Block-structured quad meshing for supersonic flow simulations

Claire Roche, Jérôme Breil, Thierry Hocquellet, Franck Ledoux

Claire ROCHE[1,3], Jérôme BREIL[1], Thierry HOCQUELLET[1], Franck LEDOUX[2,3]

[1]CEA-CESTA
[2]CEA, DAM, DIF, F-91297
[3]LIHPC, CEA, Université Paris-Saclay

FROM RESEARCH TO INDUSTRY

Block-structured quad meshing for supersonic flow simulations

March 8, 2023
Claire ROCHE

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Context

- This work aims to provide a solution to generate 3D meshes automatically for a legacy Computational Fluid Dynamics (CFD) code developed for atmospheric re-entry.

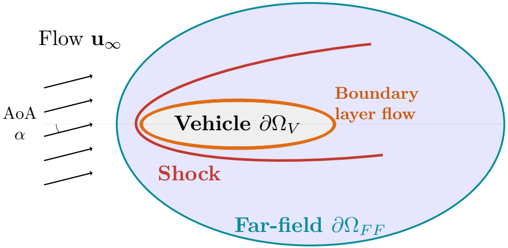


Fig. Flow around a supersonic vehicle

Ideal meshes:

- Near-wall **orthogonality**
- **Thin cells** in the boundary layer
- Smooth mesh **size transition**

Input meshes for the code:

- **Block-structured** meshes

Hypotheses on the domain:

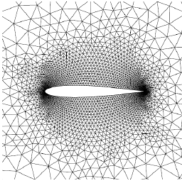
- Vehicles are **completely immersed** in the fluid
- Far-field is a **smooth boundary**
- **Single wall** vehicle

Our meshing algorithm is freely available and implemented in the open-source C++ meshing framework GMDS [LWB][a].

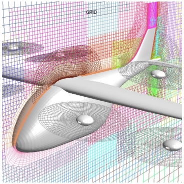
[a] `https://github.com/LIHPC-Computational-Geometry/gmds`.

State of the art

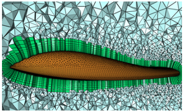
CFD Meshes [CDT16]



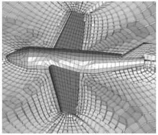
(a) Unstructured mesh [MACP10]



(b) Over-set grid [SBM21]



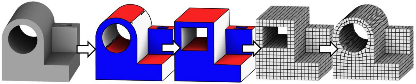
(c) Hybrid mesh[1]



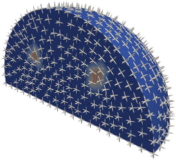
(d) **Hex mesh** [RGRS12]

Hexahedral mesh generation methods

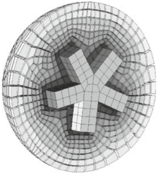
- Full surveys 2D [BLP+13], 3D surfaces [Cam17] and 3D [PCS+22]



(a) Polycube [PRR+22]



(b) Frame fields [KLF14]

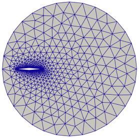


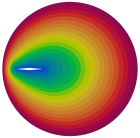
(c) **Advancing front** [RGRS12]

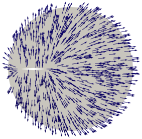
1. https://www.pointwise.com/

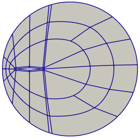
[RGRS12] Ruiz-Gironés E, Roca X, Sarrate J. The receding front method applied to hexahedral mesh generation of exterior domains. *Engineering with computers*, vol. 28, no. 4, 391-408, 2012.

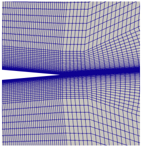
The main stages of our 2D approach

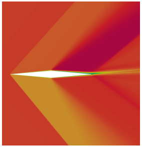

(a) Triangulation


(b) Distance Field


(c) Vector Field


(d) Blocks


(e) Mesh


(f) Results

- Starting from a triangulation of the domain (a)
- We first generate and combine distance fields (b)
- And build a vector field that ensure wall orthogonality and the alignment with the angle of attack (c)
- Using those fields, we generate curved blocks (d)
- And a final quad mesh where the element size is carefully controlled in the boundary layer (e)
- Numerical simulation can then be launched (f)

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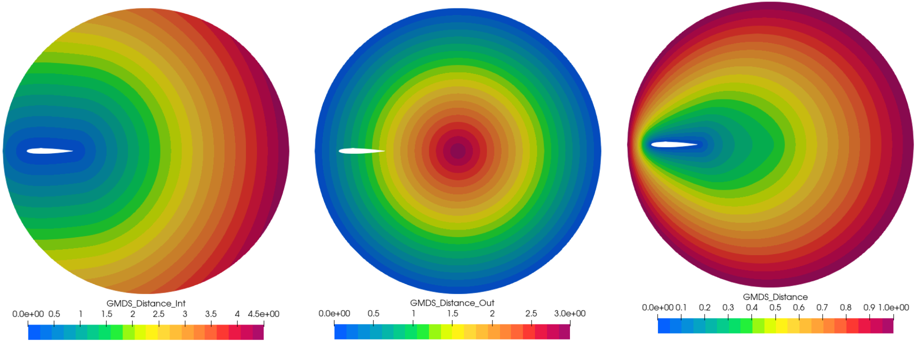
Distance field computation

Distance field computation solving Eikonal equation [RGRS12]:

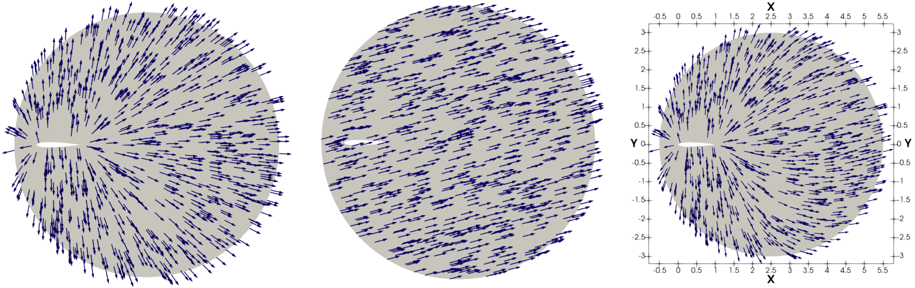
$$\begin{cases} ||\nabla d_V|| & = 1 \text{ in } \Omega \\ d_{V|\partial\Omega_V} & = 0 \end{cases} \qquad \begin{cases} ||\nabla d_{FF}|| & = 1 \text{ in } \Omega \\ d_{FF|\partial\Omega_{FF}} & = 0 \end{cases} \qquad d = \frac{d_V}{d_V + d_{FF}}$$



(a) d_V (b) d_{FF} (c) d

Fig. The distance fields on the NACA 0012 airfoil geometry.

Vector field computation



(a) ∇d_V (b) $\mathbf{u}_\infty$ (c) $\mathbf{v}$

Fig. Vector fields computed on the NACA 0012 geometry. The vector field (c) is a mixed from ∇d_V (a), and $\mathbf{u}_\infty$ (b).

For each node n_i at position $p_i = (x_i, y_i)$:

$$\begin{cases} \mathbf{v_i} &= \nabla d_v & \text{if } x_i < 1.5 \\ \mathbf{v_i} &= \mathbf{u}_\infty & \text{if } x_i > 5.0 \\ \mathbf{v_i} &= \theta \nabla d_v + (1-\theta)\mathbf{u}_\infty & \text{otherwise, with } \theta \in [0,1] \end{cases}$$

Block layer generation

Regular layer computation

Each node of the front $\mathcal{L}_i$ computes its ideal next node position in the layer $\mathcal{L}_{i+1}$ following the **vector field v** until the target distance d_{i+1} is reached in the **combined distance field** d. A 4th order Runge-Kutta method is used.

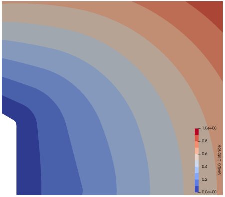


Fig. a Distance field

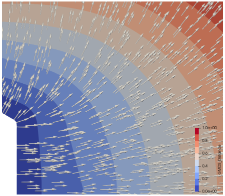


Fig. b Vector field

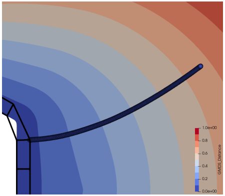


Fig. c Advected node

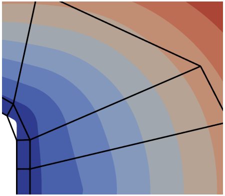


Fig. d New blocks

- All the nodes of the same layer $\mathcal{L}_i$ are at an equal distance d_i in the combined distance field d
- A front cannot separate
- Need to solve conflicts due to expansion/contraction in a layer

Block layer insertions & shrinking

- Insertions rules as in Blacker et al. [BS91], to solve conflicts on a layer
- Use both geometrical and physical criteria

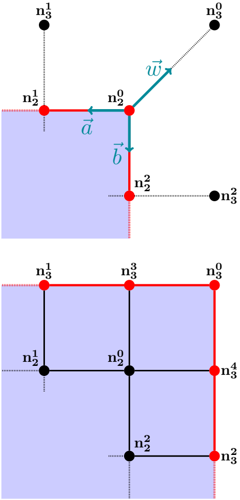


Fig. a Block insertion.

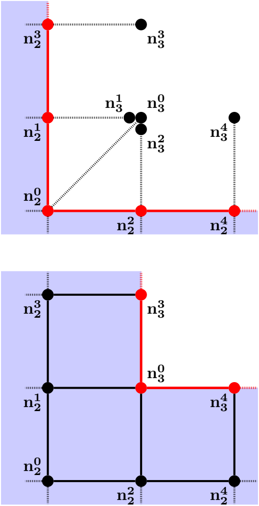


Fig. b Block shrinking.

Block layer insertions & shrinking

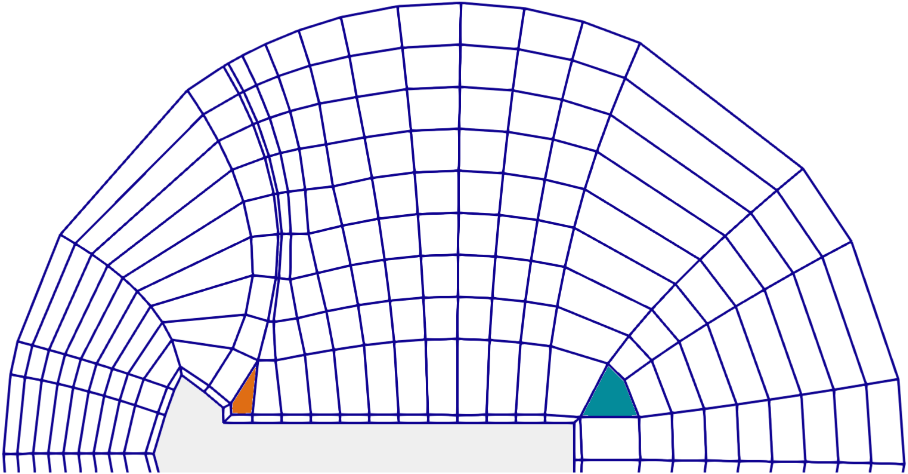
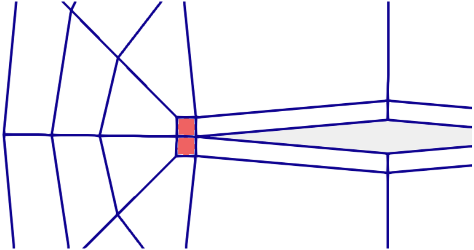


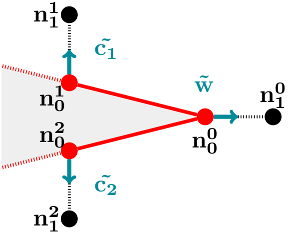
Fig. Block shrinking in orange ( ) and insertion in blue ( ) on the second layer.

First layer generation

Specific case of the first layer

- The distance field considered is d_V
- The thickness of this first layer is higher than the thickness of the boundary layer flow
- Double block insertions are the only insertions allowed in this layer





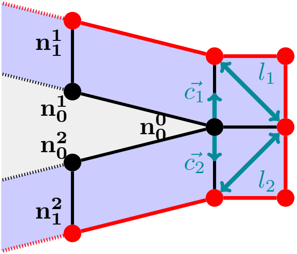


Fig. a Insertion of two blocks (▬) on the first layer for the diamond airfoil.

Fig. b Double block insertion on the boundary layer.

➤ Ensure the mesh validity

Curved blocking

- Aims to avoid smoothing on final mesh

- If the two nodes of a block edge are on a same layer
- If the edge is not on the wall or on the first layer

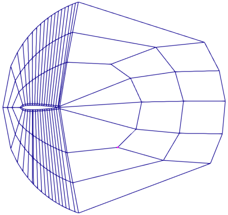


Fig. a Linear blocking

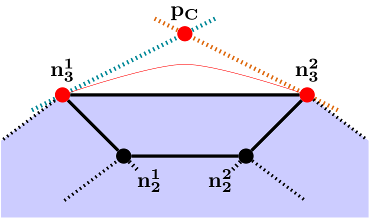


Fig. b Curve block edges as a quadratic Bézier curve.

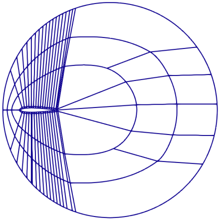
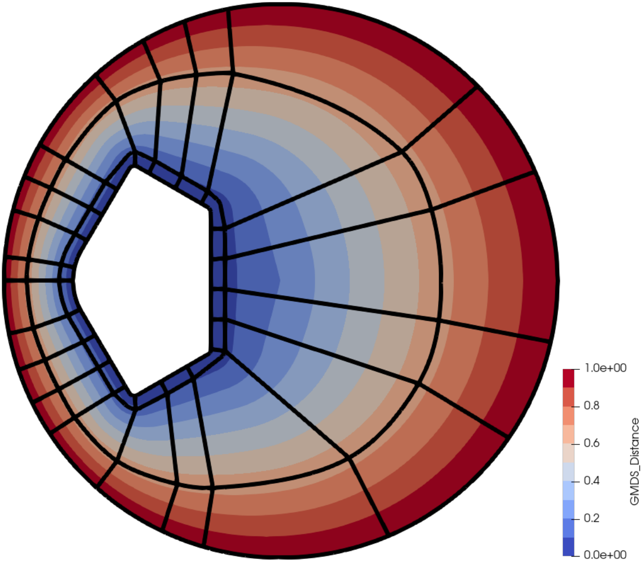


Fig. c Curved blocking

The method



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Interval Assignment

- The aim is to set the discretization of each block edge

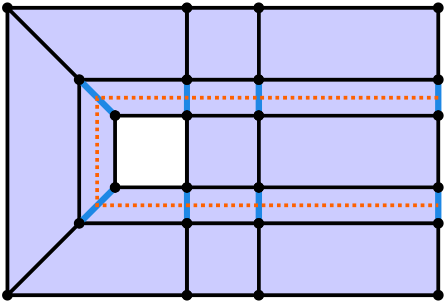

Fig. a Topological chord

- A topological chord (▪ ▪) is a set of opposite block edges (▬)
- All edges of a same topological chord share the same discretization

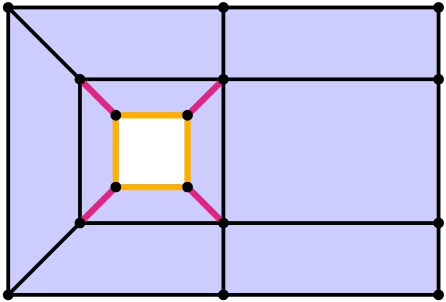

Fig. b Hard constraint

- (▬) edges: s_w, the size of the edges on the wall
- (▬) edges: $s_w^{\perp}$, the size of the edges on the first layer, on the wall-normal direction

First layer meshing

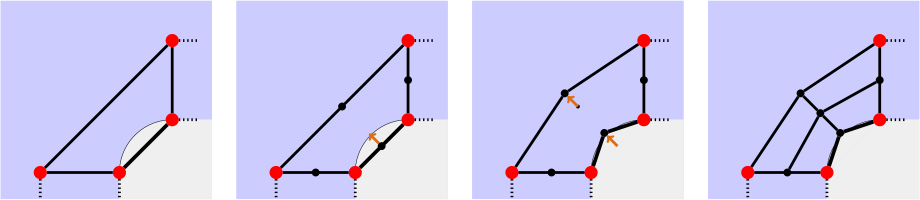

Fig. a **Fig. b** **Fig. c** **Fig. d**

- Set the block edges discretization
- Project nodes on the geometry (b)
- Add the offset on the opposite block edges (c)
- Apply transfinite in each block (d)
- Smoothing to add orthogonality on the wall
- Apply the β refinement

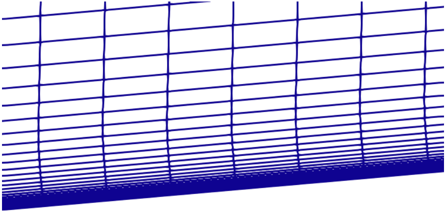

Fig. e Mesh result in near the wall

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Mesh Validity

Fig. a. Blocking without insertions

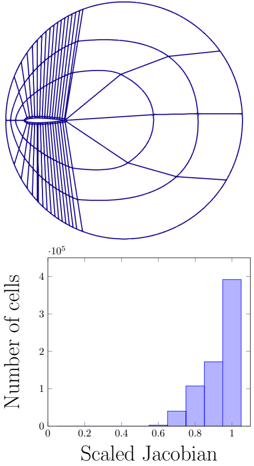


Fig. b. Blocking with insertions

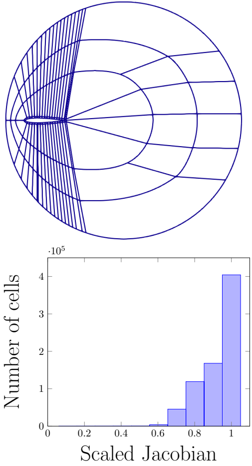
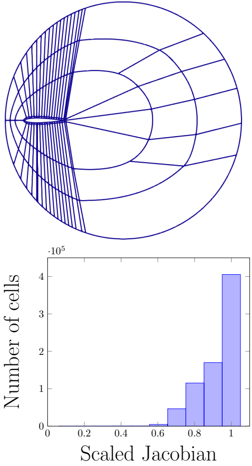


Fig. c. Blocking with insertions and $\alpha = 15°$



➤ The insertions of blocks and the adaptation to the angle of attack α doesn't degrade the mesh quality.

Subsonic NACA0012 Airfoil [Rum21]

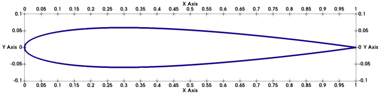


Fig. a NACA 0012 geometry.

M_∞	AoA α	R_e	T_∞
0.3	15°	3×10^6	$293K$

Table - Simulation parameters.

- The simulations are performed using the open multiphysics simulation software SU2 [EPC+16]
- Reynolds Averaged Navier-Stokes (RANS) solver
- k-ω SST turbulence model

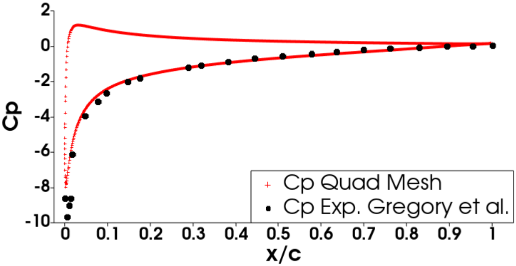


Fig. b Pressure coefficient compared to experimental data set [GO70].

Supersonic Diamond Airfoil

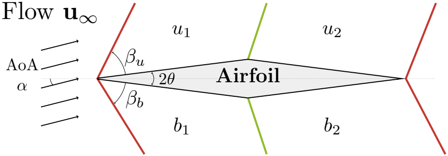


Fig. a Diamond Shaped Airfoil.

M_∞	AoA α	R_e	T_∞
1.5	$3°$	3×10^6	$293K$

Table - Simulation parameters.

- Validation on analytical case
- Shock angles captured with an error of 1° compared to analytical values
- Constant Mach number in the area u_1 and b_1 consistent with those given by the tables [rs53]

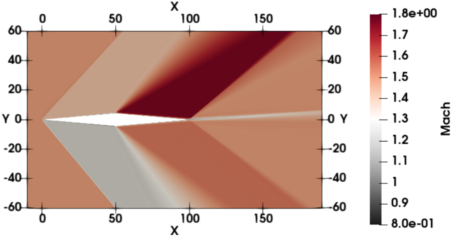


Fig. b Mach-number distribution.

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Summary

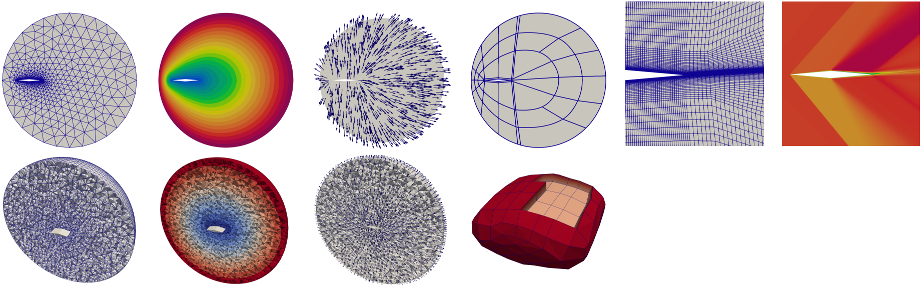
- This work proposes a solution to automatically generate 2D quad block-structured meshes dedicated to CFD
- Geometrical shape of the domain is taken into account
- Simulation parameters are taken into account (e.g the angle of attack and boundary layer thickness)
- First obtained meshes are usable for subsonic and supersonic flow simulations

Limitations of this method

- Can't handle complex geometries (multi-component, etc)
- Accuracy of the distance field computation can be improved

Perspectives

- Improving the mesh size transition
- Extension of the method to 3D
- Extend the work of Ruiz-Girones et al. [RGRS12] to high-order blocks
- Integrating some smoothing methods for the blocks
- Improving the mesh generation with a previous result of simulation



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Thank you.

Wall block discretization

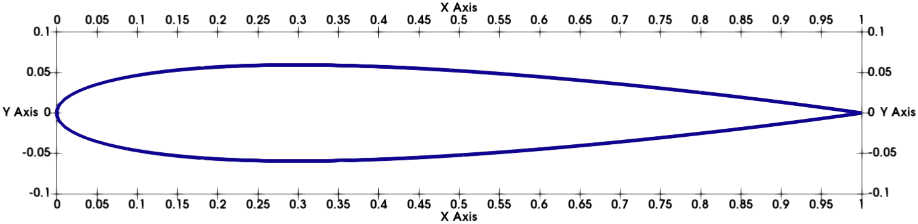

Fig. a NACA 0012 geometry.

Iteration on the ordered vertices v_i of the triangulation on the wall. We place a block corner on v_i if:

- v_i is located on an extremum of the boundary profile.
- v_i is a geometric corner of the boundary.
- the curvilinear distance from the previous selected vertex and v_i is greater than a limit length given as an input parameter.

Results on RAMCII

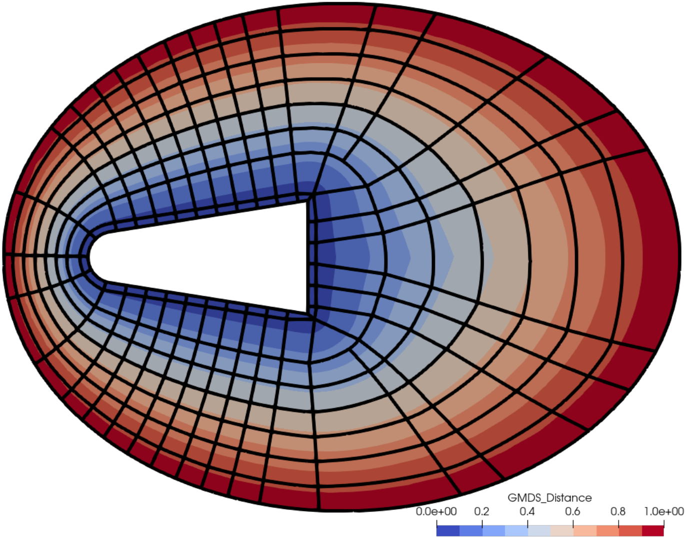

Fig. Blocking on RAMCII

Results on Orex

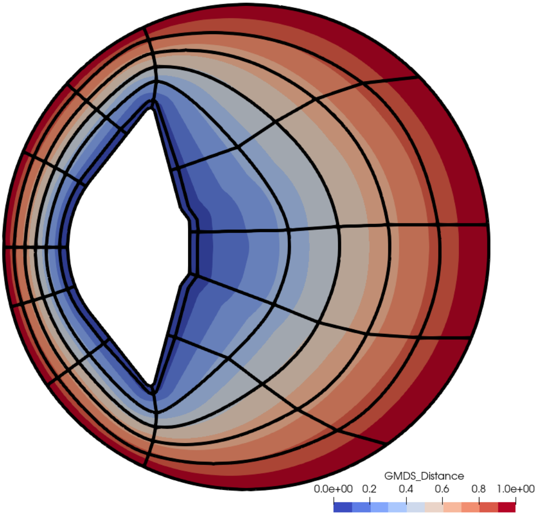

Fig. Blocking on Orex