EARSM)
- Hybrid RANS/LES (X-LES)

- MPI parallelism
- Fortran language

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Implicit accurate time integration

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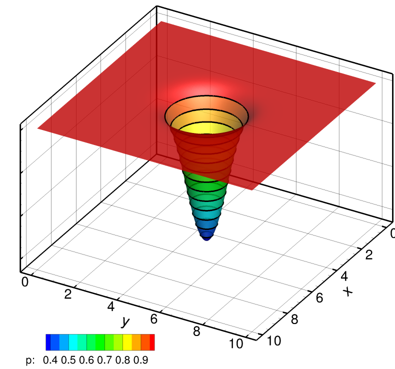
Several high-order temporal schemes are implemented

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

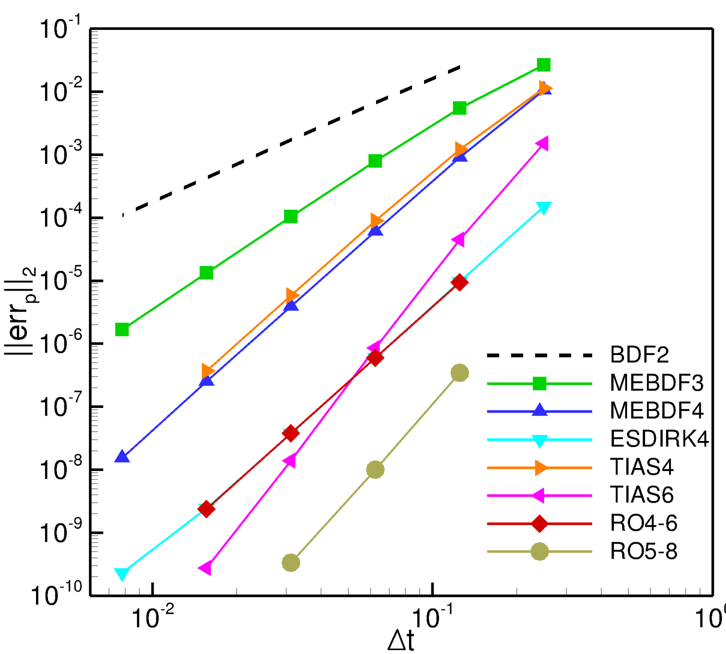
} *non-linear systems solution*

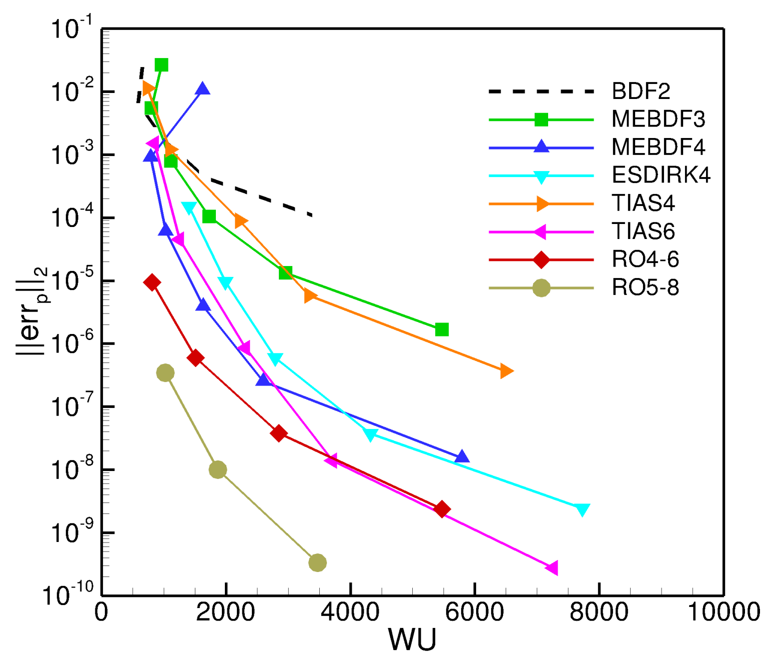
linear systems solution (here via GMRES)



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.

Rosenbrock schemes in a nutshell (I/II)

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From the DG spatial discretization we obtain a system of non-linear ODEs or DAEs

$$\mathbf{M_P}\left(\mathbf{W}\right)\frac{d\mathbf{W}}{dt}+\mathbf{R}\left(\mathbf{W}\right)=\mathbf{0} \qquad \widetilde{\mathbf{R}}=\mathbf{M_P}^{-1}\mathbf{R}$$

$$\mathbf{W}^{n+1}=\mathbf{W}^{n}+\sum_{j=1}^{s}m_j\mathbf{Y}_j$$

$$\left(\frac{\mathbf{M_P}}{\gamma\Delta t}+\mathbf{J}-\frac{\partial\mathbf{M_P}}{\partial\mathbf{W}}\widetilde{\mathbf{R}}\right)^{n}\mathbf{Y}_i=-\mathbf{M}_\mathbf{P}^{n}\left[\widetilde{\mathbf{R}}\left(\mathbf{W}^{n}+\sum_{j=1}^{i-1}a_{ij}\mathbf{Y}_j\right)-\sum_{j=1}^{i-1}\frac{c_{ij}}{\Delta t}\mathbf{Y}_j\right]$$

$$i=1,\ldots,s$$

only a linear system need to be solved for each stage

i.e. the Jacobian $\mathbf{J}=\partial\mathbf{R}/\partial\mathbf{W}$ is assembled and factored only once per time step

With orthonormal basis functions (*physical space*) $\mathbf{M_P}$ reduces to the identity for compressible flows with conservative variables

For other sets of variables their DOFs can be coupled within $\mathbf{M_P}$ thus resulting in a matrix which can not be diagonal

Rosenbrock schemes in a nutshell (II/II)

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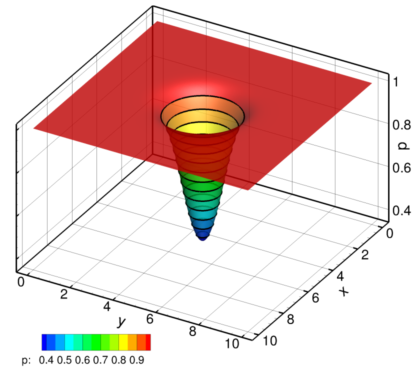
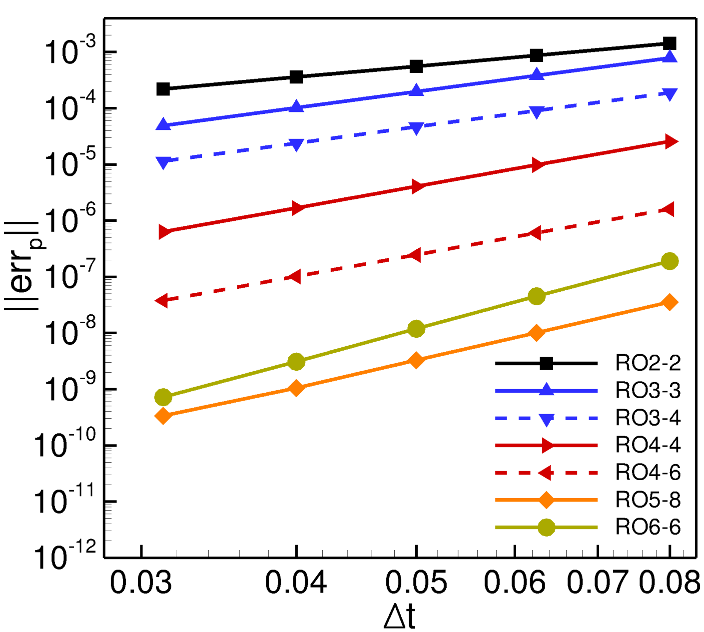
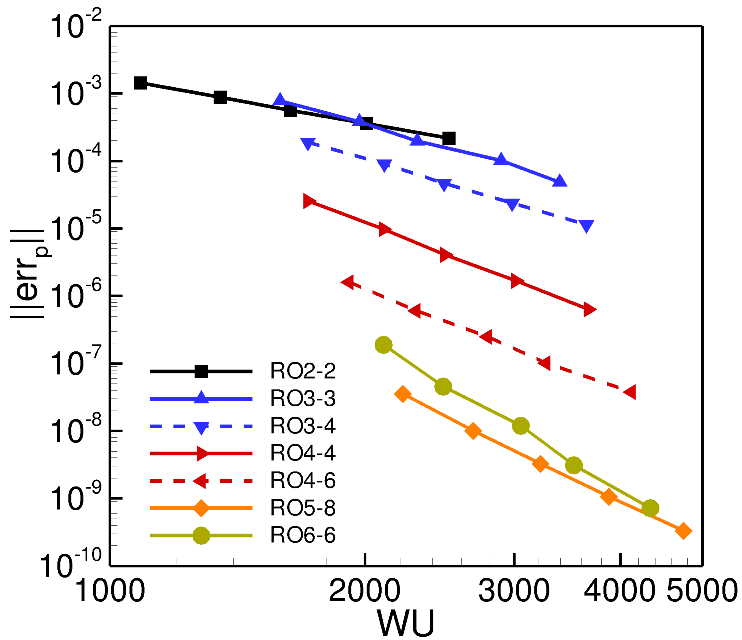
Several Rosenbrock schemes, from order two to order six, have been compared

No need to "exactly" solve systems: GMRES tolerance can be increased with confidence with a significant reduction of WU

For a given order of accuracy, among the schemes considered, those with more stages are more accurate and efficient, *e.g.* RO5-8 vs. RO6-6







Convection of an isentropic vortex P^6 solution on 50X50 el.

Bassi et al. "Linearly implicit Rosenbrock-type Runge-Kutta schemes for the Discontinuous Galerkin solution of compressible and incompressible unsteady flows" Computers & Fluids, 118 (2015) pp. 305 – 320

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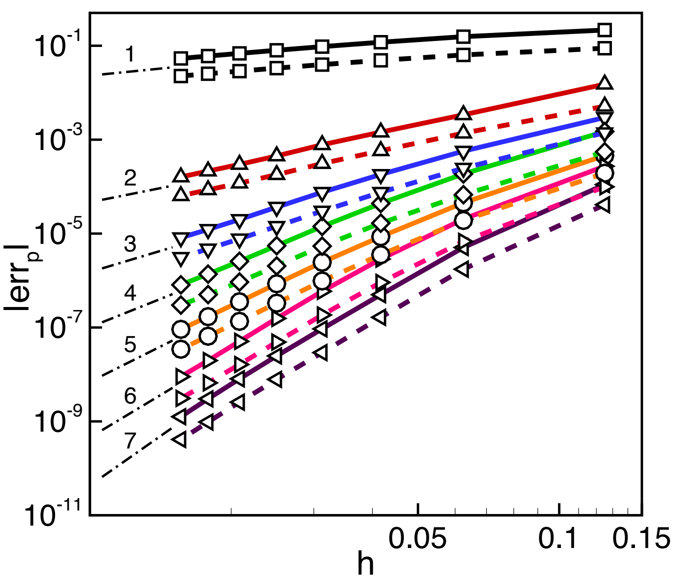
Working variables

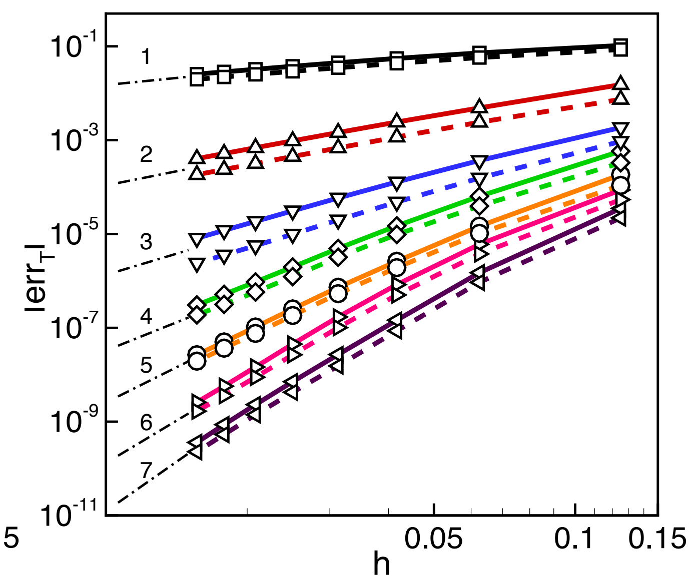
Primitive variables to ensure the positivity of all thermodynamic variables at the discrete level….

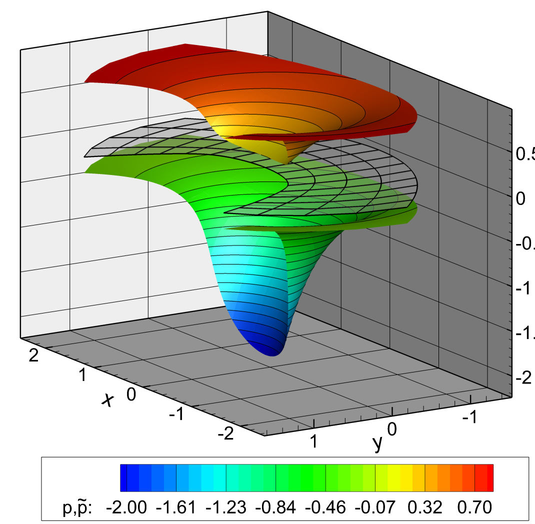
We work with polynomial approximations not directly for p and T but for their logarithms $\widetilde{p} = log(p)$ and $\widetilde{T} = log(T)$

In this way the computed values $p = e^{\widetilde{p}}$ and $T = e^{\widetilde{T}}$ are always positive

Easy to implement: almost only change $\mathbf{M_P}$…







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eXtra-Large Eddy Simulation (X-LES) in a nutshell (I/II)

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Pros

- hybrid RANS\LES formulation independent from the wall distance
- use in LES mode of a clearly defined SGS based on the k-equation
- use of a k-ω turbulence model integrated to the wall

Cons

the *filter width* parameter is often related to the local element size

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma^* \overline{\mu}_t\right)\frac{\partial k}{\partial x_j}\right] + P_k - D_k$$

$$\frac{\partial}{\partial t}(\rho \widetilde{\omega}) + \frac{\partial}{\partial x_j}(\rho u_j \widetilde{\omega}) = \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma \overline{\mu}_t\right)\frac{\partial \widetilde{\omega}}{\partial x_j}\right] + \left(\mu + \sigma \overline{\mu}_t\right)\frac{\partial \widetilde{\omega}}{\partial x_k}\frac{\partial \widetilde{\omega}}{\partial x_k} + P_\omega - D_\omega + C_D$$

…an "original" interpretation for the X-LES implementation…

Bassi et al. "Time Integration in the Discontinuous Galerkin Code MIGALE - Unsteady Problems"
In IDIHOM: Industrialzation of High-Order Methods - A Top-Down Approach, Vol. 128 of Notes on Numerical Fluid Me- chanics and Multidisciplinary Design Springer International Publishing

eXtra-Large Eddy Simulation (X-LES) in a nutshell (II/II)

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$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j}\left[(\mu + \sigma^* \overline{\mu}_t)\frac{\partial k}{\partial x_j}\right] + P_k - D_k$$

$$\overline{\mu}_t = \alpha^* \frac{\rho \overline{k}}{\hat{\omega}} \qquad D_k = \beta^* \rho \overline{k} \hat{\omega} \qquad \overline{k} = \max(0, k)$$

$$\hat{\omega} = \max\left(e^{\widetilde{\omega}_r}, \frac{\sqrt{\overline{k}}}{C_1 \Delta}\right)$$

	RANS	LES	ILES
$\overline{\mu}_t$	$\alpha^* \frac{\rho \overline{k}}{e^{\widetilde{\omega}_r}}$	$\alpha^* \rho \sqrt{\overline{k}} C_1 \Delta$	0
D_k	$\beta^* \rho \overline{k} e^{\widetilde{\omega}_r}$	$\beta^* \rho \frac{\overline{k}^{\frac{3}{2}}}{C_1 \Delta}$	0

X-LES of a shock BL interaction on a swept bump (AR2)

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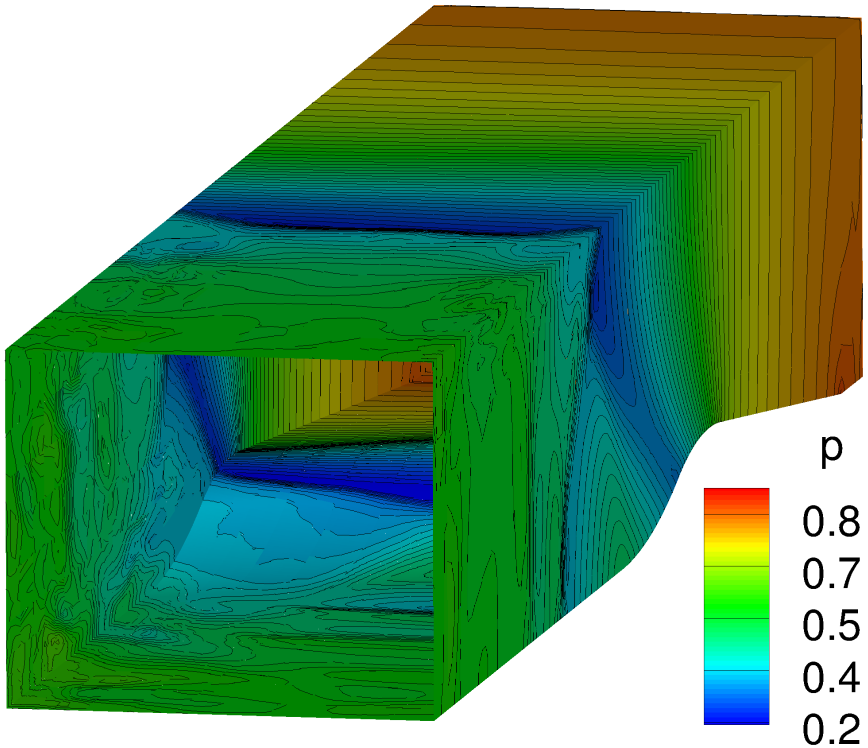
P^2 converged computations with RANS+k-ω (also in its low-Re version) and EARSM1 have been performed and used as initialization for X-LES



72960 hexahedral elements

- Inlet boundary conditions
  - p_{0i} = 92000Pa
  - T_{0i} = 300K
  - $Re_H = 1.69 \times 10^6$
- Outlet static pressure used to impose the shock position *(model dependent!)*
- LBE to quickly find the “right” pressure ratio
- RO3-3 for the time-accurate solution
- Filter width Δ = 5e-2 *(strong influence!)*
- 96 cores of our in-house Intel cluster :-(

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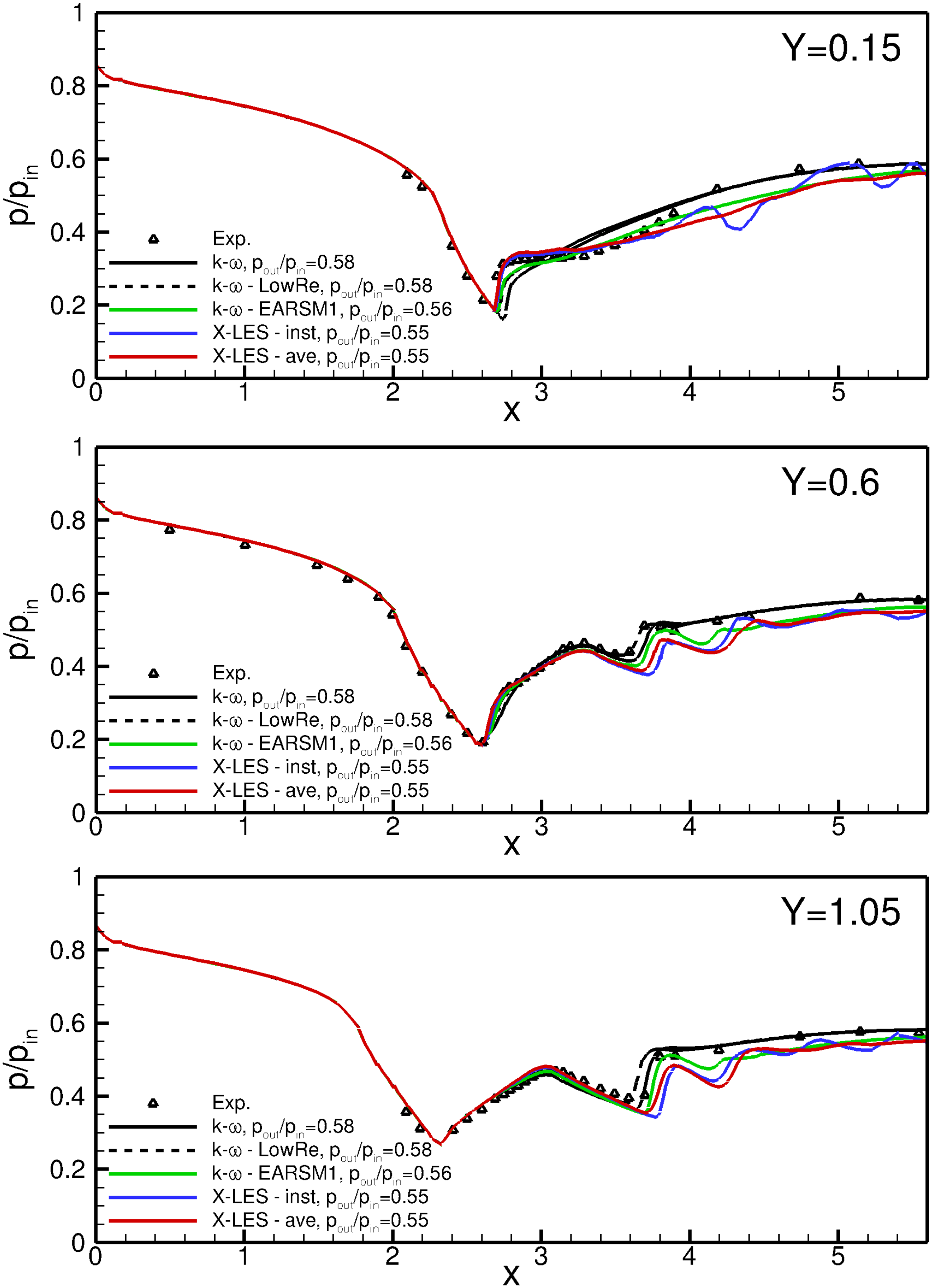
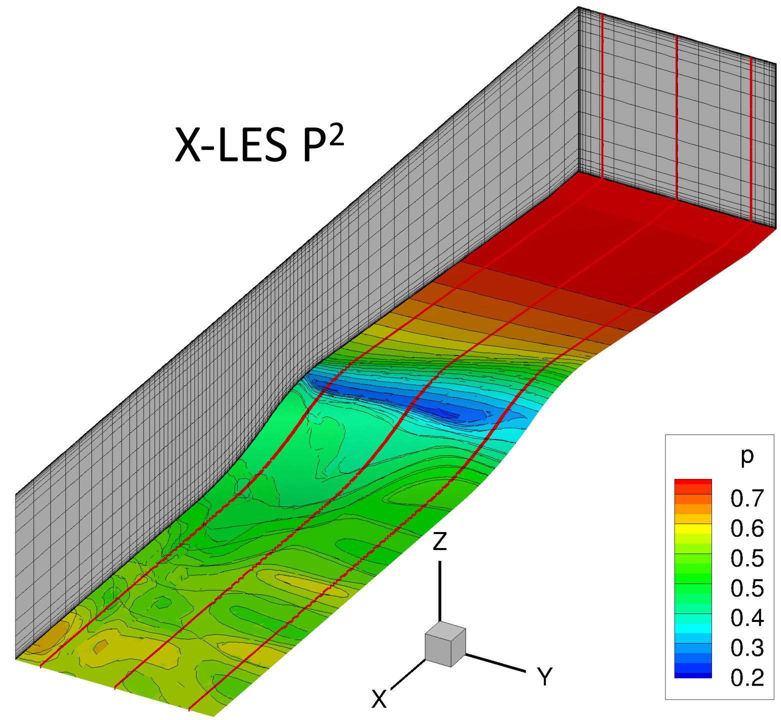
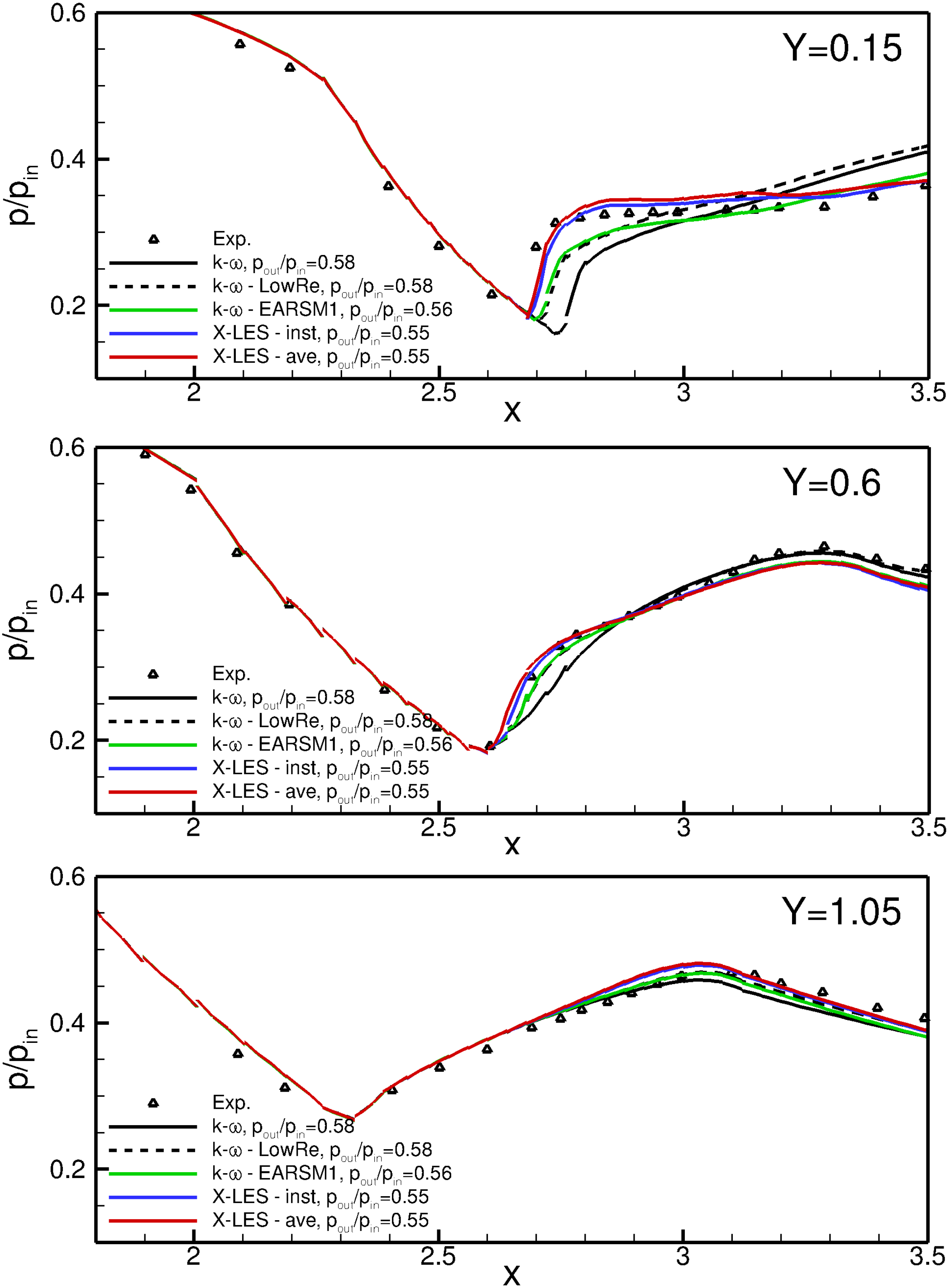
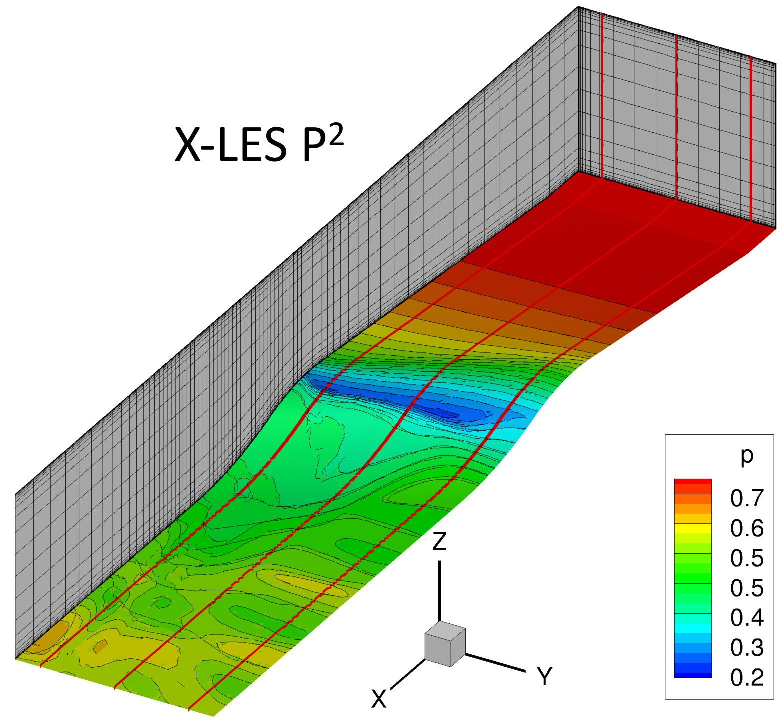




The profiles are in reasonable agreement with the experiments and the numerical results of Cahen et al.





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X-LES of the transonic flow field in the NASA Rotor 37

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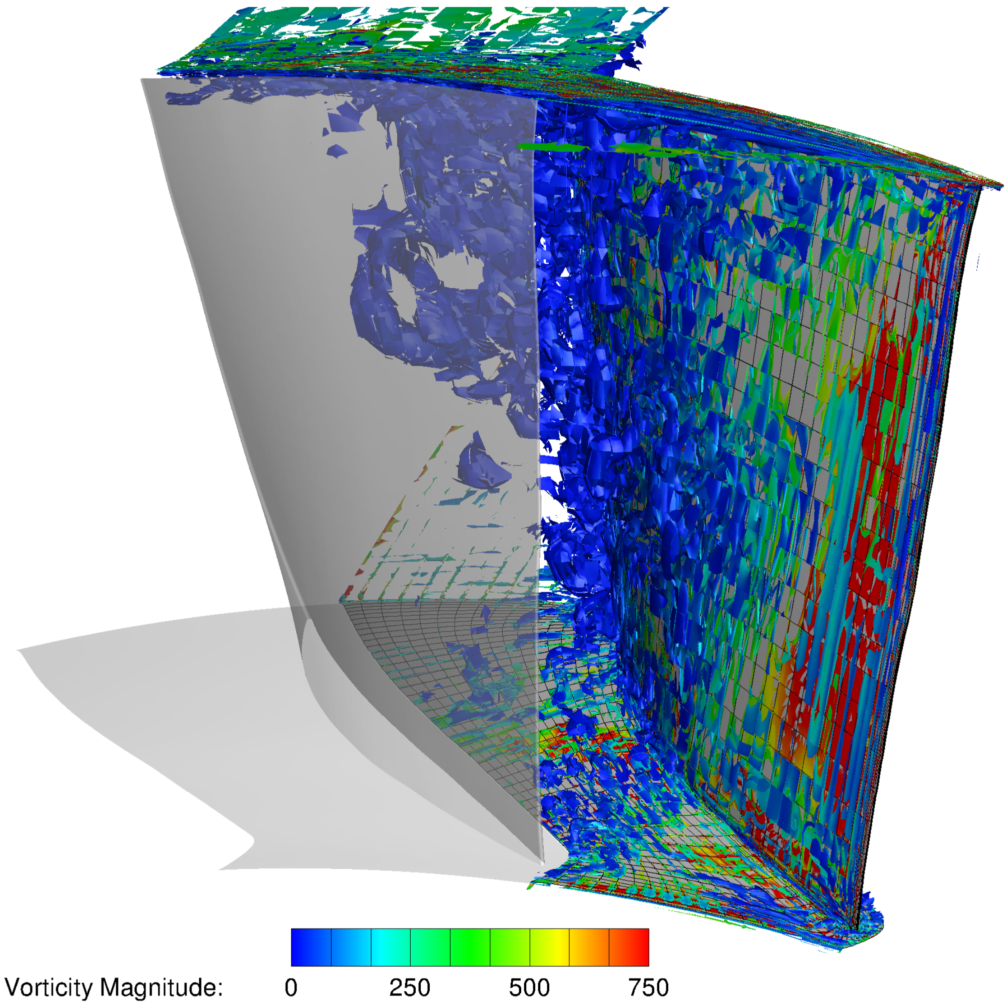

iso-surface of Q-criterion
160512 hexahedral elements

- P^2 computation using RO3-3
- Filter width Δ=5e-5
- Boundary conditions
  - p_{01} = 101325Pa
  - T_{01} = 288K
  - ω= 1800rad/s
  - Tu_1 = 3%
  - α_1 = 0°
- still 96 cores of our in-house Intel cluster :-((

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

X-LES of the transonic flow field in the NASA Rotor 37

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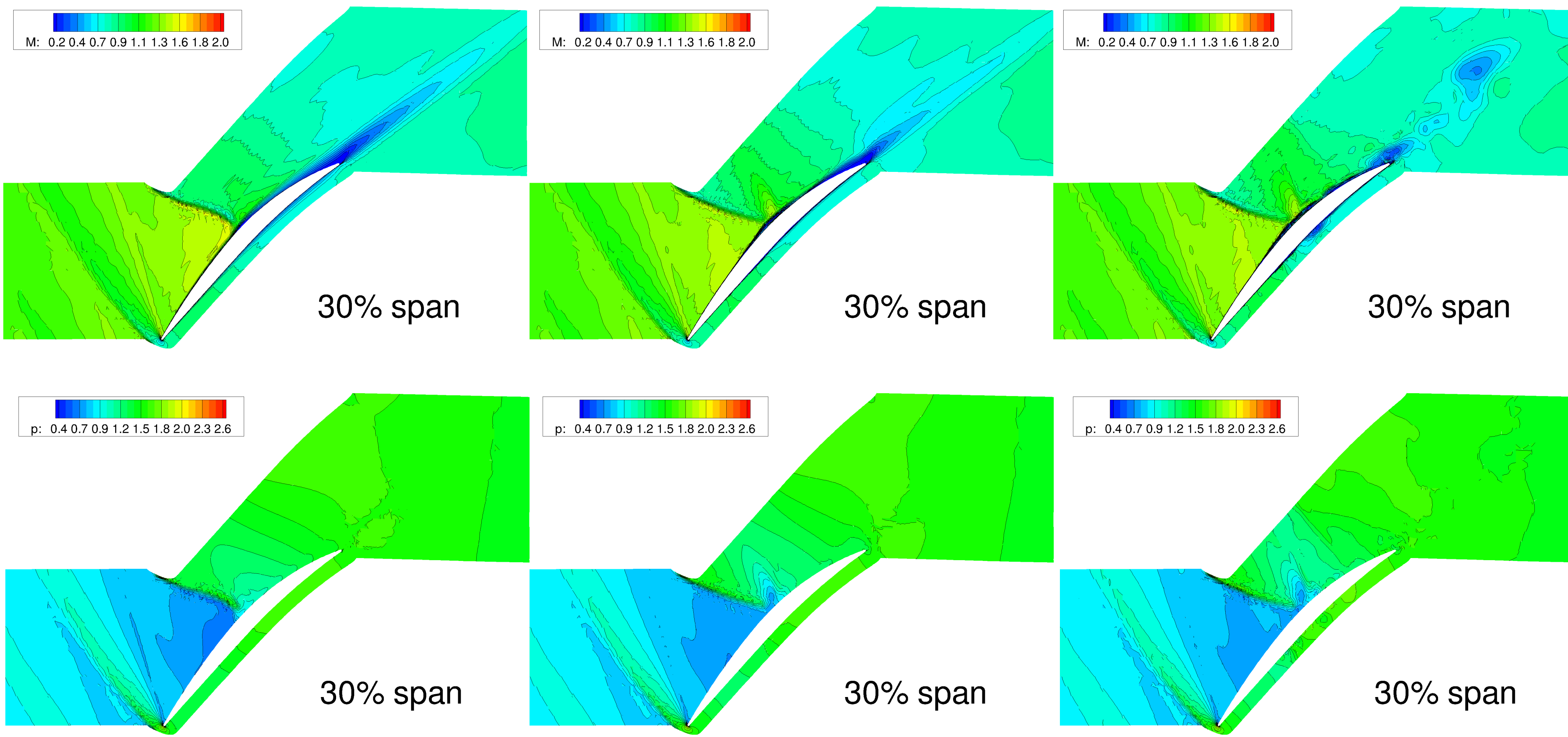
RANS | X-LES ave. | X-LES inst.



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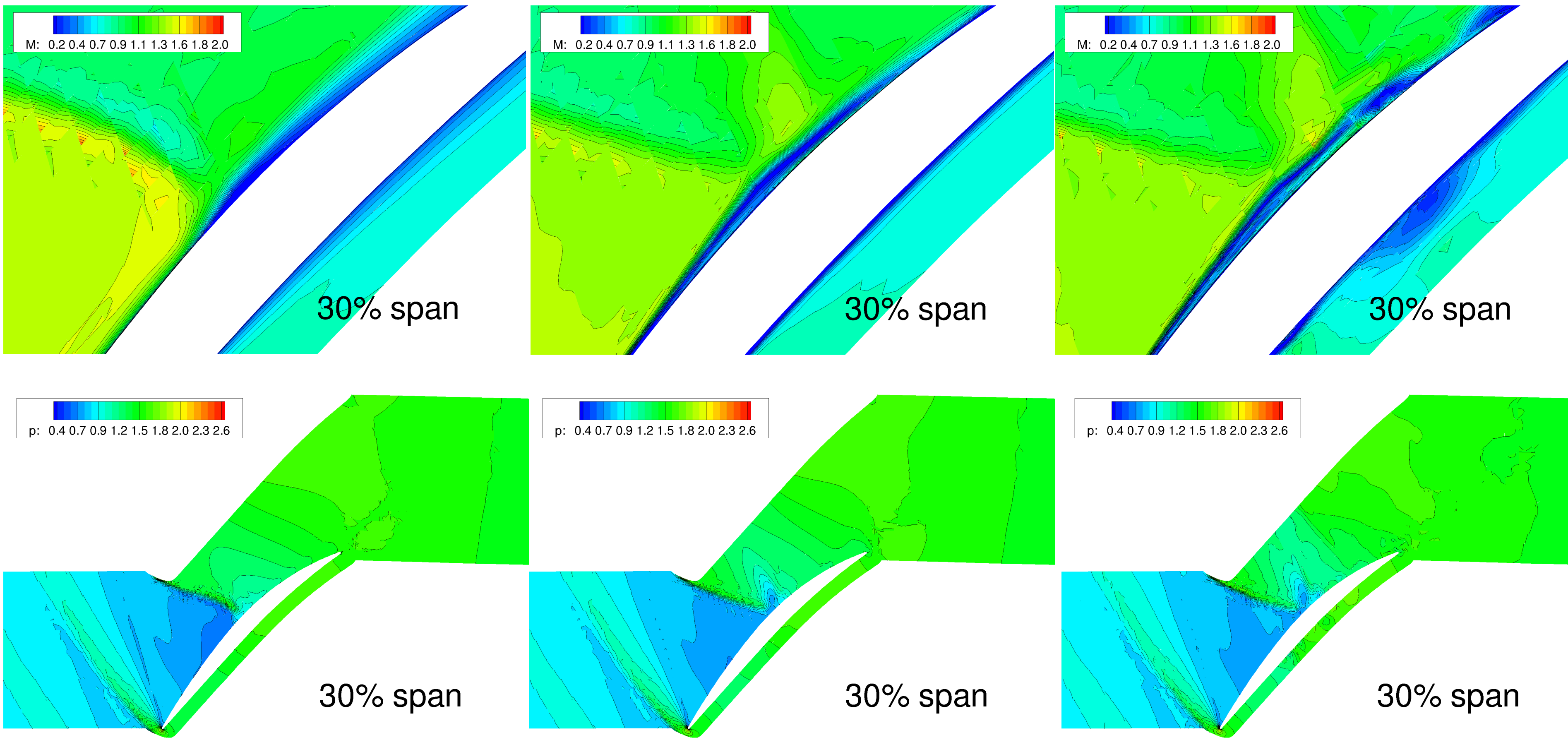

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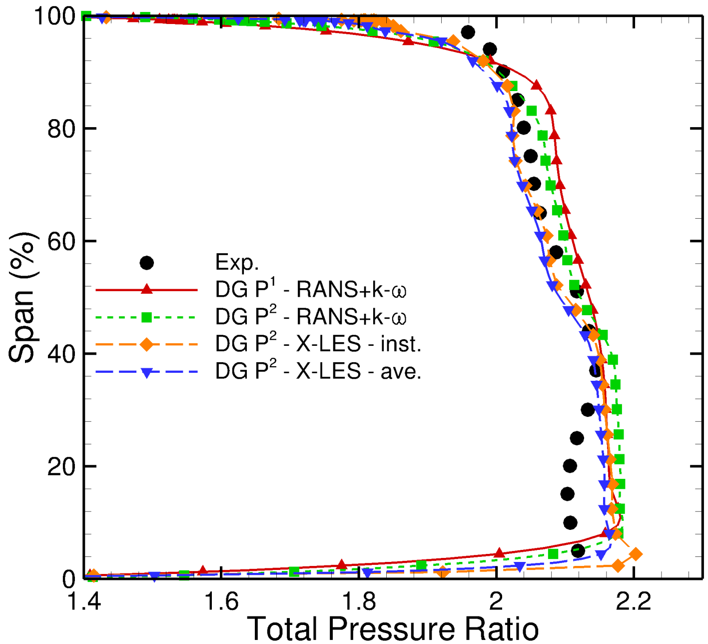
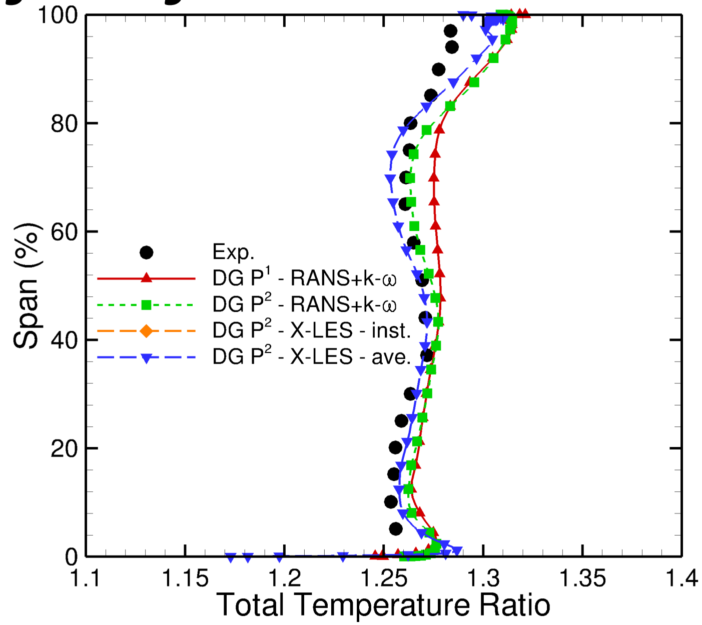
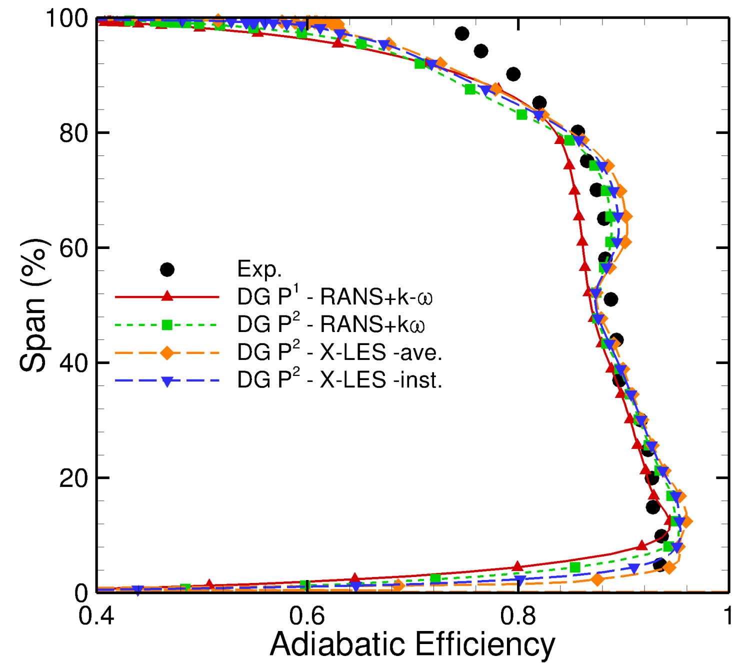
X-LES of the transonic flow field in the NASA Rotor 37

Spanwise distributions







Initializing the solution from a flow field corresponding
to a normalized mass flow,
resulting from a RANS computation, of ≈0.98
X-LES moved towards ≈0.996

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Implicit time integration

Thursday, June 9 8:30-10:30 - MS 905 - 2 (Room 20)
Alessandra Nigro, Carmine De Bartolo, Andrea Crivellini, Francesco Bassi
MATRIX-FREE MODIFIED EXTENDED BACKWARD DIFFERENTIATION FORMULAE APPLIED TO THE DISCONTINUOUS GALERKIN SOLUTION OF COMPRESSIBLE UNSTEADY VISCOUS FLOWS

Thursday, June 9 14:30-16:30 - MS 905 - 3 (Room 20)
Francesco Carlo Massa, Gianmaria Noventa, Francesco Bassi, Alessandro Colombo, Antonio Ghidoni, Marco Lorini
HIGH-ORDER LINEARLY IMPLICIT TWO-STEP PEER METHODS FOR THE DISCONTINUOUS GALERKIN SOLUTION OF THE INCOMPRESSIBLE RANS EQUATIONS

Turbulence Modeling

Thursday, June 9 17:00-19:00 - MS 905 - 4 (Room 20)
Antonio Ghidoni, Marco Lorini, Gianmaria Noventa, Francesco Bassi, Alessandro Colombo
DISCONTINUOUS GALERKIN SOLUTION OF THE REYNOLDS- AVERAGED NAVIER–STOKES AND KL-KT-LOG(W) TRANSITION MODEL EQUATIONS

Friday, June 10 9:00-11:00 - MS 910 - 2 (Room 15)
Francesco Bassi, Lorenzo Botti, Alessandro Colombo, Andrea Crivellini, Antonio Ghidoni, Marco Lorini, Francesco Carlo Massa, Gianmaria Noventa
ON THE IMPLEMENTATION OF X-LES IN A HIGH-ORDER IMPLICIT DG SOLVER

HPC

Tuesday, June 7 8:30-10:30 - CS 930 - 3 (Room 15)
Francesco Bassi, Alessandro Colombo, Andrea Crivellini, Matteo Franciolini
HYBRID OPENMP/MPI PARALLELIZATION OF A HIGH–ORDER DISCONTINUOUS GALERKIN CFD SOLVER