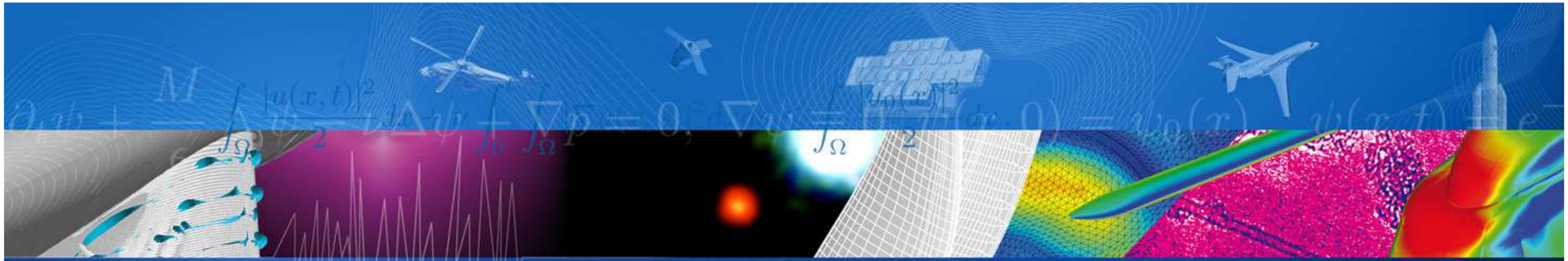


Status and Challenges of CFD at ONERA

Future CFD Technolgies Workshop
Kissimmee, Florida, January 2018

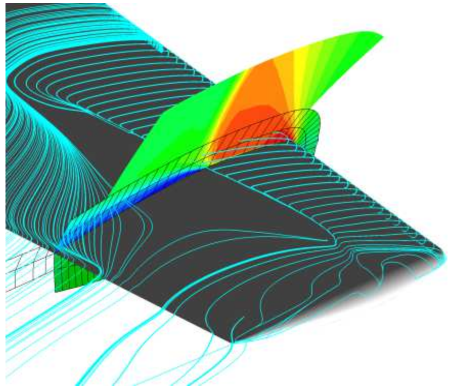
Presented by
Vincent Couaillier

prepared by ONERA/DAAA & ONERA/DMPE

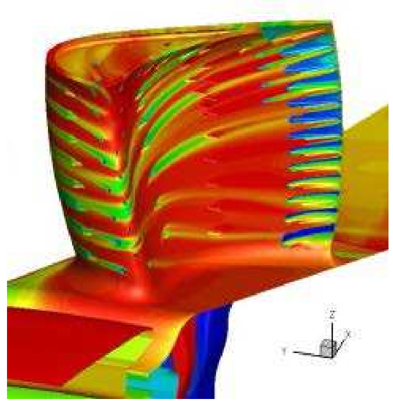
return on innovation

Introduction : Some aspects of CFD

- CFD considered as mature technology for nominal flow configurations
  - Many CFD codes and assessed models are daily used in industrial design
  - At ONERA the main CFD codes are :
    - elsA for aerodynamics, aeroelasticity, aeroacoustics
    - CEDRE for energetics, aeroacoustics, mutiphysics
    - These codes are used by industrial partners Airbus, Safran, CNES, EDF and ONERA CFD expertise used by Dassault



- But main key points have to be solved to put CFD a step further
  - Expertise of end-users still needed to provide « correct results »
  - Error margins still not mastered
    - Computational errors (Verification process)
    - Uncertainties due to physical model, boundary/initial conditions
  - Efficiency (cost) in particular for unsteady CFD dealing with scale-resolving problems for new computers architecture
  - CFD used in a multiphysics environment

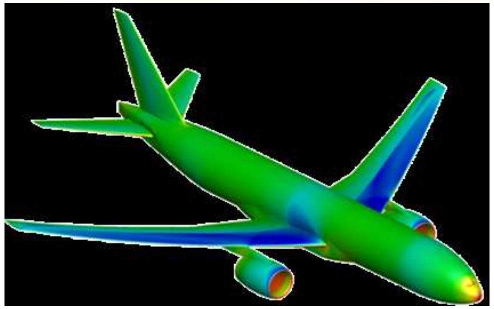


- Outline
  - Status of elsA and CEDRE ONERA CFD codes
  - ONERA CFD challenges & roadmap

*elsA** : general description

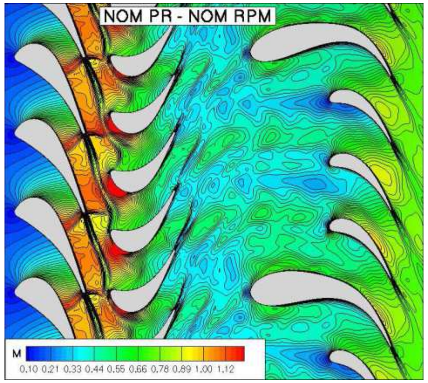
❑ Multi-purpose CFD simulation platform

- Internal and external aerodynamics
- From low subsonic to high supersonic
- Compressible 3-D Navier-Stokes equations
- Moving deformable bodies
- Aircraft, helicopters, turbomachinery,
- CROR, missiles, launchers…



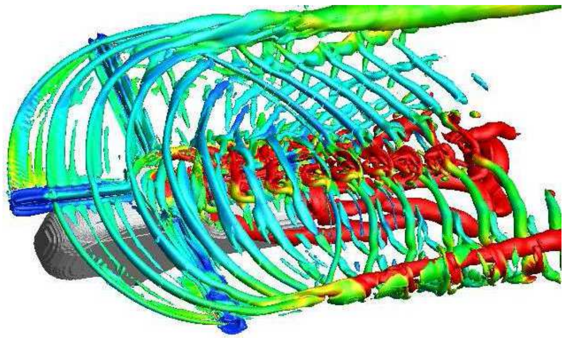
❑ Design and implementation

- Object-Oriented with Kernel in C++/Fortran
- User interface in Python
- Python-CGNS interface for CGNS extraction
- and coupling with external software



❑ Models and numerics

- Turbulence : RANS, HRLES (ZDES), LES
- MB meshes : Str with Chimera, Uns, Hybrid Str/Uns
- CC for discretization : 2nd order Jameson, Roe, …
- HO FV for MB/Str meshes
- Implicit (LUSSOR, GMRES), Multigrid
- DTS, TSM/HBT for unsteady simulations



*** : elsA is ONERA-Airbus-Safran property**

Main turbulence & transition models in elsA

Turbulence model for RANS

Eddy viscosity models : k-ε (JL,LS,Chien), k-ω (Wilcox, Menter BSL & SST, Kok) + buoyancy, k-l (Smith), SA, and curvature correction, …

Algebraic Reynolds stress models :

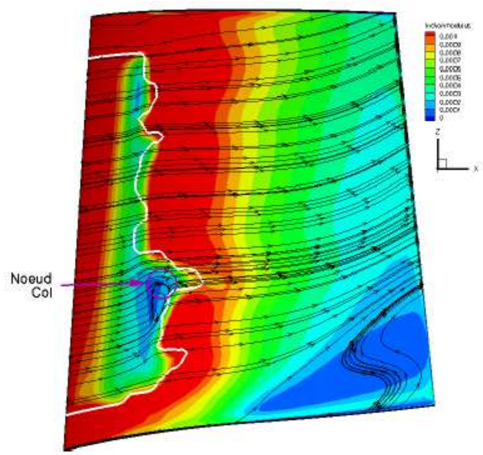
- ASM-ε Shi-Zhu-Lumley
- EARSM k-ω Hellsten + EAHFM (thermal)

Reynolds stress models

- Speziale-Sarkar-Gatski (SSG) + ω Menter
- Other DRSM models

Scale Adaptive Simulation

- Original version (Menter)
- Improved version (ONERA)



Non local criteria

Transition

- Local correlation
- γ-Re_θ
- Local criteria
- Criteria with transport equations / Non local criteria

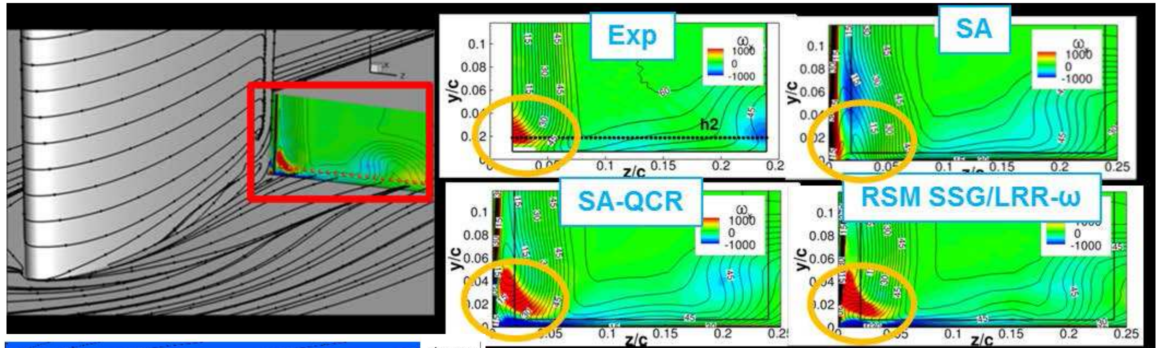
Wall roughness

- Dynamic model
- Thermal model
- Model for transition

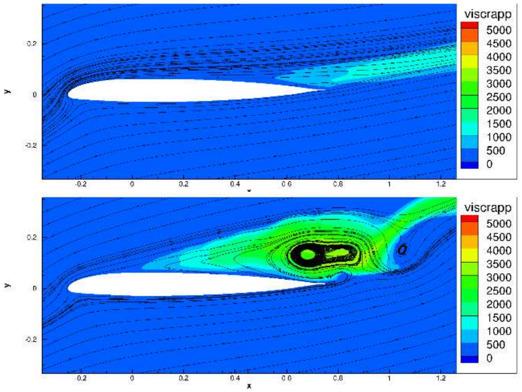
ONERA participates to AIAA Turbulence Discussion Group

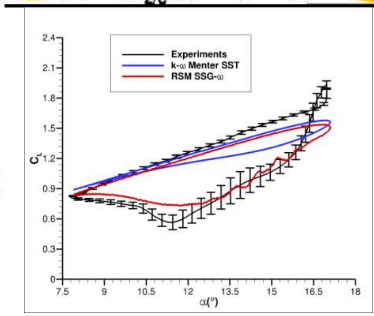
elsA : RSM / K-omega

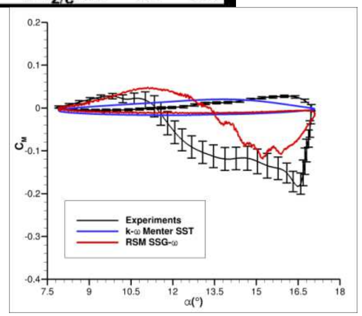
- Reynolds-Stress-Modelling (RSM) less restrictive than classical one/two eq. models (kε, …) using Boussinesq hypothesis
- For steady simulation of turbulence
- Robustness has to be improved for industrial test cases

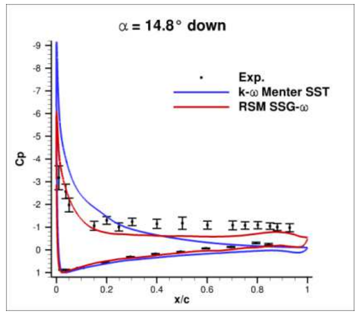


RSM assessment - Corner flow
M = 0.2







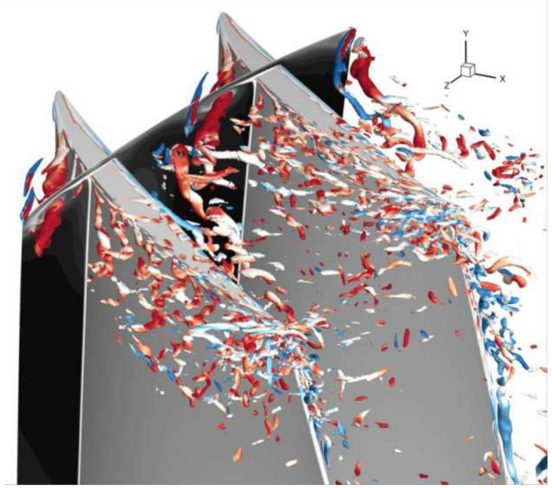


Dynamic stall - OA209 airfoil - V=55 m/s - α=12.5° + sin(0.1t).4.6°
Rec=106 - F2 exp.

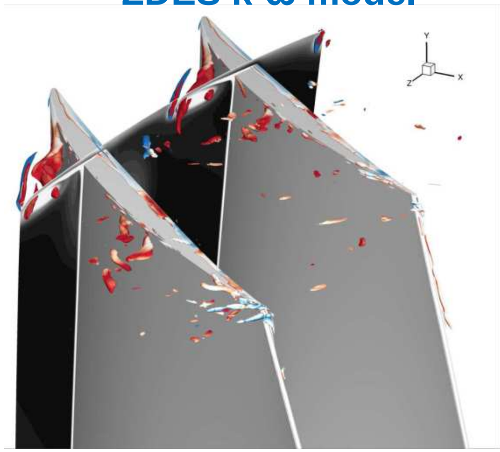
ZDES with elsA

Hybrid RANS-LES models are strongly progressing

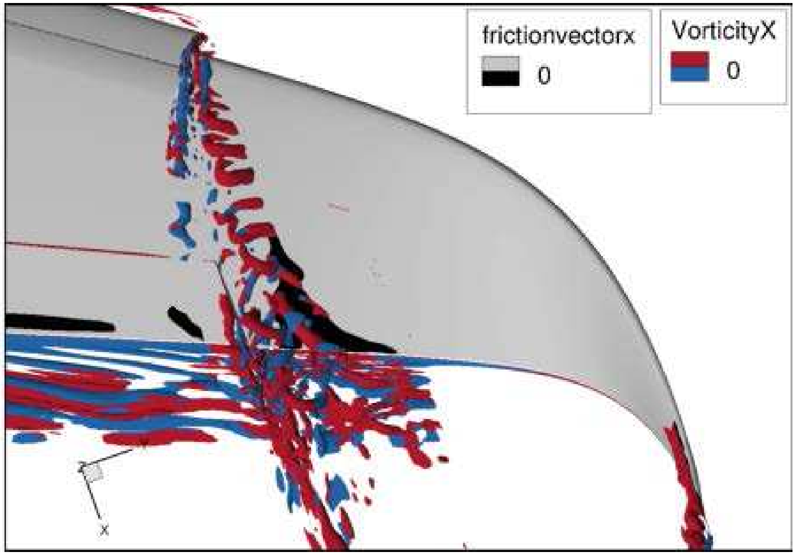
- Strong cost reduction compared to pure LES
- Demonstration of good capacities for massively separated flows on fundamental configurations
- Nevertheless cost still prohibitive for realistic cases (eg: complete aircraft at cruise Re number, multistage compressor...)



ZDES k-ω model



SAS Menter Model
Comparison on tip-leakage vortex



ZDES for winglet stall

Theoretical background

The adjoint solver in elsA gives solution to : $\lambda^T \dfrac{\partial R}{\partial W} = -\dfrac{\partial J}{\partial W}$

with R : discrete residual ot the RANS equations
J : function of interest
W : discrete conservative field
λ : adjoint vector associate to J

Main use for shape gradient computation (but not only) :*

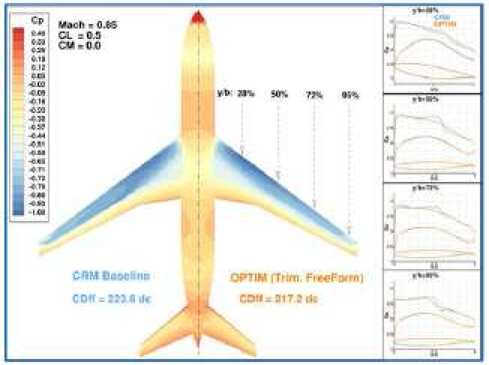
$$\frac{dJ}{d\alpha} = \left(\frac{\partial J}{\partial X} + \lambda^T \frac{\partial R}{\partial X}\right)\frac{dX}{d\alpha} = \frac{dJ}{dX}\frac{dX}{d\alpha}$$

with α : shape parameter
X : volumic mesh

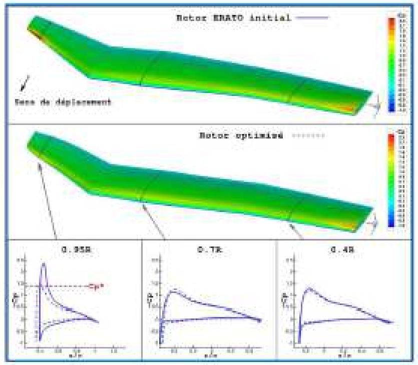
** Also error estimation and goal-oriented mesh refinement see work of J. Peter and M. Nguyen-Dinh*

Shape optimization applications

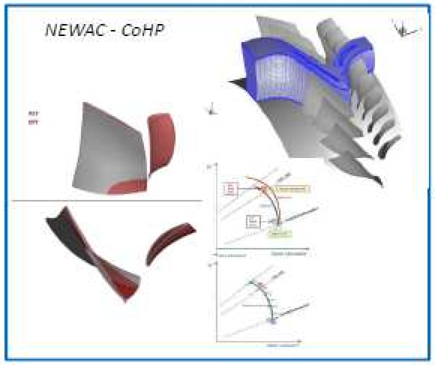
- Adjoint framework developed for multiple application context :



Aircraft context : AIAA-ADODG test case n°5 Optimization of the wing with lift and pitching moment constraints (C-P 3.2)



Helicopter context : ERATO blade performance optimization in hover (compliancy with propeller application)



Turbomachinery context : NEWAC High Pressure Compressor efficiency optimization under mass flow and pressure ratio constraints

On going developments and perspectives

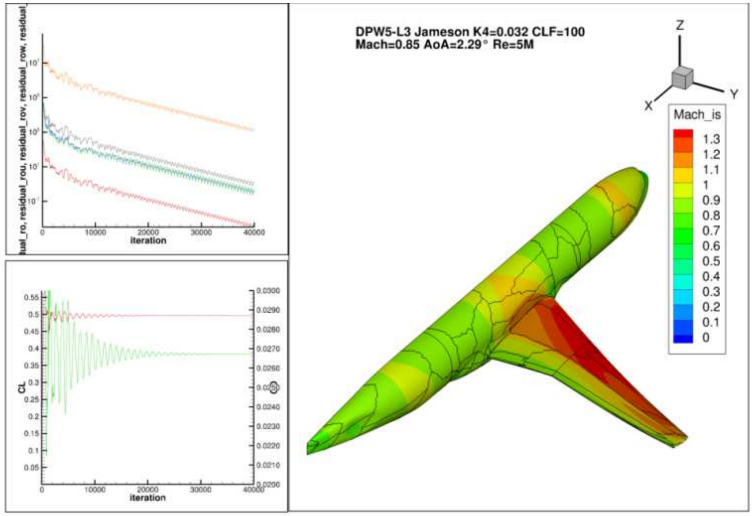
- Adjoint functionalities available and validated inside FSDM (C-P 1.7)

- Use of dJ/dX mode ('adjoint_mesh') for memory efficiency (aircraft context only):

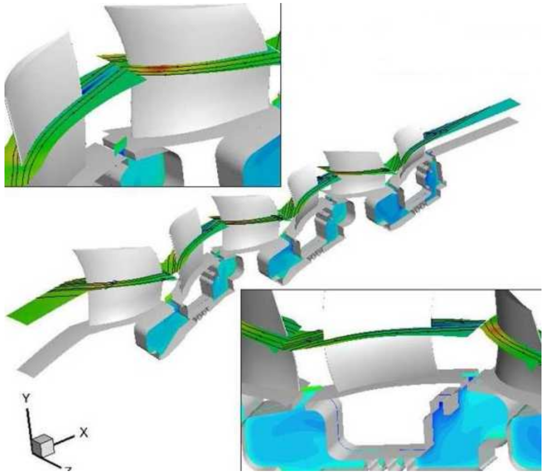
Status of elsA : Unstructured and hybrid mesh/solver

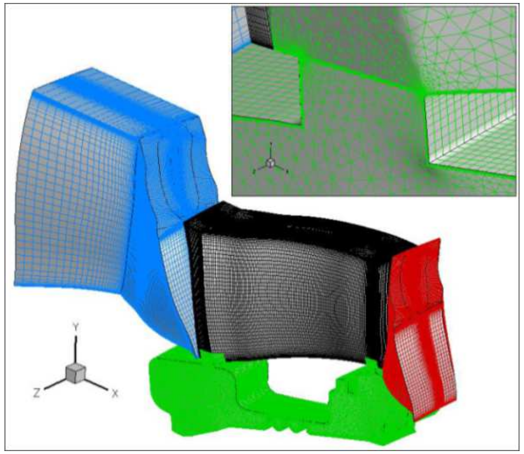
The process to set-up high-quality and efficient CFD methods needs flexible, robust and accurate meshing/solver strategies

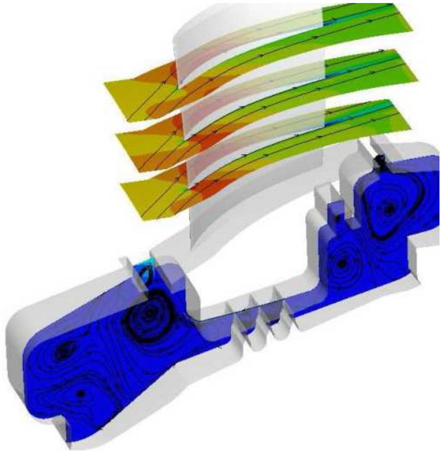
- elsA initially developed with SMB approach (CANARI,FLU3M) : Accuracy and efficiency of the solvers
- Capacity of Overset grid (chimera grids) approach to account for rigid body motion and to add grid components
- Cartesian meshes for High Order accurate simulations in the flow field without body-fitted region
- Extension of elsA to unstructured grids (UNS MB solver) and to hybrid grids mixing ijk structured blocks and unstructured blocks : **mesh flexibility and CFD accuracy**



Unstructured and hybrid CRM







Hybrid : Compressor CREATE : Structured grids on blades / unstructured seal cavity

ONERA/DAAA contribution

CFD for Energetics at ONERA : Main topics

Fluid flows

- Mach : from incompressible to hypersonics
- Reynolds : from laminar to full turbulent
- Complex thermodynamics (Cp(T), mixing gaz laws, state laws of real gases,…)
- Complex molecular diffusion
- Chemical reactions Combustion instabilities
- Multiphase flows (dense or disperse phases)

Coupling with other physical systems :

Other states of the matière : solid, plasma

- Electromagnetics waves

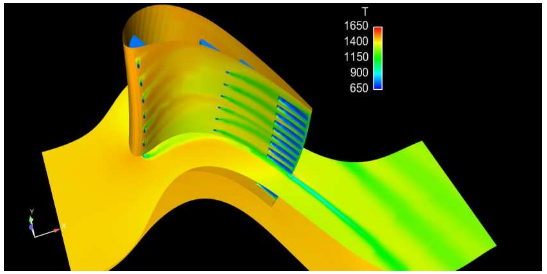
CEDRE: Flow simulation for Energetics

- CEDRE : CFD multi-physics software for energetics and propulsion organized as a set of solvers
- CHARME : Reacting gas solver
- SPIREE : Eulerian dispersed phase solver
- SPARTE : Lagrangian solver
- ACACIA : Conduction
- FILM : Study of liquid films ASTRE and REA – radiation

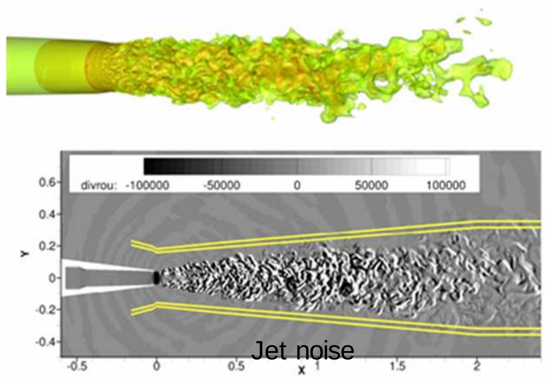
- Numerics
- General Polyhedral meshes with multidomain approach
- 2nd Order Muscl schemes or HO FV (k-exact)
- Code architecture well adapted to HPC and of pre- / post-processing utilities
- GMRES implicit time integration
- Coupling for Multiphysics : Use of in-house library CWIPI

- Key points in energetics : Stiff PDE with high dispersion of time/space physical scales :
    - for instance multiphase, characteristic times of liquid oxygen injection / gas oxygen dynamics

TBD



CM2012 case: cooled blade

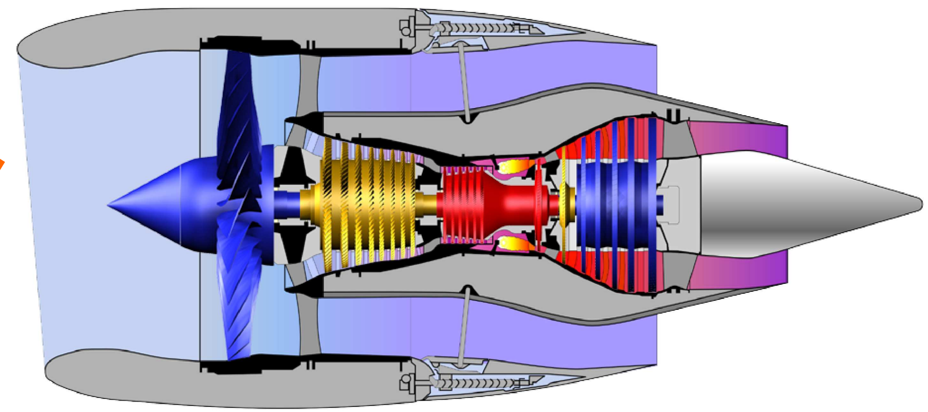


Jet noise

CEDRE : Civil aircraft

Lightning

Icing



Fire resistance of
composite materials

Numerical methods for Ice accretion prediction

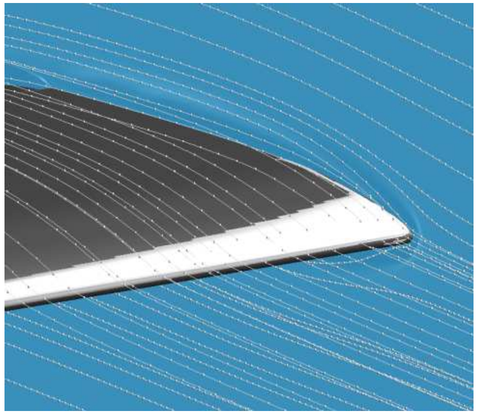
Regulation is strengthening following recent accidents

- Take into account Ice Crystals and SLD (Super-cooled Large Droplets)
- Necessity to improve simulation tools (trajectories, complex impacts, erosion, ... + deicing and anti-icing)

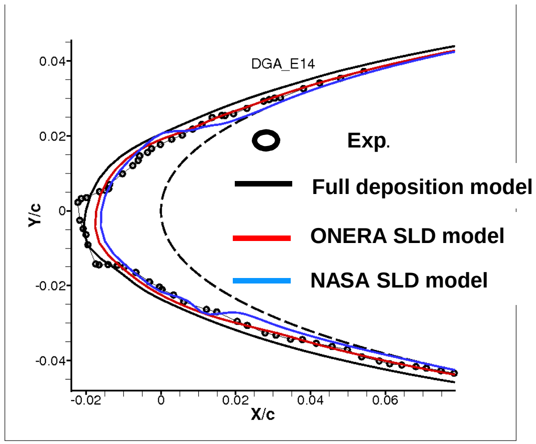
Examples of recent simulations

- Modeling of ice accretion (predictor / corrector or multistep approaches, structured or unstructured meshes, SLD, crystals ...)
- Modeling protection systems (deicing, anti-icing)

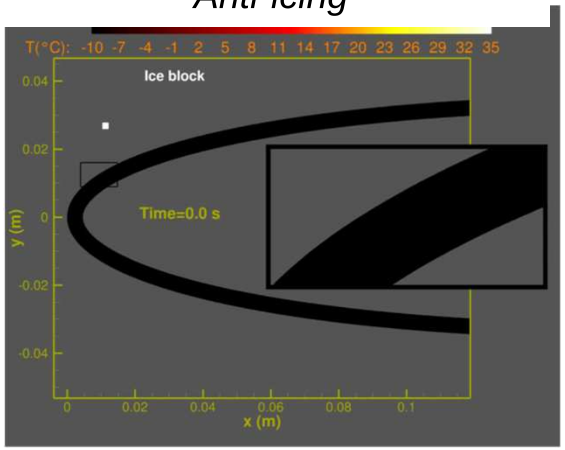
Ice shape in 3D



SLD : EXTICE project database



Anti-icing



Status of CEDRE : Contrails

From few seconds...

... Until several hours

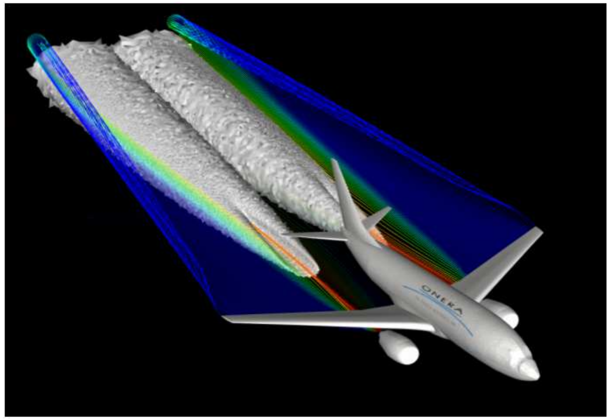
Artificial regional cloudiness

Physical aspects

- Generation of contrails : ice crystals from condensation nuclei (essentially soot particles)
- Possible evolution in artificial cirrus
- Modification of radiative forcing
- Possible impact on climate

Key points

- Importance of wingtip vortices on component dispersion
- Disparity of the scales involved
- Complexity of the microphysical model



ONERA CFD Challenges / Roadmap

- ❑ Automatization and Accuracy Control : From End-users expertise to Expert CFD system
  - Automatic mesh generation/adaptation for geometric complexity and high accuracy including flexible Pre-, Post and Co- Processing
  - Mastering Computational errors thanks to High-Fidelity methods using mathematical & physical indicators and h-p adaptation
  - Develop robust methods for stiff system and multiscale with model adaptation : → m-adaptation
  - Low Cost CFD for pre-design loops
- ❑ HPC and efficiency of integration methods
  - Management of exaflopic for advanced numerical simulations : efficient parallel integration methods using advanced linear algebra
  - Efficient programming on heterogeneous platforms : Close cooperation with computer manufacturers
- ❑ CFD into the certification process
  - Manage operational/model uncertainties : introduction of CFD into certification processes
  - Synergy (hybridization) processes between CFD and experience for aerodynamic data production representative of the model in flight
  - Adjoint approaches necessary for optimization and data assimilation
- ❑ Advanced multiphysics simulation
  - Numerical methods for robust and accurate system coupling
  - Standardization of interface for mesh/solver/multiphysics
- ❑ Integrate CFD platforms for research and industry : software architecture with interoperable components to manage complex physical/numerical modelling and multidisciplinary simulations

Immersed boundary method on Cartesian grids

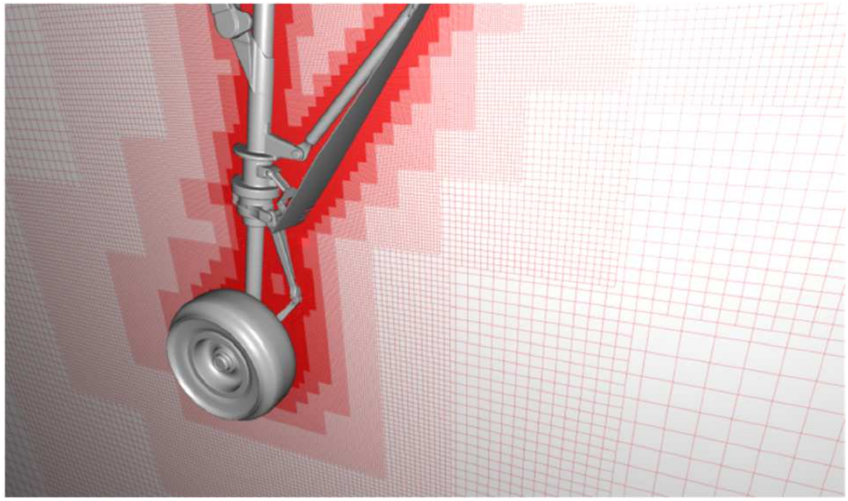
Automatic workflow from CAD surface

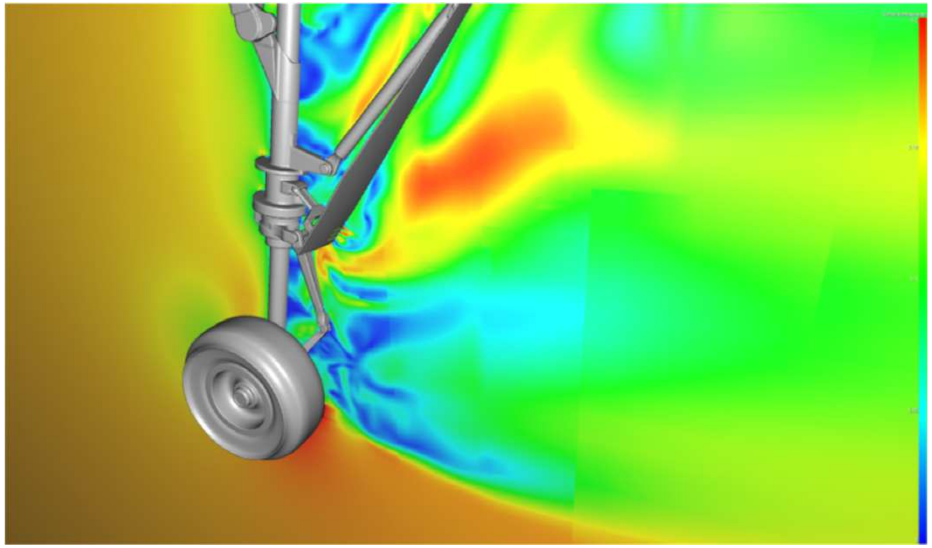
Automatic Adaptive Cartesian Grids

Immersed boundaries (Ghost Cell Direct Forcing Approach, wall-modeled for RANS and RANS-LES simulations)

Use in combination with the Cartesian solver of FastS HPC Navier-Stokes solver developed by ONERA

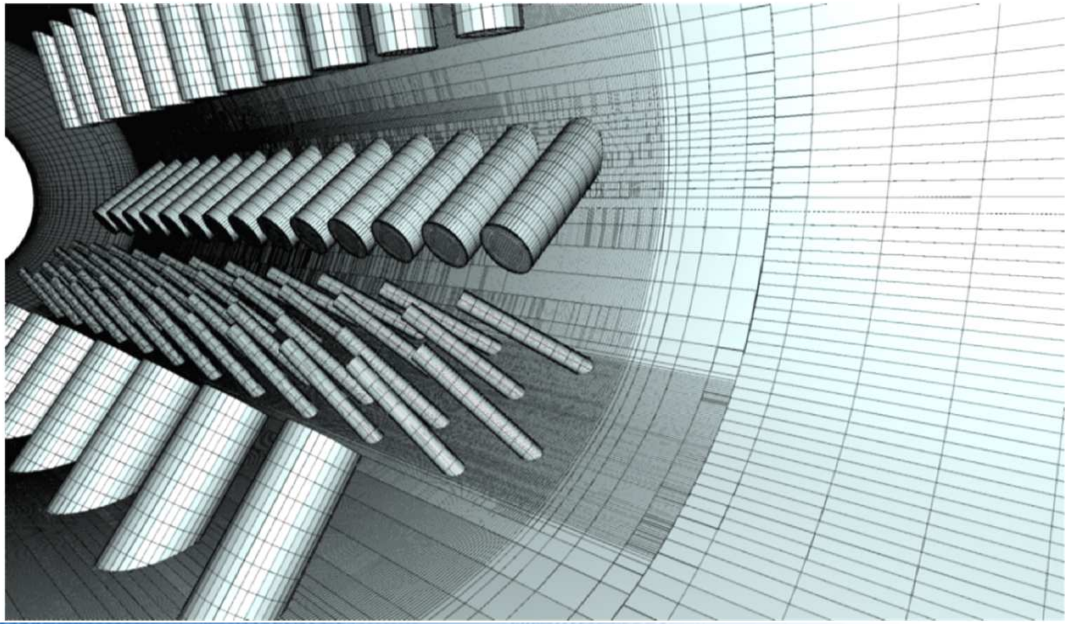
Réf : S. Péron et al., An Immersed Boundary Method for preliminary design aerodynamic studies of complex configurations, AIAA paper 2017-3623





Mesh Intersections

- The kernel is a Boolean operator for 3D-arbitrary meshes
- Multiple applications:
  - ➢ 2nd-order Conservative Remapping
  - ➢ Mesh generation by assembling pre-meshed components
  - ➢ Applications with an overset grid strategy :
    - o *Pre-processing : Blanking*
    - o *Conservative Interpolations*
    - o *Post-processing*



Boolean Operator
CAD-2017 Landier

Conservative interpolations & Chimera applications
AIAA-2018 Landier et al.

MVC-06, Meshing Techniques, January 10, 2018

AGHORA : ONERA HPC code based on Discontinuous Galerkin method

Scientific challenge

- High accuracy and efficiency for complex turbulent flows on HPC plateformes

Physical modeling and numerics

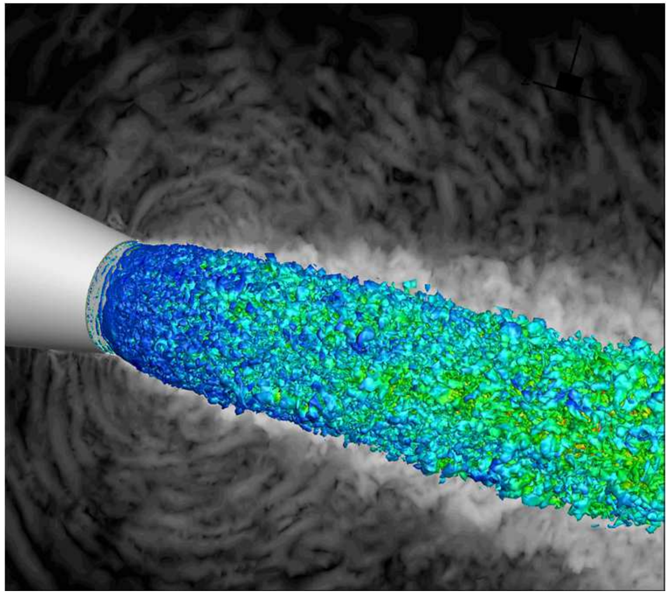
- DG modal or nodal approach
- Unstructured High-Order polyhedra
- Efficient integration for steady and time-accurate
- Internal and external flows
- Turbulence modeling : RANS, DES, LES, DNS
- Local automatic h/p adaptation, multiscale VMS

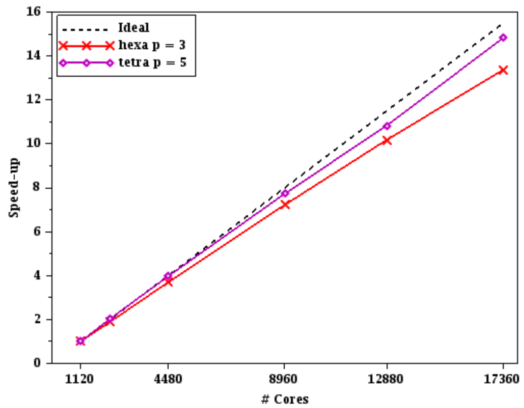
Aghora software prototype

- Efficient HPC programming on advanced architectures
- Collaboration INRIA, BULL, INTEL
- Multiphysics using code coupling with CWIPI library
- Real Gas effects / Aeroelasticity
- Adjoint method for data assimilation and flow control

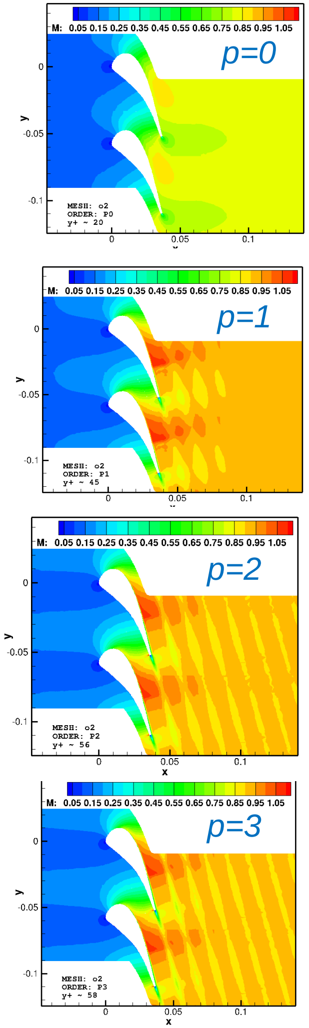
Collaborations / Benchmarking

- European projects IDIHOM, TILDA, ANADE, SSeMID
- International High-Order Workshops

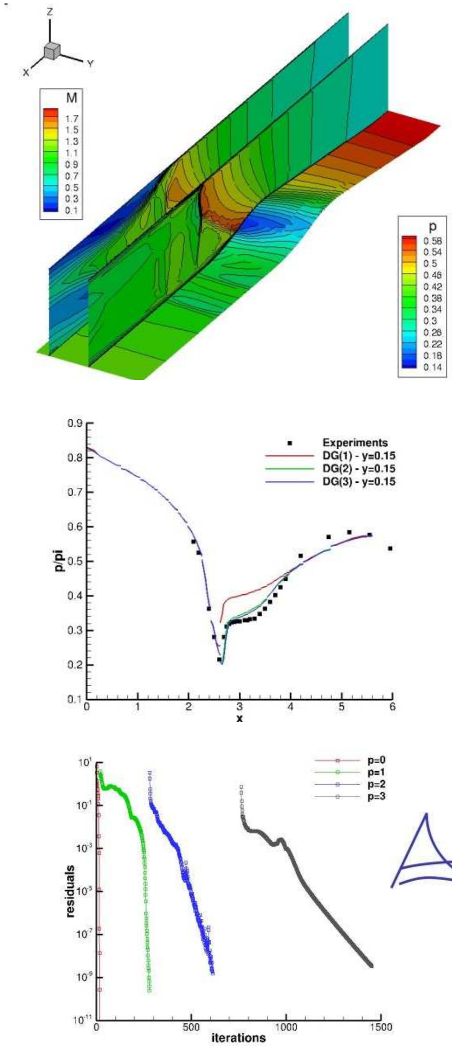




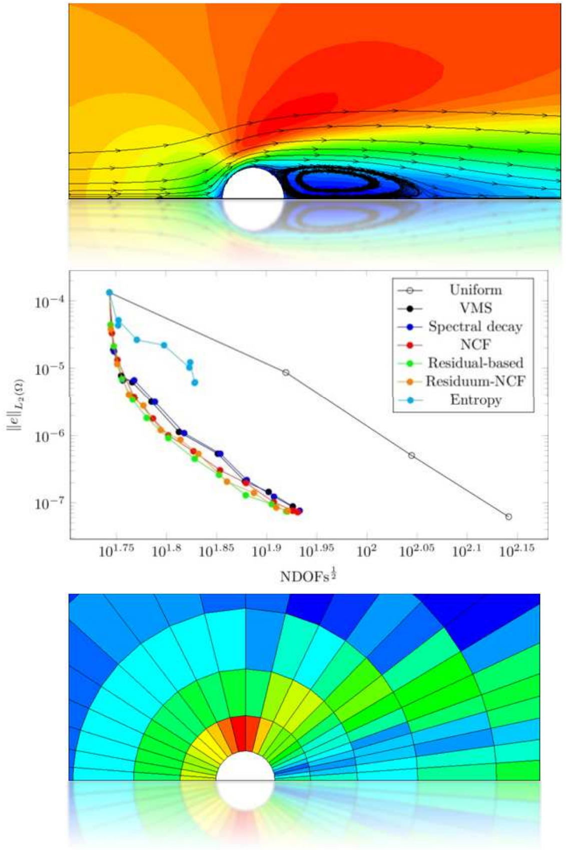
JEAN nozzle - Strong scalability : 218M DoFs/eq
Comparison of parallel efficiency at Iso-DoFs



Transonic VKI turbine
at iso-Mesh : from p=0 to p=3



ONERA 3D swept Bump (Exp. J. Délery)
Efficient implicit method for HO-DG



FD-09. CFD Solver Techniques
AIAA-2018-0368.
Fabio Naddei et al.

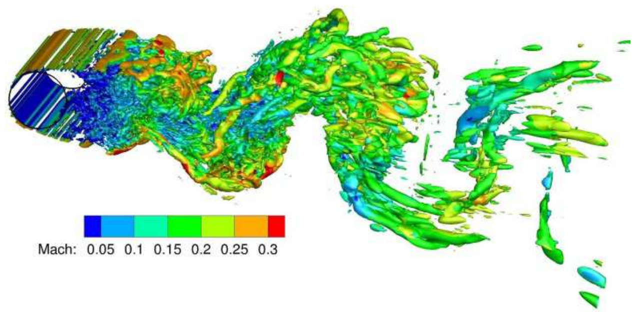
Laminar cylinder - Efficiency of local p-refinement with various error indicators

Aghora : Analysis of DG for LES Flow Simulations

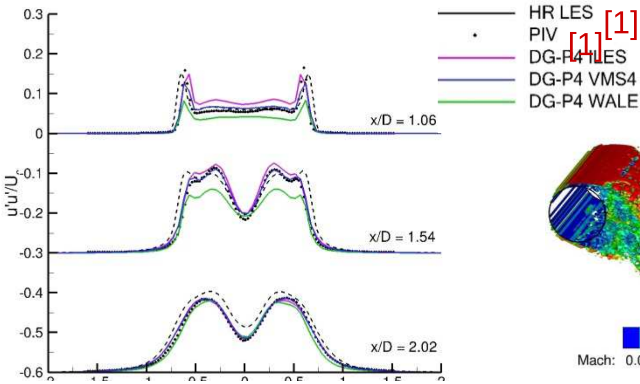
LES with HO-DG method : Analysis of ILES / WALE / VMS-LES

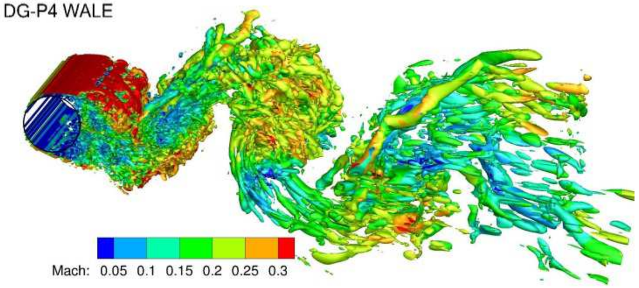
DG-P4 (5th order) - VMS approach assessed on the cylinder teste case

DG-VMS provides best match with experimental data compared to no-model (ILES) and WALE

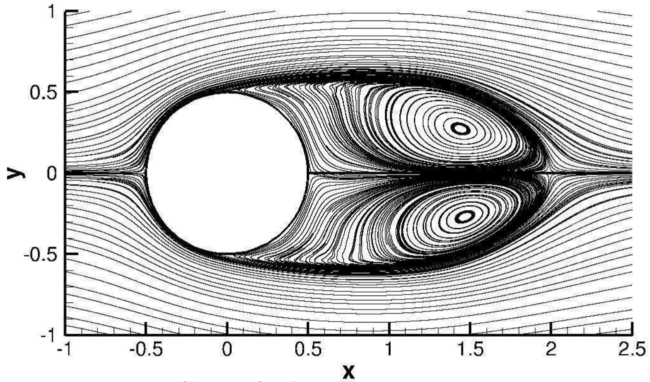


Re = 3900

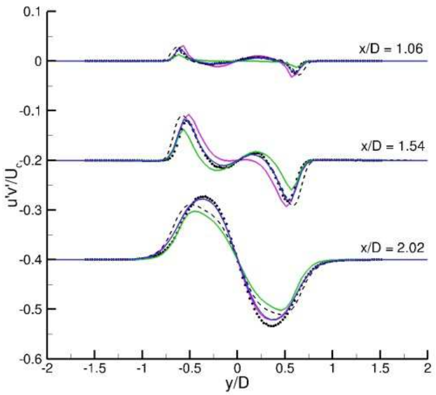




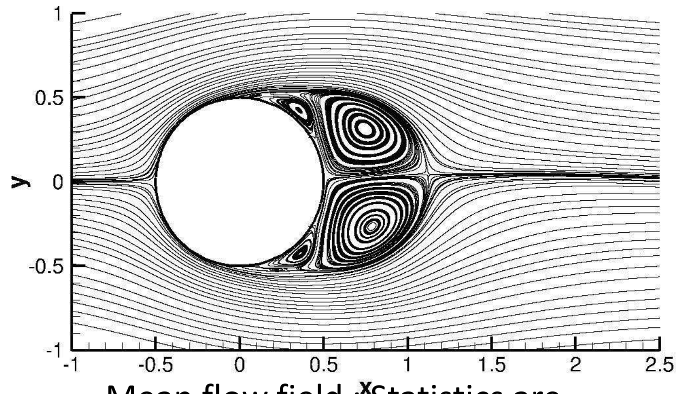
Re = 20000



Mean flow field : Statistics are gathered over ~ $100T_{vs}$ for Re = 3900



Cross-correlation - Re = 3900



Mean flow field : Statistics are gathered over ~ $40T_{vs}$ for Re = 20000

ONERA & HPC computer : 2017

IN House :

SGI ICE : NHM (**2009**) + WESTMERE + upgrade (**2013)** (2880 cores Ivy Bridge) - 01/2014 : 7872 Intel cores – Peak performance 115 Tflops

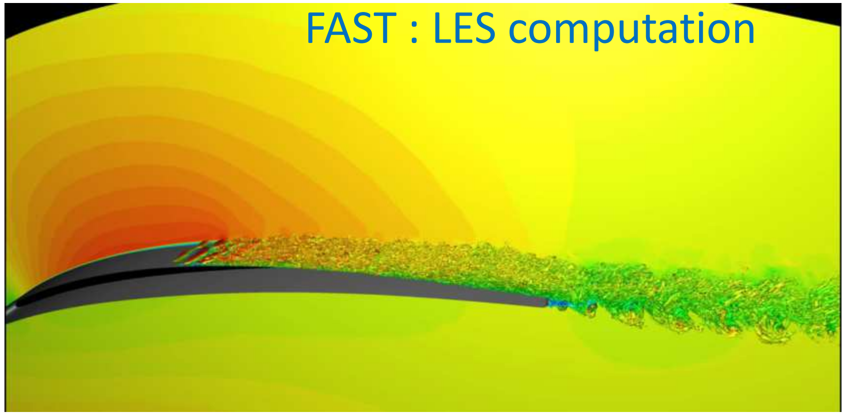
Spring 2017 : NEC - 17360 cores BDW > 579 Tflops
Linpack : 342 position TOP 500 June 2017

End 2018 option Skylake -> 1 Pflops

- CCRT / TGCC – Partner

Access to GENCI : 35 Mh in 2017

PRACE : Several preparatory access



<u>ONERA partner in :</u>

ORAP, Ter@tec

shareholder in CERFACS

ETP4HPC

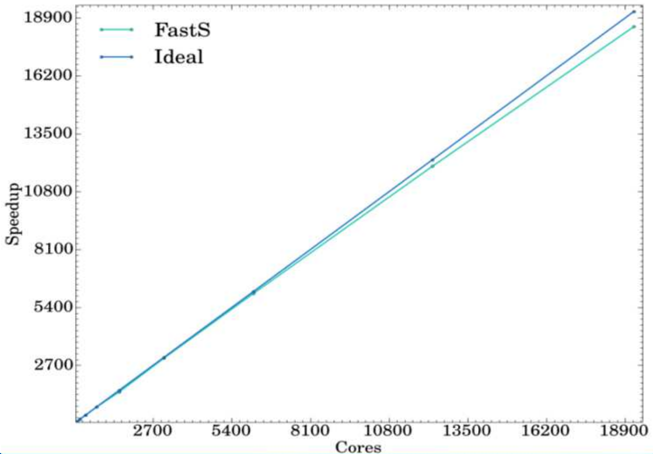
Project with computer manufacturer Atos/Bull

Intel labeling : ONERA **IPCC 2017-2018**

(Intel Parallel Computing Center) solver optimization for KNL / Skylake

FAST S : structured implicit solver for LES / RANS

- On the fly optimized I J K subpartitions in OpenMP shared memory for cache filling
- SIMD Vectorization along I ; Performance 600 M cell*ite/s on XeonPHI KNL socket (72 cores)



Cluster MareNostrum IV (Barcelone)

PRACE Preparatory Project

95% parallel efficiency 19200 cores

~147 Tflops

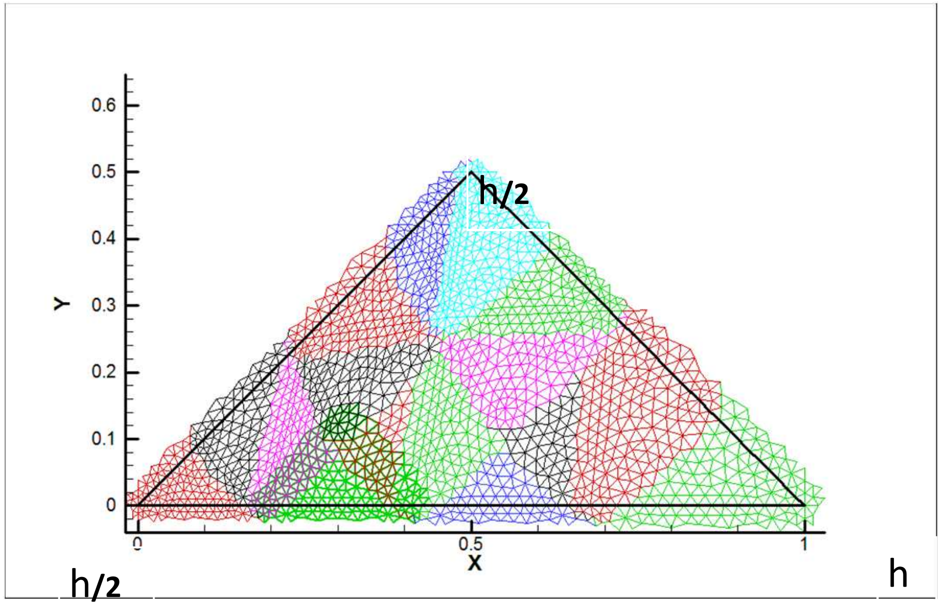
Many-core programming optimization for node performance

keywords : « Mpi / OpenMP / AVX512 / cache filling / deep memory»

IPCC 2017-2018 : solver optimization for KNL / Skylake

NXO unstructured explicit solver (DTS implicit) for grid templates
Grid and memory hierarchy : embedded conforming triangular grids in quadtrees (here in 2D)

- L2 cache filling with the OpenMP stack
- Topological vectorization
  along the subpartition index
  full vector data model for flow / metric
- Performance in 2D for Navier-Stokes RHS
  - 110 M Rhs /s on KNL socket
  - 160 M Rhs /s on dual Skylake node



Self-vectorized grid embedded in a coarse octree
16 subpartitions with identical connectivity / halos

GPU implementation of the NextFlow solver
3D k-exact reconstruction of flux density tensor components
2.5D periodic spanwise, MULTI-GPU / MPI

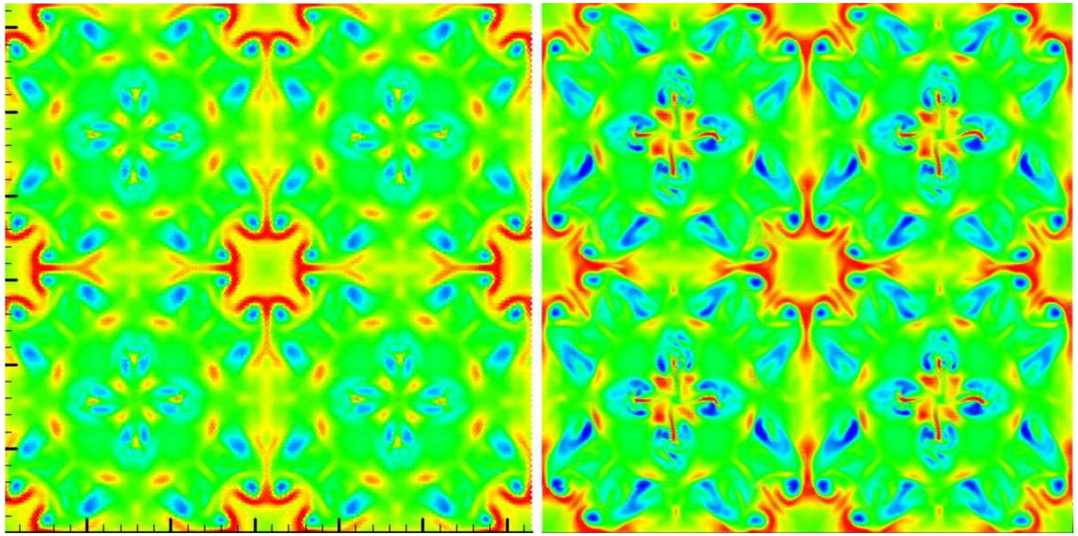
TAYLOR-GREEN Vortex on respectively

256^3 and 512^3 wedges

Total energy slice

at z=-pi/2,

t=8 dissipation peak



Performance on one GPU :

in k3 25 ns per Rhs, 40 M Rhs /s

in k4 42 ns per Rhs, 24 M Rhs /s

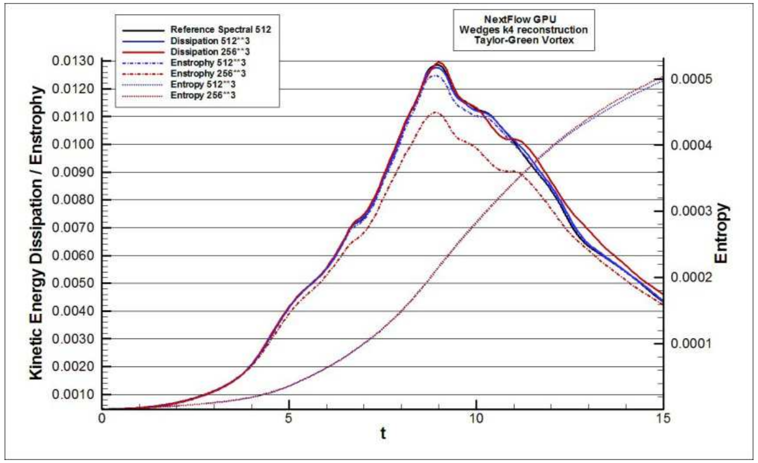
Taylor Green vortex 2563 : wall-clock 1600 Hours CPU Intel core :**

<u>12 hours</u> on 16 IVY-Bridge processors (128 cores)

<u>25 minutes</u> on 16 Tesla K20M GPUs

Taylor Green vortex 5123 : wall-clock**

<u>4 hours</u> on 16 Tesla K20M GPUs



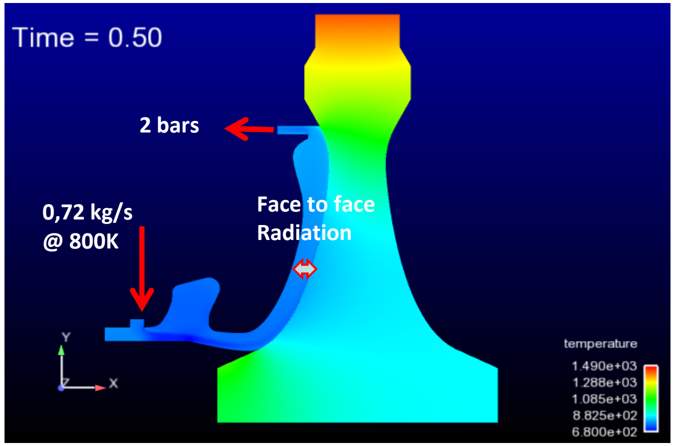
ONERA
THE FRENCH AEROSPACE LAB

High-Precision Methods For Coupled Fluid-Structure Problems

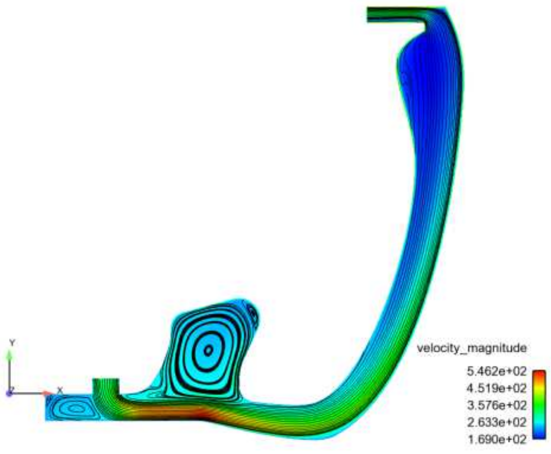
<u>**New Interface Treatments for Conjugate Heat Transfer (CHT) Problems**</u>

- **<u>From a Simplified Coupled Model Problem</u> :**
  Normal mode decomposition -Stability analysis – Godunov-Ryabenkii theory…
- **A fundamental transition has been highlighted !**
- **Optimal coupling coefficients :**
  - Monotonic convergence
  - Unconditional stability of the coupled problem
  - Fastest convergence rate
- **Optimal coefficients mature enough to be used in the industry**
- **Used in a variety of applications :**

- **Steady (weak coupling) :** CPU time divided by 5 !
- **Unsteady (strong coupling) :** analysis of the metallic heat load (turbine disk) over the duration of a flight cycle



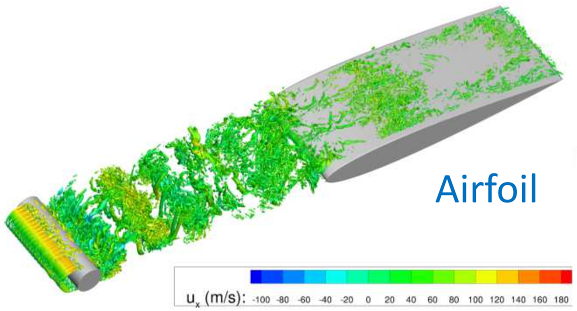
<u>Coupled Computation</u> : Cooling of an HP Turbine Disk



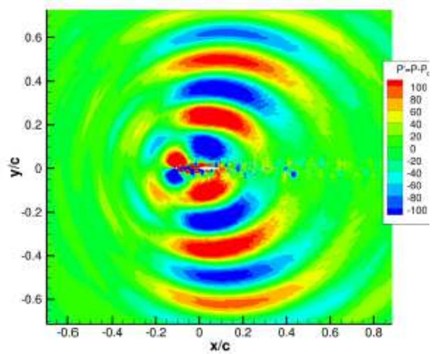
<u>CFD Computation</u> : Cooling circuit

Lattice-Boltzmann : ONERA's activities in the ProLB project

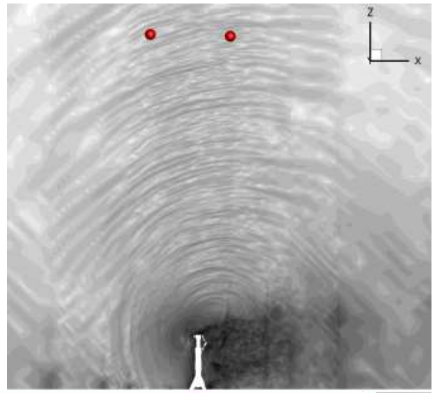
- Developments/improvements
  - Efficient wall laws for attached boundary layers
  - Reliable conditions for 2-1 resolution boundaries in octree grids
  - Others : Mach > 0.4, plasmas, multi-phase, GPU, fluid/structure, optics
- Evaluation of the solver for aeronautic configurations (acoustics, aerodynamics …)

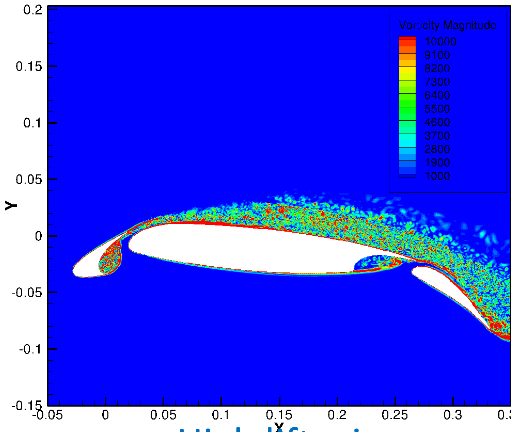


Airfoil

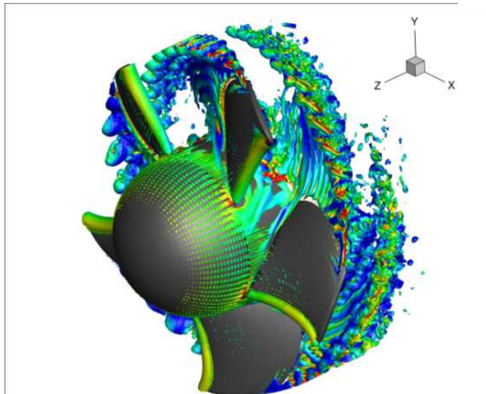


Landing gear

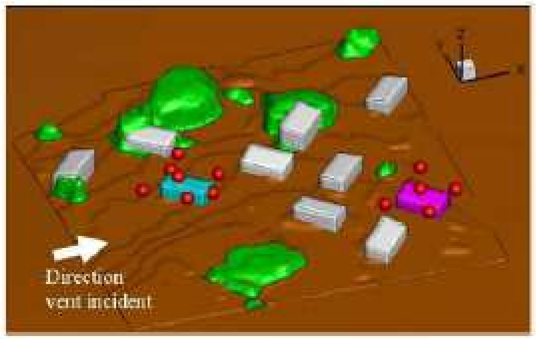




High lift wing



Turboengine



Urban flow

ONERA/DAAA & ONERA/DMPE contributions

Roadmap for softwares

<u>Research studies with elsA</u>

Turbulence and transition modelling
Numerical methods
Unstructured and hybrid meshes
Aerothermics, Aeroelasticity, Aeroacoustics
Cartesian/IBC capacities
Co-/post-processing, easy management of Boundary conditions

<u>Prepare the future</u>

FV-HPC prototype Fast
DG-HPC prototype Aghora
Funded by 2 internal projects

<u>Research studies with CEDRE</u>

Thermic, Multiphase, Combustion, Radiation, Acoustics
ZDES, LES
Hybrid Eulerian-Lagragian (sues…)
…

Premio (ONERA)

- Component approach
- Aerodynamics, Energetics, Multiphysics
- Sustainability and sharing of CFD tools including elsA modernization, CEDRE modules, prototypes

Strong interaction with Mosaic (Safran)

- Component approach of **PREMIO** to be shared thanks to common module interfaces

RHEA NewGen CFD code (Airbus/DLR/ONERA)

- New cooperation launched end 2017
- Integrating FV, DG, hybrid approaches with various levels of turbulence modelling for aerodynamics