



# Block-structured quad meshing for supersonic flow simulations

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<sup>3</sup>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.

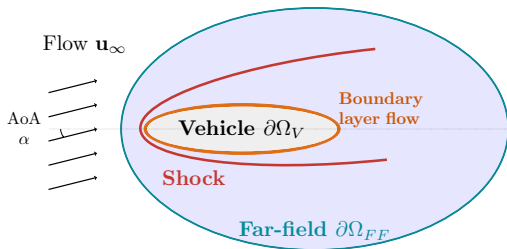


Fig. Flow around a supersonic vehicle

### Ideal meshes:

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

### Input meshes for the code:

- ◆ **Block-structured** meshes

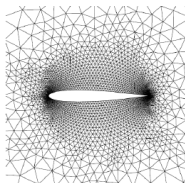
### Hypotheses on the domain:

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

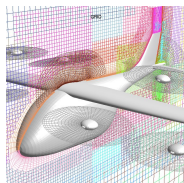
Our meshing algorithm is freely available and implemented in the open-source C++ meshing framework GMDS [LWB]<sup>a</sup>.

<sup>a</sup><https://github.com/LIHPC-Computational-Geometry/gmds>.

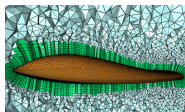
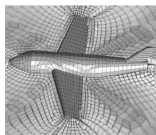
## State of the art

CFD Meshes [CDT16]

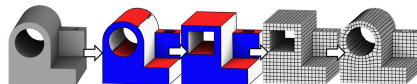
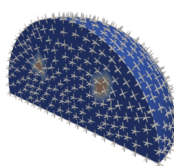
(a) Unstructured mesh [MACP10]



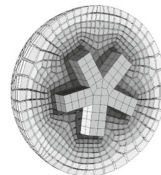
(b) Over-set grid [SBM21]

(c) Hybrid mesh<sup>1</sup>(d) **Hex mesh** [RGRS12]Hexahedral mesh generation methods

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

(a) Polycube [PRR<sup>+</sup>22]

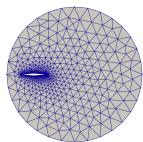
(b) Frame fields [KLF14]

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

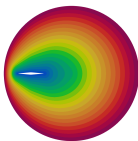
1. <https://www.pointwise.com/>

[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.

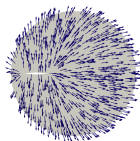
## The main stages of our 2D approach



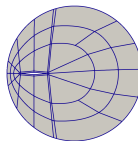
(a)  
Triangulation



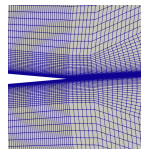
(b) Distance  
Field



(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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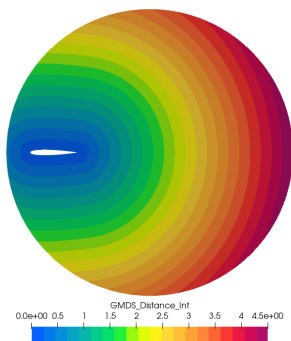
## Distance field computation

Distance field computation solving Eikonal equation [RGRS12]:

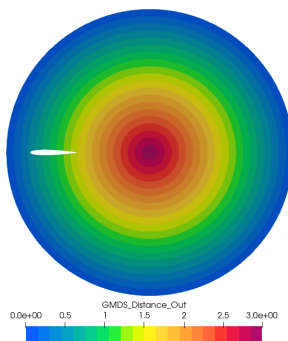
$$\begin{cases} \|\nabla d_V\| &= 1 \text{ in } \Omega \\ d_V|_{\partial\Omega_V} &= 0 \end{cases}$$

$$\begin{cases} \|\nabla d_{FF}\| &= 1 \text{ in } \Omega \\ d_{FF}|_{\partial\Omega_{FF}} &= 0 \end{cases}$$

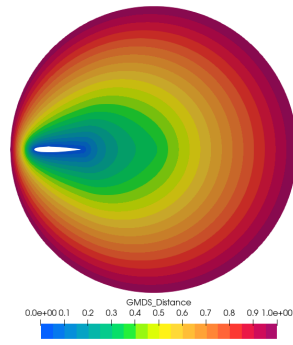
$$d = \frac{d_V}{d_V + d_{FF}}$$



(a)  $d_V$



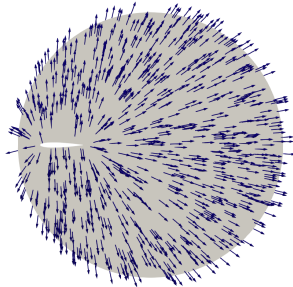
(b)  $d_{FF}$



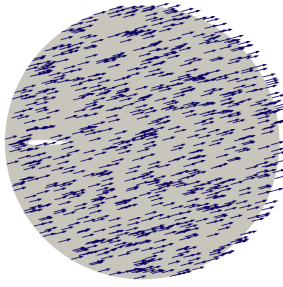
(c)  $d$

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

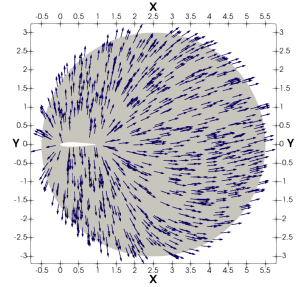
## Vector field computation



(a)  $\nabla d_v$



(b)  $\mathbf{u}_\infty$



(c)  $\mathbf{v}$

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

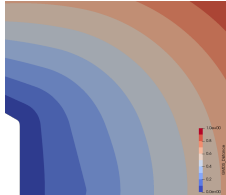
For each node  $n_i$  at position  $p_i = (x_i, y_i)$  :

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

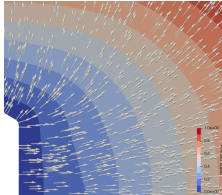
## Block layer generation

### Regular layer computation

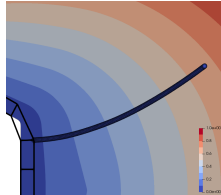
Each node of the front  $\mathcal{L}_i$  computes its ideal next node position in the layer  $\mathcal{L}_{i+1}$  following the **vector field**  $\mathbf{v}$  until the target distance  $d_{i+1}$  is reached in the **combined distance field**  $d$ . A 4th order Runge-Kutta method is used.



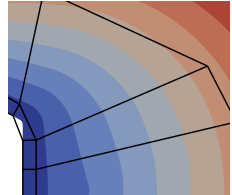
**Fig. a** Distance field



**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

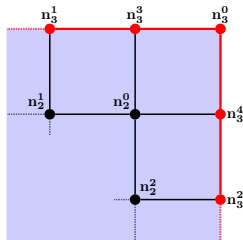
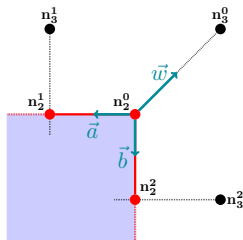


Fig. a Block insertion.

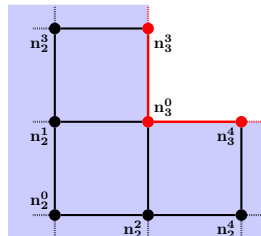
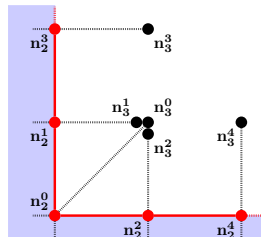
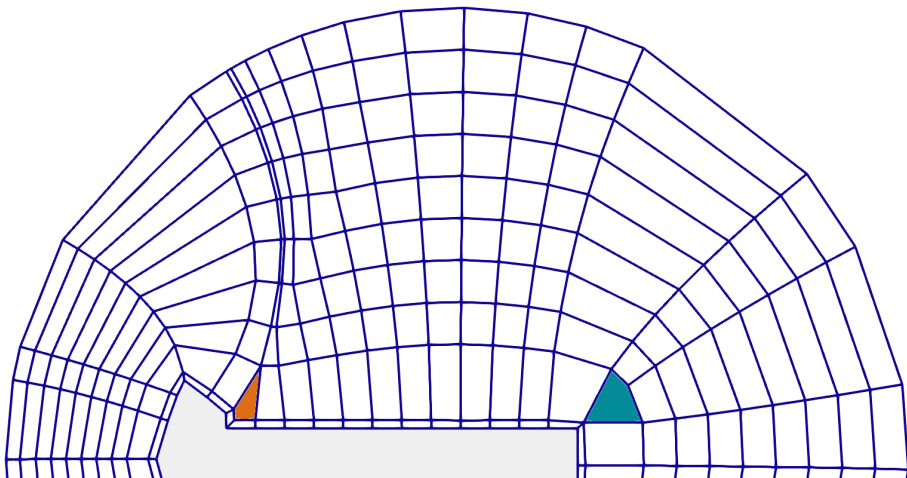


Fig. b Block shrinking.

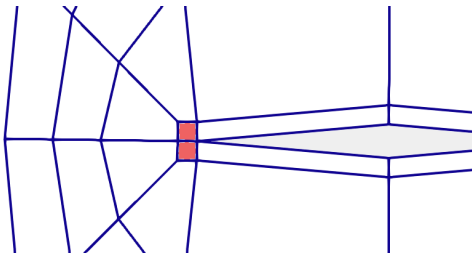
## Block layer insertions & shrinking



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

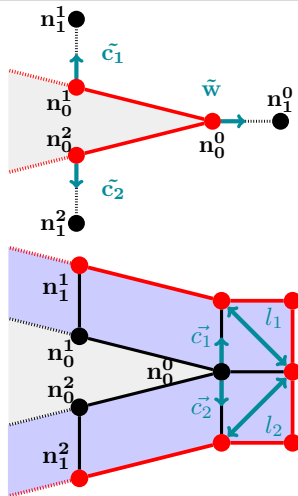
## Specific case of the first layer

- ◆ 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.

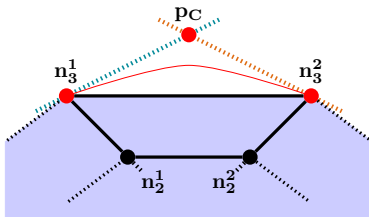
- Ensure the mesh validity



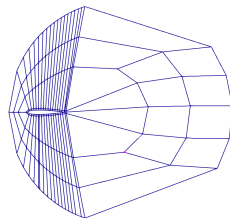
**Fig. b** Double block insertion on the boundary layer.

## Curved blocking

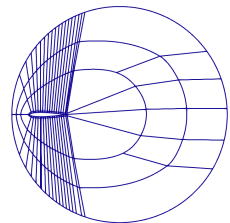
- Aims to avoid smoothing on final mesh
- ◆ If the two nodes of a block edge are on a same layer
- ◆ If the edge is not on the wall or on the first layer



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



**Fig. a** Linear blocking



**Fig. c** Curved blocking

# The method

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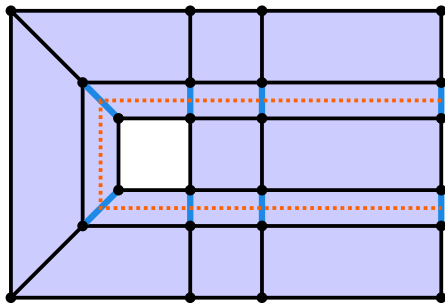
## 4 Results & Applications

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- Supersonic Diamond Airfoil

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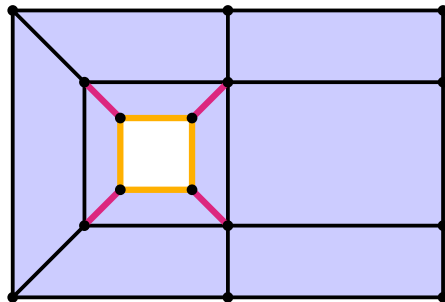
## Interval Assignment

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



**Fig. a** Topological chord

- ◆ A topological chord (  $\text{---}\text{---}$  ) is a set of opposite block edges (  $\text{---}$  )
- ◆ All edges of a same topological chord share the same discretization



**Fig. b** Hard constraint

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

## First layer meshing

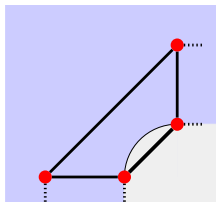


Fig. a

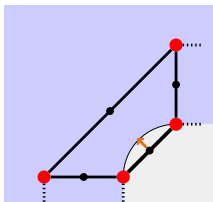


Fig. b

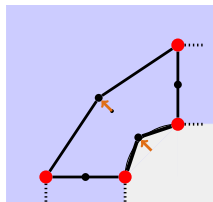


Fig. c

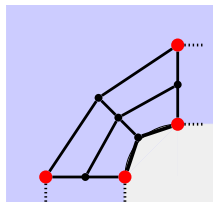


Fig. d

- 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  $\beta$  refinement

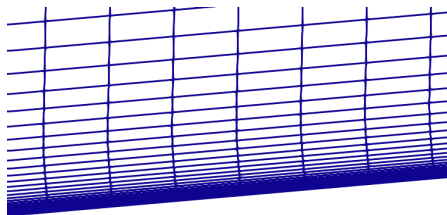


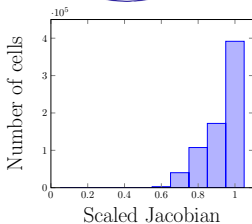
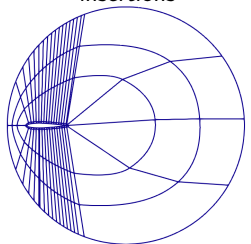
Fig. e Mesh result in near the wall

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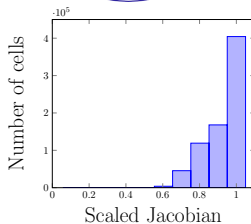
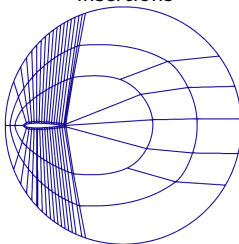
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# Mesh Validity

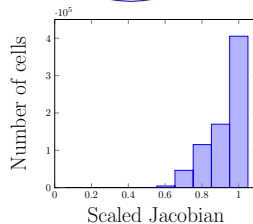
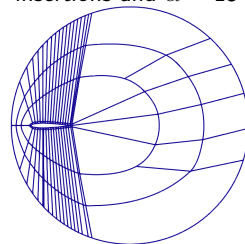
**Fig. a.** Blocking without insertions



**Fig. b.** Blocking with insertions

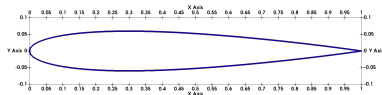


**Fig. c.** Blocking with insertions and  $\alpha = 15^\circ$



- The insertions of blocks and the adaptation to the angle of attack  $\alpha$  doesn't degrade the mesh quality.

## Subsonic NACA0012 Airfoil [Rum21]

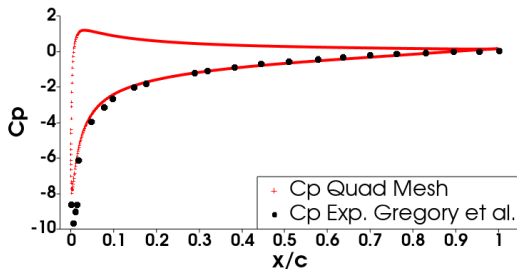


**Fig. a** NACA 0012 geometry.

| $M_\infty$ | AoA $\alpha$ | $R_e$           | $T_\infty$ |
|------------|--------------|-----------------|------------|
| 0.3        | $15^\circ$   | $3 \times 10^6$ | 293K       |

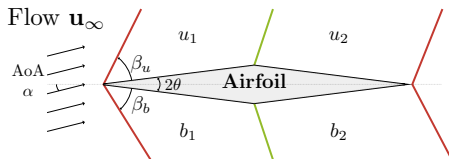
**Table** - Simulation parameters.

- The simulations are performed using the open multiphysics simulation software SU2 [EPC<sup>+</sup>16]
- Reynolds Averaged Navier-Stokes (RANS) solver
- $k-\omega$  SST turbulence model



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

# Supersonic Diamond Airfoil

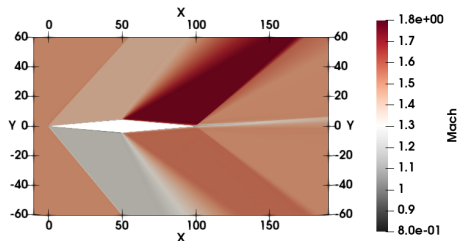


**Fig. a** Diamond Shaped Airfoil.

| $M_\infty$ | AoA $\alpha$ | $R_e$           | $T_\infty$ |
|------------|--------------|-----------------|------------|
| 1.5        | 3°           | $3 \times 10^6$ | 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

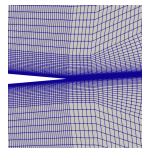
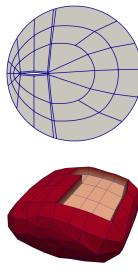
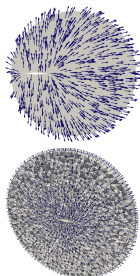
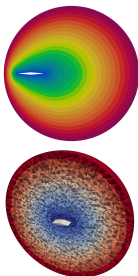
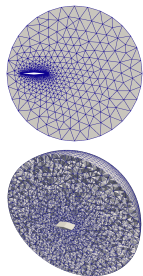
- ◆ This work proposes a solution to automatically generate 2D quad block-structured meshes dedicated to CFD
- ◆ Geometrical shape of the domain is taken into account
- ◆ Simulation parameters are taken into account (e.g the angle of attack and boundary layer thickness)
- ◆ First obtained meshes are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



## Références



David Bommes, Bruno Lévy, Nico Pietroni, Enrico Puppo, Claudio Silva, Marco Tarini, and Denis Zorin, *Quad-mesh generation and processing: A survey*, Computer Graphics Forum **32** (2013), no. 6, 51–76.



Ted D Blacker and Michael B Stephenson, *Paving: A new approach to automated quadrilateral mesh generation*, International journal for numerical methods in engineering **32** (1991), no. 4, 811–847.



Marcel Campen, *Partitioning surfaces into quadrilateral patches: A survey*, Computer graphics forum, vol. 36, Wiley Online Library, 2017, pp. 567–588.



John R Chawner, John Dannenhoffer, and Nigel J Taylor, *Geometry, mesh generation, and the cfd 2030 vision*, 46th AIAA Fluid Dynamics Conference, 2016, p. 3485.



Thomas D Economon, Francisco Palacios, Sean R Copeland, Trent W Lukaczyk, and Juan J Alonso, *Su2: An open-source suite for multiphysics simulation and design*, AIAA Journal **54** (2016), no. 3, 828–846.



Nigel Gregory and CL O'reilly, *Low-speed aerodynamic characteristics of naca 0012 aerofoil section, including the effects of upper-surface roughness simulating hoar frost*.



N Kowalski, F Ledoux, and P Frey, *Block-structured hexahedral meshes for cad models using 3d frame fields*, Procedia Engineering **82** (2014), 59–71.



Franck Ledoux, Jean-Claude Weill, and Yves Bertrand, *Gmsh: A generic mesh data structure*.



Mario J Martin, Esther Andres, Carlos Carreras, and Francisco Palacios, *Solving the euler equations for unstructured grids on graphical processor units*, Publ. Online (2010).



Nico Pietroni, Marcel Campen, Alla Sheffer, Gianmarco Cherchi, David Bommes, Xifeng Gao, Riccardo Scateni, Franck Ledoux, Jean-François Remacle, and Marco Livesu, *Hex-mesh generation and processing: A survey*, ACM Trans. Graph. (2022), Just Accepted.



François Protais, Maxence Reberol, Nicolas Ray, Etienne Corman, Franck Ledoux, and Dmitry Sokolov, *Robust quantization for polycube maps*, Computer-Aided Design (2022), 103321.

# Références



Eloi Ruiz-Gironés, Xevi Roca, and Josep Sarrate, *The receding front method applied to hexahedral mesh generation of exterior domains*, *Engineering with computers* **28** (2012), no. 4, 391–408.



Ames research staff, *Raport 1135: Equations, tables, and charts for compressible flow.*, Tech. report, Ames Aeronautical Laboratory, 1953.



Christopher Rumsey, *2DN00: 2D NACA 0012 Airfoil Validation Case*, [https://turbmodels.larc.nasa.gov/naca0012\\_val.html](https://turbmodels.larc.nasa.gov/naca0012_val.html), 2021, [Online; accessed 5-August-2022].



Benjamin M Simmons, Pieter G Buning, and Patrick C Murphy, *Full-envelope aero-propulsive model identification for lift+ cruise aircraft using computational experiments*, AIAA AVIATION 2021 FORUM, 2021, p. 3170.

Thank you.

## Wall block discretization

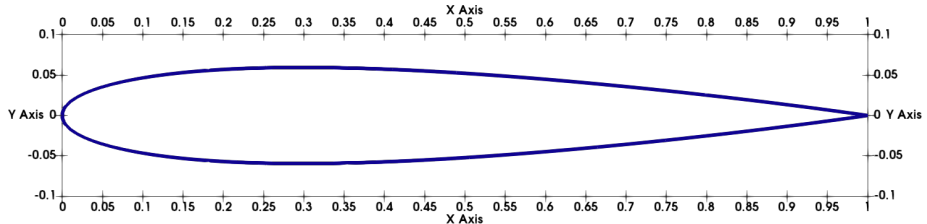
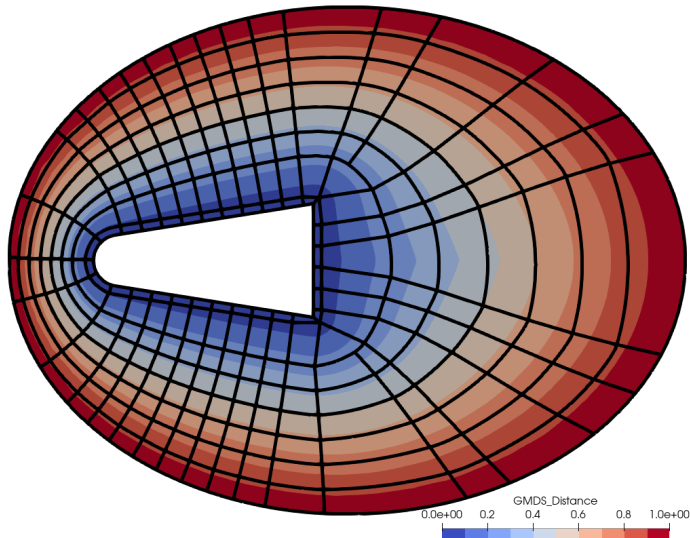


Fig. a NACA 0012 geometry.

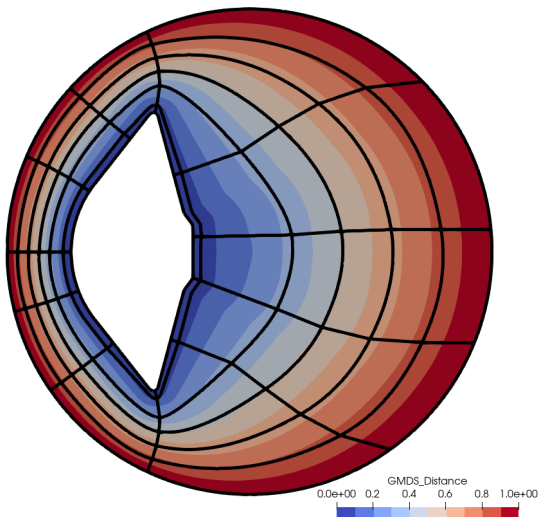
Iteration on the ordered vertices  $v_i$  of the triangulation on the wall. We place a block corner on  $v_i$  if:

- ◆  $v_i$  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