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Radial Basis Function Mesh Deformation Methods for Icing and Rotorcraft Simulations in SU2

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Icing Environment

- Icing encounters can jeopardise the performance and handling qualities of aircraft.

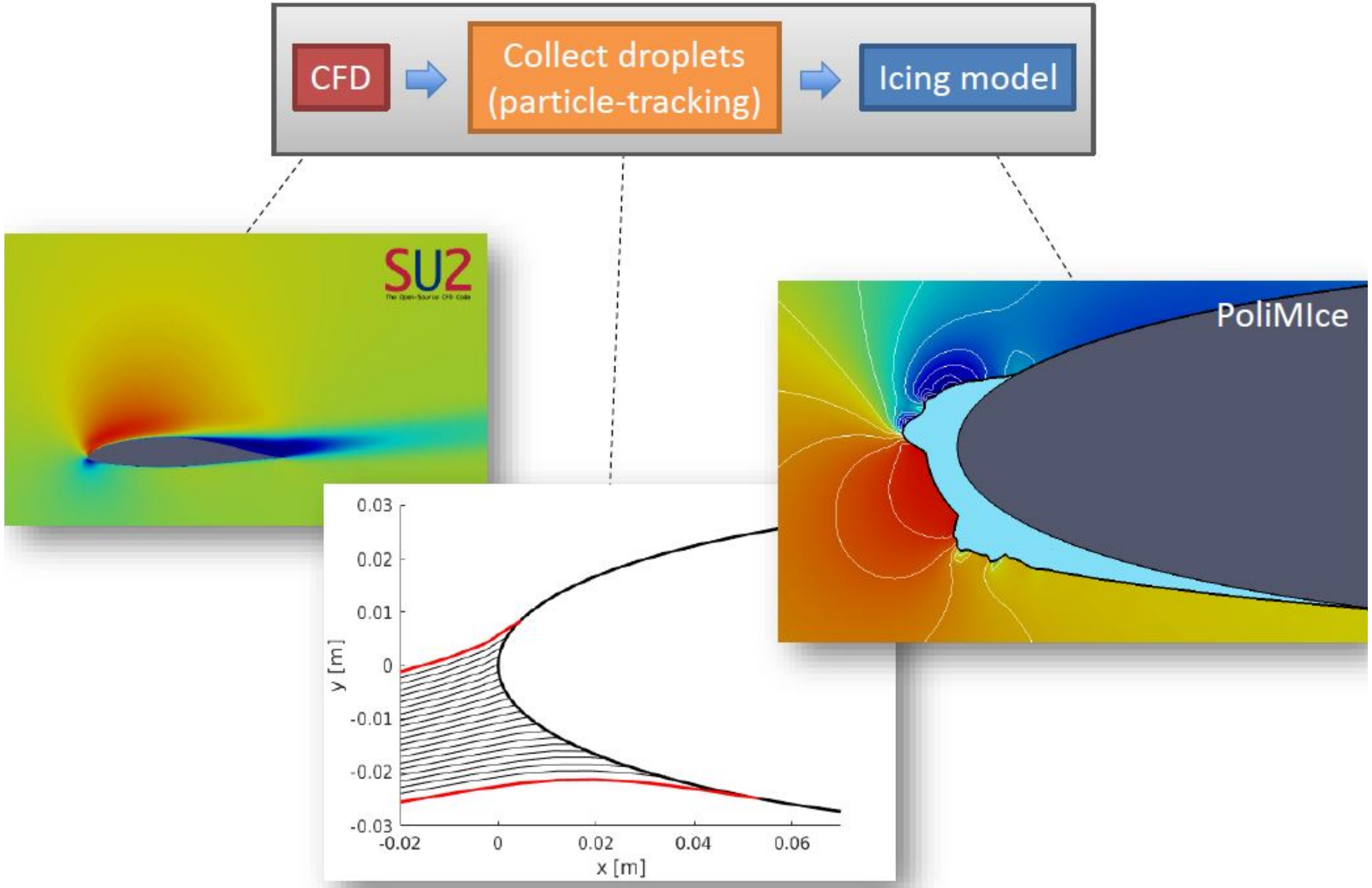
- Ice can significantly change geometry of aerodynamic lifting surfaces.

- Computational techniques provide an alternative to expensive in-flight icing trails and experimental tests.

Source: BBC NEWS, Mar 2nd 2006

Computational Modelling of Ice Accretion

Ice accretion is simulated as a quasi-steady process following a multi-step procedure



MESH DEFORMATION

Originally developed for moving boundary problems present in simulations such as fluid-structure interaction problems and aerodynamic shape optimization.

- **Spring Analogy:**
  - Models each edge of the mesh as a linear (and torsional) spring connected together at corresponding nodes
  - \- Solves system on whole domain
  - \- Cannot guarantee valid mesh during large deformations.

- **Linear Elasticity Analogy:**
  - Models each mesh element as an elastic solid.
  - \+ Outputs a valid mesh.
  - \- Solves system on whole domain.

- **Radial Basis Function Interpolation:**
  - Interpolation based approach.
  - \+ High mesh quality.
  - \- Lots of free parameters.

- Surface displacement field is approximated using a set of basis functions defined on surface nodes

$$f(\mathbf{r}) = \sum_{i=1}^{N} \alpha_i \phi\left(\frac{||\mathbf{r}-\mathbf{r_i}||}{R}\right)$$

- Collocation on surface nodes allows to solve for coefficients

$$\mathbf{\Phi}_{s,s}\alpha = \Delta\mathbf{S}$$

- Displacement is then interpolated to the volume points

$$\Delta\mathbf{V} = \mathbf{\Phi}_{v,s}\alpha$$

Greedy Surface Point Selection

- A reduced set of surface points is used to solve for RBF coefficients

- Greedy surface point selection starts with an initial control point and sequentially uses radial basis function interpolation to find the subsequent control point with the largest error signal:

$$E^{(n)} = ||\Delta S - \Phi^{(n)}\alpha^{(n)}||$$

- This control point is then added to the next step for the process to then repeat itself until the interpolation meets a sufficient tolerance.

$$\frac{E^{(n)}_{max}}{\Delta S_{max}} < \epsilon$$

MULTI-LEVEL GREEDY SURFACE POINT SELECTION

- The greedy point selection alone is not enough to reduce computational cost.

- Multi-level procedure addresses this where, at the end of each level, the error of the surface displacement approximation is used as the object for the subsequent approximation step

$$\Delta S^{(l+1)} = \Delta S^{(l)} - \mathbf{\Phi}_{s,c}^{(l)} \alpha^{(l)}$$

- The Multi-level greedy surface point selection can be summarised and becomes:

$$\Delta S = \sum_{i=1}^{l} \mathbf{\Phi}_{s,c}^{(l)} \alpha^{(l)}$$

$$\Delta V = \sum_{i=1}^{l} \mathbf{\Phi}_{v,c}^{(l)} \alpha^{(l)}$$

Volume Point Reduction

- Finally, also the cost of the interpolation step can be reduced by exploiting locality of basis functions

$$f(\mathbf{r}) = \psi\left(\frac{d(\mathbf{r})}{D}\right)\sum_{i=1}^{N}\alpha_i\phi\left(\frac{||\mathbf{r}-\mathbf{r_i}||}{R}\right)$$

- Wall distance d is used to restrict domain points subject to deformation and volume

$$D = k\Delta S_{max}^{(l)}$$

SU2 Implementation

CVolumetricMovement

↑

CVolumetricMovementRBF
SetVolume_Deformation()

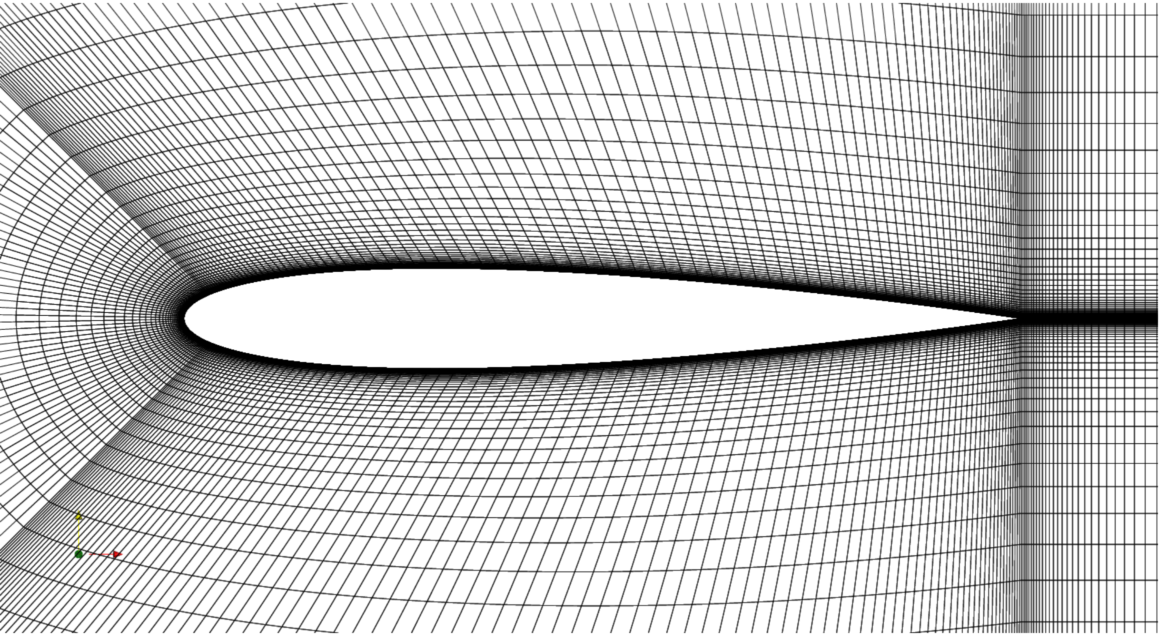
- Class CVolumetricMovementRBF overloads function SetVolume_Deformation() and contains private functions to perform basic RBF operations (assemble regressor matrix, perform greedy selection, multi-level loops etc.)
- Support radius, RBF type, number of levels, volume reduction factor can be set in config file
- High communication cost, system is solved on global control points to avoid invalid mesh at MPI boundaries
    - control point with greatest error is BCasted
    - system is solved in each rank
    - each rank propagates the boundary deformation to the domain

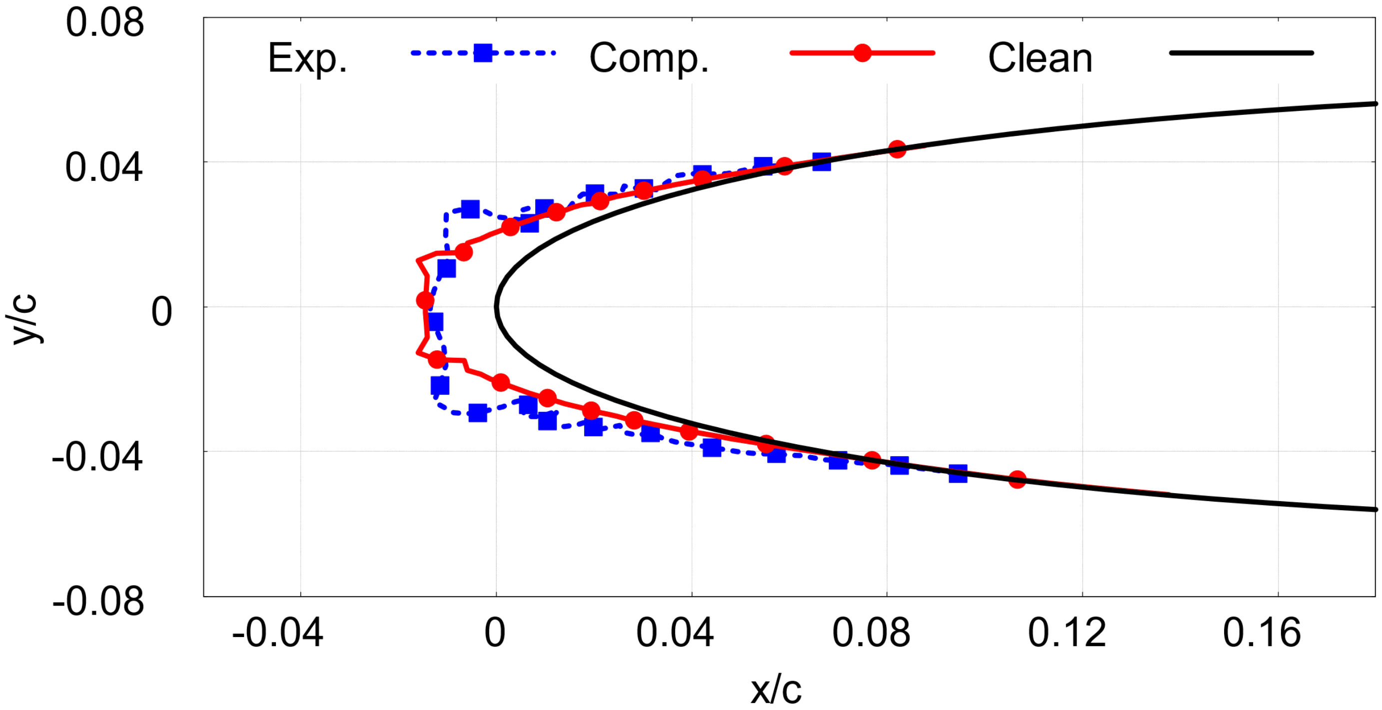
RESULTS: NACA0012 AIRFOIL

- Icing Conditions:

Airfoil [-]	Accretion Time [s]	Angle of Attack [°]	Chord [m]	Pressure [Pa]	Airspeed [m/s]	Outside Air Temperature [K]	Liquid Water Content [g/m^3]	Mean Volume Diameter [μm]
NACA0012	120	0	0.3	90,700	129	260.55	0.5	20

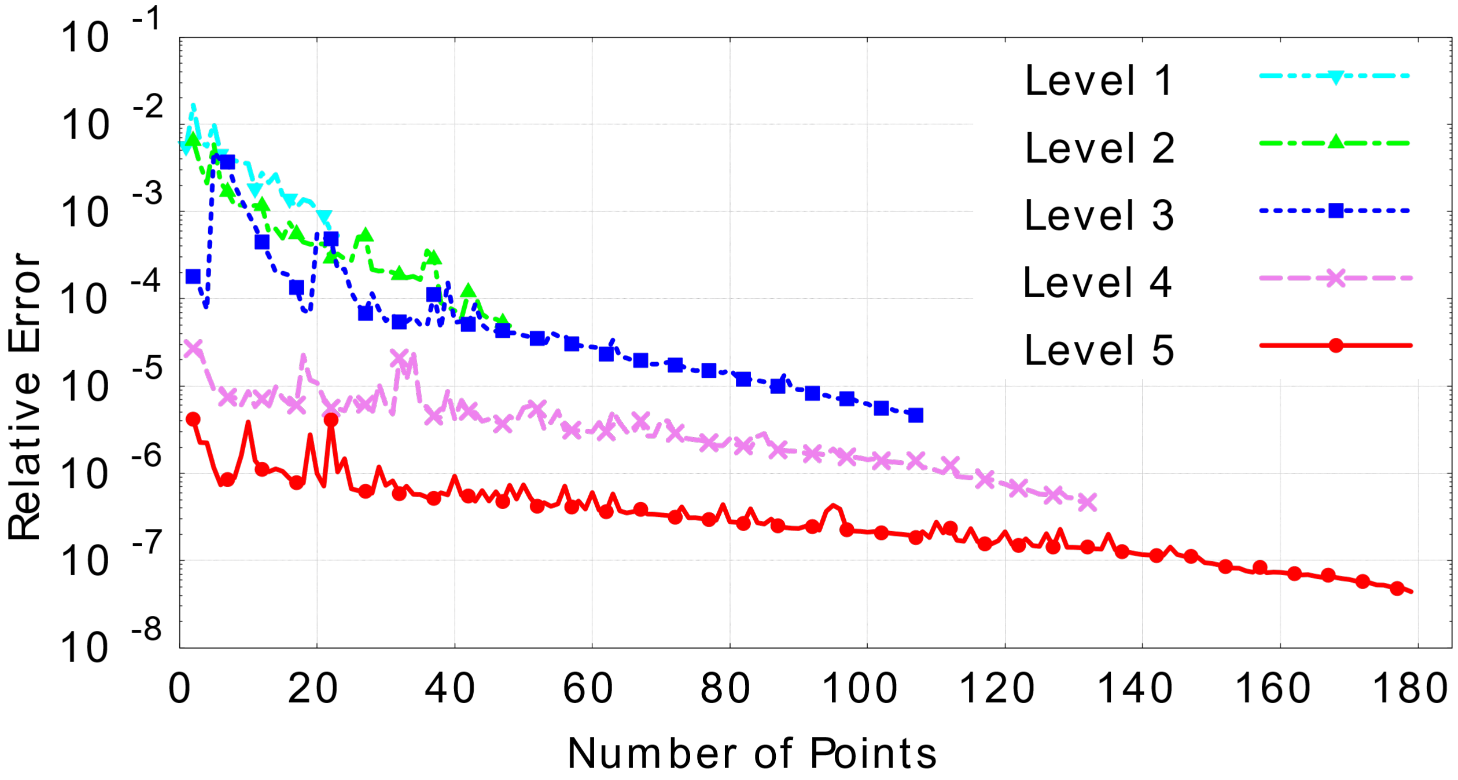
- Structured Mesh:
- Ice Shape:



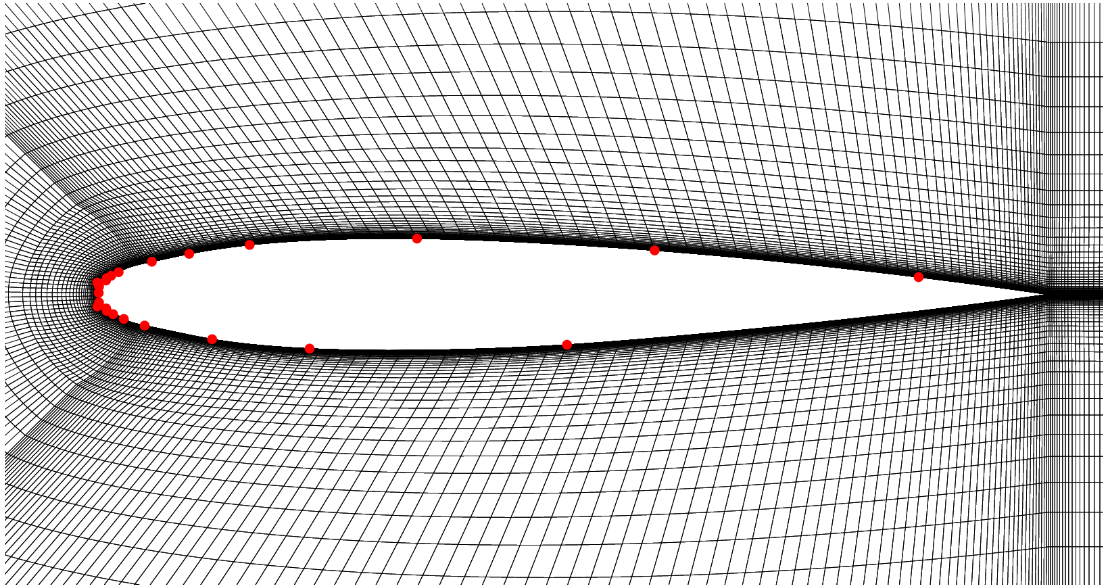


Results: NACA0012 Airfoil

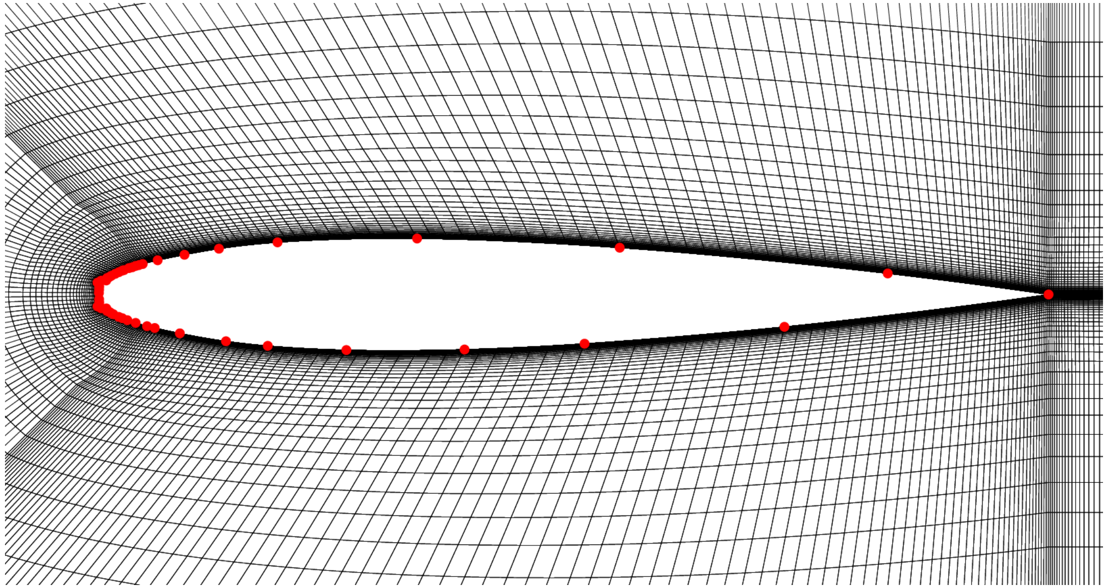
- 5-Levels greedy surface point data reduction.
- Max Number of Control Points 176.



Results: NACA0012 Airfoil

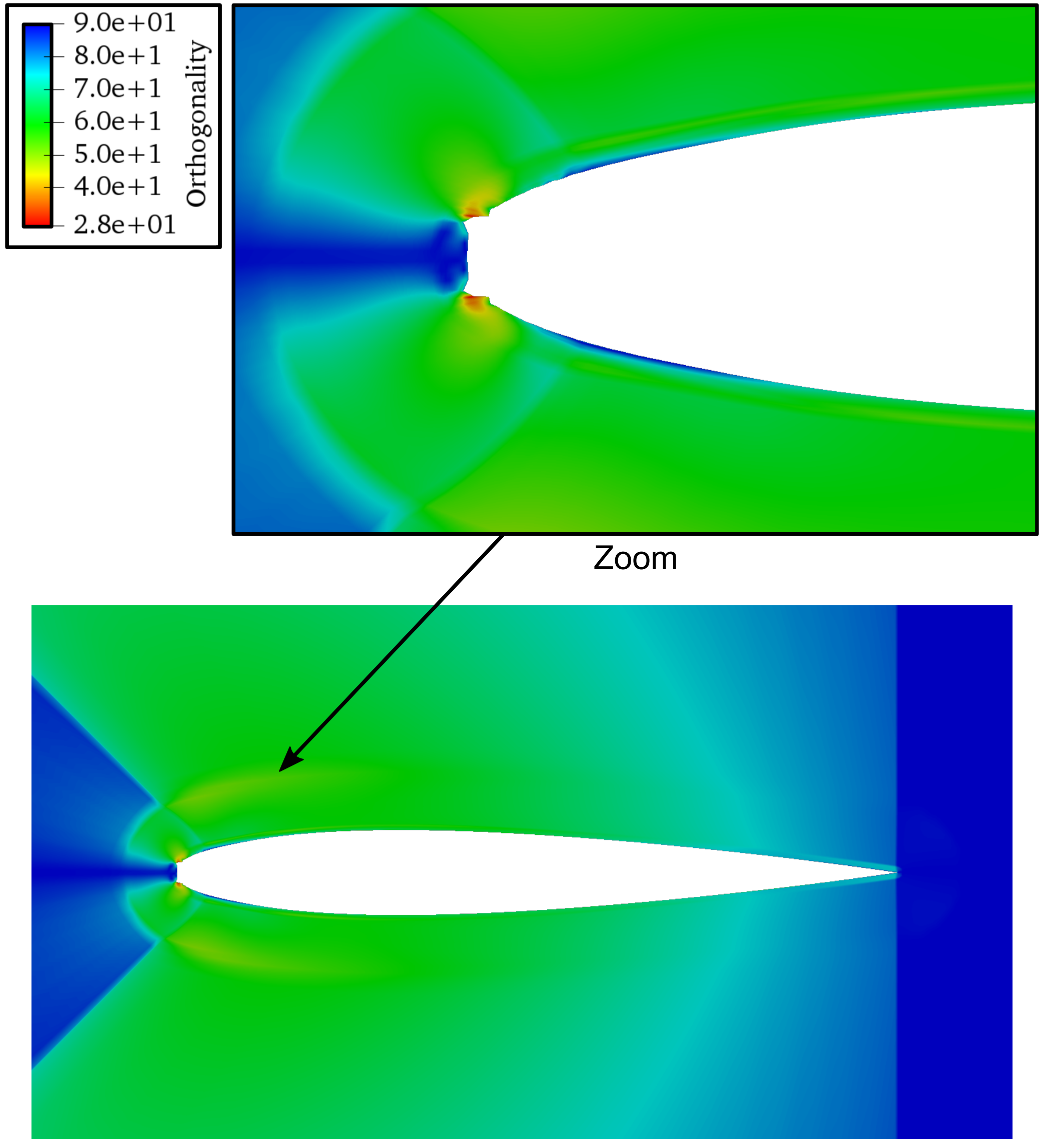


Level 1: 23 Control Points

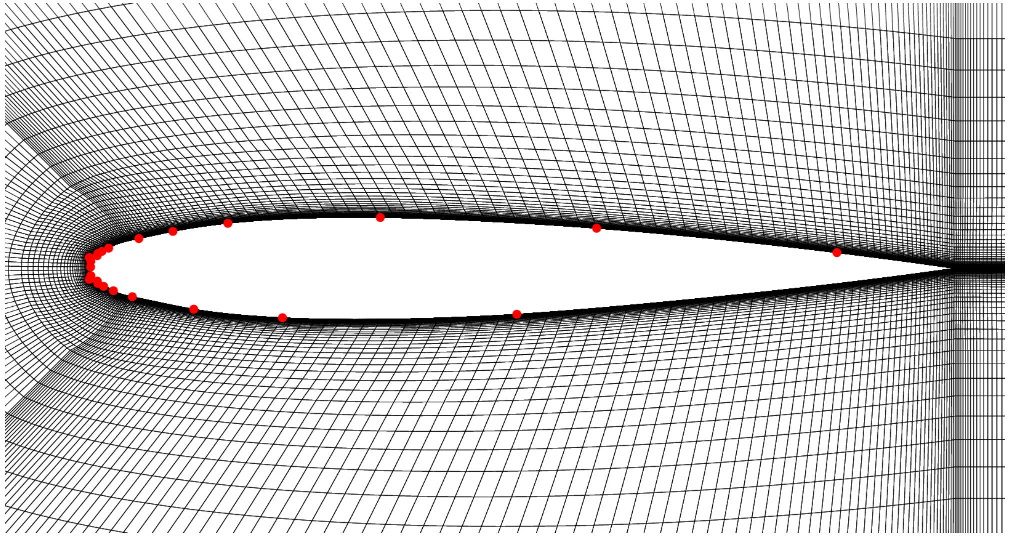


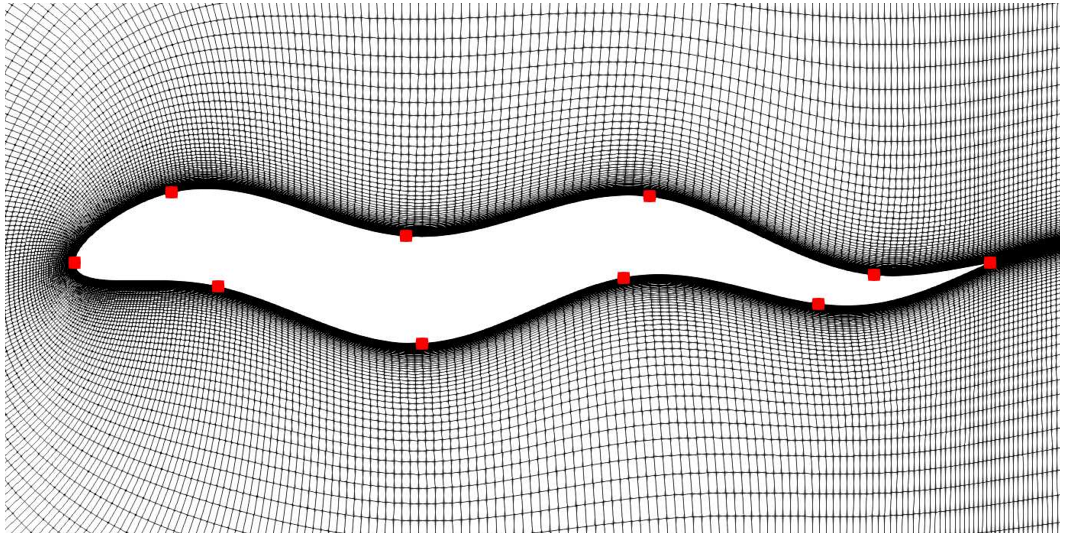
Level 2: 48 Control Points

Results: NACA0012 Airfoil

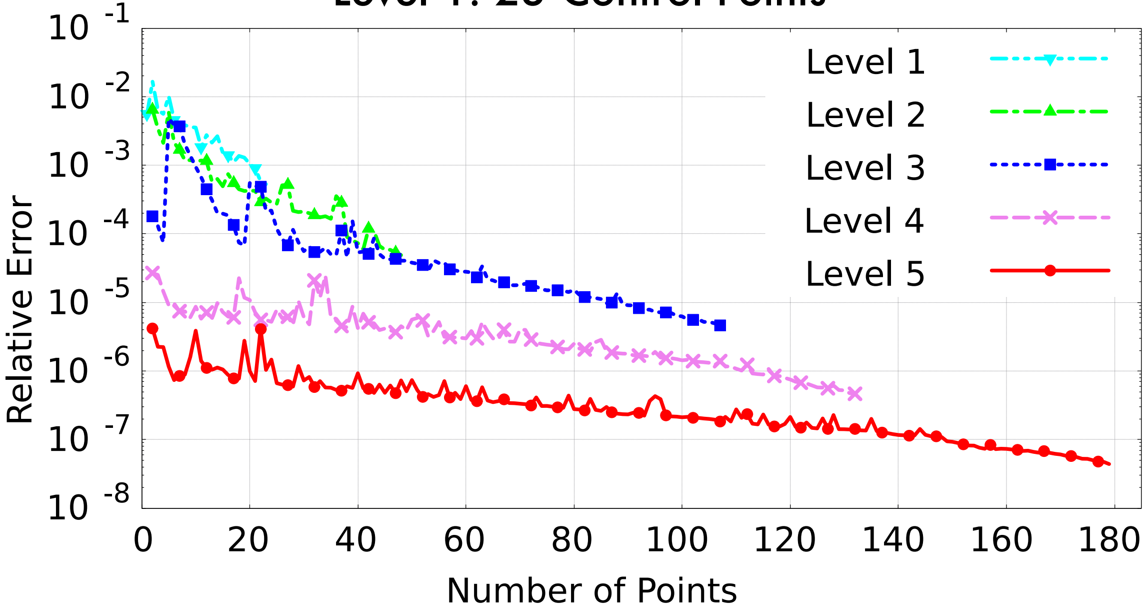


Results: Local vs. Global Deformation

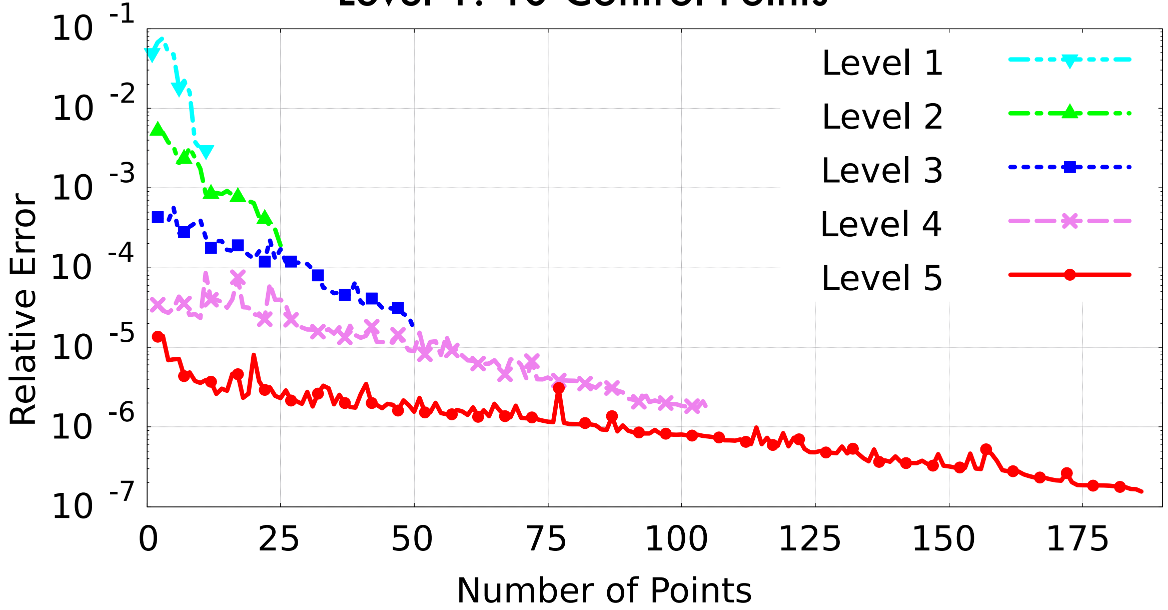




Level 1: 23 Control Points



Level 1: 10 Control Points



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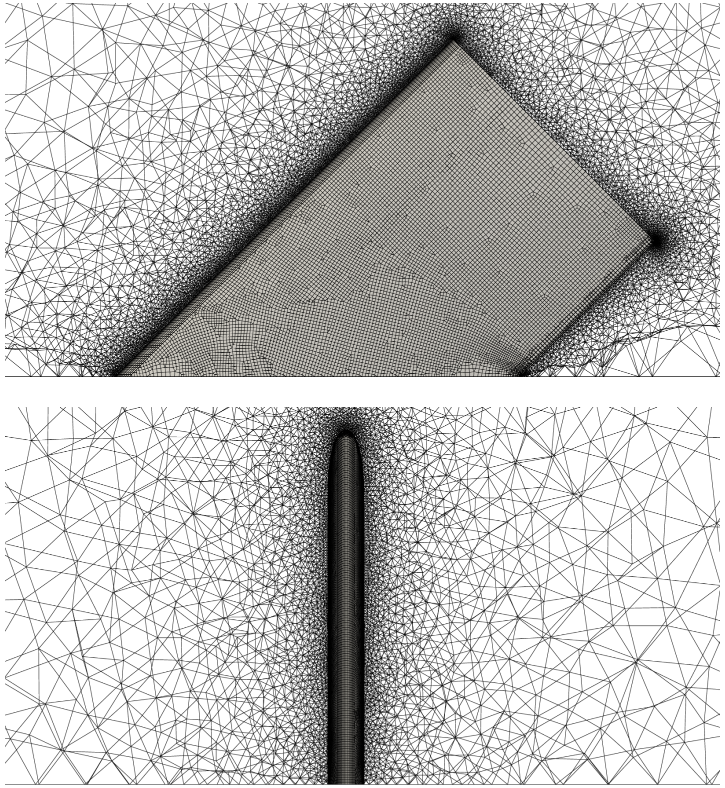
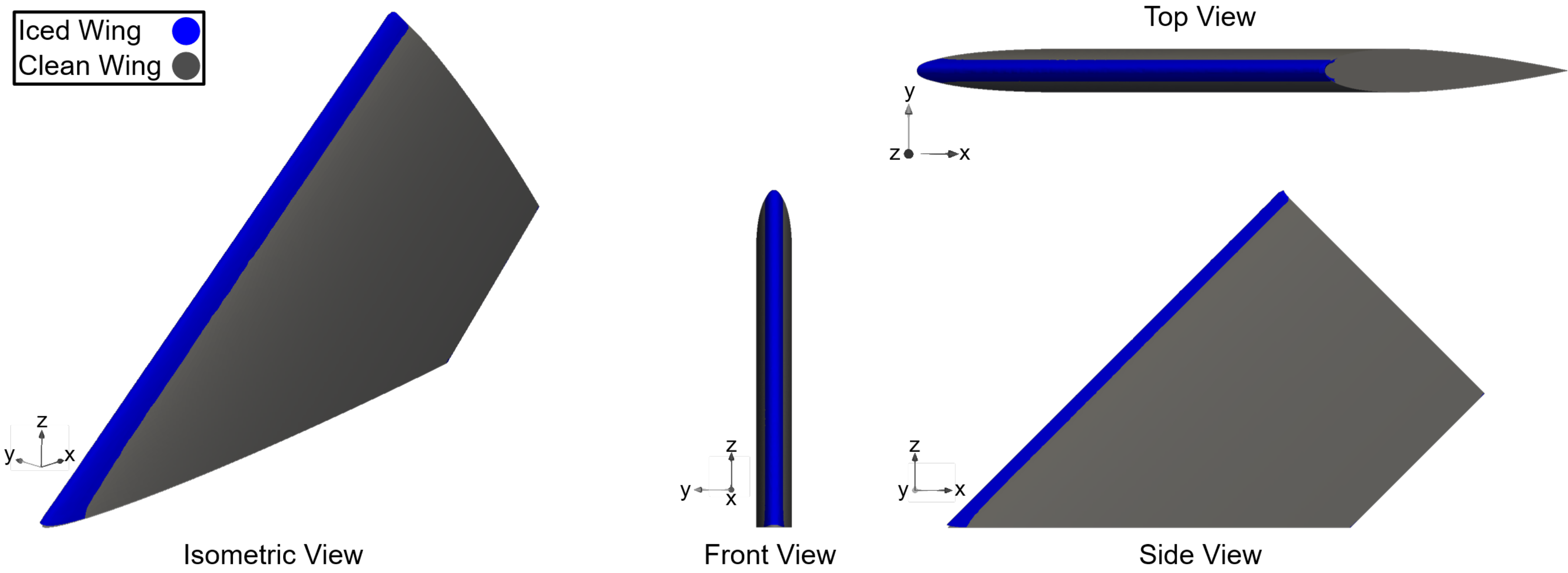
- Icing Conditions:

Wing Profile [-]	Sweep Angle [°]	Accretion Time [min]	Angle of Attack [°]	Chord [m]	Airspeed [m/s]	Total Air Temperature [K]	Liquid Water Content [g/m^3]	Mean Volume Diameter [μm]
NACA0012	45	19.8	0	0.914	51.44	260.55	0.57	44

- Unstructured Mesh:

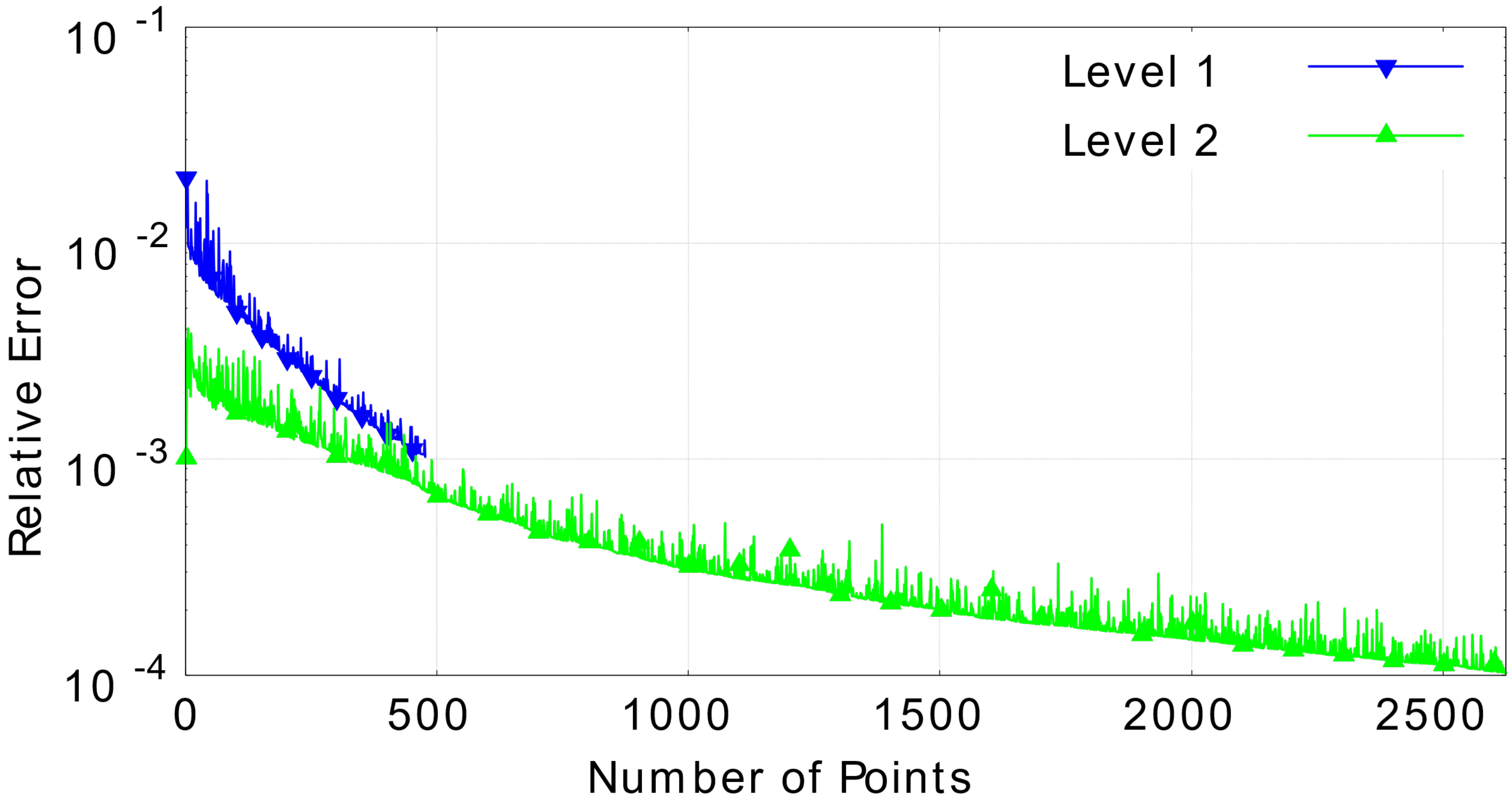
- Ice Shape:





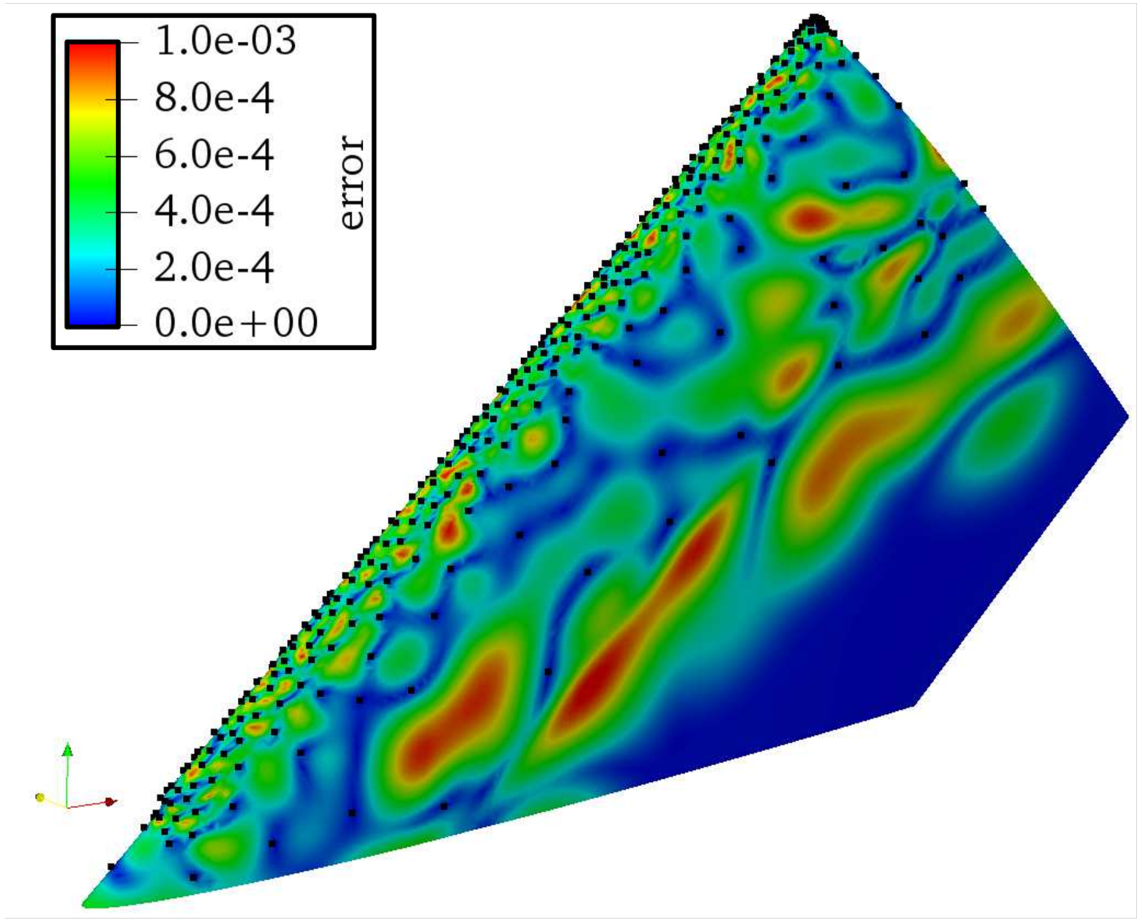
Results: Swept Wing

- 2-Levels greedy surface point data reduction.
- Max Number of Control Points 2625.

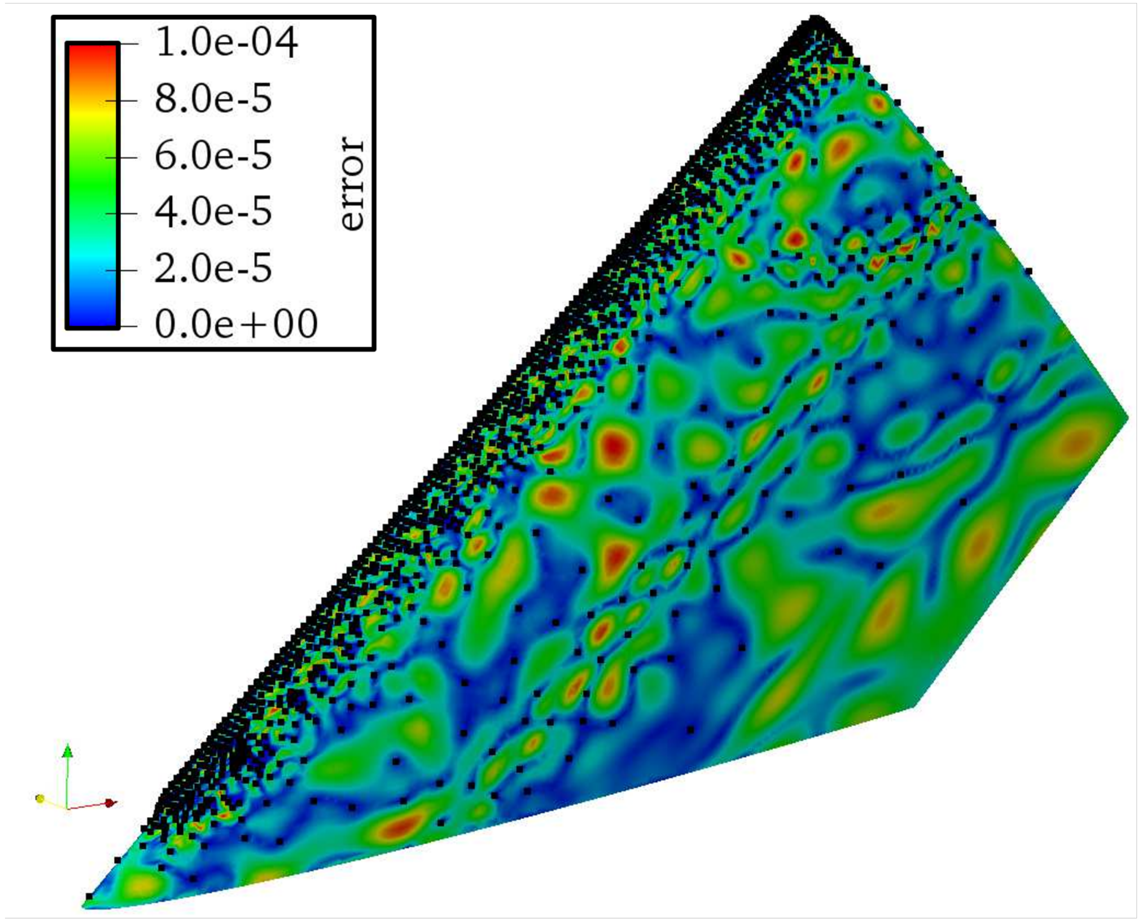


Results: Swept Wing

- Contour map of the normalized surface error with the control points:



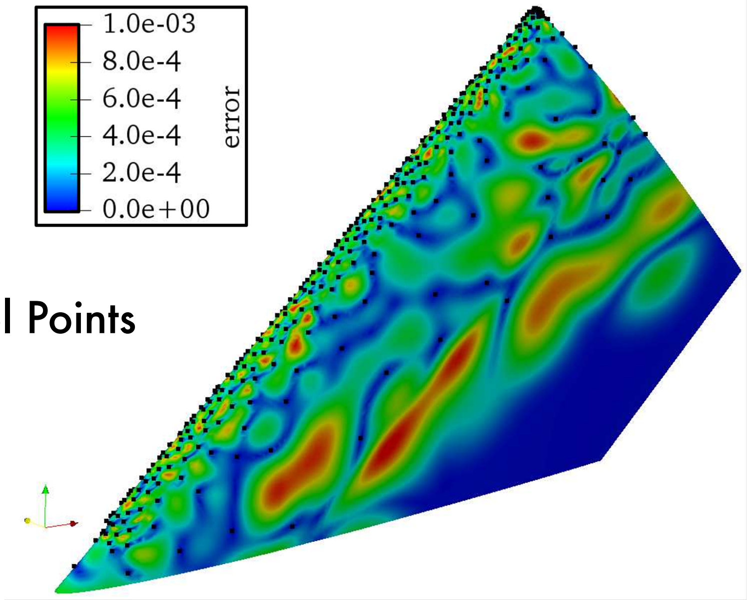
Level 1: 477 Control Points



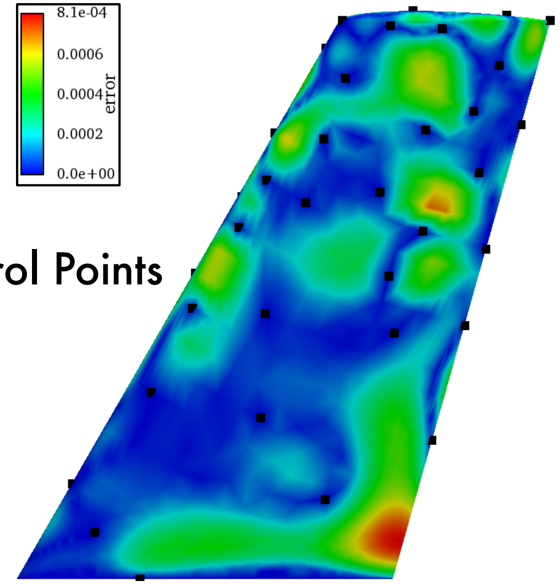
Level 2: 2625 Control Points

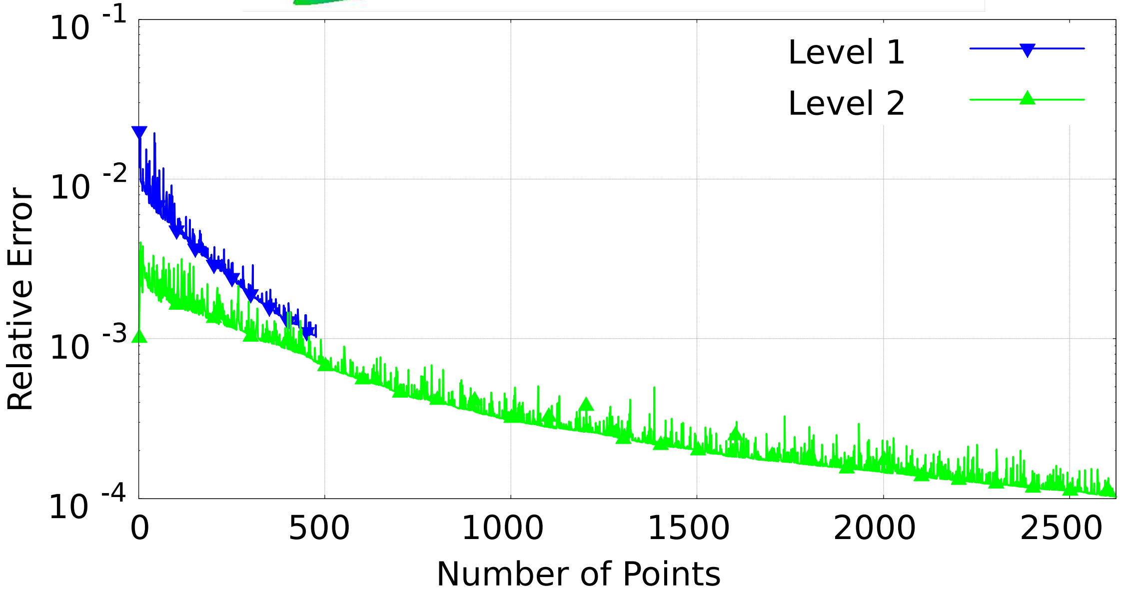
Results: Local vs. Global Deformation

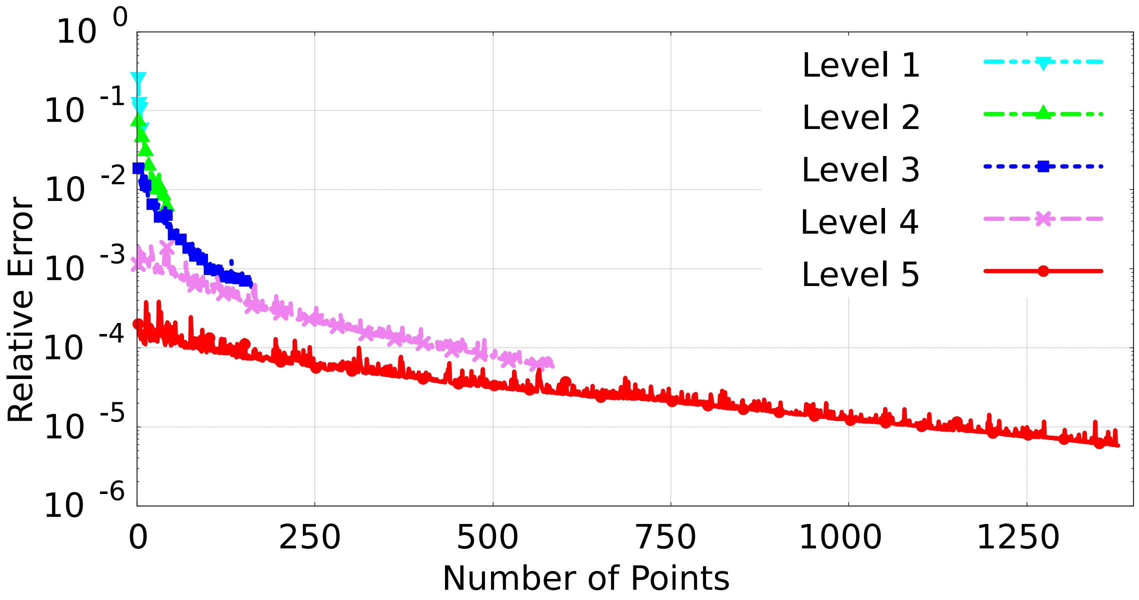
Level 1:
477 Control Points



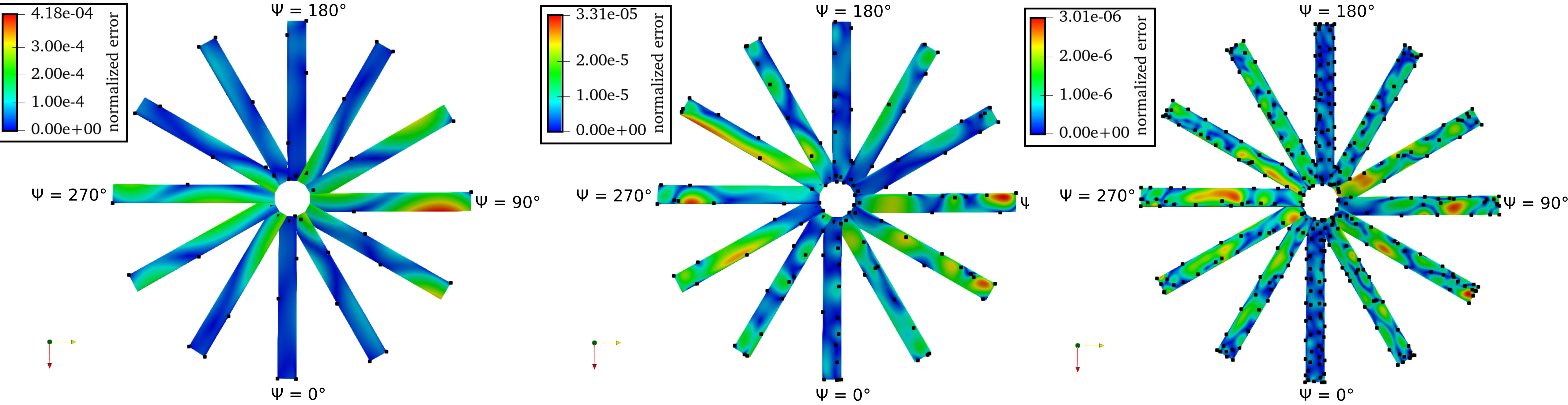
Level 2: 32 Control Points



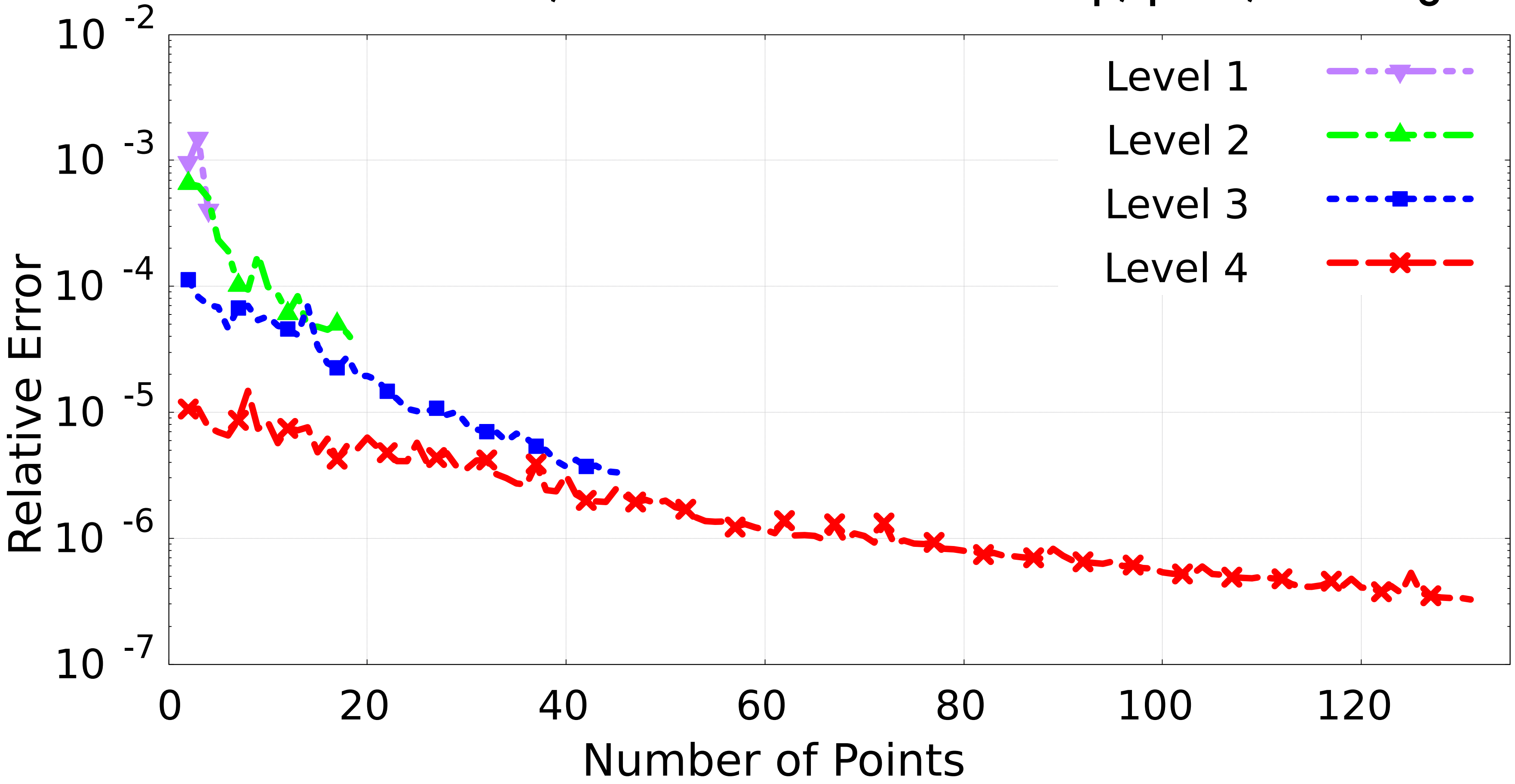




- Forward flight case with prescribed blade kinematics
- Sliding mesh for rotation around hub, mesh deformation for flap, pitch, lead-lag



- Forward flight case with prescribed blade kinematics
- Rigid rotor
- Sliding mesh for rotation around hub, mesh deformation for flap, pitch, lead-lag



CONCLUSIONS - QUESTIONS?

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