A Cartesian Adaptive Methodology For Helicopter Flows

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Outline

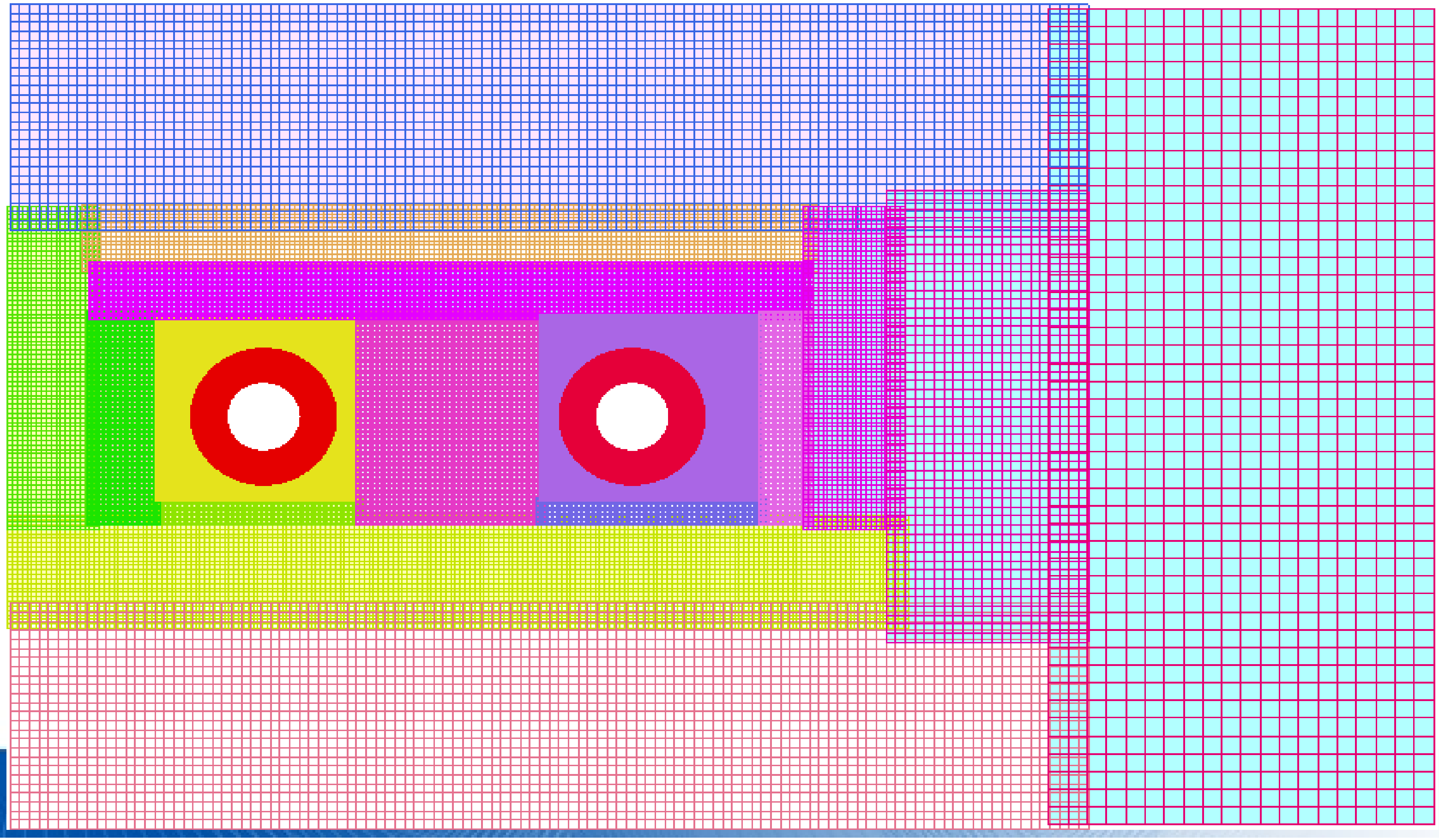
- Overset Cartesian Mesh method
- Adaptation of centered schemes
- Time refinement procedure
- Conclusion

Overset Cartesian Grids method

- Introduced by R. Meakin (2000)
- Input: body grids
  - Accurate description of geometry
  - Short extension

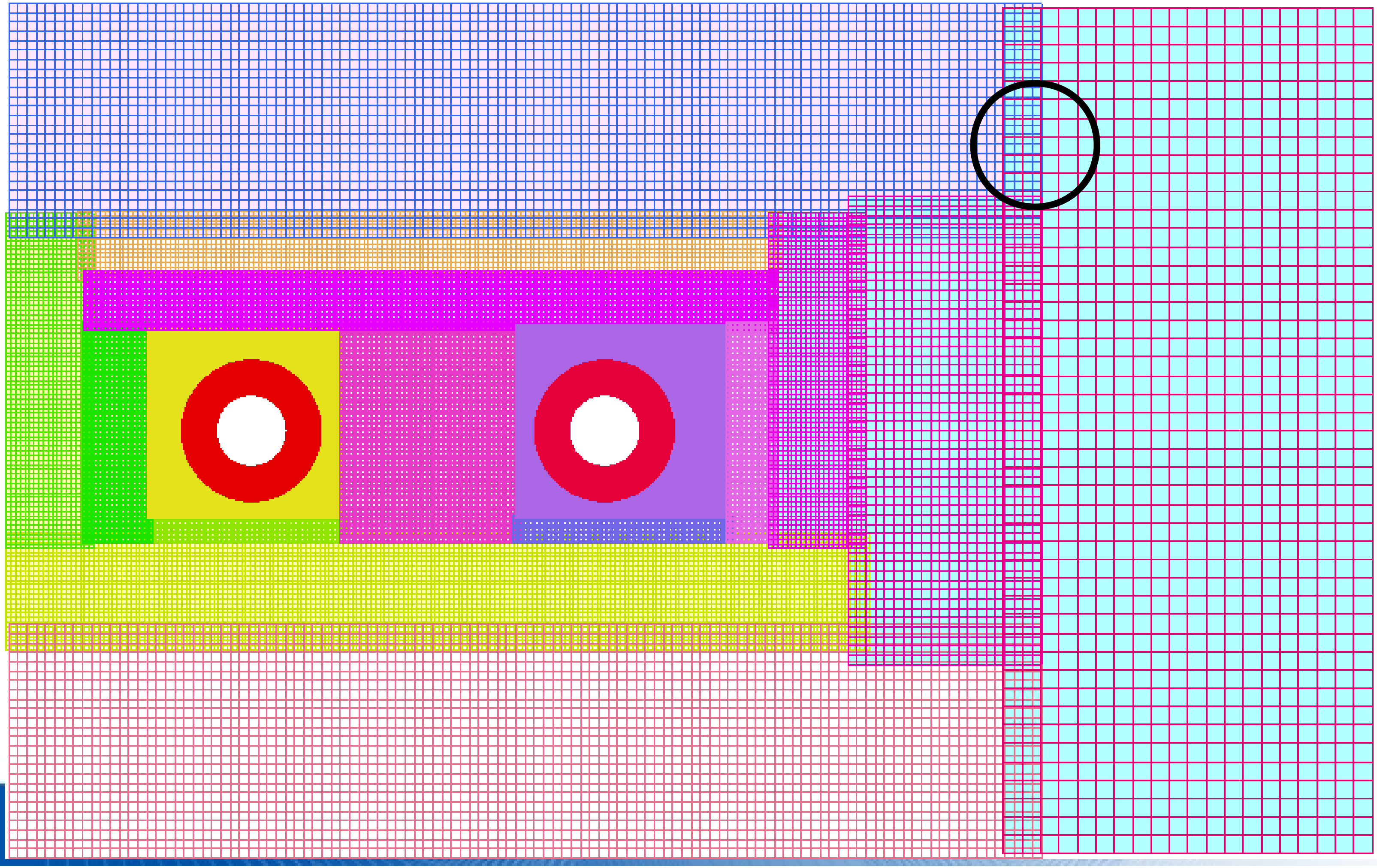
Overset Cartesian Grids Method

- Initial Cartesian mesh generation
  - Set of regular Cartesian grids
  - Finer step near bodies
  - Control of the minimum number of points per grid



Overset Cartesian Grids Method

- Initial Cartesian mesh generation
  - Cartesian Grids overlap each other with minimum overlap

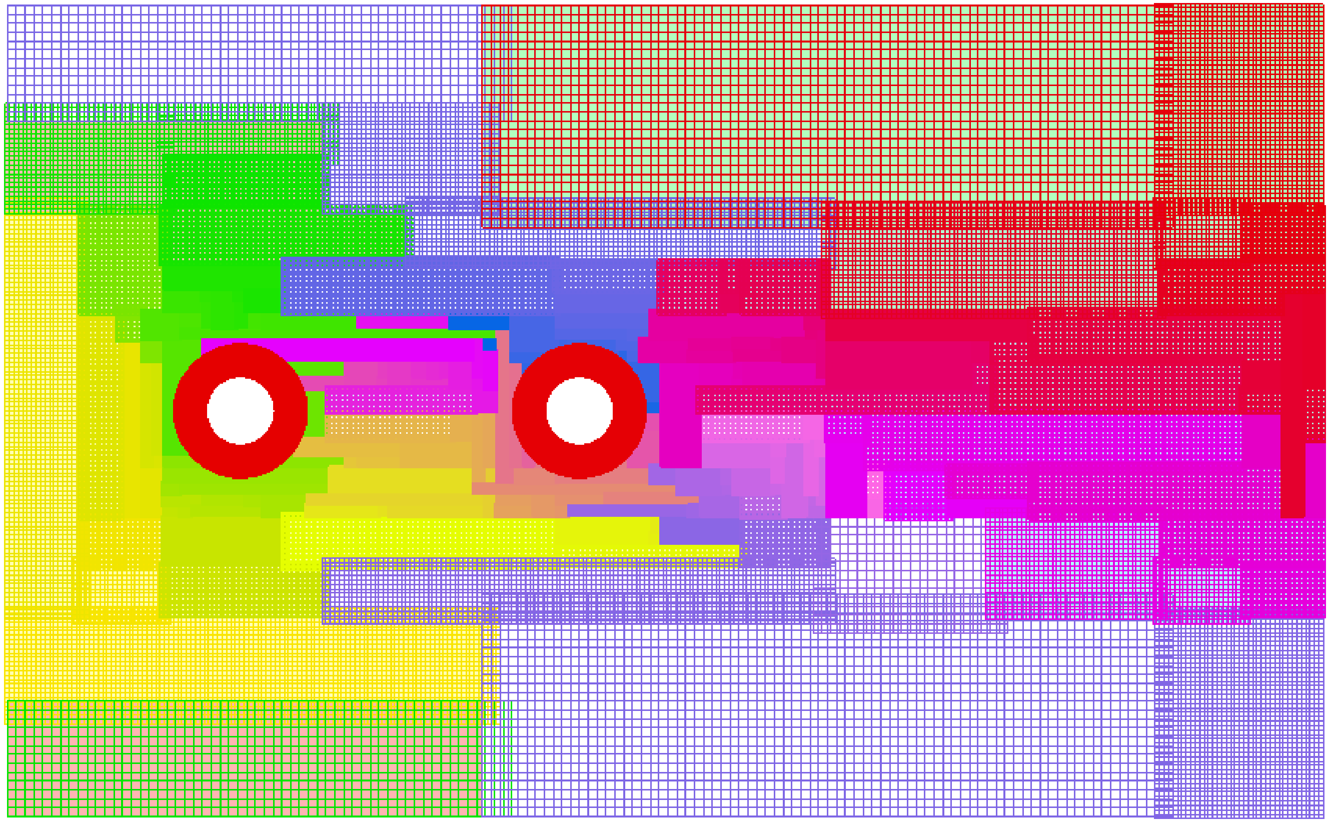


Overset Cartesian Grids Method

- Overlap regions
  - Transfer by interpolation of conservative field
  - Minimum overlap between grids ensured
  - Mesh size coherent between curvilinear body grids and Cartesian grids in overlap regions
  - Matching boundary conditions between Cartesian grids of finest level

Cartesian Overset Grids Method

- Cartesian mesh adaptation
  - Cartesian grids can be regenerated following a criteria evaluated on the previous mesh



Adaptation of centered schemes

- Starting point:
  - Jameson scheme (order 2)
  - Finite volume formulation on curvilinear structured grids
  - Artificial dissipation

Centered schemes

- Adaptation to regular Cartesian grids:
  - Face normal is constant
  - Cell volume is constant

  → No metric storage
  - The flux $\int_{\partial\Omega} F(w).n \, d\Gamma$ can be simplified
  - Implicit matrix is sparser
  - Interpolation cell search is simple and fast

  → Gain of 40% in CPU and memory

Order 3 centered scheme

- Extension to third order on curvilinear structured grids:

  Introduced by Rezgui, Cinella, Lerat (2001)

  - Third order estimation of flux integral
  - Third order estimation of volume integral
  - Correction of centered approximation of interface fluxes

  → Order 3 on deformed meshes

  → But: requires new local metrics (distance from cell-center to interface center, …)

  → Expensive in memory and CPU time

Order 3 centered scheme

- Extension to third order on curvilinear structured grids:
  - Hypothesis of regular meshes with small rotation between cells
    - Simplification in integral formulae
    - Simplification in Taylor expansions

    → Order 3 on regular meshes only
  - Flux is approximated at interface center by (FV3):

$$F_{i+\frac{1}{2},j,k} = [(I - \frac{1}{8}\delta_1^2 + \frac{1}{24}\delta_2^2 + \frac{1}{24}\delta_3^2)\mu_1\phi]_{i+\frac{1}{2},j,k}$$

  - With:

$$(\mu f)_{i+\frac{1}{2}} = \frac{1}{2}(f_i + f_{i+1}), \quad (\delta f)_{i+\frac{1}{2}} = f_{i+1} - f_i$$

$\Phi = F(w).n$

Order 3 centered scheme

- Extension to third order on Cartesian grids:
  - Finite volume formulation reduce to finite difference formulation!
  - Complete scheme reads (DNC):

$$\left[w_t + \frac{\delta_1}{\delta x}(I - \frac{1}{6}\delta_1^2)\mu_1 f + \frac{\delta_2}{\delta y}(I - \frac{1}{6}\delta_2^2)\mu_2 g + \frac{\delta_3}{\delta z}(I - \frac{1}{6}\delta_3^2)\mu_3 h\right]_{i,j,k} = 0$$

→ Easy to implement

→ Only 5% CPU overhead than Jameson scheme

Order 3 centered scheme

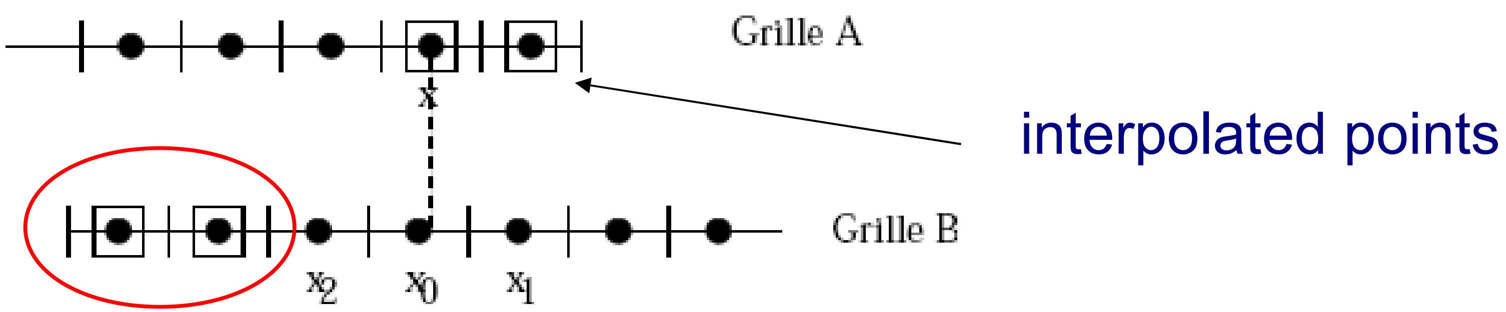
- Numerical dissipation:
    - Same as Jameson scheme:

$$F_{j+\frac{1}{2},k} = (F - D)_{j+\frac{1}{2},k}$$

$$(D)_{j+\frac{1}{2},k} = \rho(\bar{A}_{j+\frac{1}{2},k})(\epsilon_2\delta_1 w - \epsilon_4\delta_1^3 w)_{j+\frac{1}{2},k}$$

$O(h^3)$ $O(h^3)$

Chimera interpolation



- Interpolation through Lagrangian polynomials of degree 2

$$P_n(x) = \sum_{i=0}^{n} l_i(x) w(x_i)$$

$$l_i(x) = \prod_{\substack{j=0 \\ j \neq i}}^{n} \frac{(x - x_j)}{(x_i - x_j)}, \qquad 0 \leq i \leq n$$

With n=2

Order 5 centered scheme

- Introduced by Lerat, Corre (2003)
- Only for Cartesian grids
- Finite difference centered scheme
- Artificial dissipation of higher order
- Only 10% CPU overhead than Jameson (DNC5):

$$(w_t)_j + \frac{\delta}{\delta x}\left[\left(I - \frac{1}{6}\delta^2 + \frac{1}{30}\delta^4\right)\mu f\right]_j = \frac{\delta}{\delta x}\left(\frac{1}{60}|A_R|\delta^5 w\right)_j$$

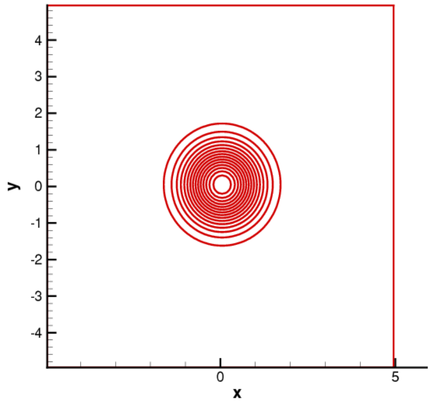
Convective flux

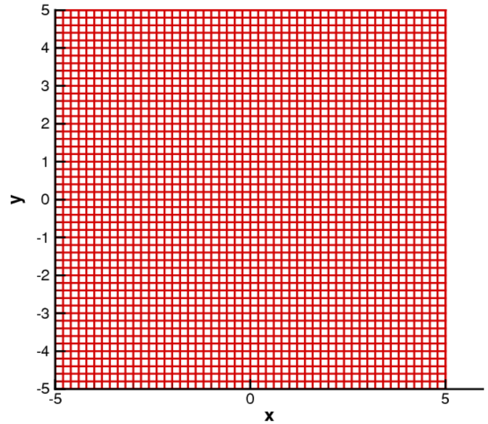
Dissipation

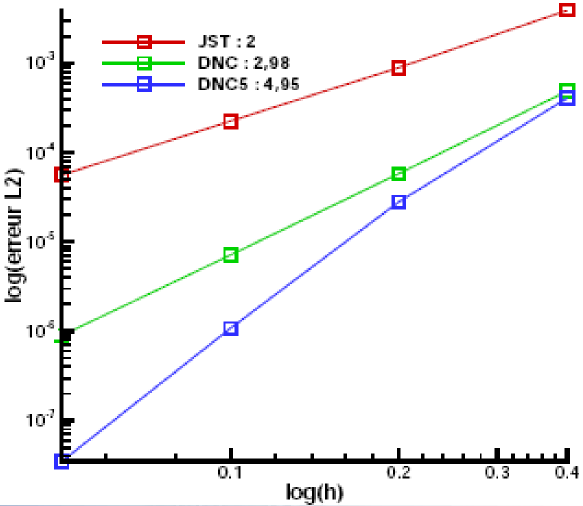
Validation: vortex advection

- Test case: Yee (2000)
- Inviscid flow, M=0.4225
- Regular Cartesian mesh

→ Accuracy order is achieved

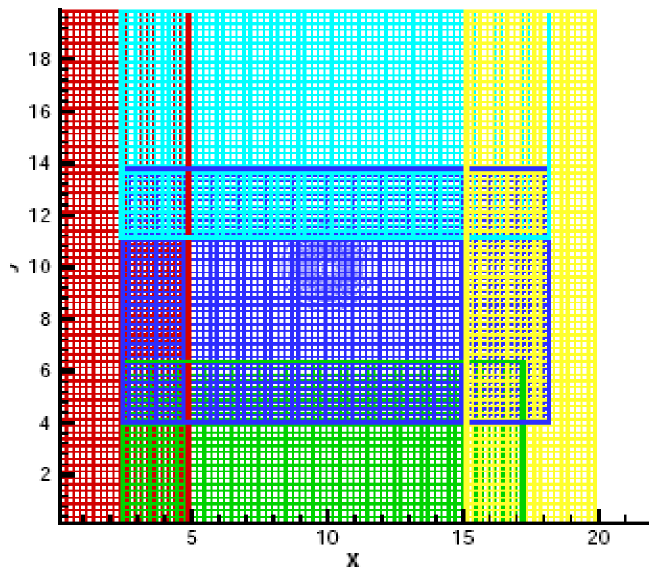


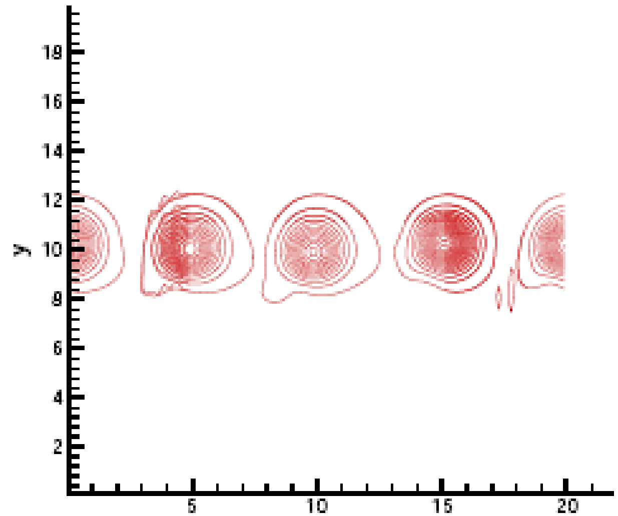




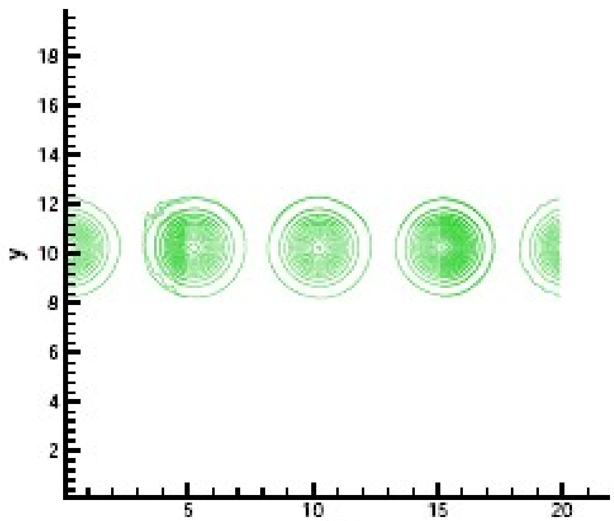
ONERA

Validation: vortex advection

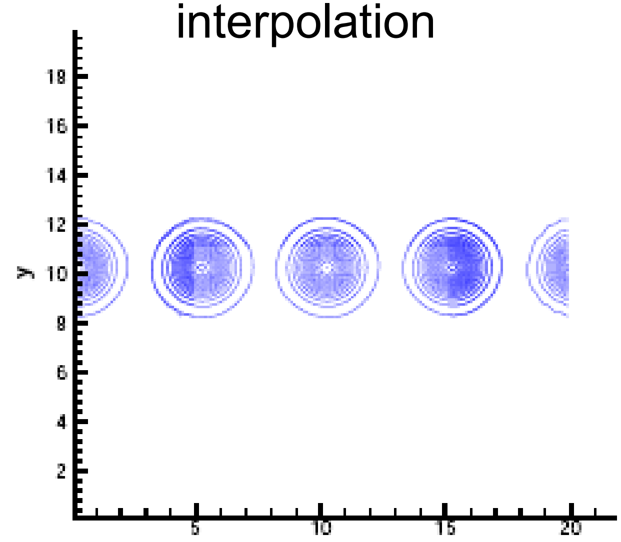




JST + order 2 interpolation



DNC + order 2 interpolation



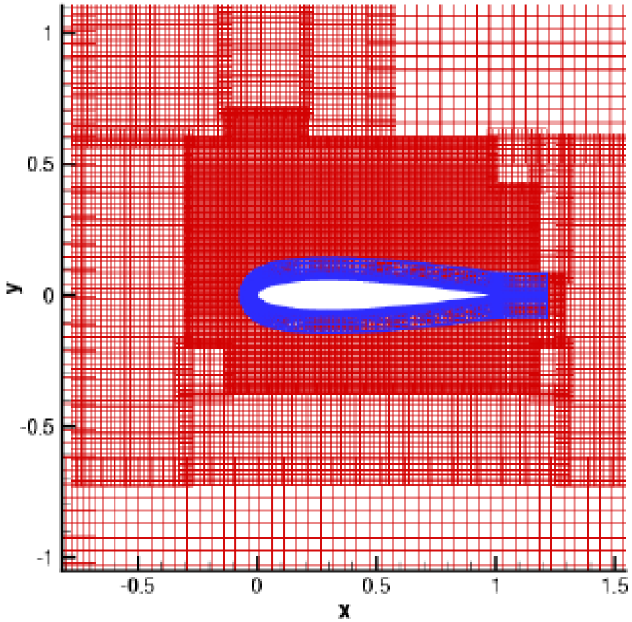
DNC + order 3 interpolation

→ Interpolation order must be compatible with scheme order

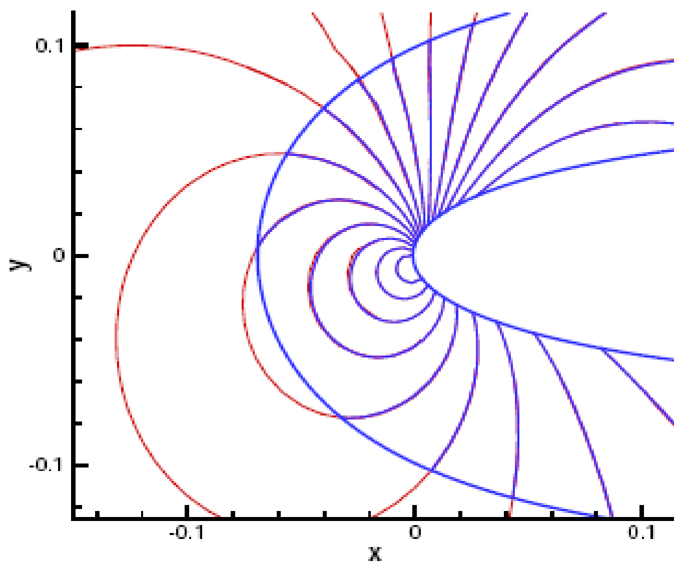
Validation: order of accuracy

Subsonic flow around a NACA profile, M=0.63, 2 degrees of incidence

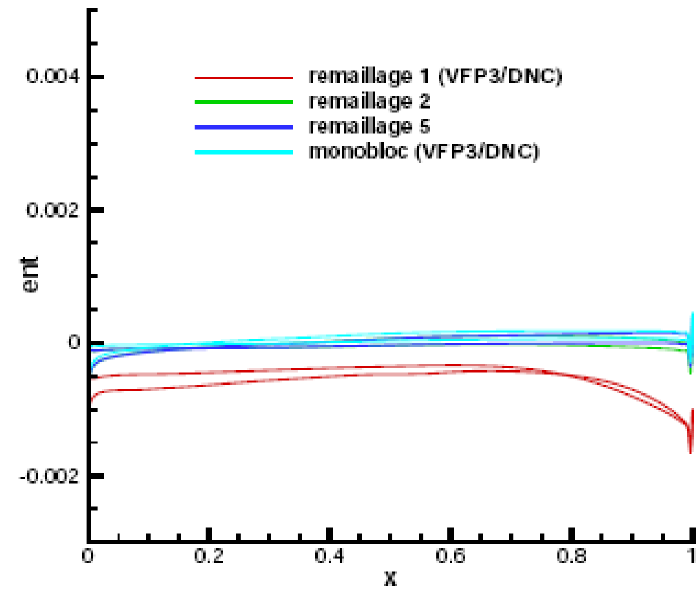
- Generation + 5 mesh adaptations
- FV3 + DNC + order 3 interpolations



Adapted mesh



Iso-density lines

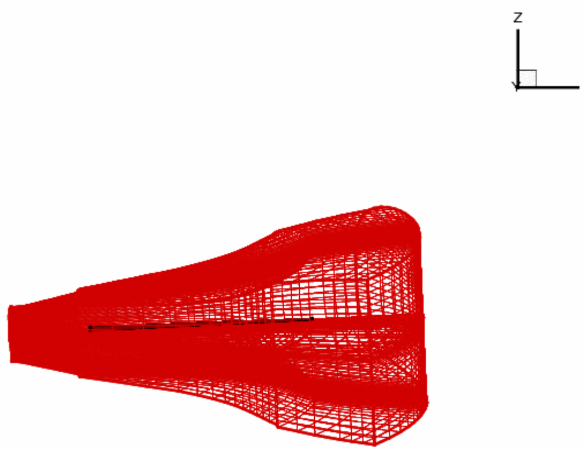


Wall entropy

→ Order 3 is achieved

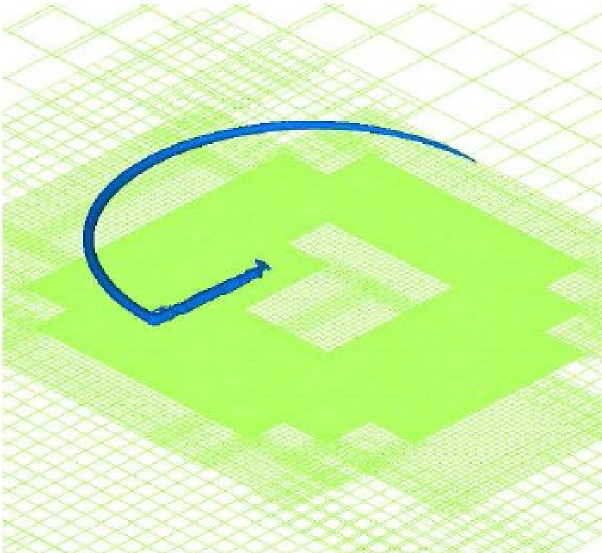
Validation: isolated blade in hover

- 7A blade in hover
- Mtip = 0.662, collective pitch = 10 degrees
- 9 remeshings following rotational of speed

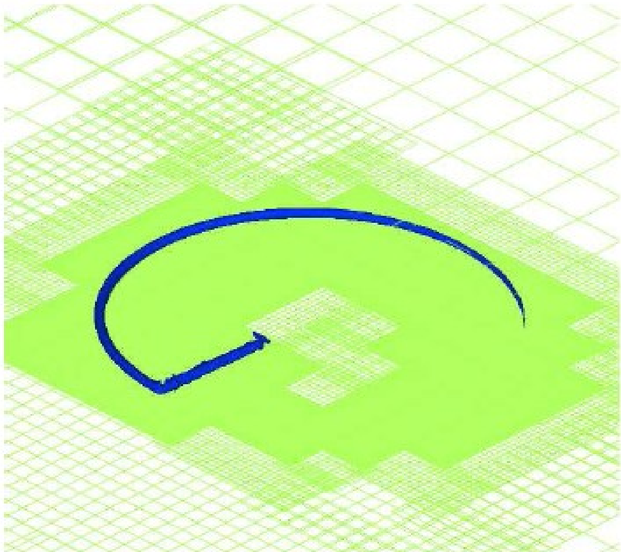


Blade mesh

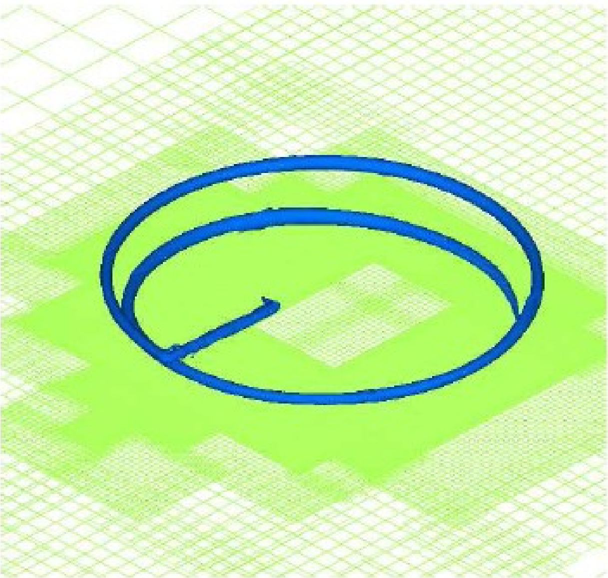
Validation: isolated blade in hover



JST



FV3 + DNC



DNC5 (Cartesian grids)
DNC (Blade grid)

Simulation of inviscid airfoil-vortex interaction (1)

Goal : Compare the preservation of the vortex during the advection phasis with 2nd order, 3rd order and 5th order methods

Test-case :

2D NACA0012 airfoil

Scully vortex

M_{tip} = 0.714

μ=0.198 advance ratio

α=0°, parrallel interaction

y0 =-0.25 c

Initial vortex location : 10 chords ahead of the airfoil

Simulation of inviscid airfoil-vortex interaction (2)

Curvilinear near-body grid : 449x17 points

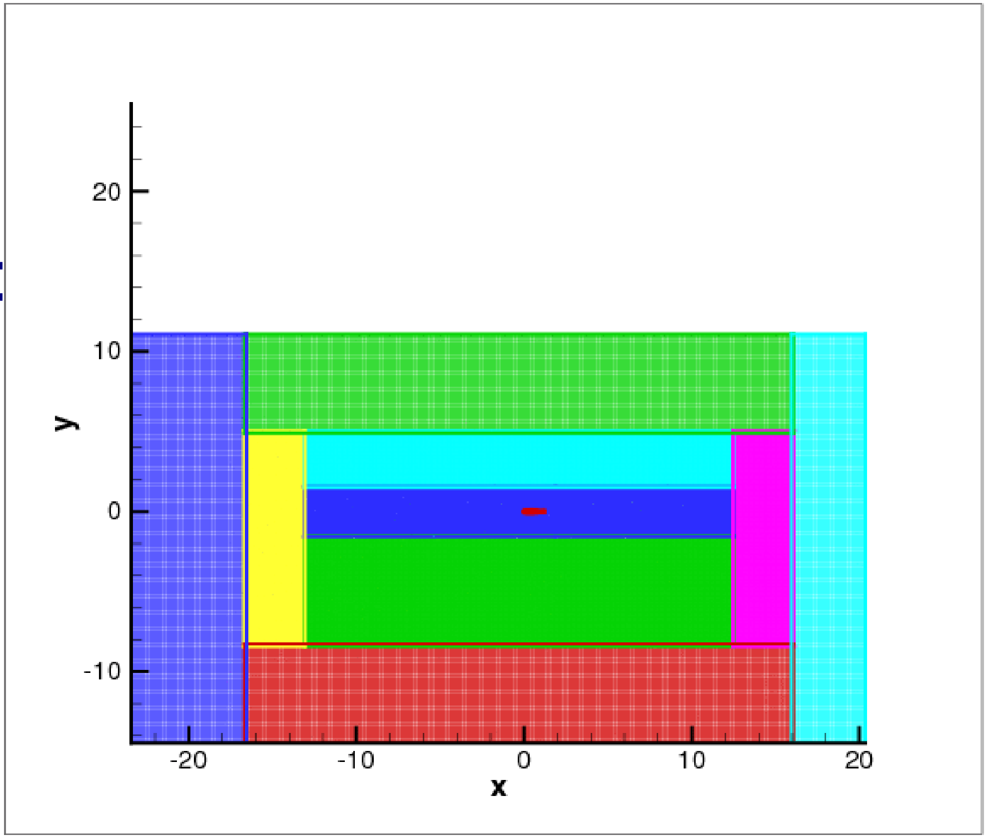
Cartesian background grids :

Finer in the vortex region : 1026x126 points

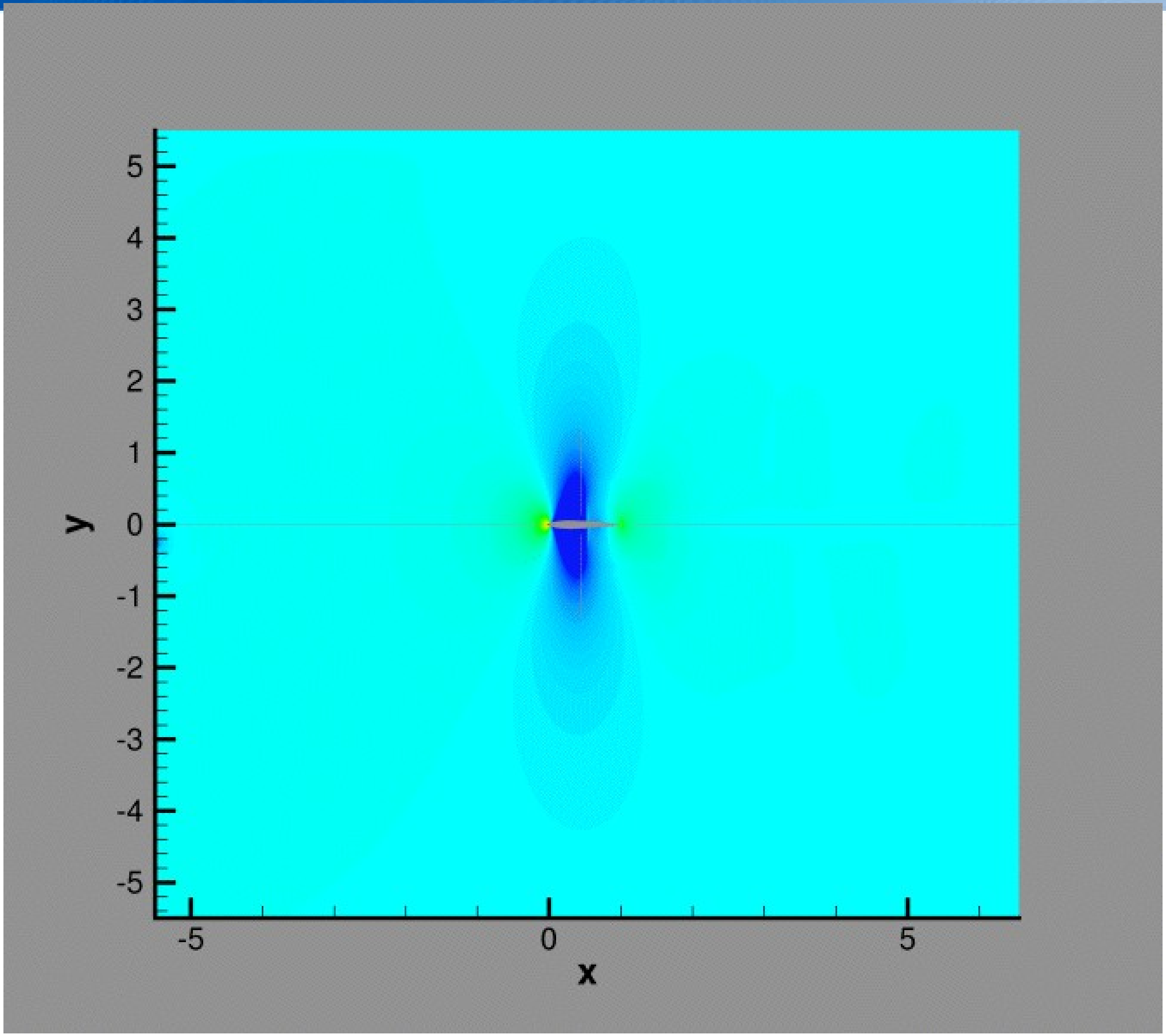
Coarser grids far from the airfoil to avoid boundary effects

Total: 230000 points

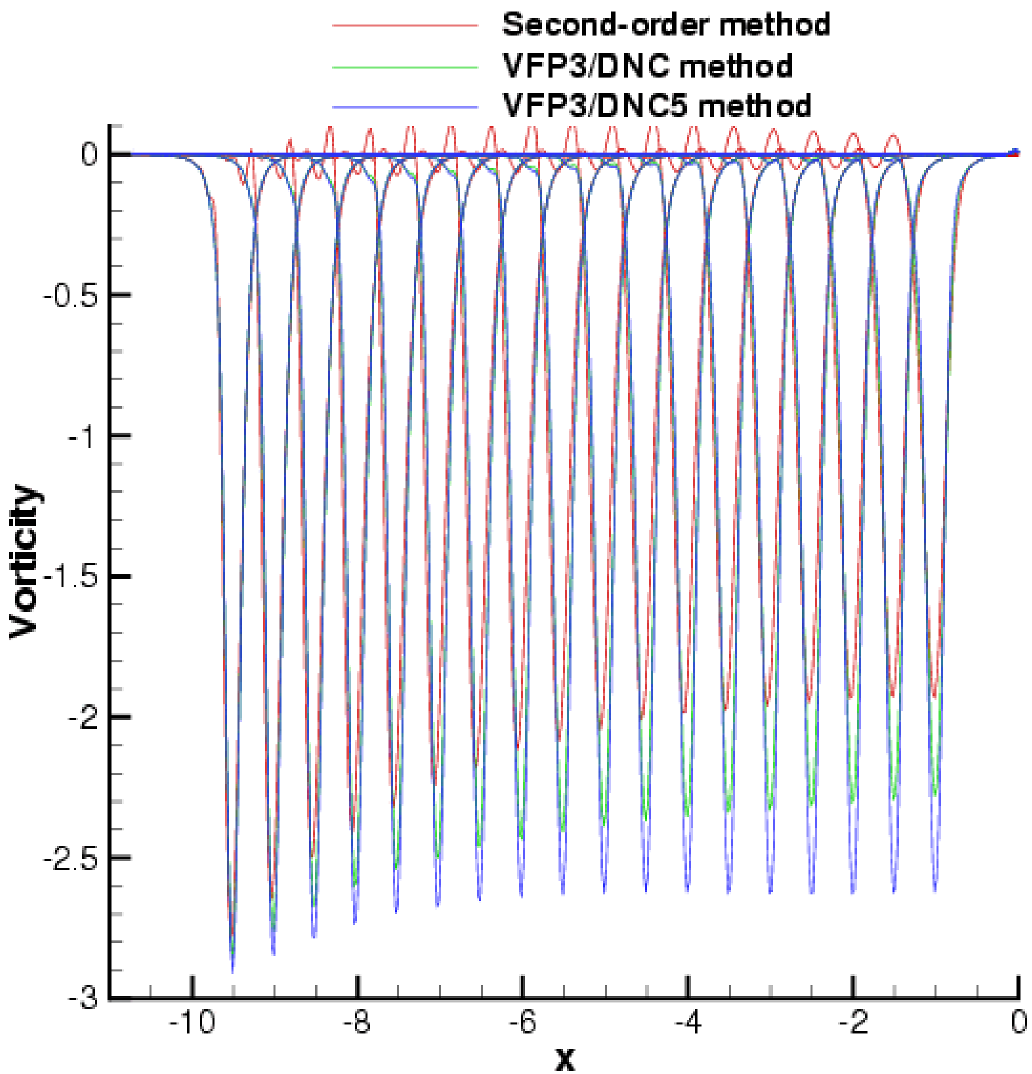
6 points in the vortex core radius



Simulation of blade vortex interaction



Simulation of inviscid airfoil-vortex interaction (4)



Isolated blade in forward flight

7A blade, R=15c, c=0.1

M=0.4 and Mtip=0.646

Numerical schemes:

- Test 1: JST/JST/interp O2
- Test 2: FV3/DNC/interp O3
- Test 3: FV3/DNC5/ interp O5

Isolated blade in forward flight

Automatic mesh generation:

- 3 M points
- Comp. Domain [-5,5]x[-5,5]x[-5,5]

Automatic mesh adaptation:

- 6 remeshings
- Indicator: rotational
- 19 M points

Q criterion

JST

Q criterion

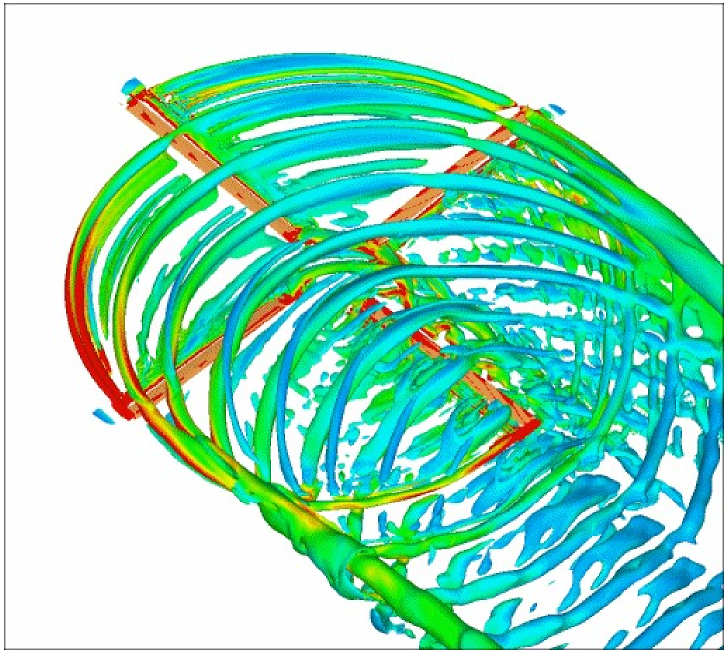
DNC

Q criterion

DNC5

Application to the BVI capture

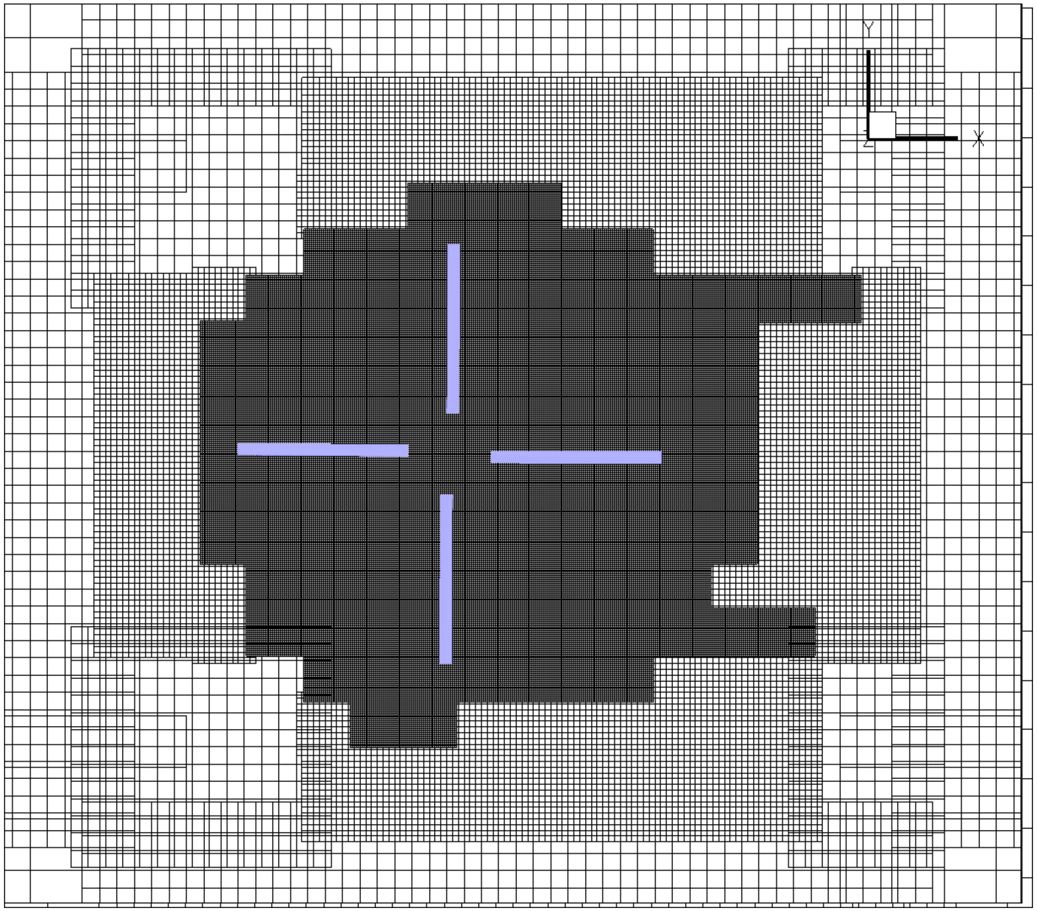
- Blade-vortex interaction:
  - Dominating in low speed descent flight
  - Due to the parallel interaction between blades and blade tip vortices
- Objective: to capture accurately and efficiently the main features of the blade-vortex interaction



Achieved during the first phase of the French-German SHANEL project (ONERA / DLR / ECD / EC SAS / IAG)

Effects of the solver accuracy

- Initial mesh: 1.1 million Pts on Cart. grids
- Spatial resolution in the finer grids: Δh=0.15c
- Adaptation w.r.t. the vorticity magnitude
- Final mesh: 5.93 on Cart. grids



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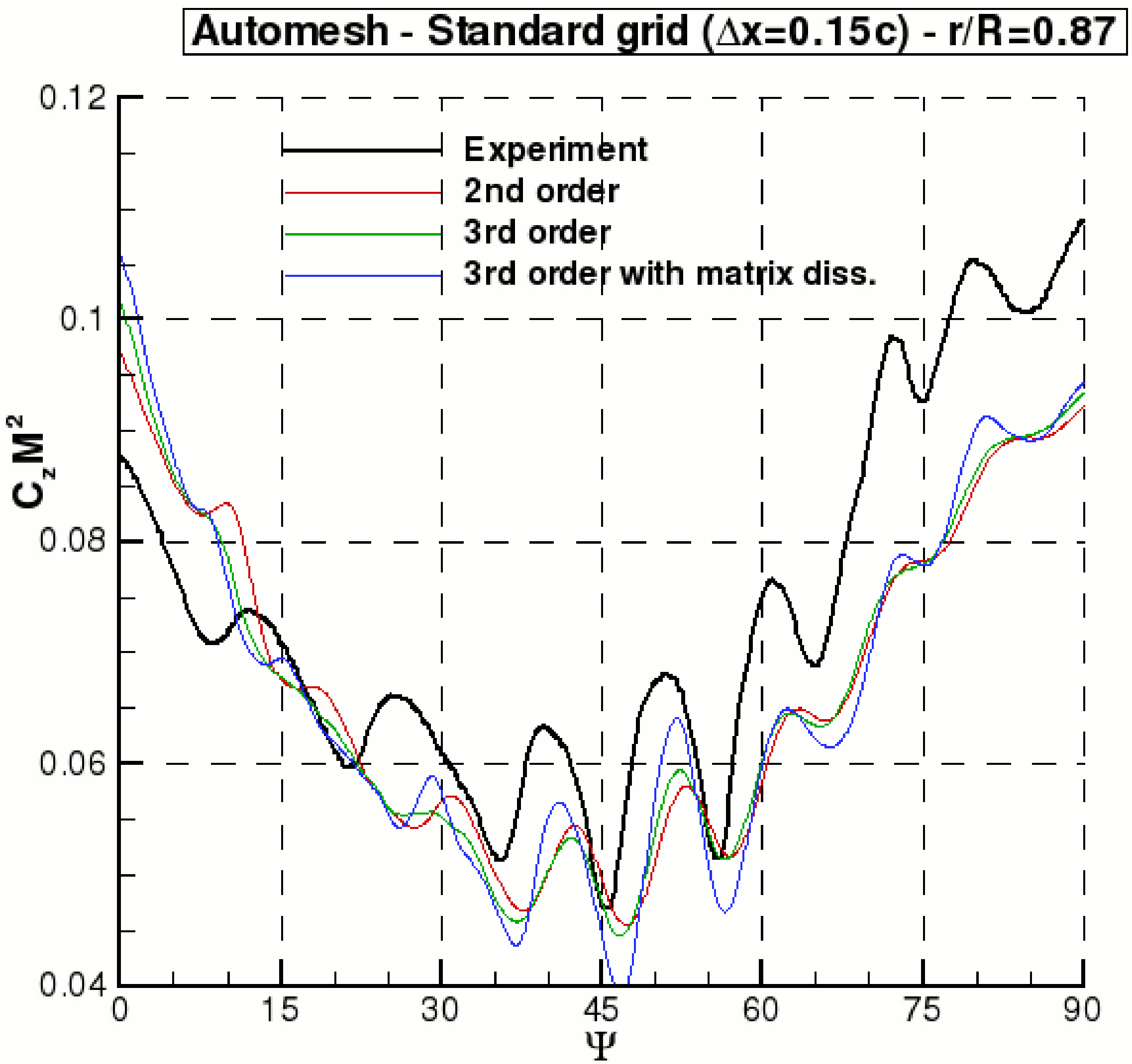
Airloads: advancing side



Time refinement procedure

Berger, 1982:

- Denote
  - $A = \frac{\Delta\ h_{l+1}}{\Delta\ h_l}$ (usually 2 or 3),
  - $\Delta t_0 = \Delta t$ be the global time step.
  - CFL the CFL number
- For any grid of level l:

$$\Delta t_l = A^l \Delta t_0 = \frac{CFL}{max_j(\| \mathbf{U_j} \| + \mathbf{a})} \Delta h_0 A^l$$

- So, the time step for grids of level l is majorated by:

$$\Delta t_l \leq CFL \frac{\Delta h_l}{\| \mathbf{U_l} \| + \mathbf{a}}$$

Time refinement procedure

Level 1 grids perform 1 iteration

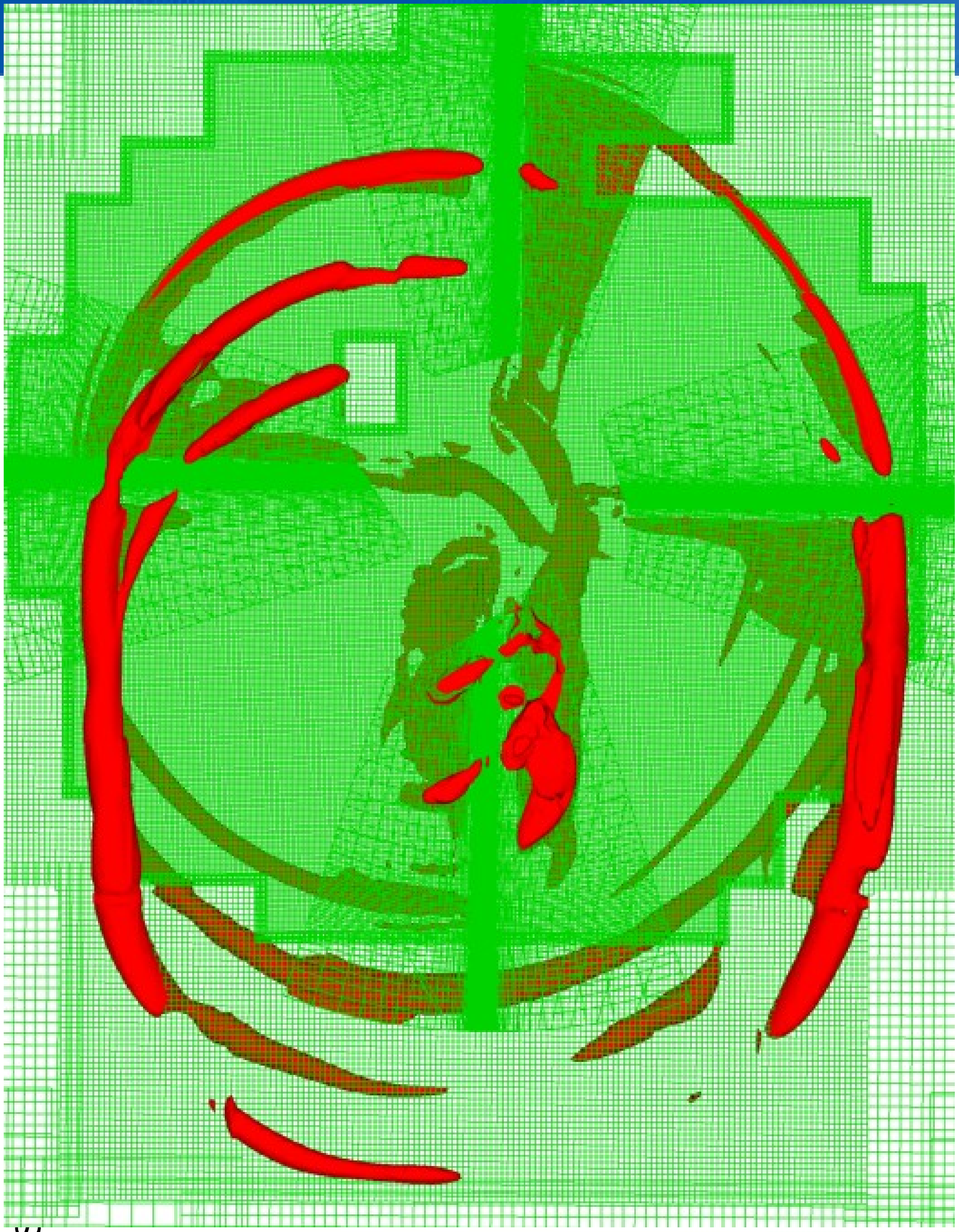
Level 2 grids perform A iterations

- Level 3 grids perform A*A iterations, etc...

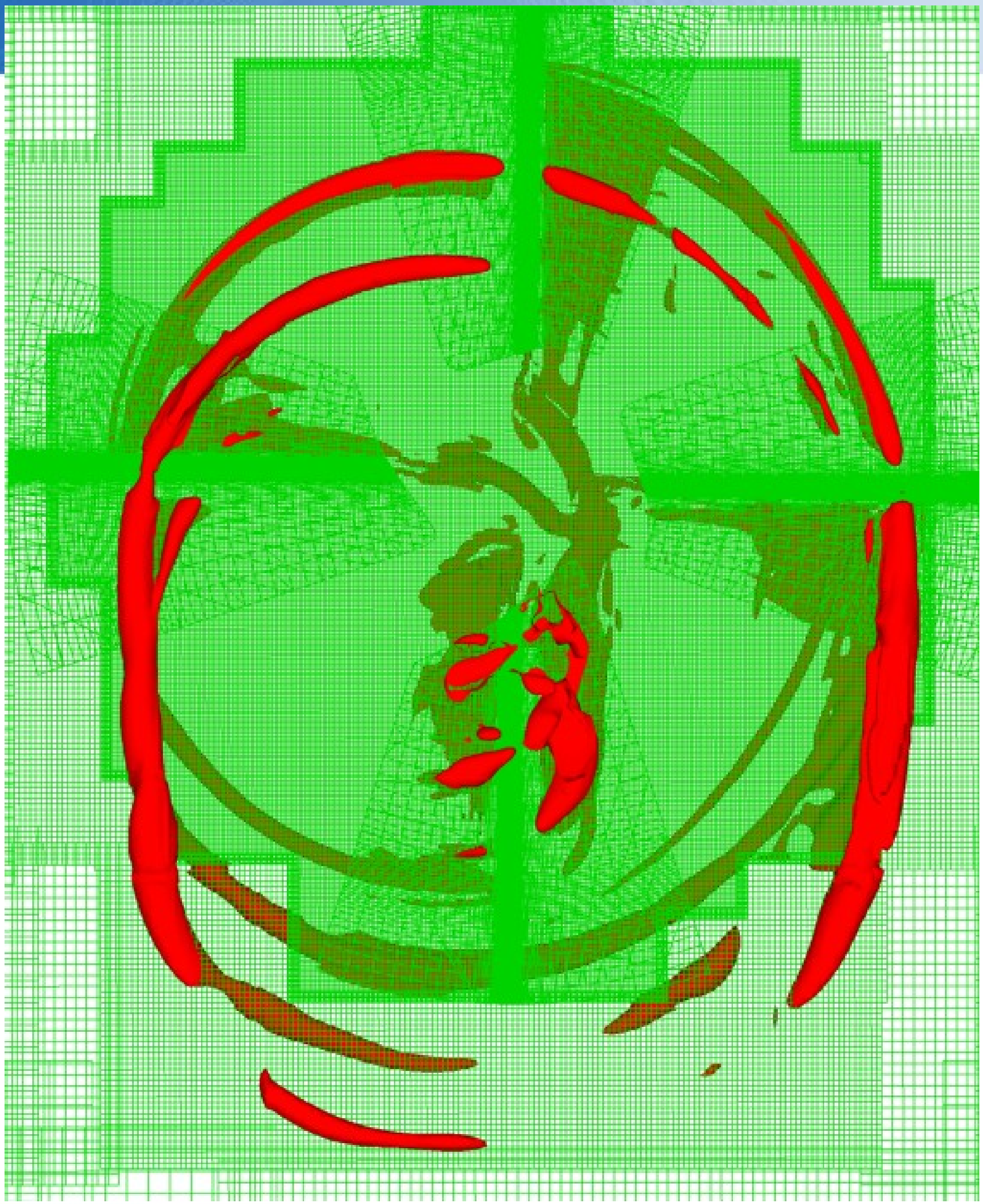
Time interpolation is used in chimera transfers

This procedure adds error of order 2

→ Gain of 30% in sequential mode



Without time refinement



With time refinement

Conclusion

- High potential of Structured Cartesian Overset grids:
  - Accuracy / efficiency of a large panel of solvers
  - No metric storage
  - Very fast interpolation cell search
  - Numerical schemes are easy to implement

- Perspective: full extension of the method to order 5