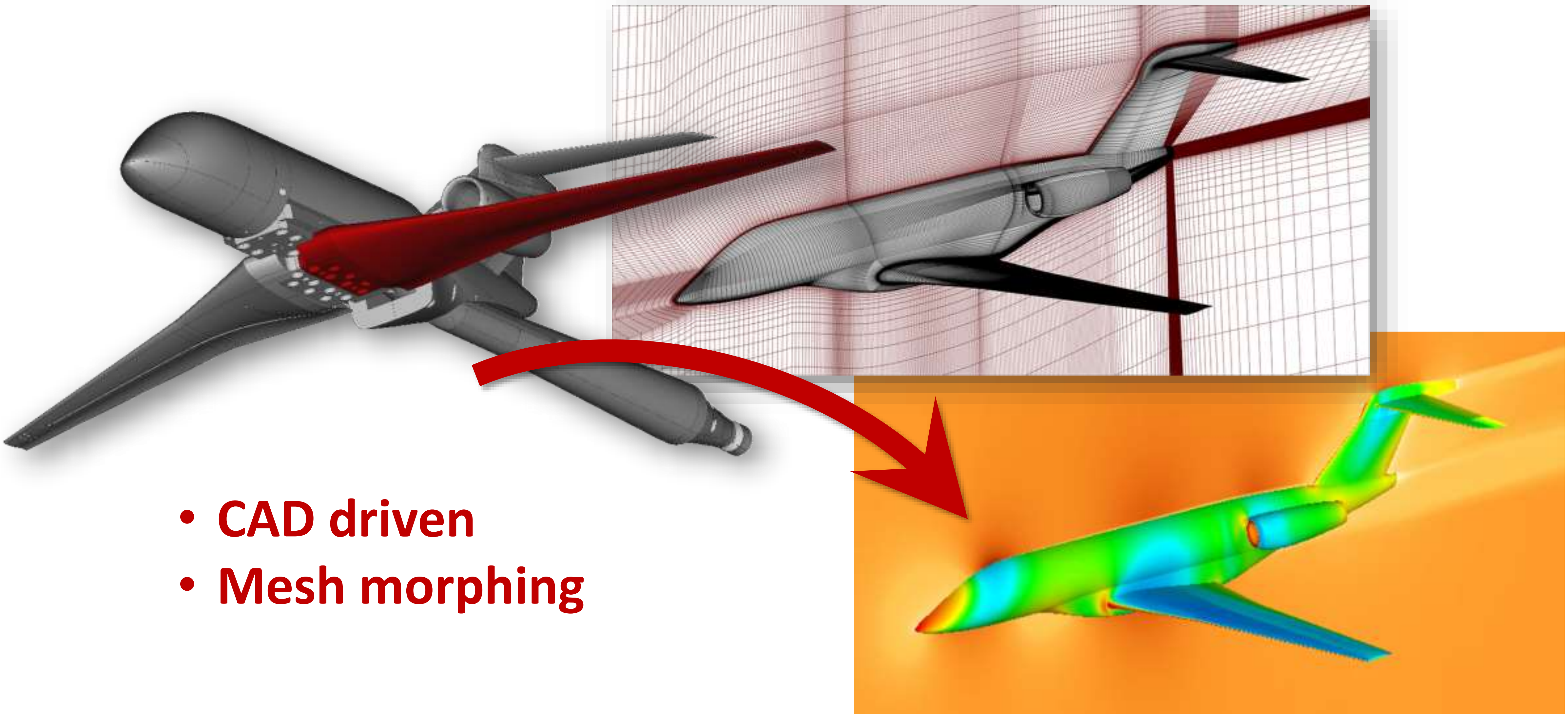
ANSYS (rbf-morph)™

# High performance RBF mesh morphing solutions to face typical aerospace problems

**Ubaldo Cella**

# Geometry parameterization

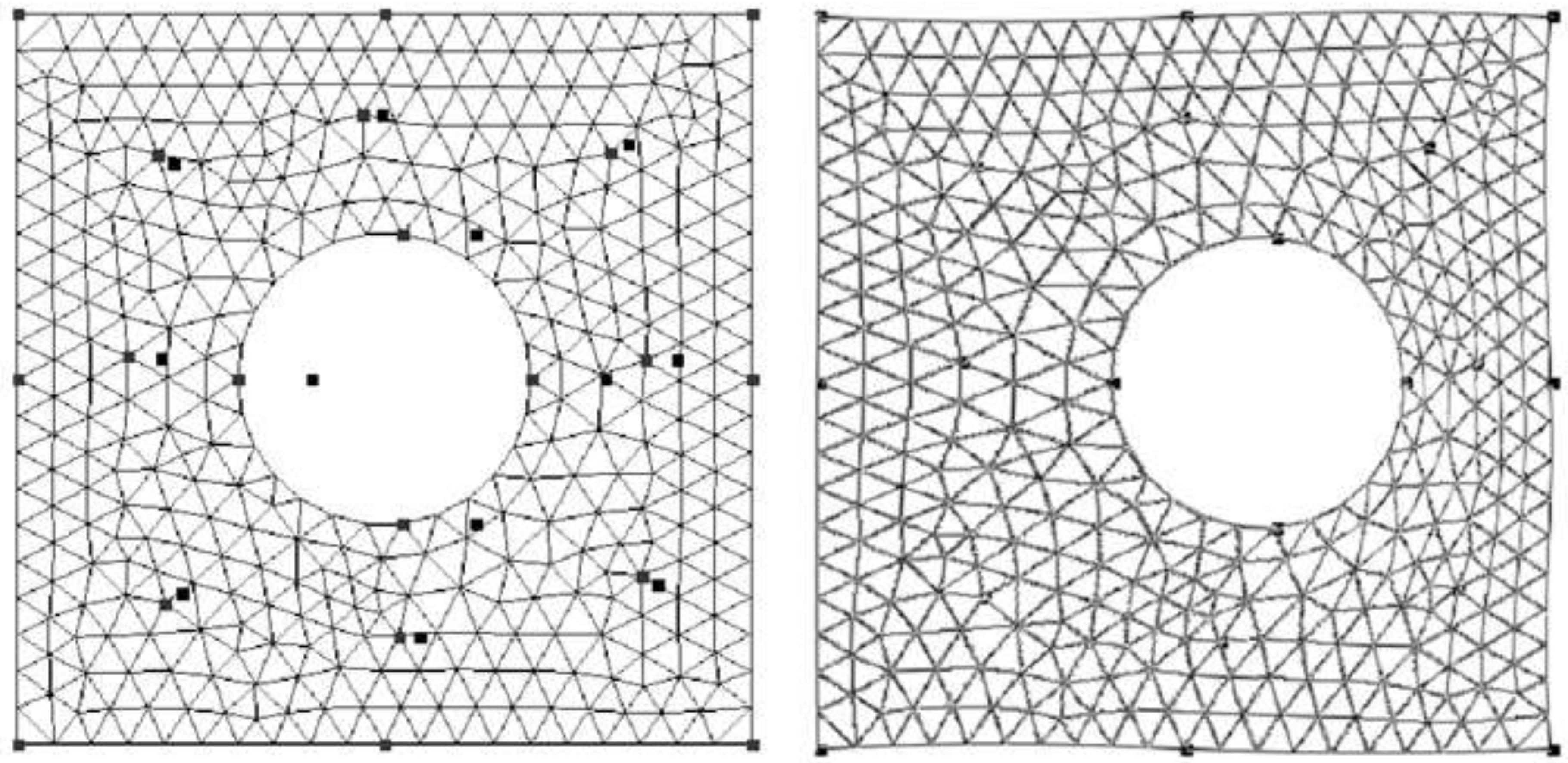


- CAD driven
- Mesh morphing

# CAD driven approach

- Main advantages
  - Accurate geometry quality control
  - High constraints setup flexibility
  - No “back to CAD” required
- Main disadvantage
  - Complex and not generalizable setup
  - Highly skilled CAD user required
  - Robustness
  - Remesh required
    - Structured grids
    - Simple geometries

# Mesh morphing

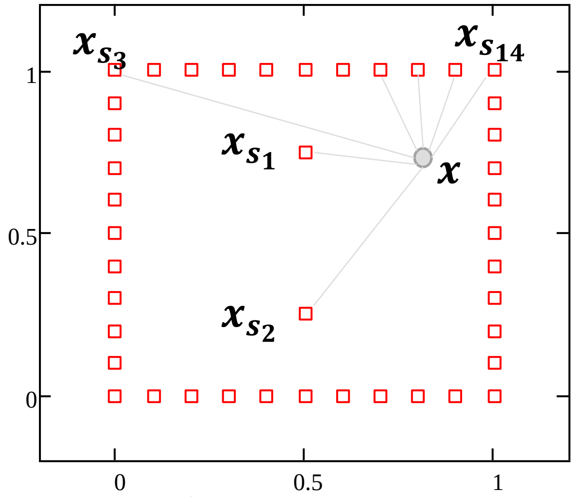


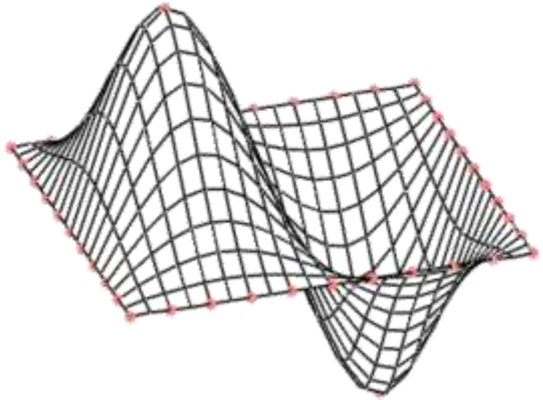
# RBF mesh morphing

- Main advantages
  - No re-meshing
  - Can handle any kind of mesh (meshless method)
  - Can be integrated in the CFD solver
  - Highly parallelizable
  - Robust process (consistency)
- Main disadvantage
  - Limitation in the deformation amplitude
  - Computationally expensive (HPC for large grids)
  - Back to CAD procedure required
  - Uncertainness in the capability to setup complex parameterizations

# RBF background

- RBF - class of functions introduced as interpolators of scattered data



$$s(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i \cdot \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{s_i}\right\|\right) + h(\boldsymbol{x})$$

Scalar function at evaluation point

Weights of sources

Polynomial

Radial function

Source points

Evaluation point

# RBF background

$$s(\boldsymbol{x}_{s_i}) = \boldsymbol{g}_{s_i},\ h(\boldsymbol{x}_{s_i}) = 0 \qquad 1 \le i \le N$$

- A radial basis fit exists if
  - desired values are matched at source points
  - with the orthogonality condition

$$\sum_{i=1}^{N} \gamma_i = \sum_{i=1}^{N} \gamma_i x_{s_i} = \sum_{i=1}^{N} \gamma_i y_{s_i} = \sum_{i=1}^{N} \gamma_i z_{s_i} = 0$$

- The fit problem is associated with the solution of a linear system
  - $\boldsymbol{M}$ is the interpolation matrix
  - $\boldsymbol{P_s}$ is the constraint matrix

$$\begin{pmatrix} \boldsymbol{M} & \boldsymbol{P_s} \\ \boldsymbol{P_s^T} & 0 \end{pmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g_s} \\ 0 \end{pmatrix}$$

$$\boldsymbol{M}_{ij} = \varphi\left(\left\|\boldsymbol{x}_{s_i} - \boldsymbol{x}_{s_j}\right\|\right), 1 \le i, j \le N$$

$$\boldsymbol{P_s} = \begin{pmatrix} 1 & x_{s_1} & y_{s_1} & z_{s_1} \\ 1 & x_{s_2} & y_{s_2} & z_{s_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{s_N} & y_{s_N} & z_{s_N} \end{pmatrix}$$

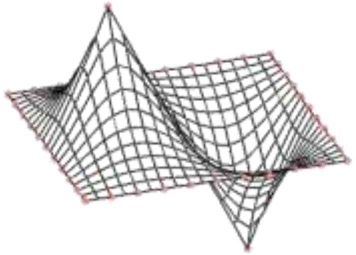
# Radial functions

- RBF with compact support
  - Local interactions
  - Sparse systems of equations to be solved
- RBF with global support
  - Far field interactions
  - Dense system of equations to be solved

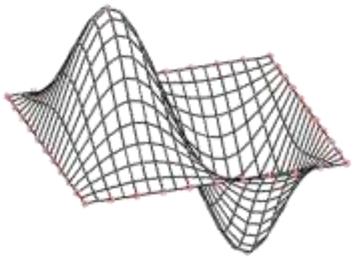
| Name | Abbreviation | $\phi(\zeta)$ |
|---|---|---|
| Wendland $C^0$ | $C0$ | $(1-\epsilon\zeta)^2$ |
| Wendland $C^2$ | $C2$ | $(1-\epsilon\zeta)^4(4\epsilon\zeta+1)$ |
| Wendland $C^4$ | C4 | $(1-\epsilon\zeta)^6(\frac{35}{3}\epsilon\zeta^2+6\epsilon\zeta+1)$ |

Table I. Compactly supported RBF

$\varphi(r) = r$



$\varphi(r) = r^3$



| Name | Abbreviation | $\phi(r)$ |
|---|---|---|
| Polyharmonic spline | $PHS$ | $r^n$, $n$ odd |
| | | $r^n log(r)$, $n$ even |
| Thin plate spline | $TPS$ | $r^2 log(r)$ |
| Multiquadric biharmonics | MQB | $\sqrt{a^2+(\epsilon r)^2}$ |
| Inverse multiquadric biharmonics | IMQB | $\frac{1}{\sqrt{a^2+(\epsilon r)^2}}$ |
| Quadric biharmonics | QB | $1+(\epsilon r)^2$ |
| Inverse quadric biharmonics | IQB | $\frac{1}{1+(\epsilon r)^2}$ |
| Gaussian biharmonics | GS | $e^{-\epsilon r^2}$ |

Table II. Globally supported RBF

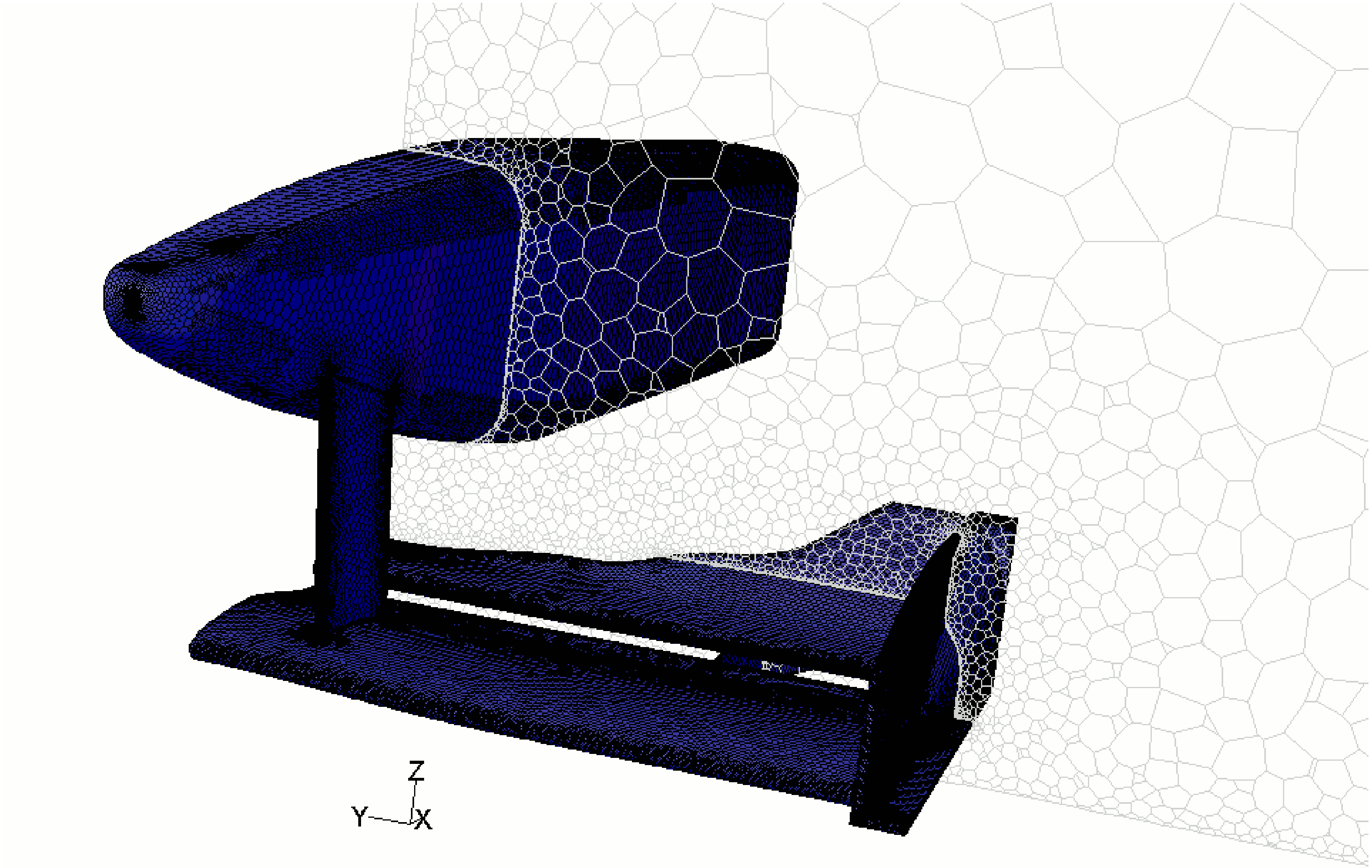
# Cost of the RBF solution

- The fit has a cost of order $N^3$ for a direct fit (full populated matrix).
  - limit to ~10.000 the number of source points that can be used in a practical problem.

- Methods to accelerate RBF solutions:
  - Limit the number of source points
  - Iterative solvers with a pre-conditioner -> cost of order $N^2$ (practical limits ~70.000 nodes).
  - Space partitioning and POU decomposition (up to ~300.000 nodes).
  - Fast pre-conditioner building and FMM (Fast Multipole Method) RBF approximation.
  - Distributing the calculation on multiple cores (CPU and GPU)

(rbf-morph)™

Welcome to the World of Fast Morphing!



# Research and development

RBF4AERO

Università di Roma Tor Vergata

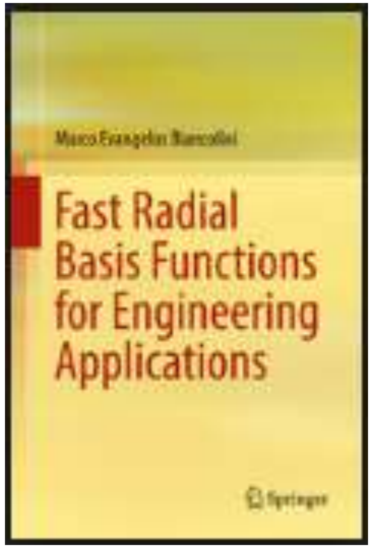
RIBES

(rbf-morph)™

SEVENTH FRAMEWORK PROGRAMME

FORTISSIMO

CloudiFacturing

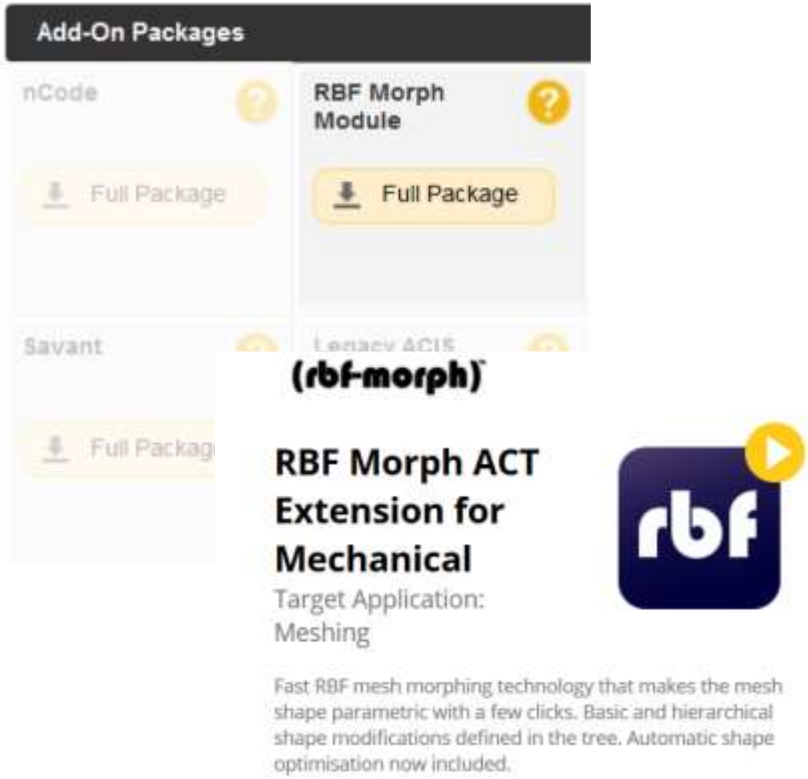



Biancolini M.E. (2018), *Fast radial basis functions for engineering applications,* Springer.
ISBN 978-3-319-75009-5, https://doi.org/10.1007/978-3-319-75011-8.

# Two ANSYS-integrated solutions

## Fluent Add On

- Released in **2009**
- Fully integrated within Fluent (GUI, TUI & solving stage), Workbench and **Adjoint Solver**
- Multi physics features (**FSI**)

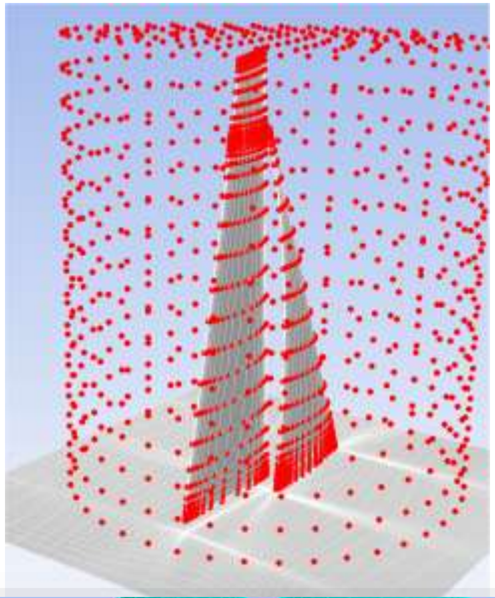


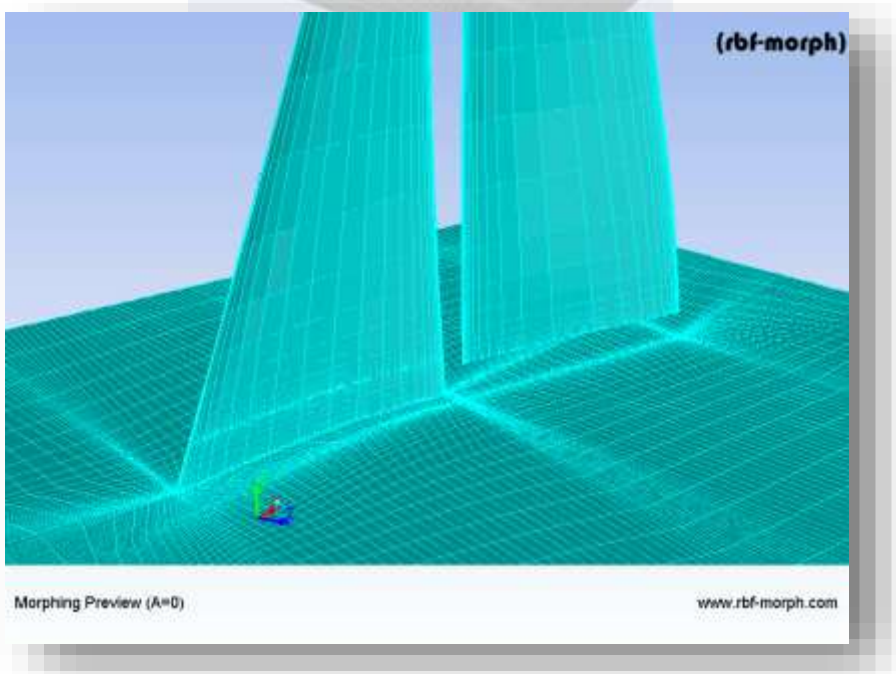

## ACT Extension

- Released in **2015**
- Fully embedded in ANSYS **Mechanical** (parametric)
- Benefits of **underlying geometry** (or aux geo with dead meshes)
- …**Workbench** Meshing

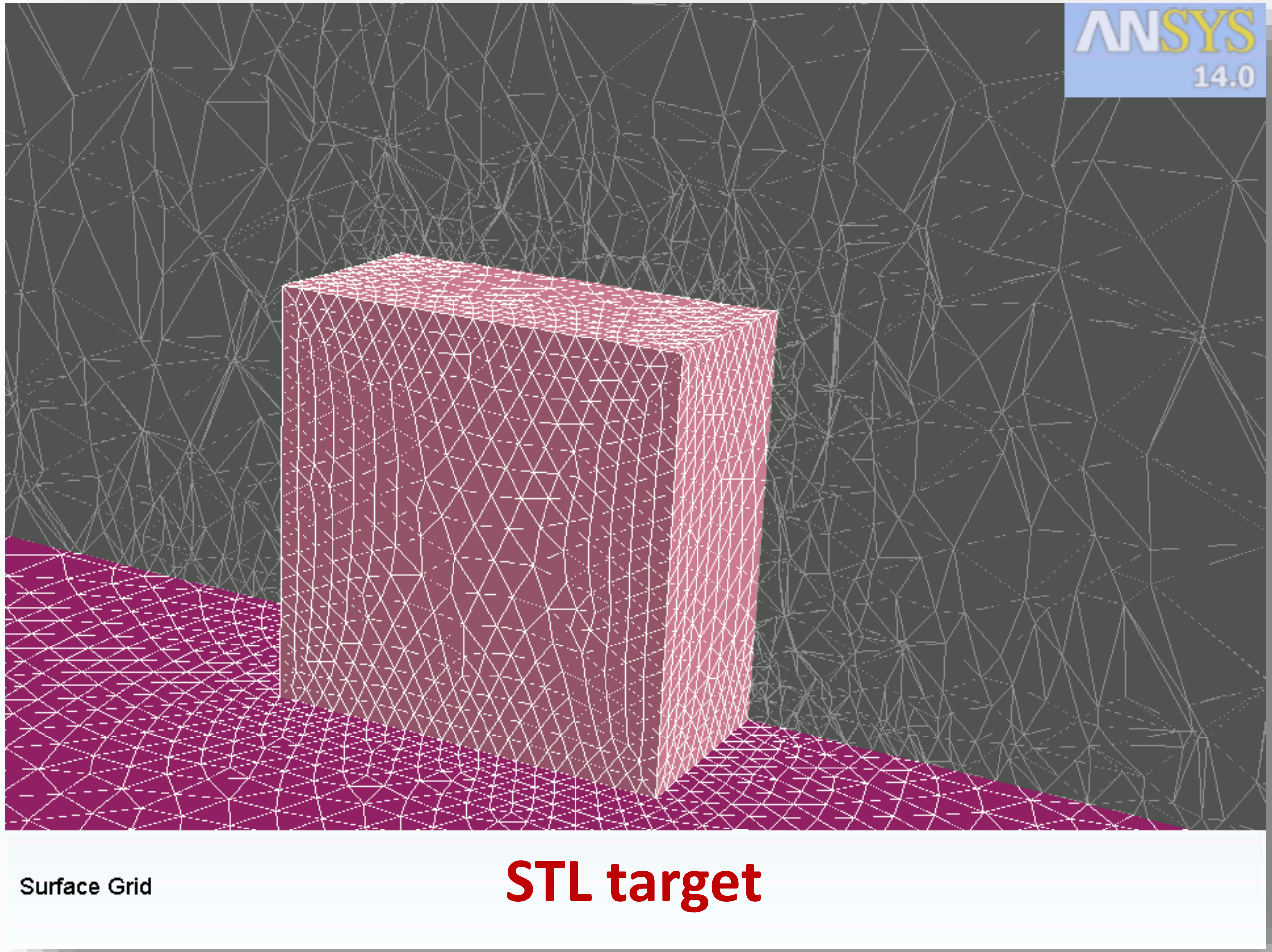
# How it works

- Setup
  - Select fixed and moving walls by source points
  - Prescribe the displacements (or a combination of)
- Fitting
  - Solving the RBF system and storing the solution
- Smoothing
  - Application of the morphing action on surfaces and volume





# CAD controlled surfaces




STL target

# Solver performance samples 2013

- **14 mill**. cells, 60.000 points, PC 4 cpu 2.67 GHz
  - fitting time: **53 sec**. (serial)
  - smoothing: **3.5 min**.
- **50 mill.** cells, 30.000 points, HPC 140 cpu
  - fitting time: **25 sec**. (serial)
  - smoothing: **1.5 min**.
- **100 mill.** cells, 200.000 points, HPC 256 cpu
  - fitting time: **25 min**.
  - smoothing: **5 min**.
- Largest fitted cloud **2 mill.** points on 32 cpu in **3 hours**.
- Largest model morphed (in our knowledge) **700.mill.** cells on 768 cpu in **45 min**.

Perspectives for 2019…

Extend from SSE to AVX (from 128 bit up to 1024bit) … -> target of 100 millions points with GPU

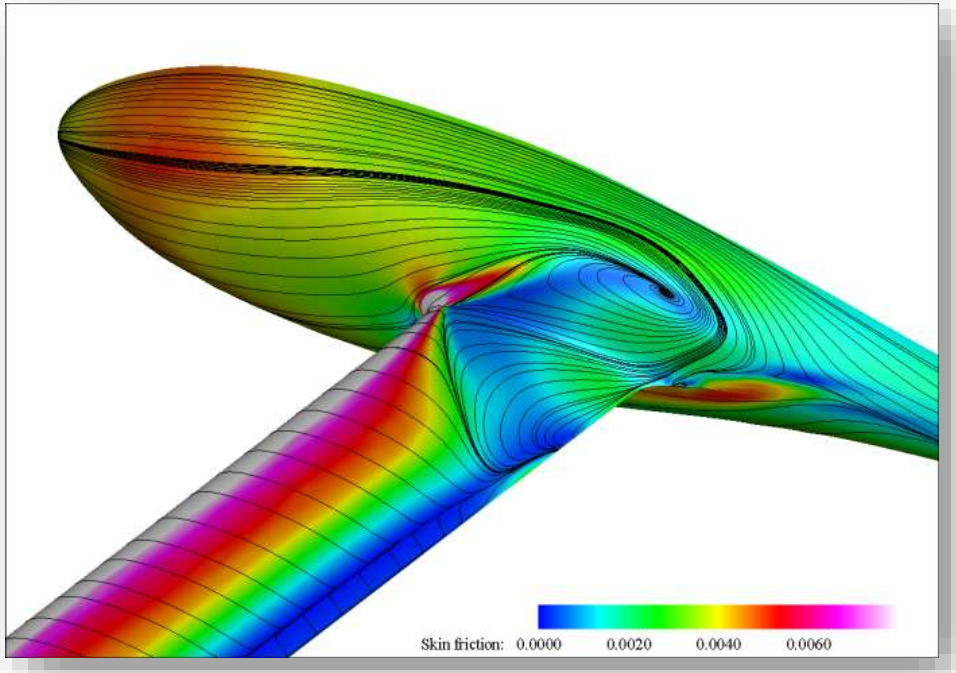
# RBF Morph to face…

- Geometry parameterization
- Shape optimization
- 6DOF (small movements)
- Ice accretion
- CFD-CSM coupling
- Modal FSI analyses
- …

Some examples: …

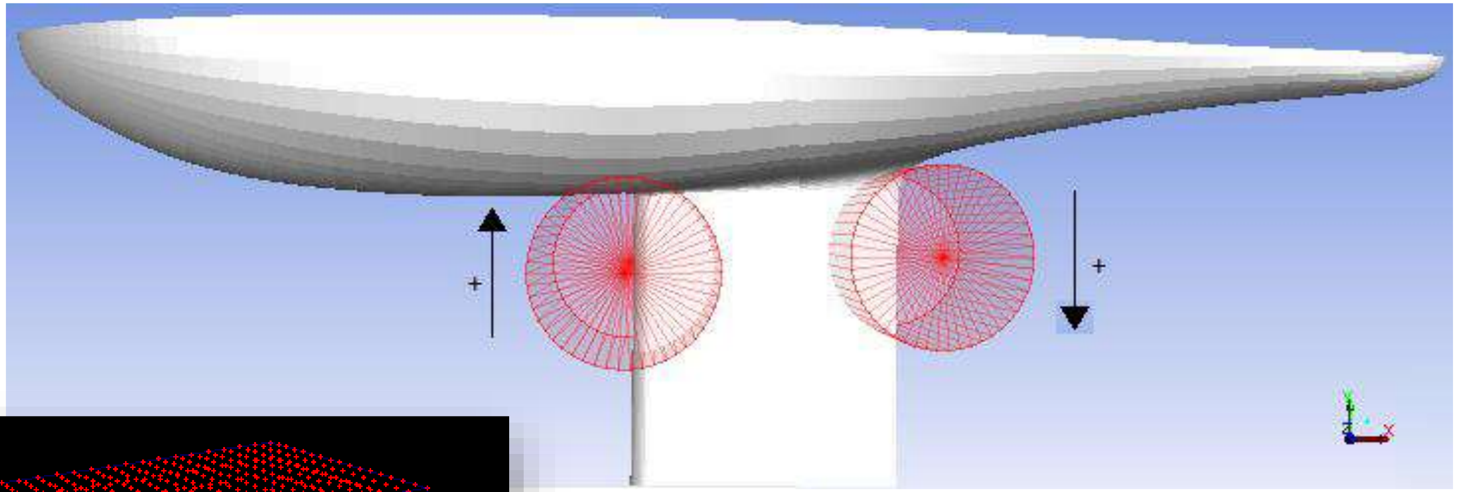
# Aerodynamic shape optimization

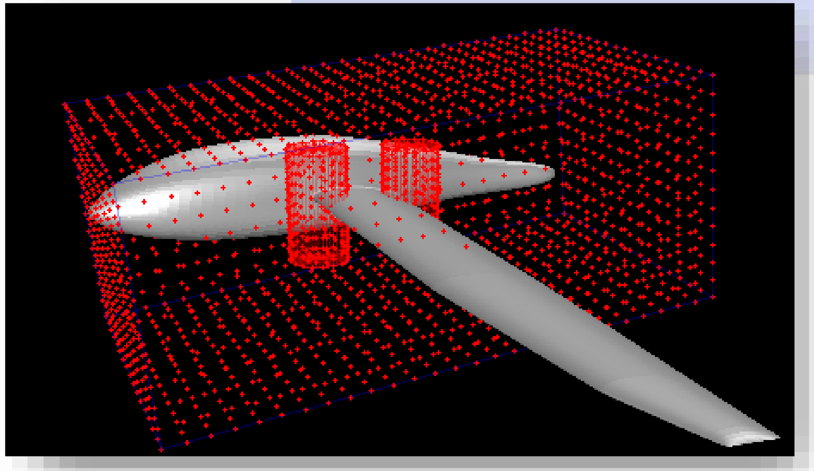
# Wing/fuselage interference

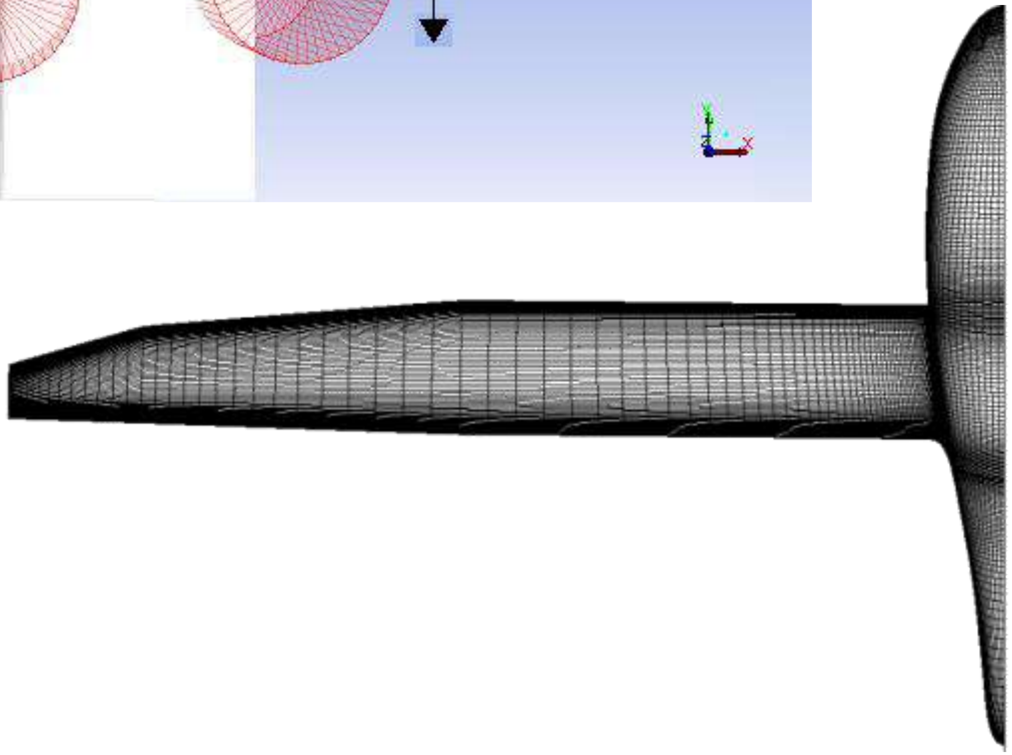



Reynolds 1.24 mill. (c 0.8 m)
Alpha 8 deg

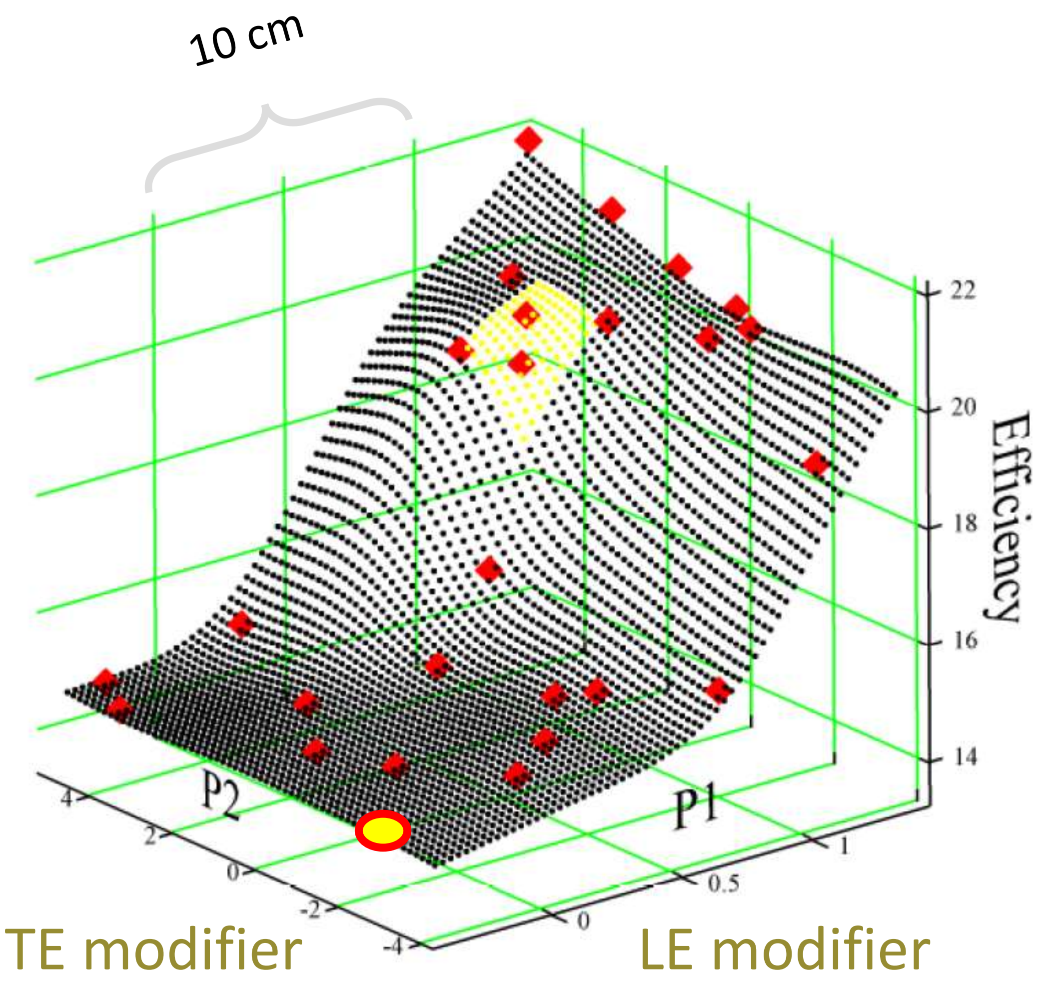
# Problem setup





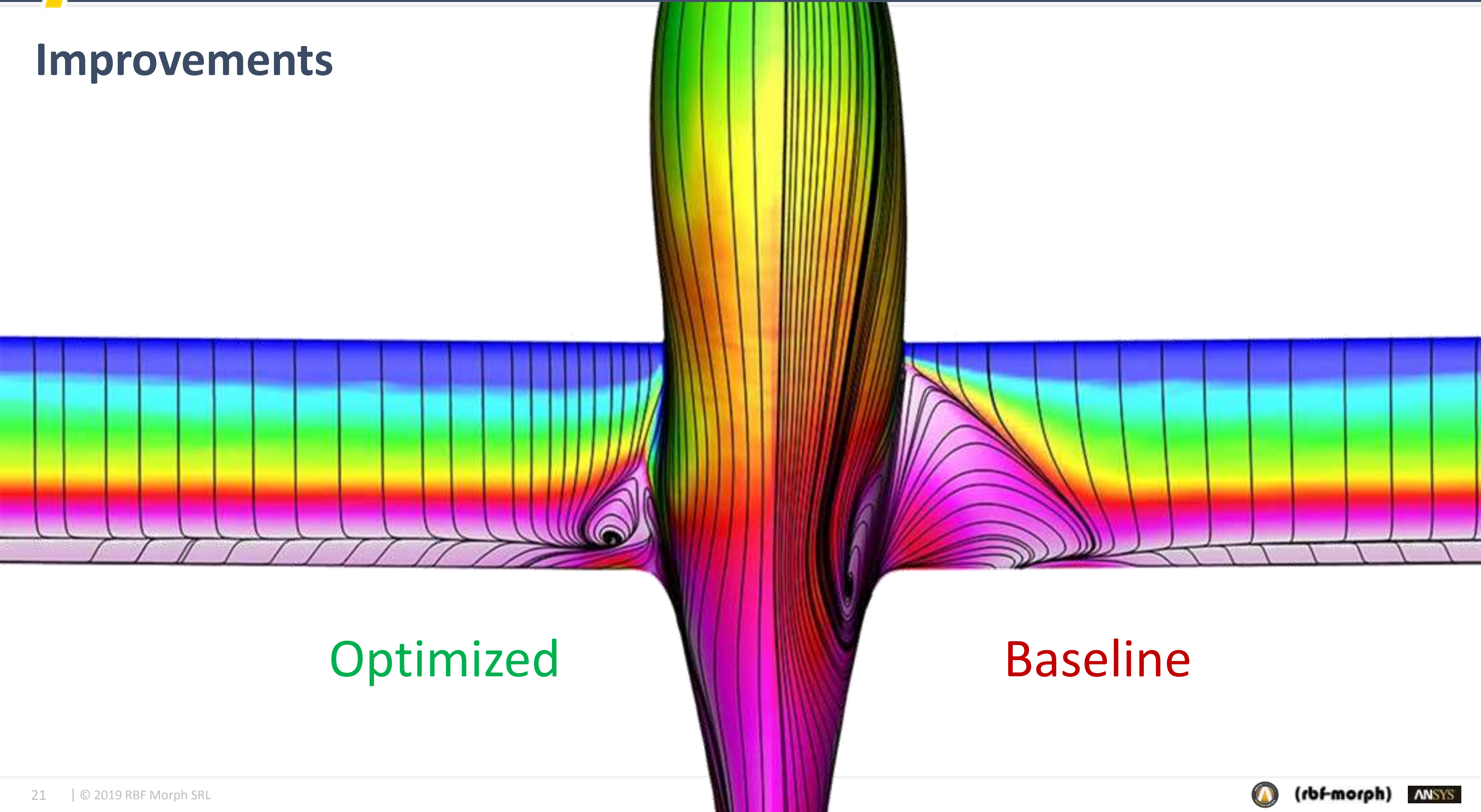


# Optimized solution

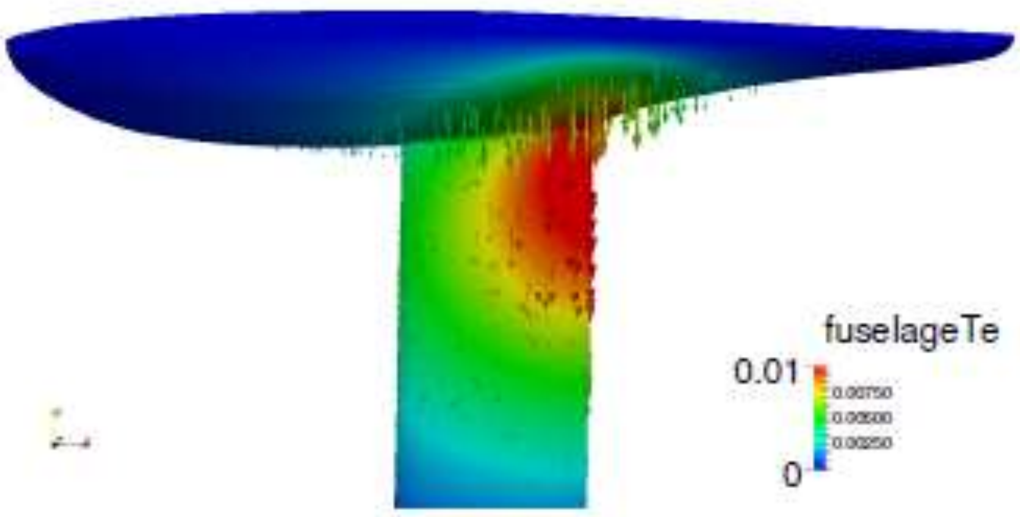


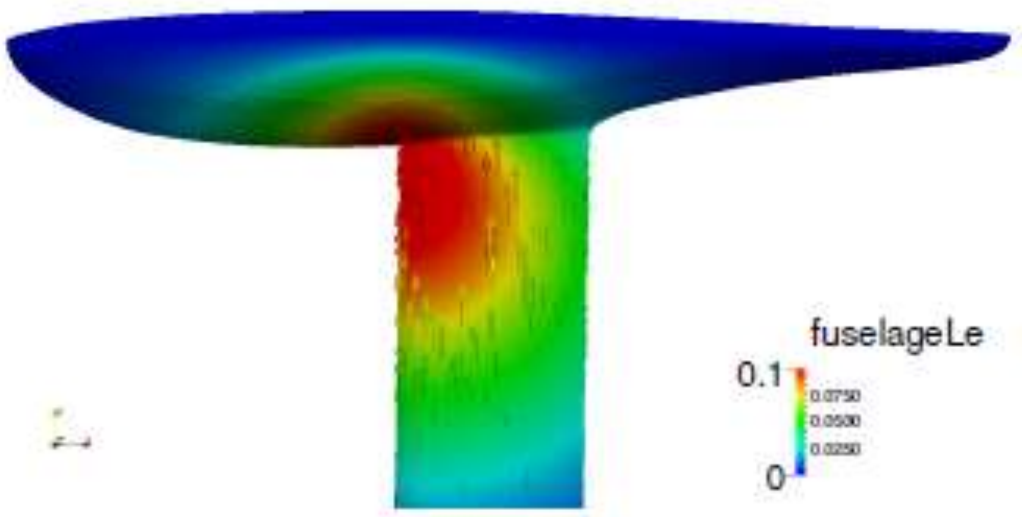

| | $C_L$ | $C_D$ | E |
|---|---|---|---|
| **Baseline** | 1.131 | 760 dc | 14.9 |
| **Optimised** | 1.216 | 605 dc | 20.1 |
| **Variation** | **+7.5%** | **-20.4%** | **+35.0%** |

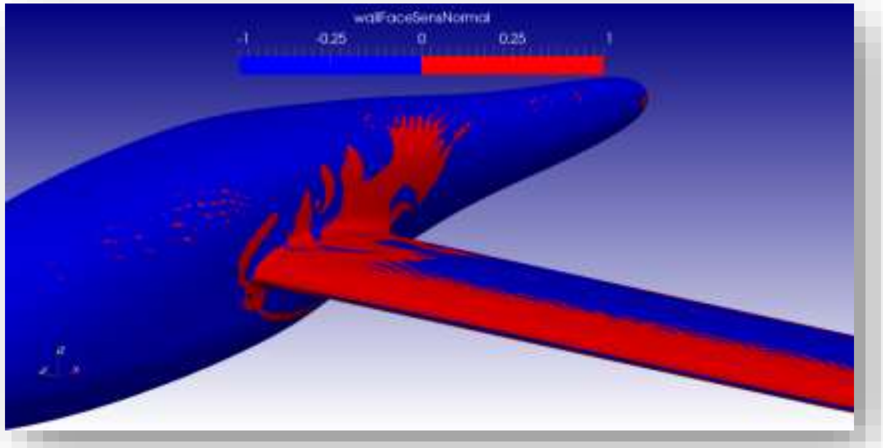
# Improvements



# Adjoint coupling

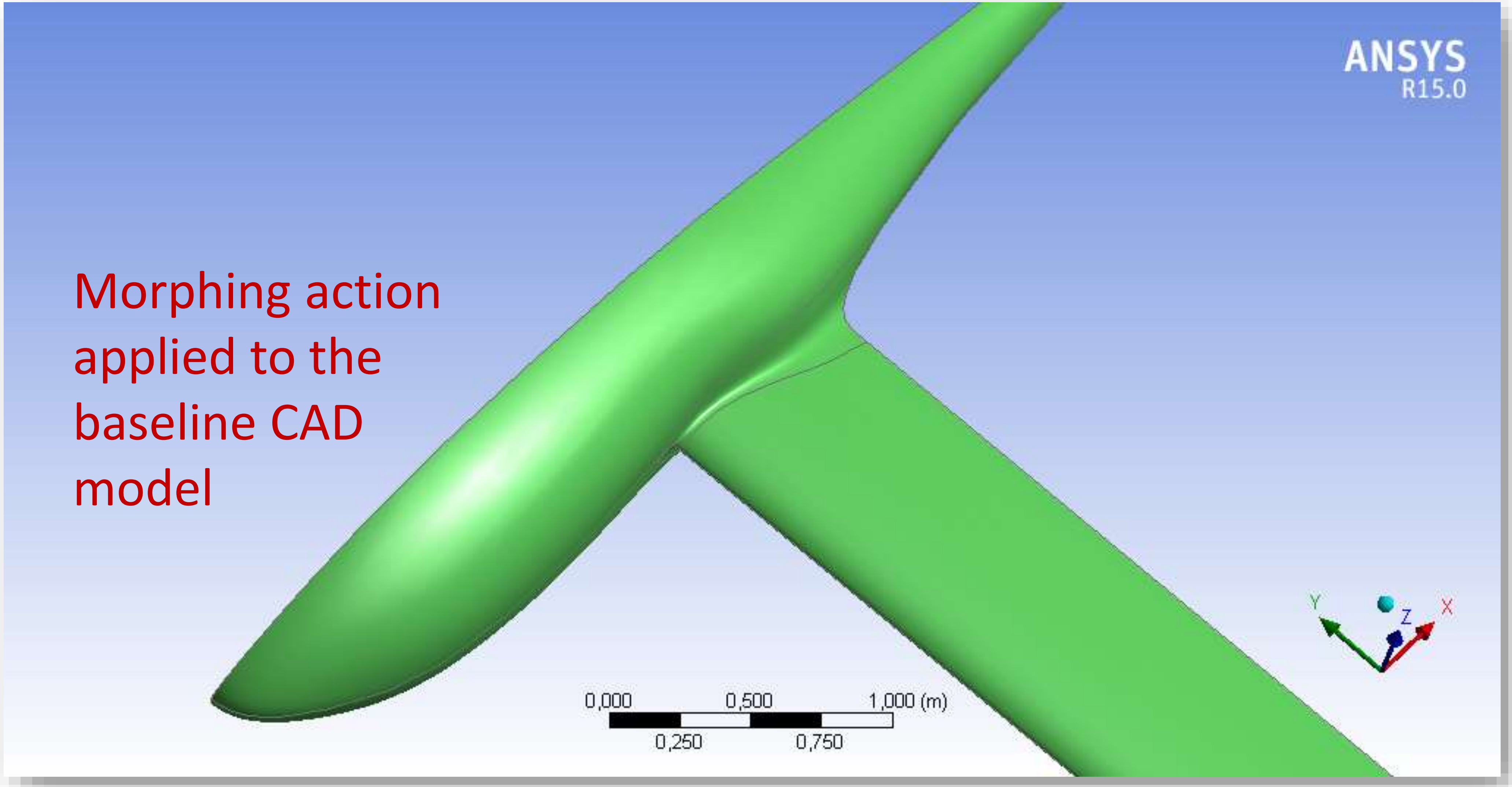



Sensitivity with respect to normal displacement

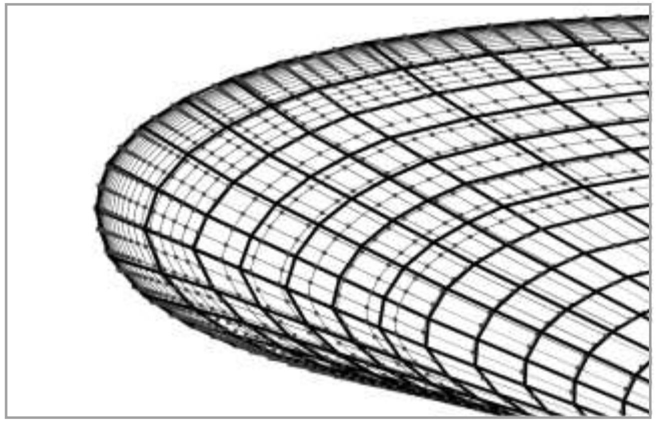
# Back to CAD

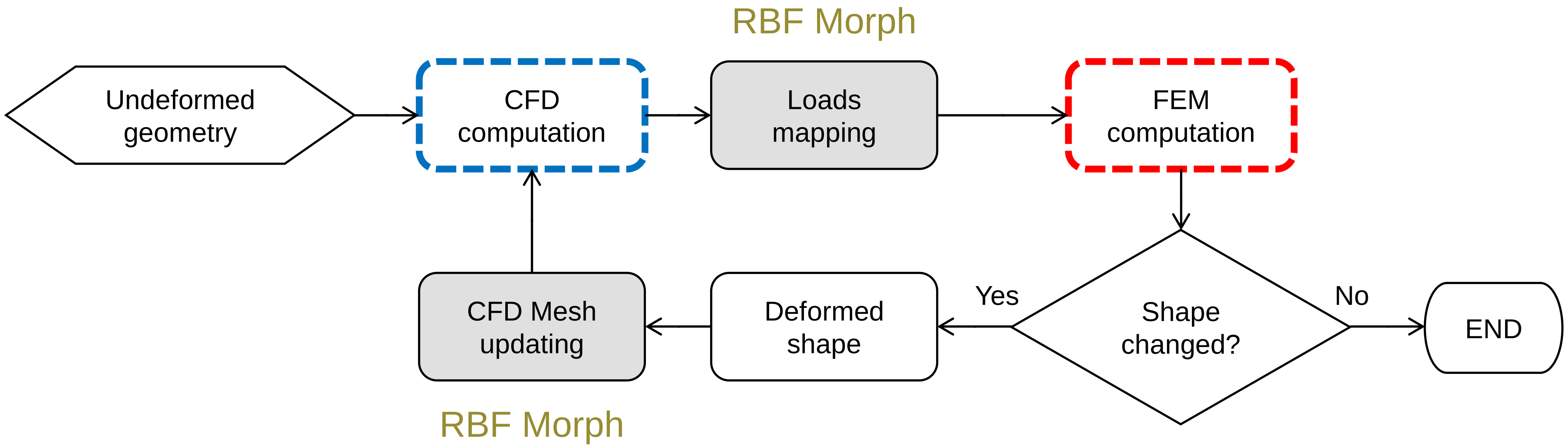

ANSYS
R15.0
Morphing action applied to the baseline CAD model
0,000
0,500
1,000 (m)
0,250
0,750
Y
Z
X

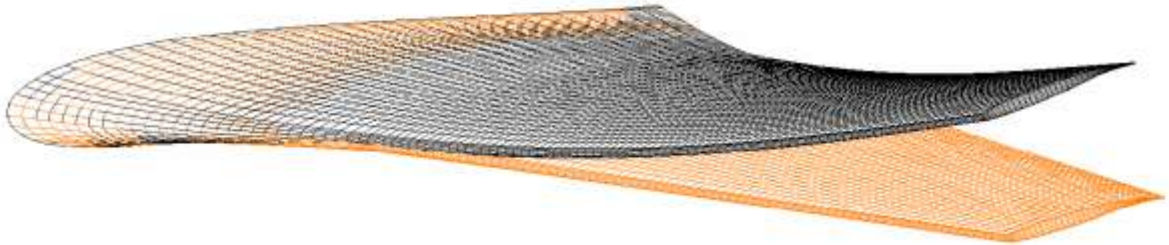
# Fluid-Structure Interaction (FSI) analysis and validation

PIAGGIO AEROSPACE

# 2-way Fluid-Structure Interaction



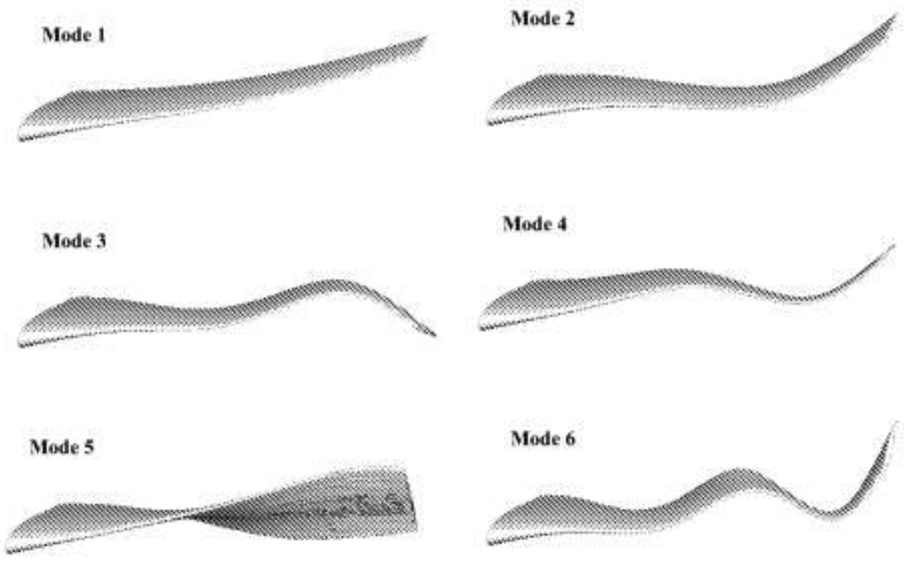


# Modal FSI approach

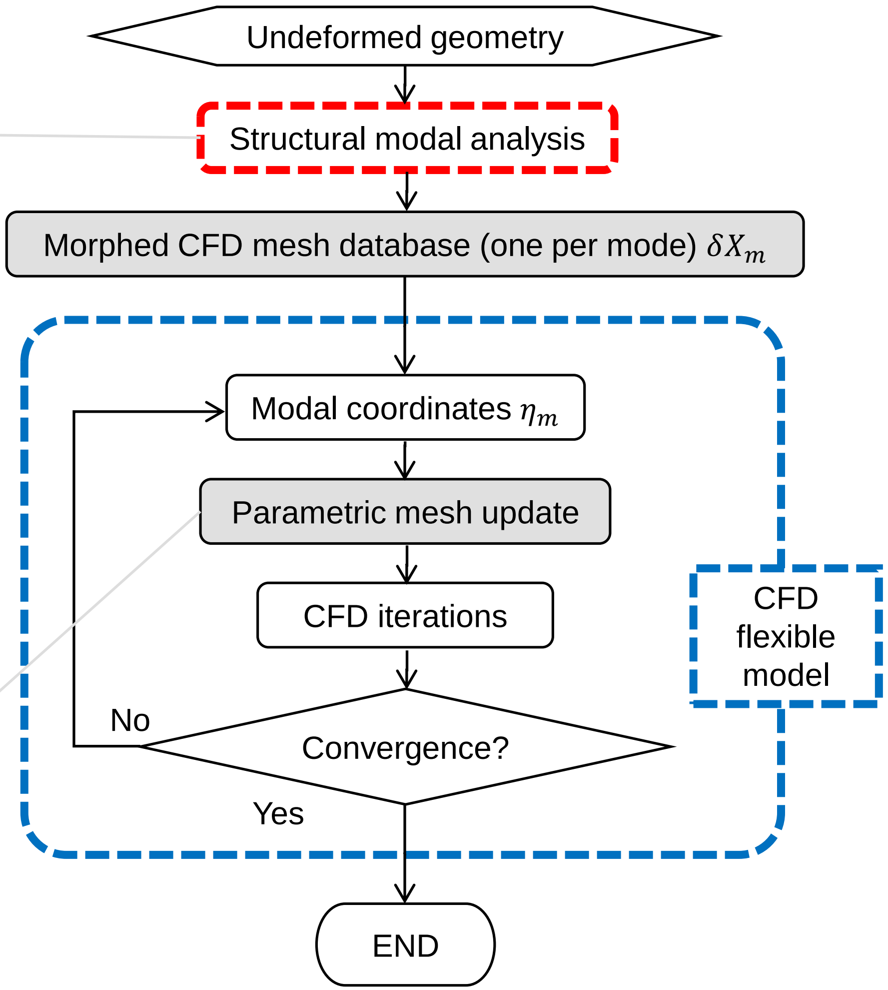
undamped vibration modes

$$[M]\ddot{q} + [K]q = Q$$

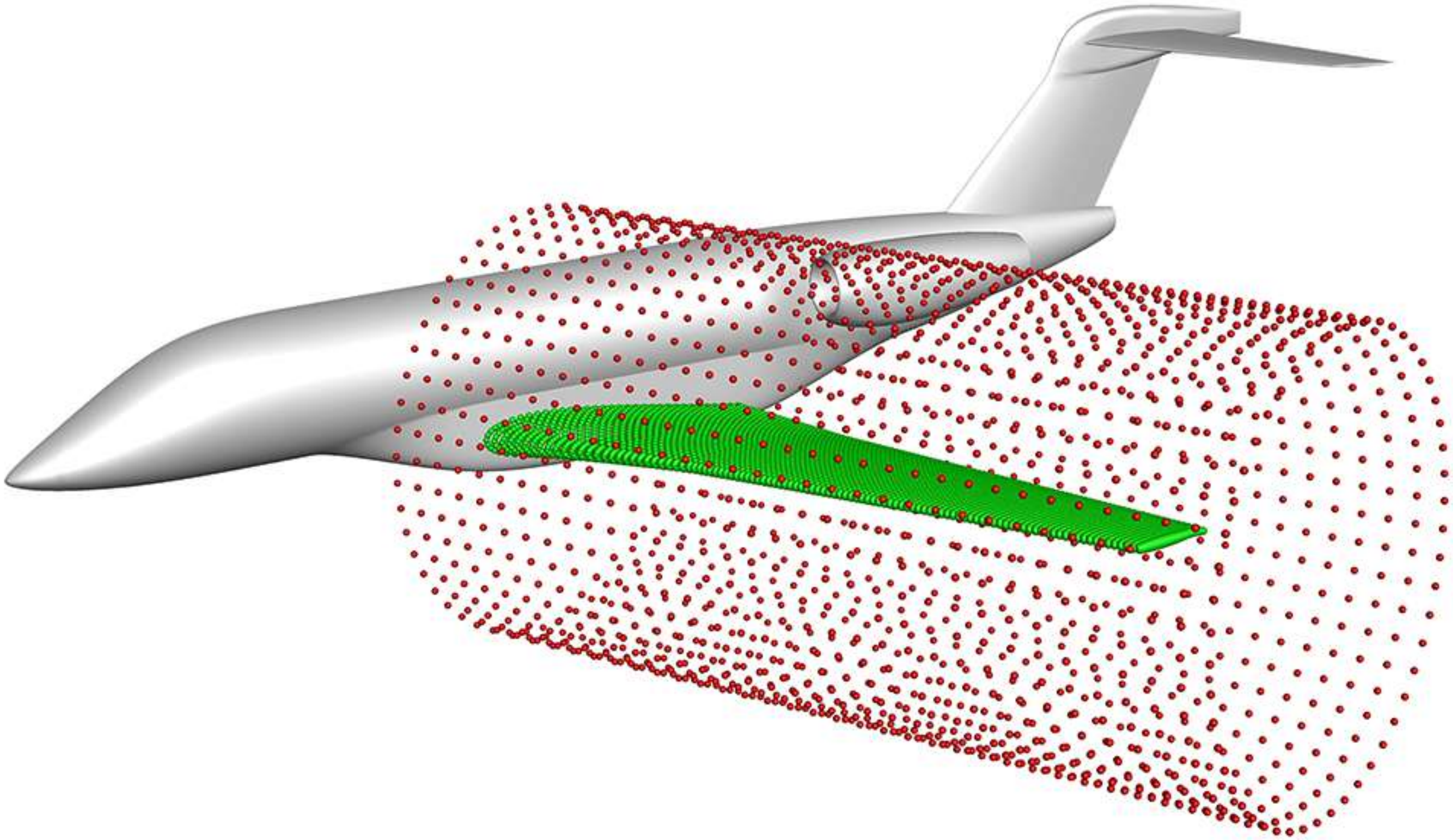



Parametric mesh formulation

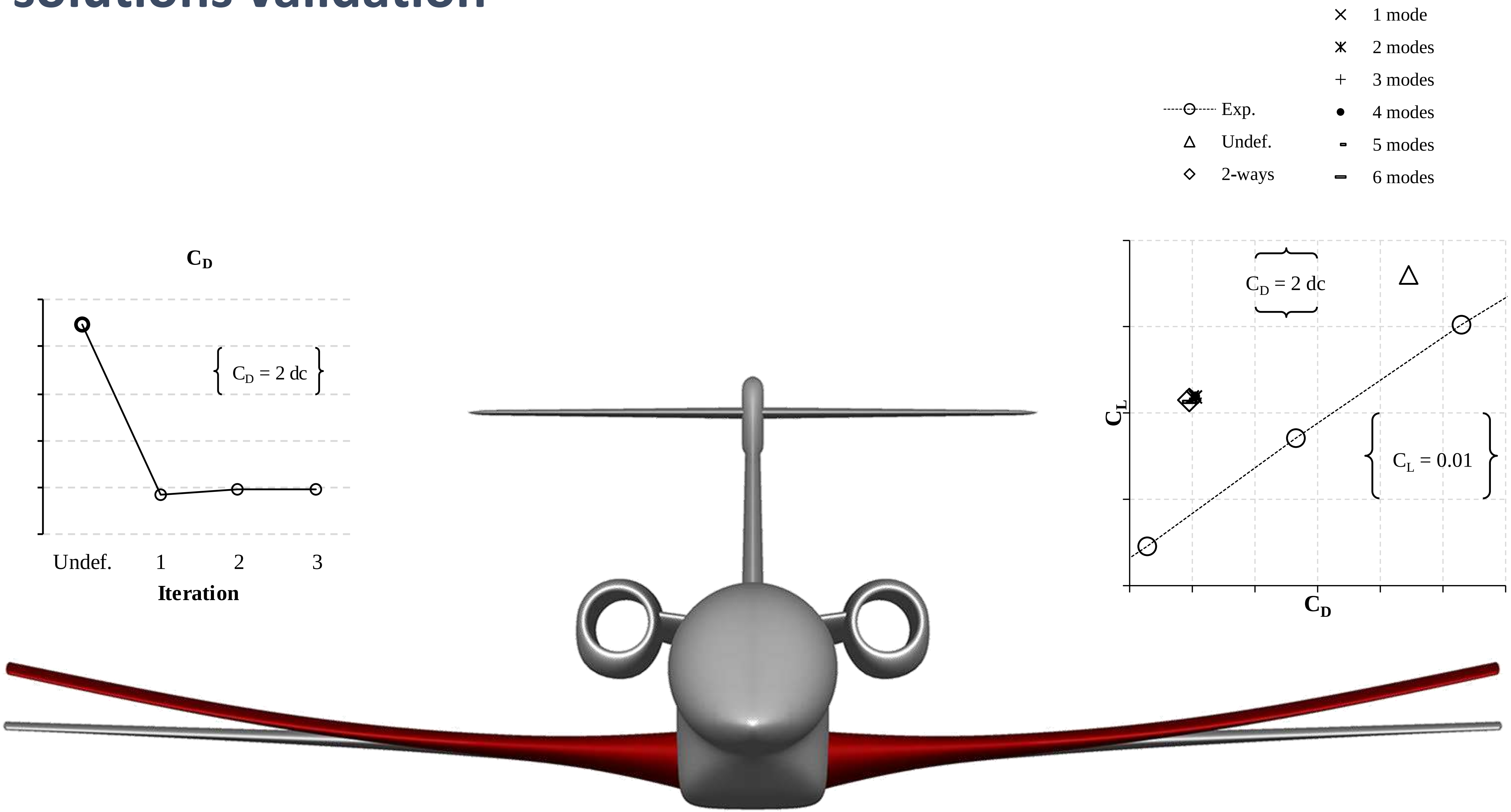
$$X_{CFD} = X_{CFD0} + \sum_{m=1}^{n_{modes}} \eta_m \delta X_m$$



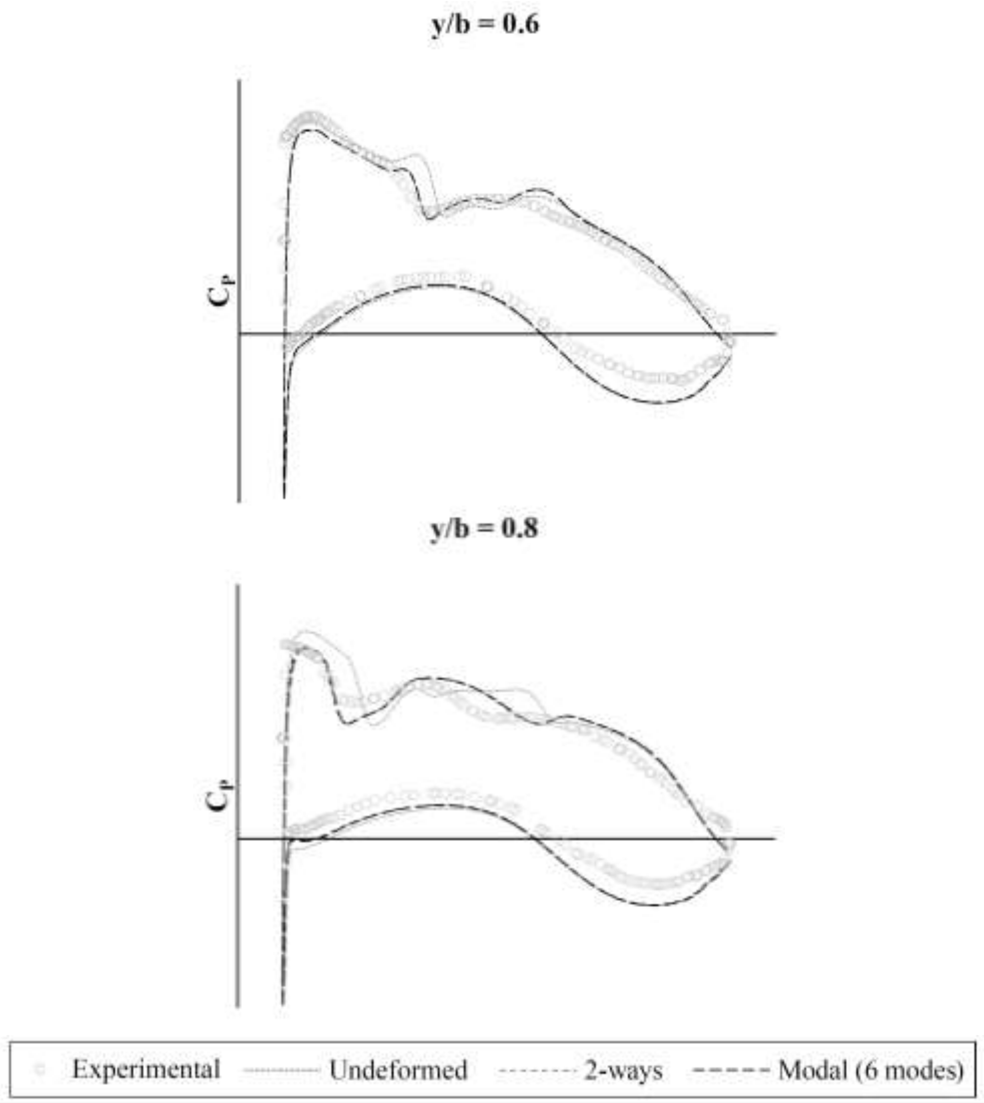
# RBF problem setup

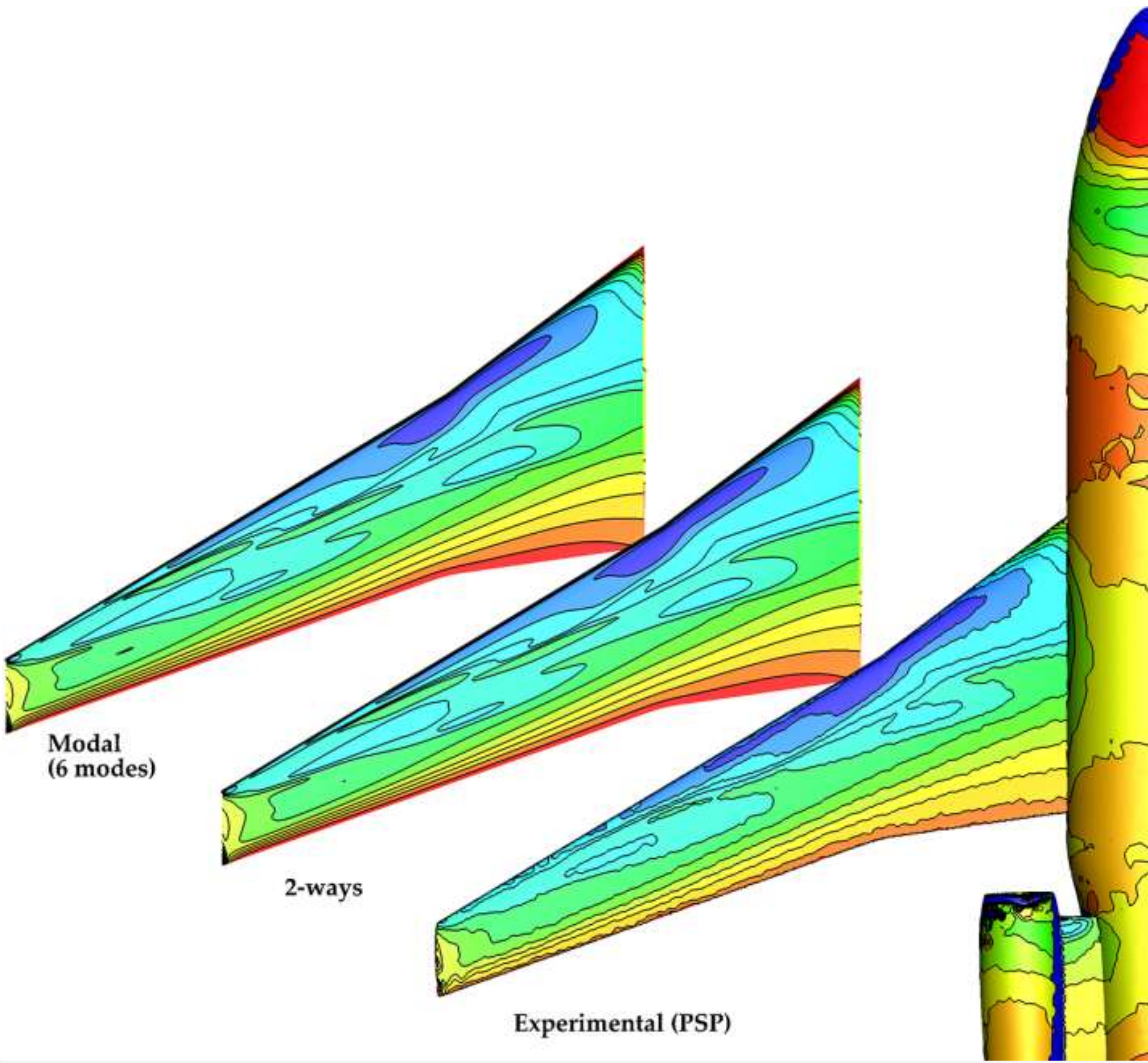


# FSI solutions validation



# Surface pressure

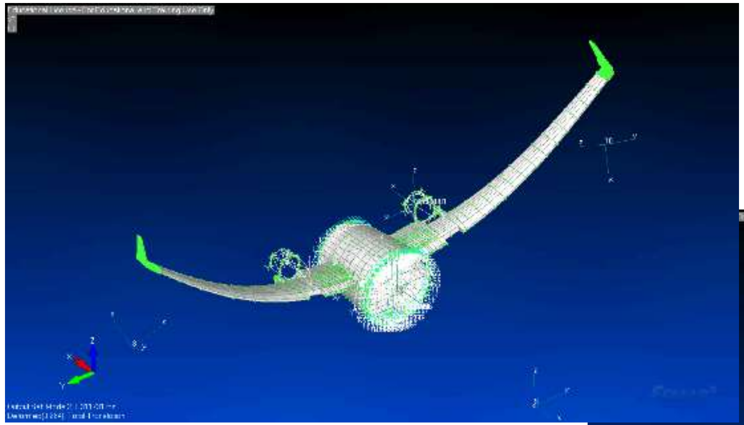


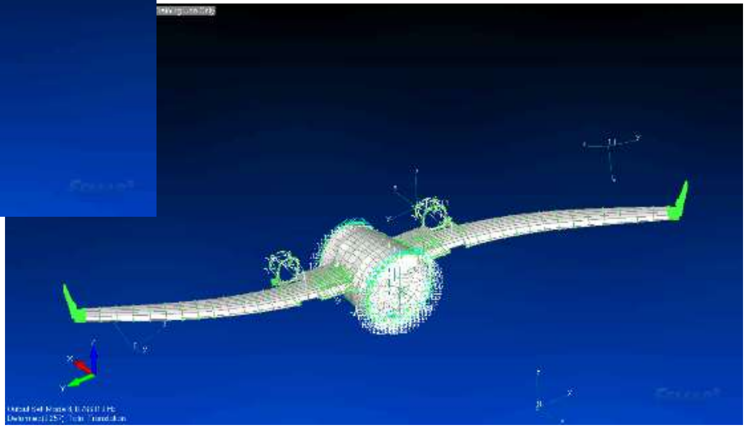



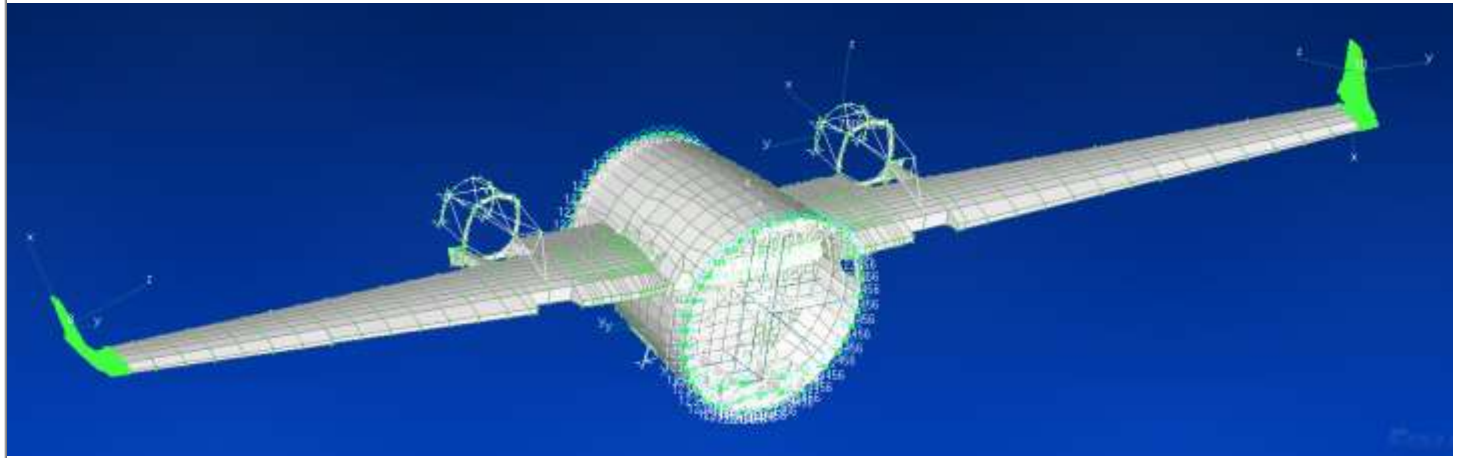
# Aeroelastic shape optimization


PIAGGIO AEROSPACE

# Structural model

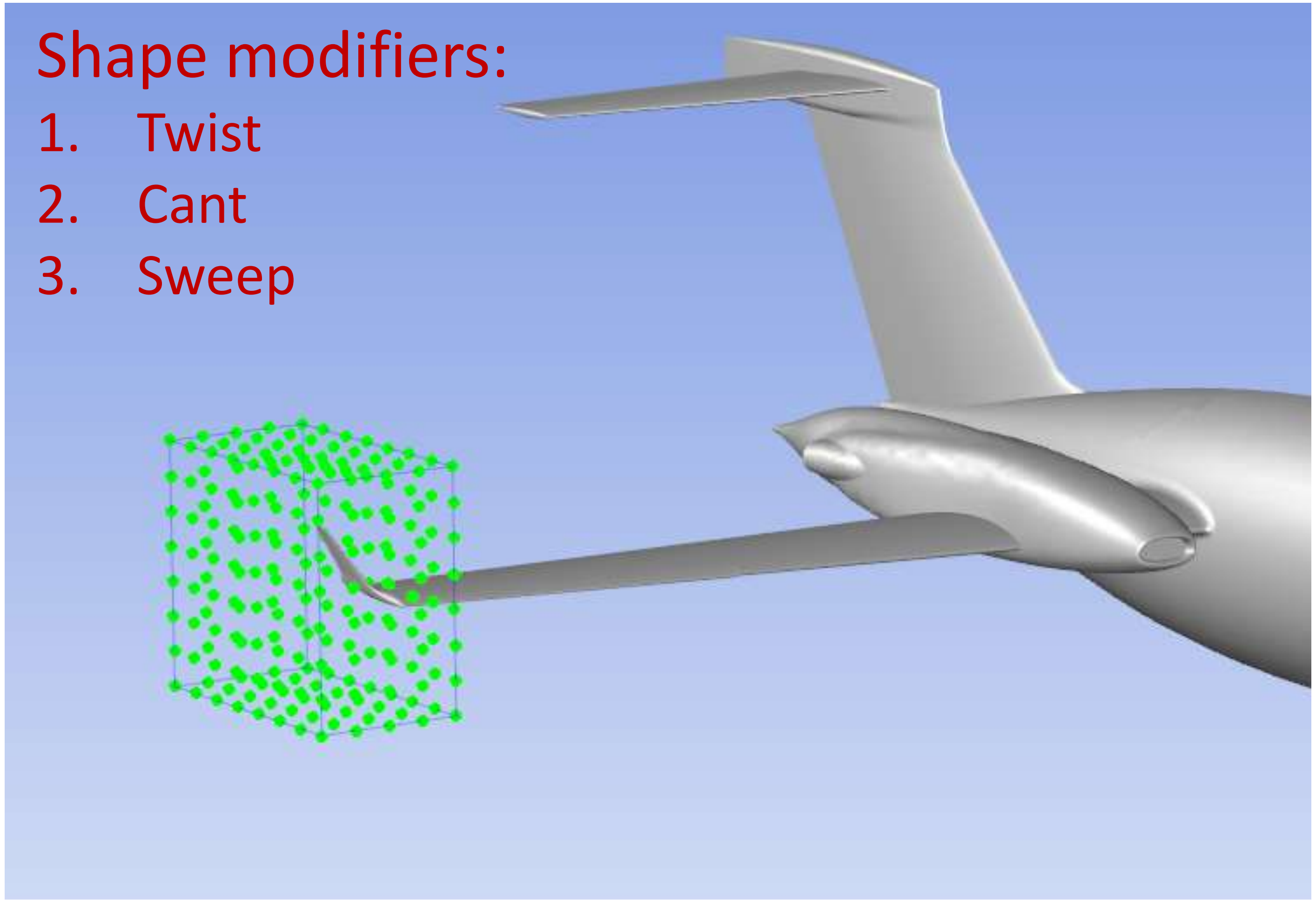


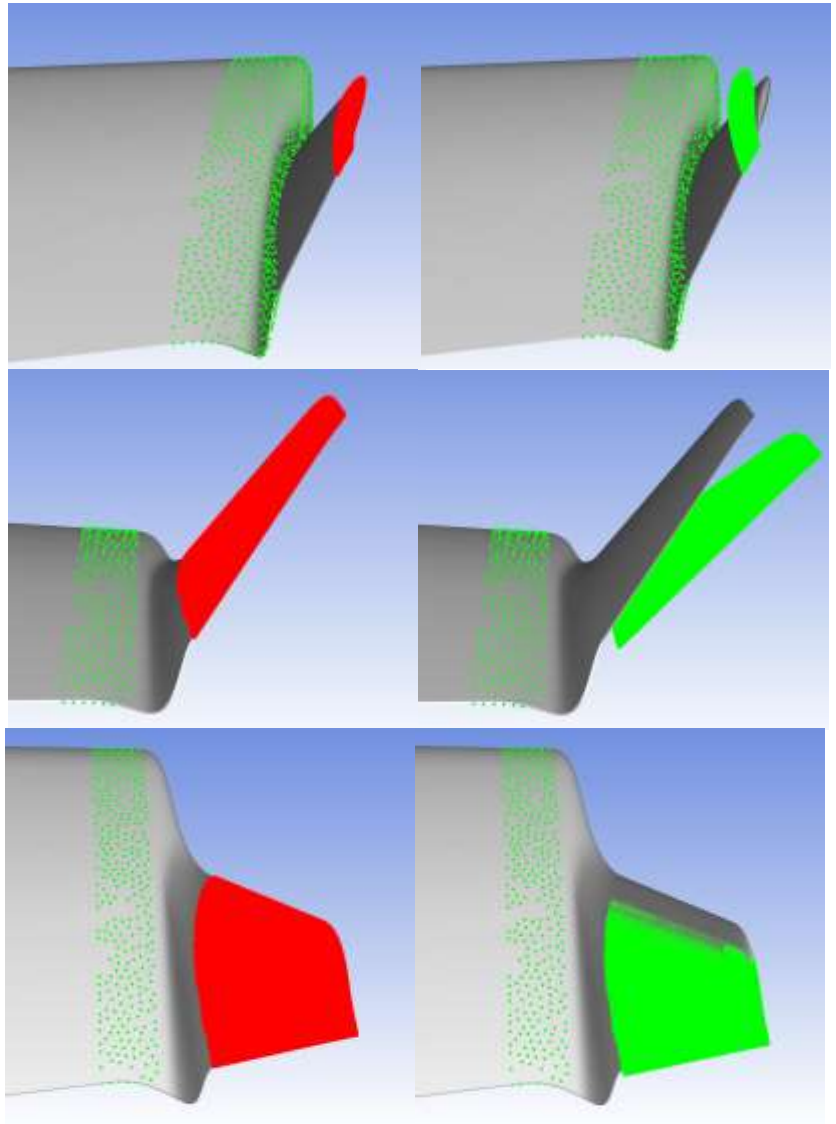




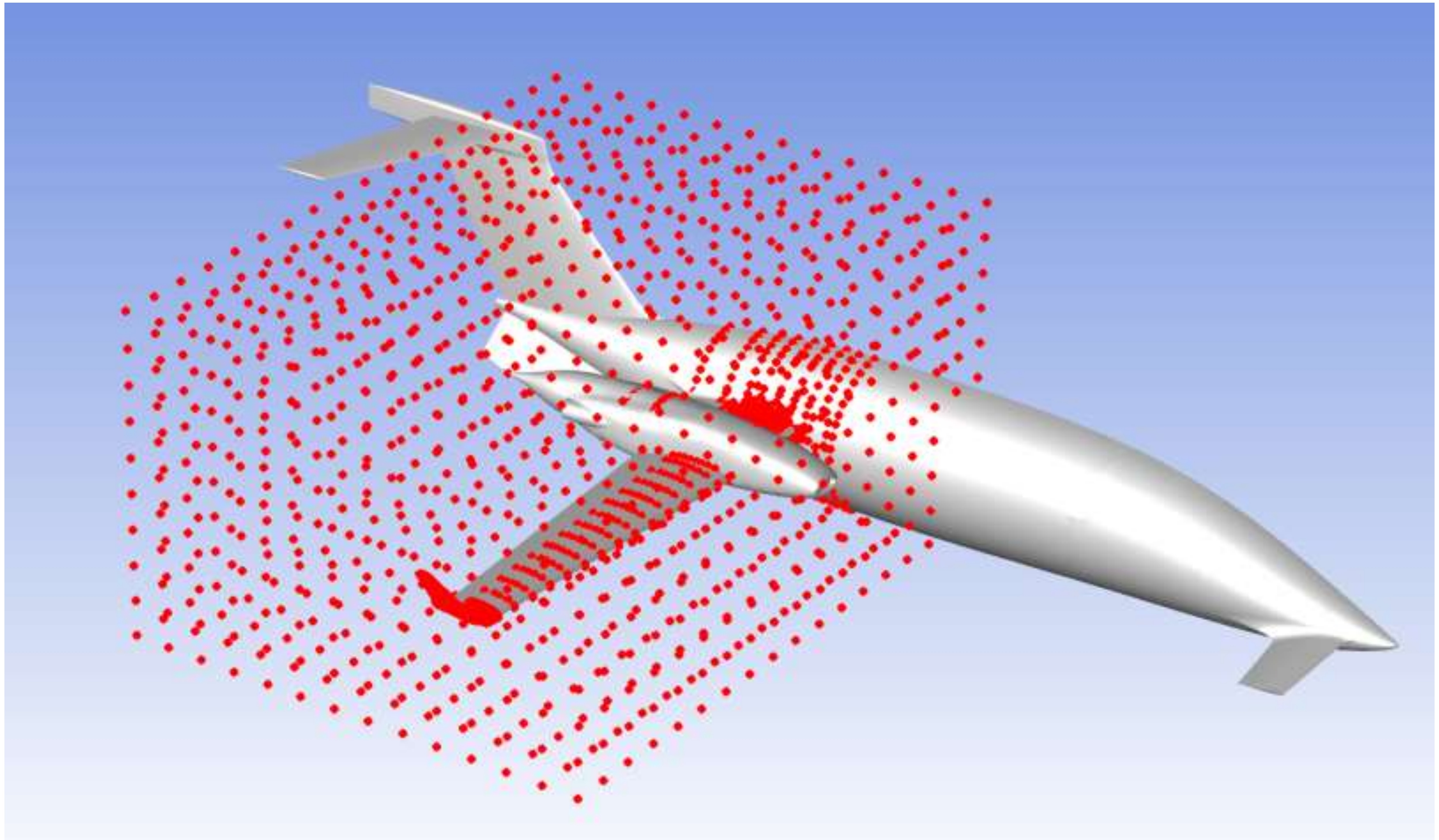

 

# First RBF setup



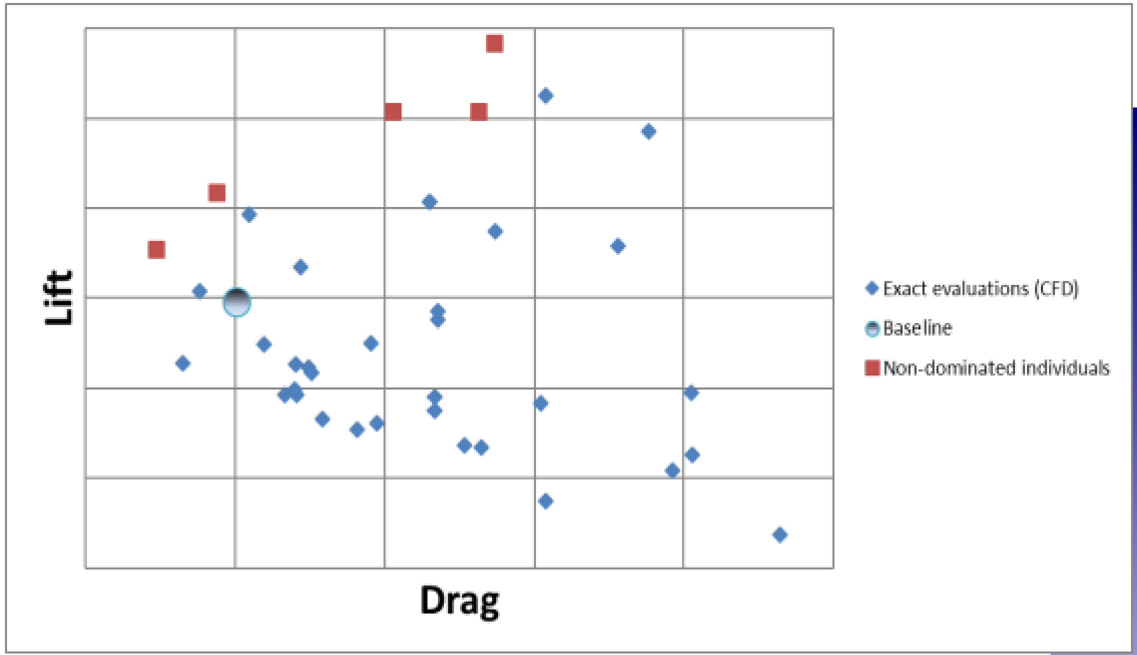



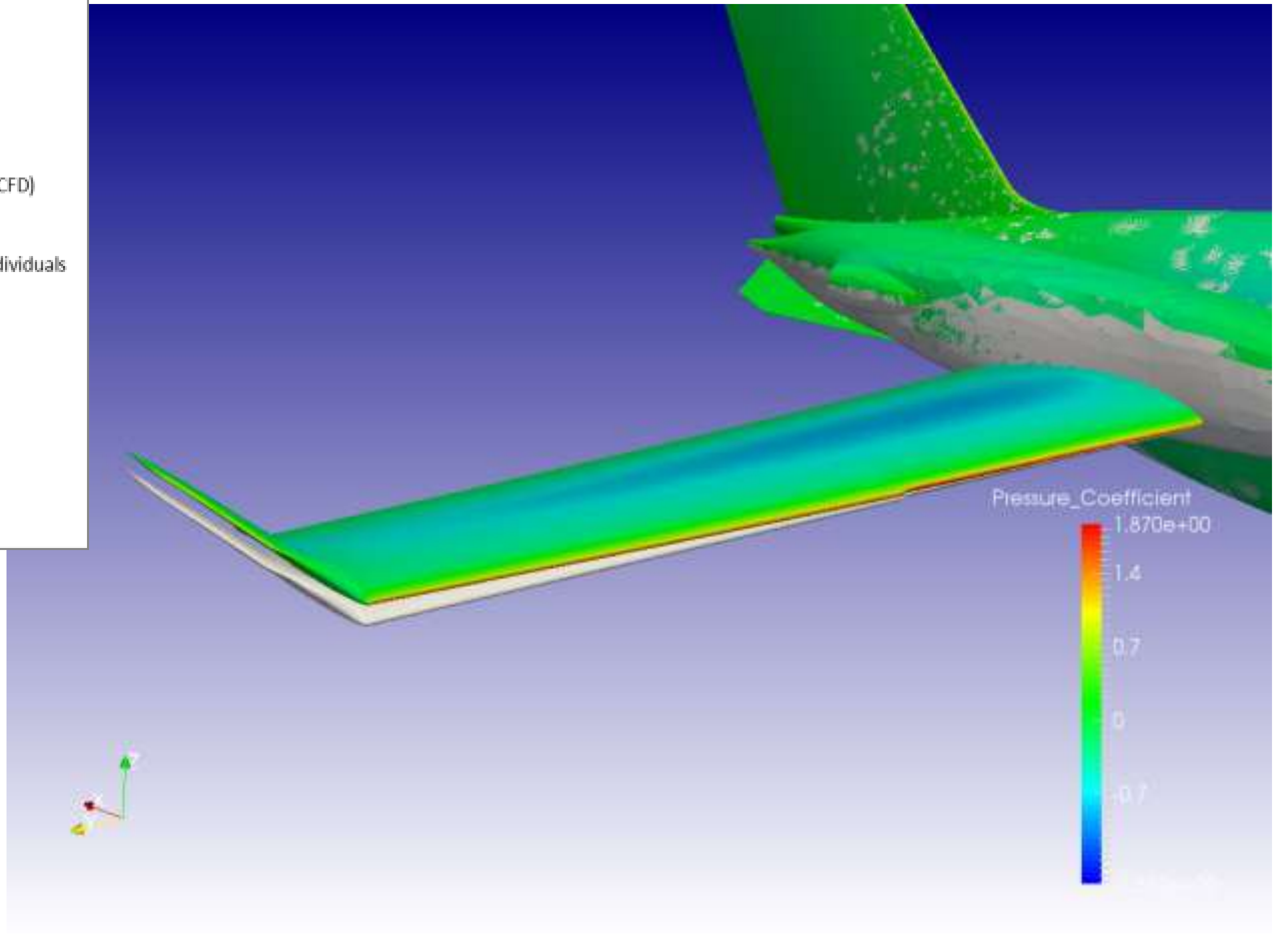
# Second step RBF setup



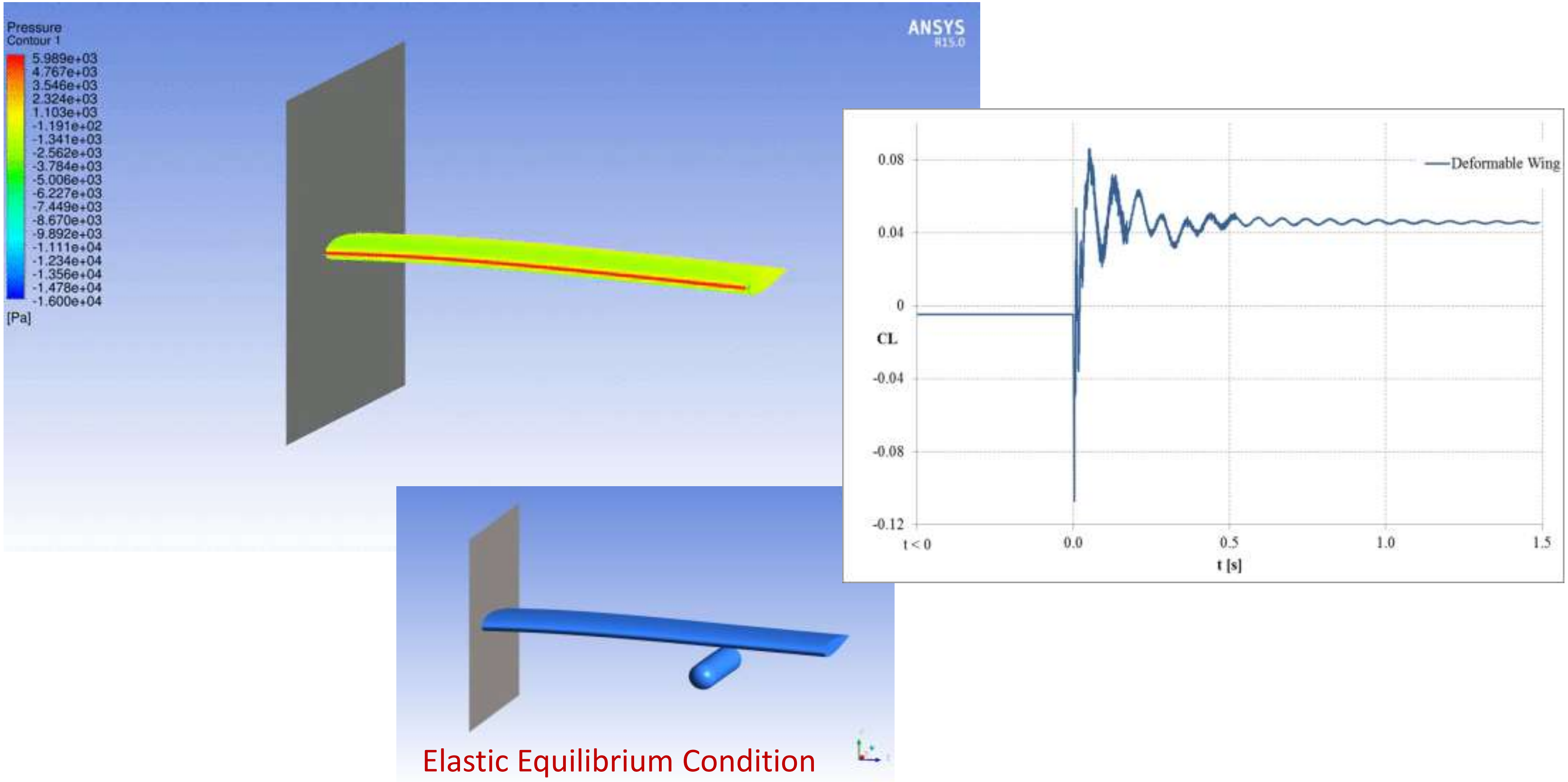
 

# Results

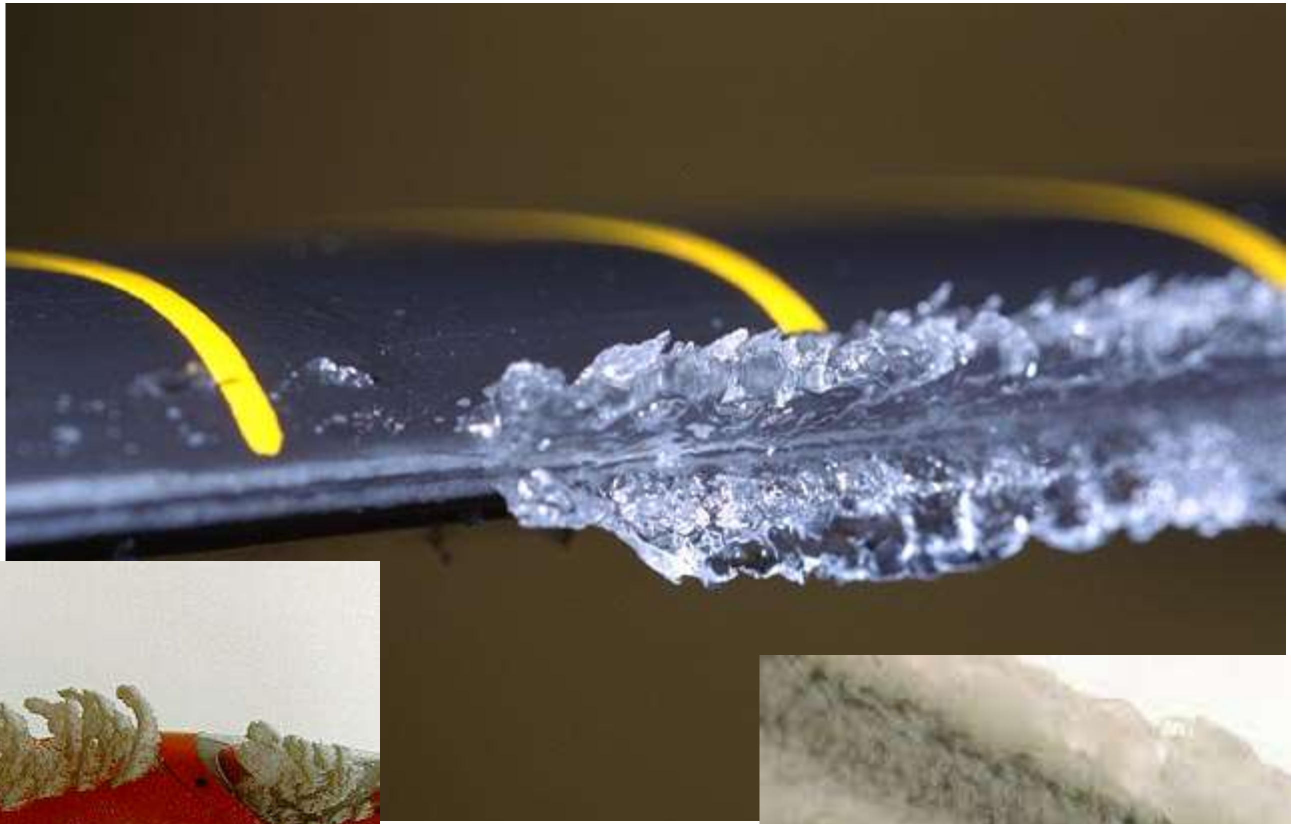

Lift
Drag
Exact evaluations (CFD)
Baseline
Non-dominated individuals

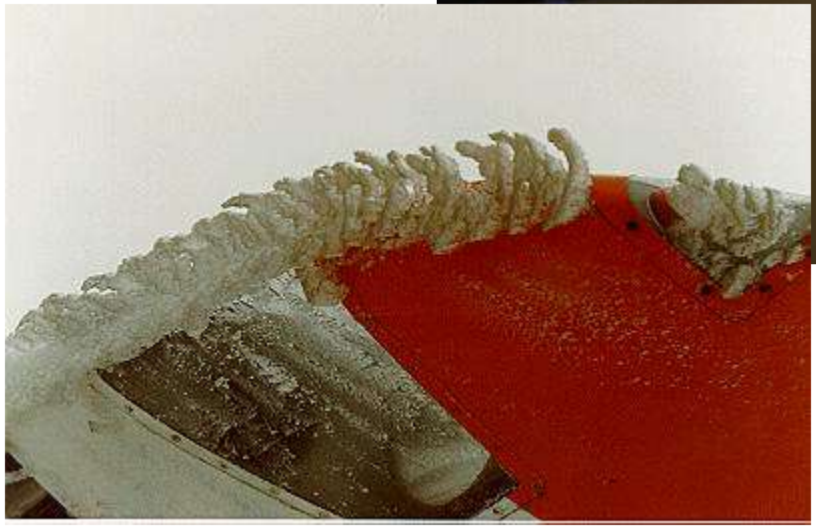

Pressure_Coefficient
1.870e+00
1.4
0.7
0
-0.7

# Unsteady Fluid-Structure Interaction analysis

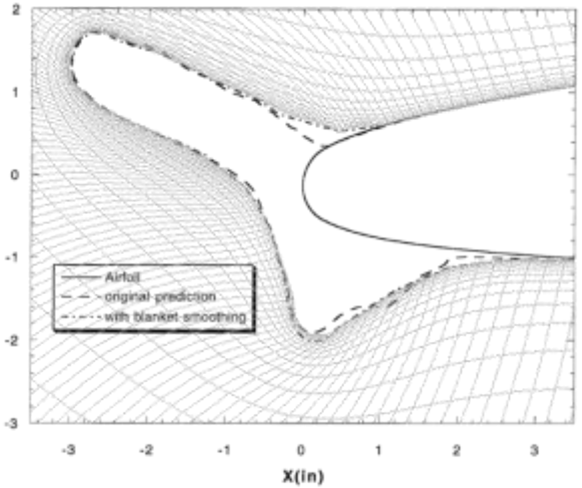


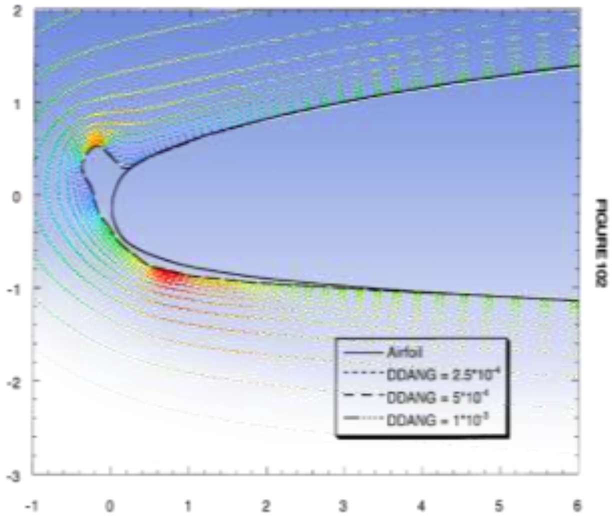
# Extreme morphing

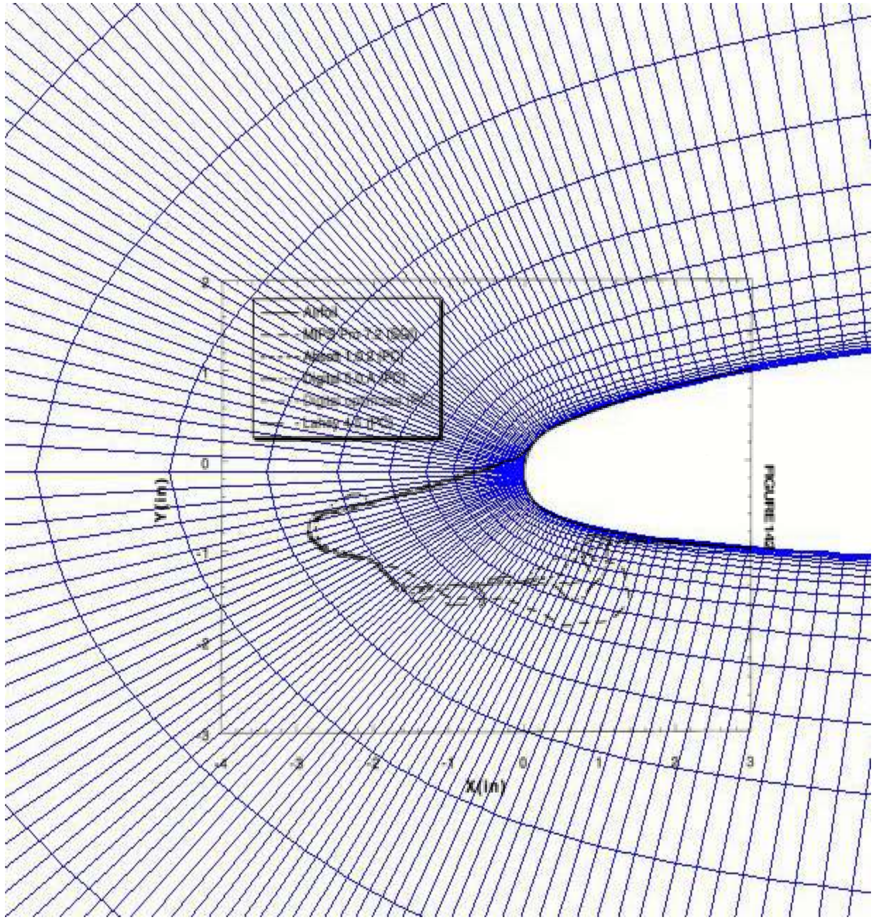




# Ice accretion

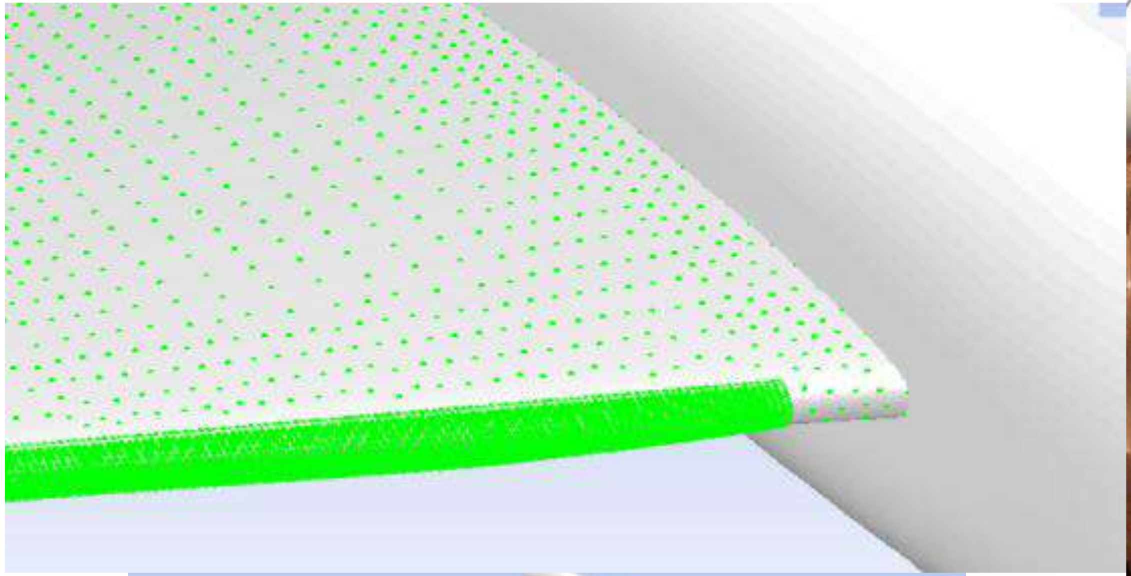


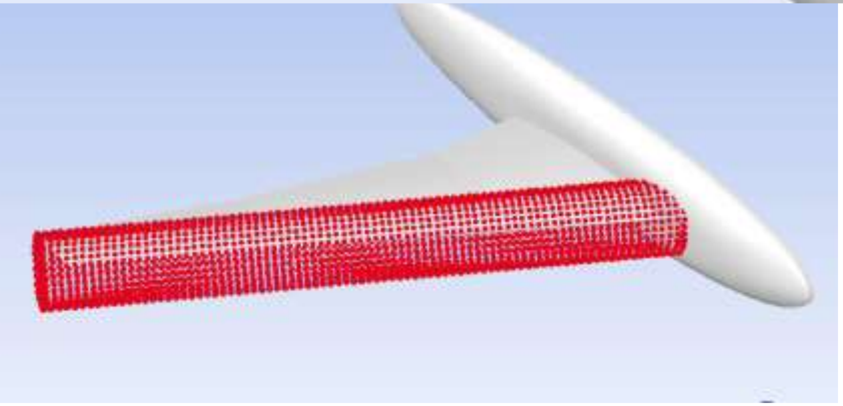




Nasa Lewice 2.0 validation results

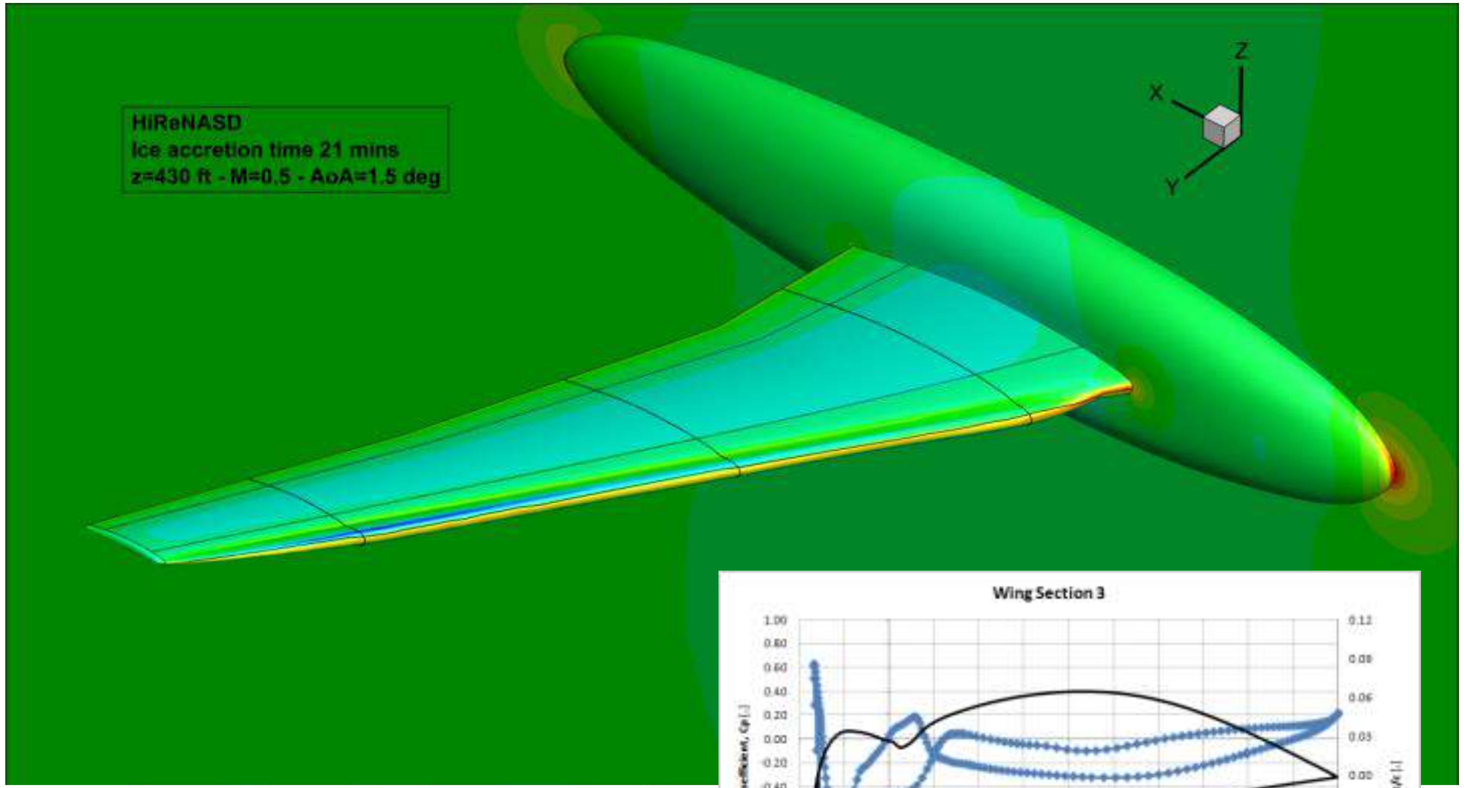
# 3D RBF setup

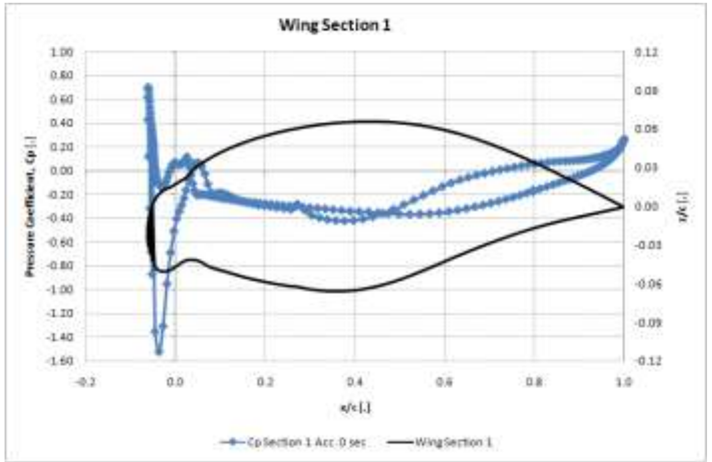


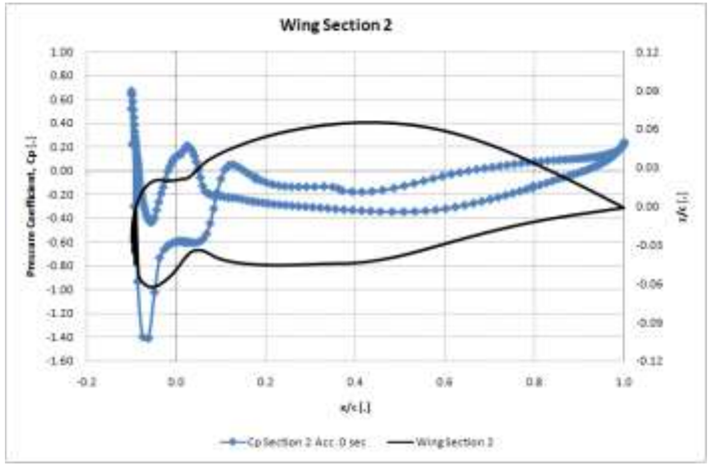


HiReNASD

# 3D solution



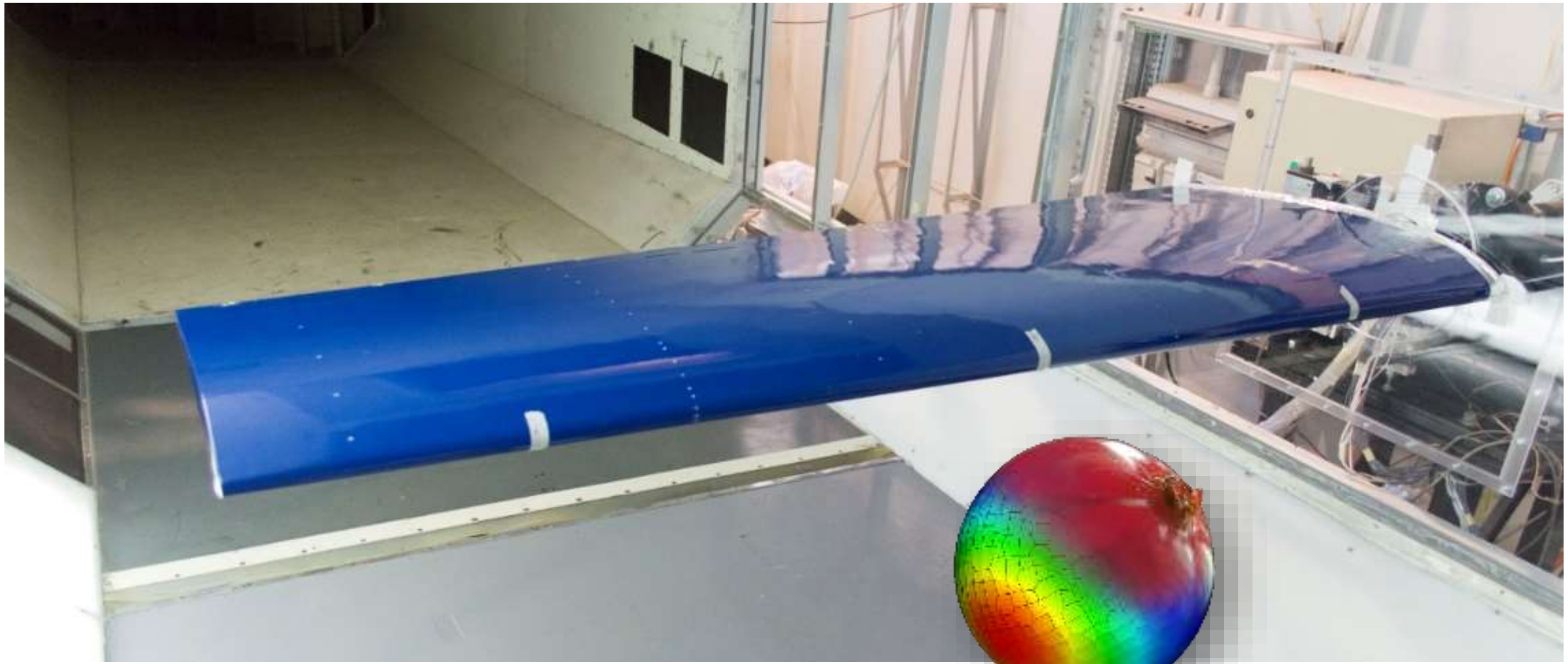





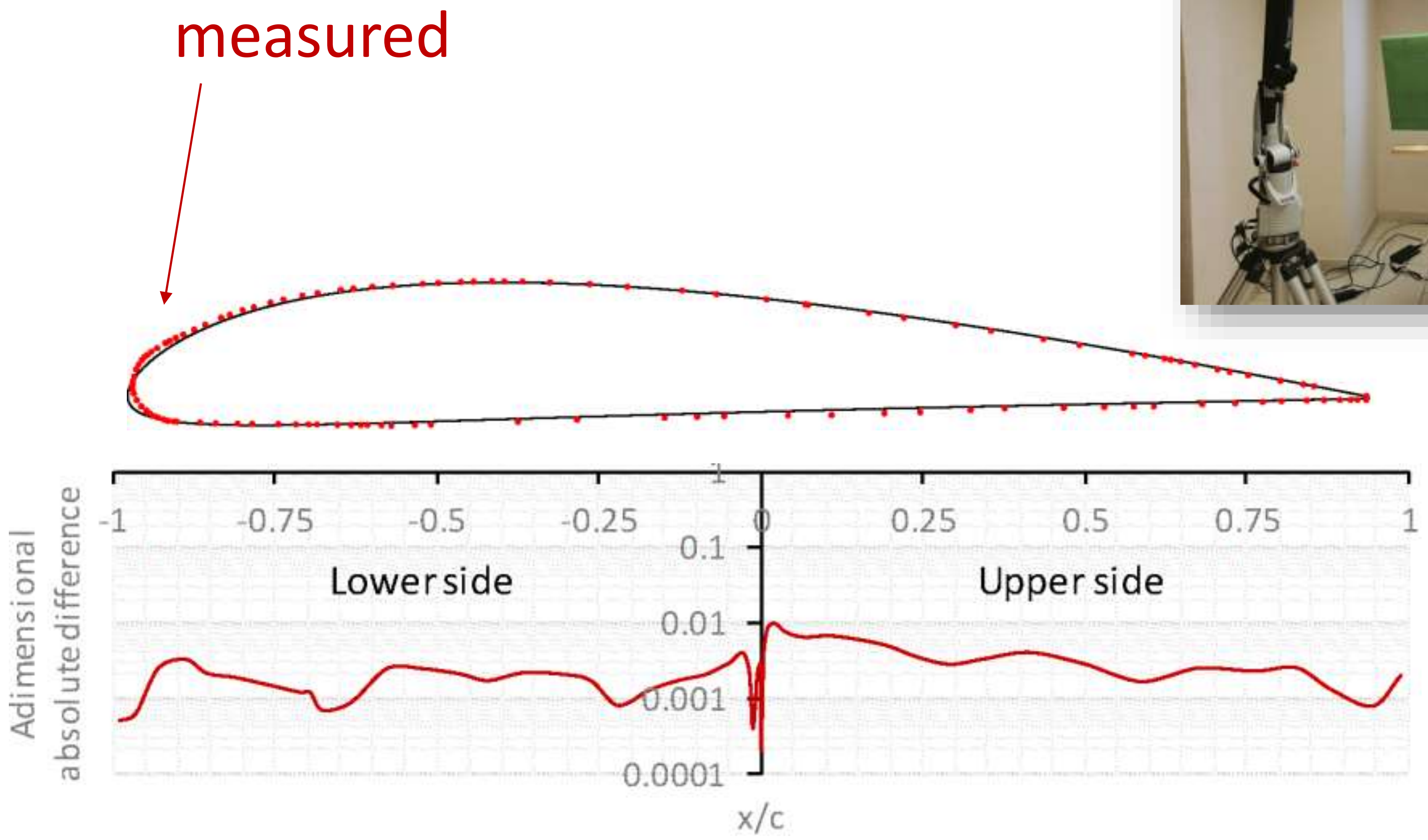
Accretion time t = 21 min

# Digital reconstruction

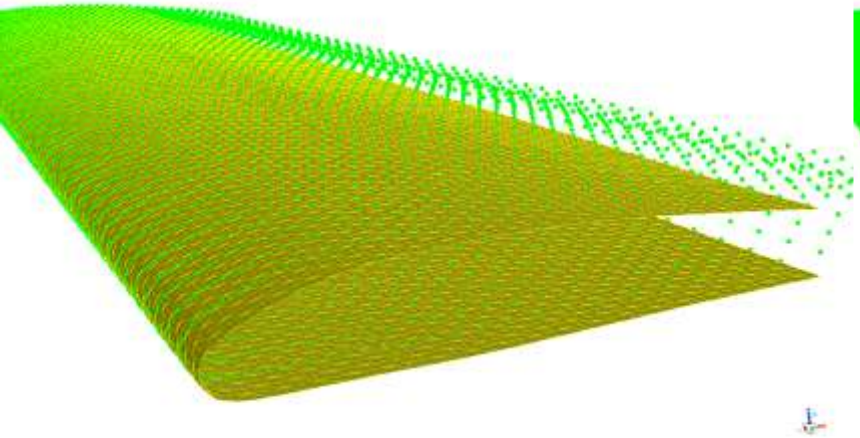


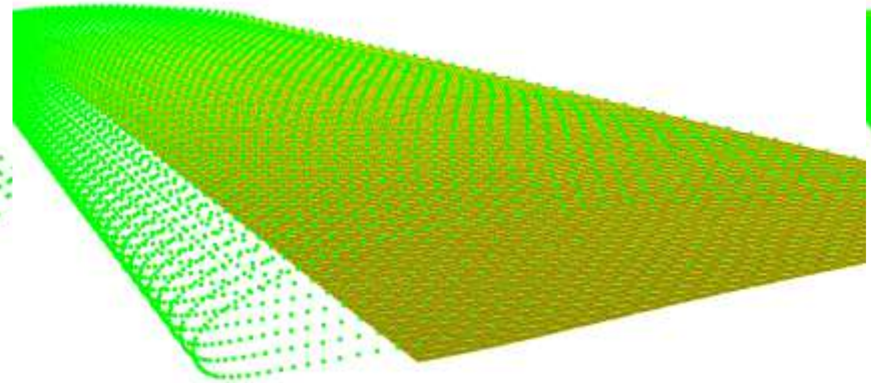
RIBES

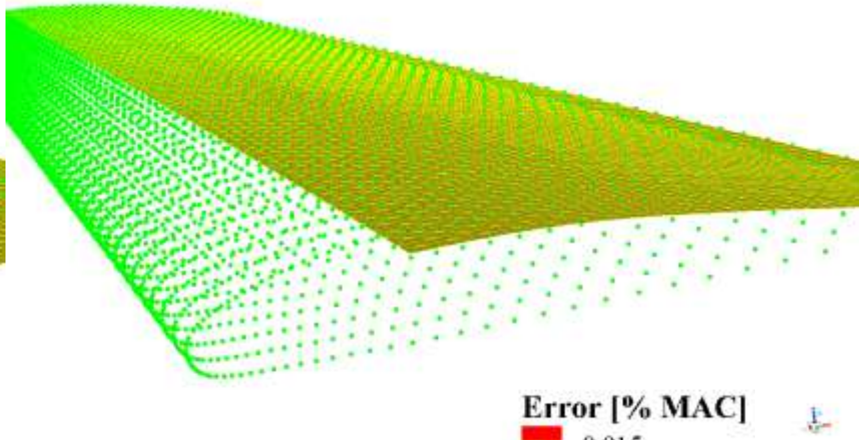
# Measured geometry

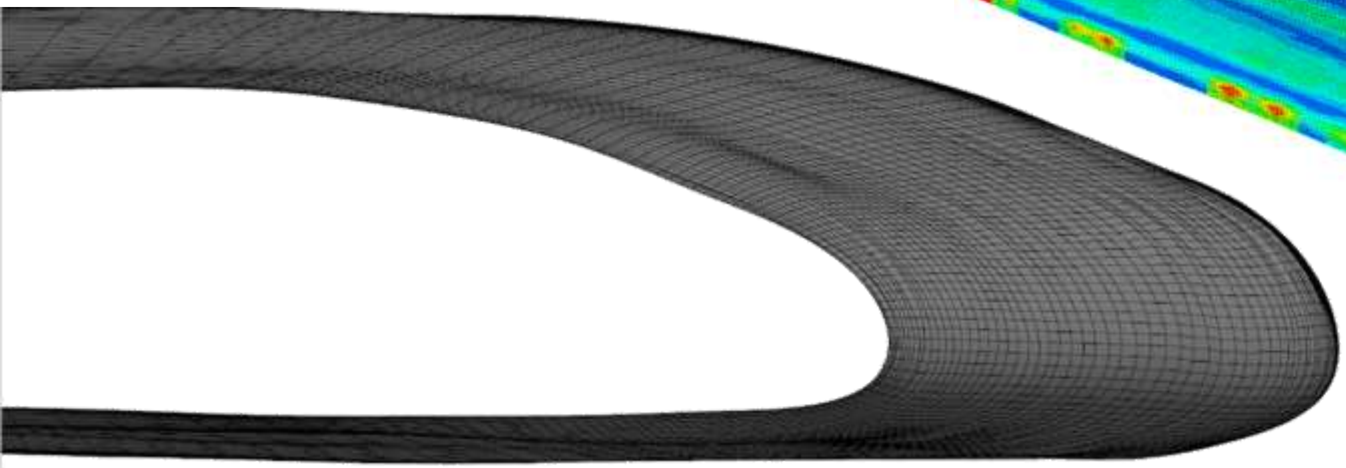


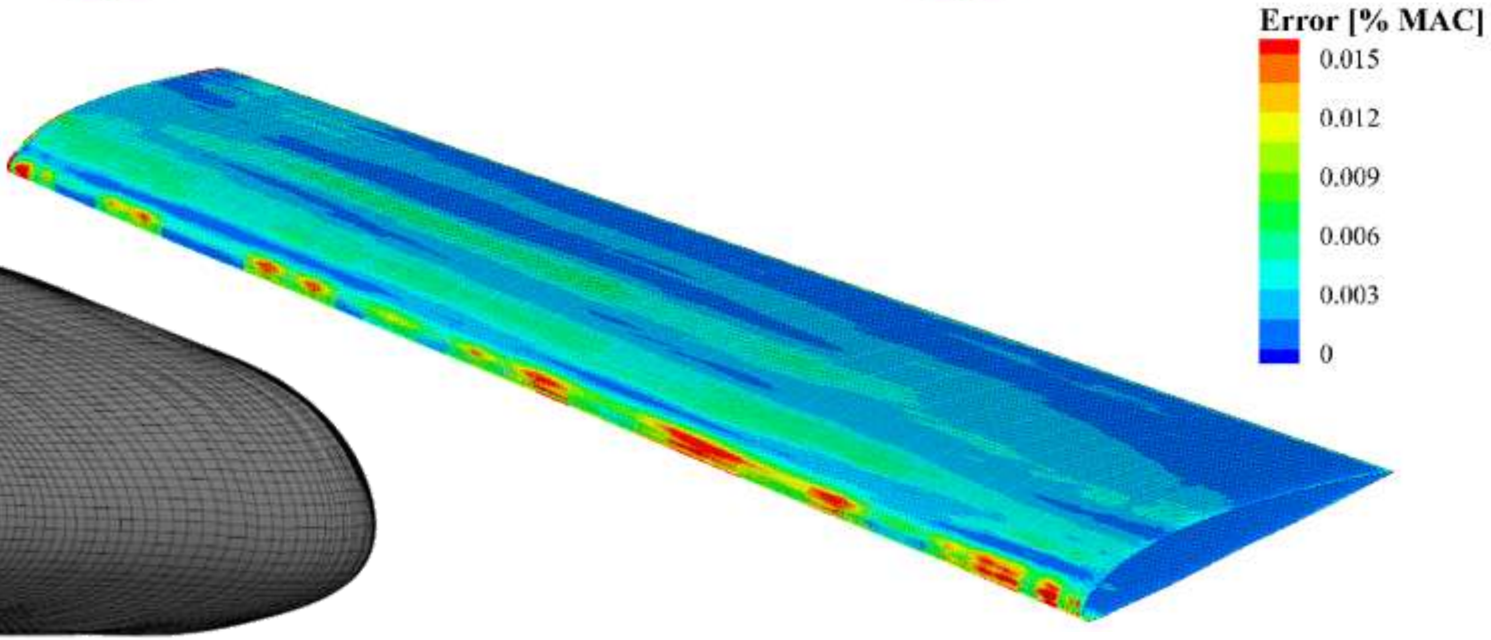
# STL target projection









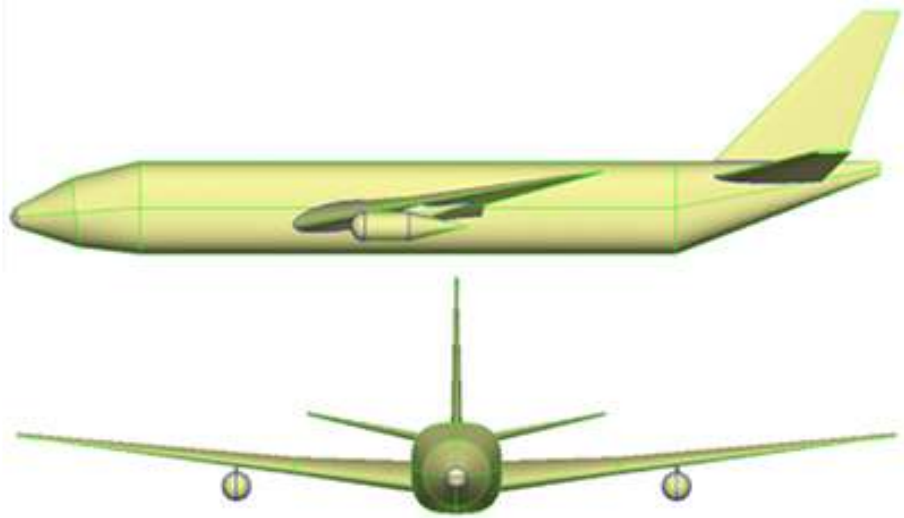


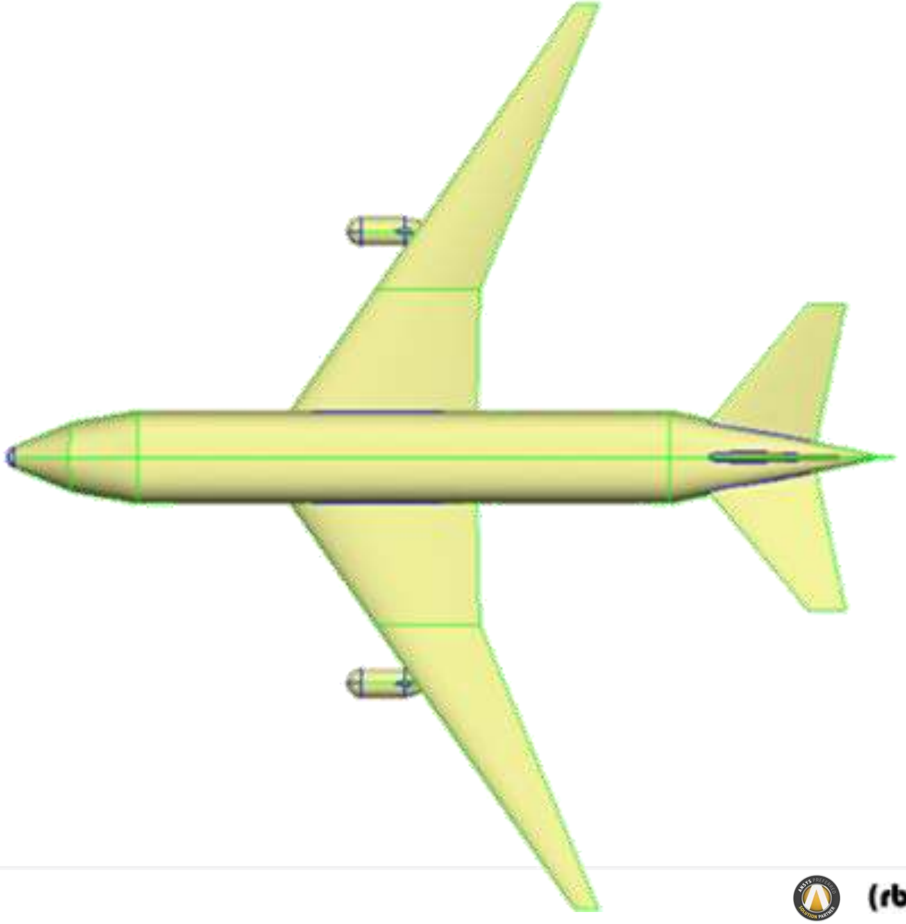
# AIAA GMGW-2

2nd AIAA Geometry and Mesh Generation Workshop
Sponsored by the Meshing, Visualization, and Computational Environments Technical Committee
AIAA
Shaping the Future of Aerospace

# Case 3: OPAM-1 Parametric Remeshing

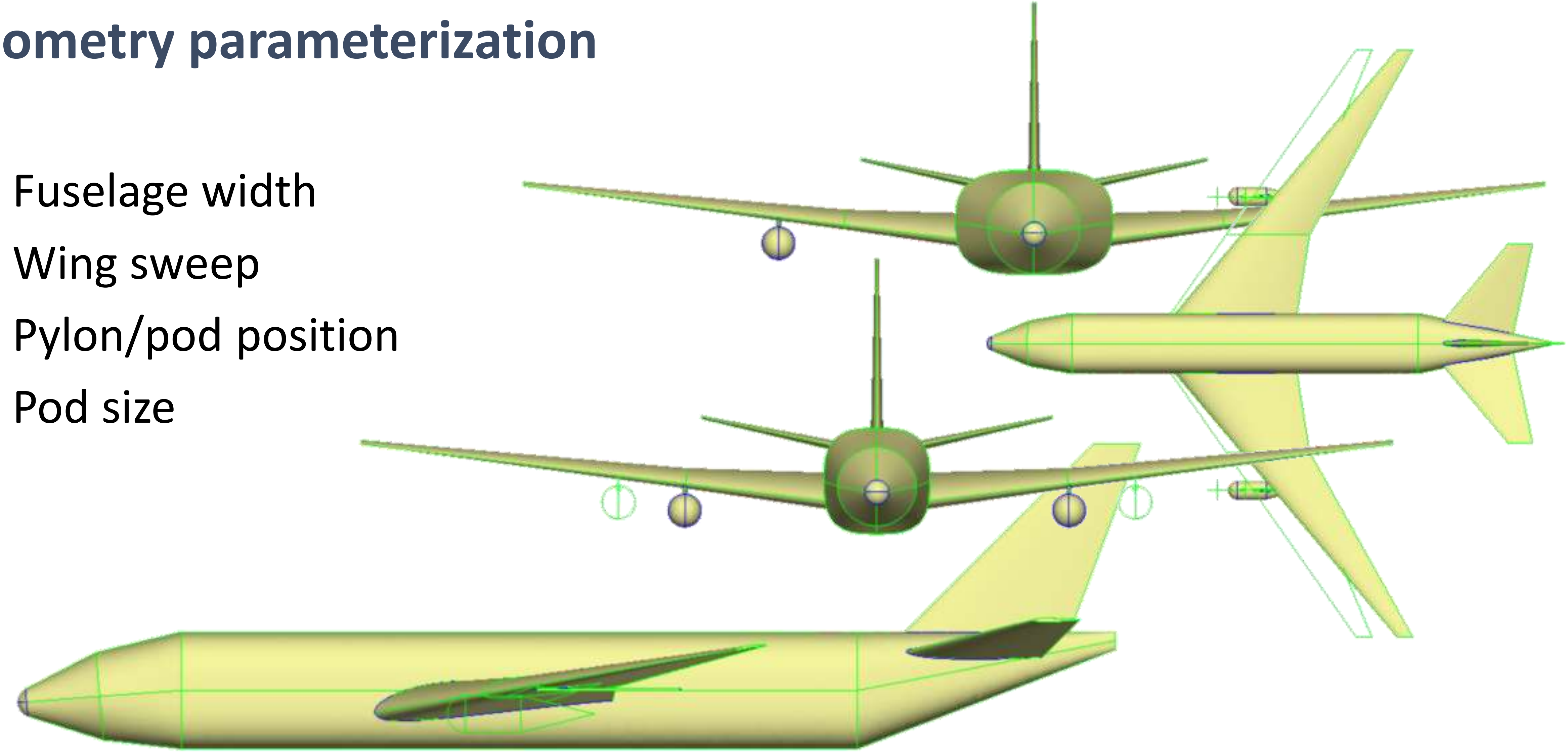
- Objectives:
  - explore the ability to rapidly and robustly mesh parametric variations of a geometry model.
  - Rapid generation of geometry models.



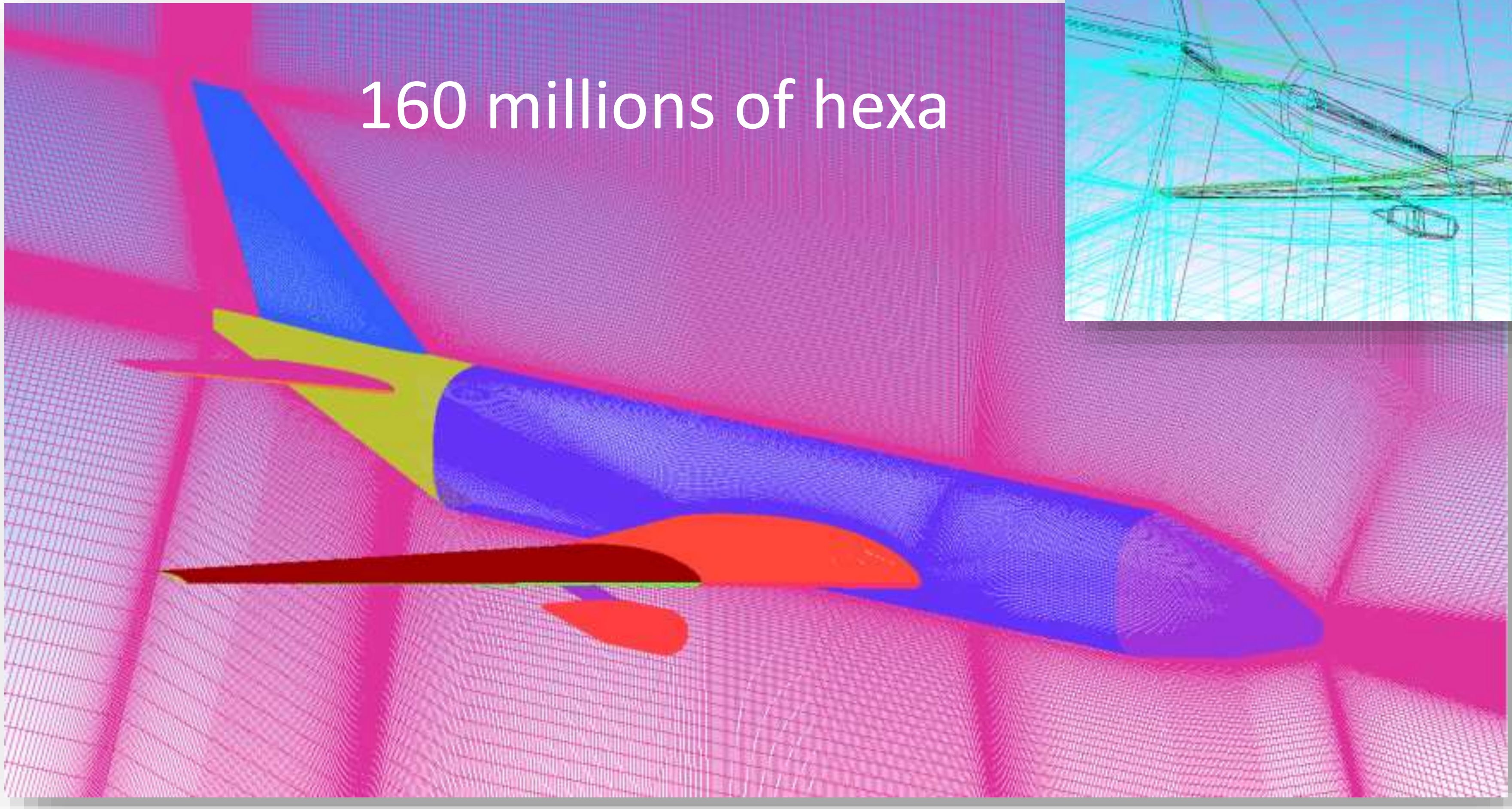


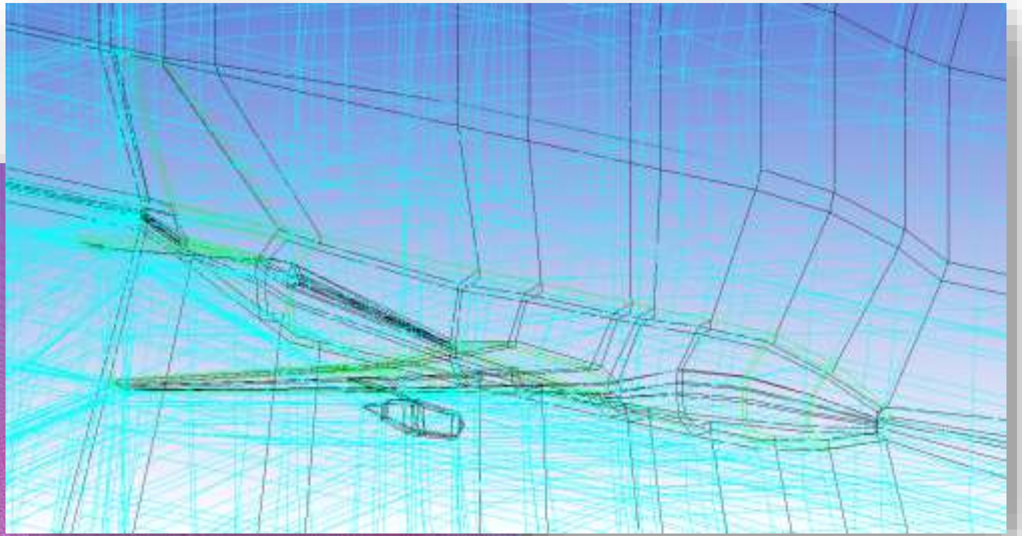
# Geometry parameterization

1. Fuselage width
2. Wing sweep
3. Pylon/pod position
4. Pod size



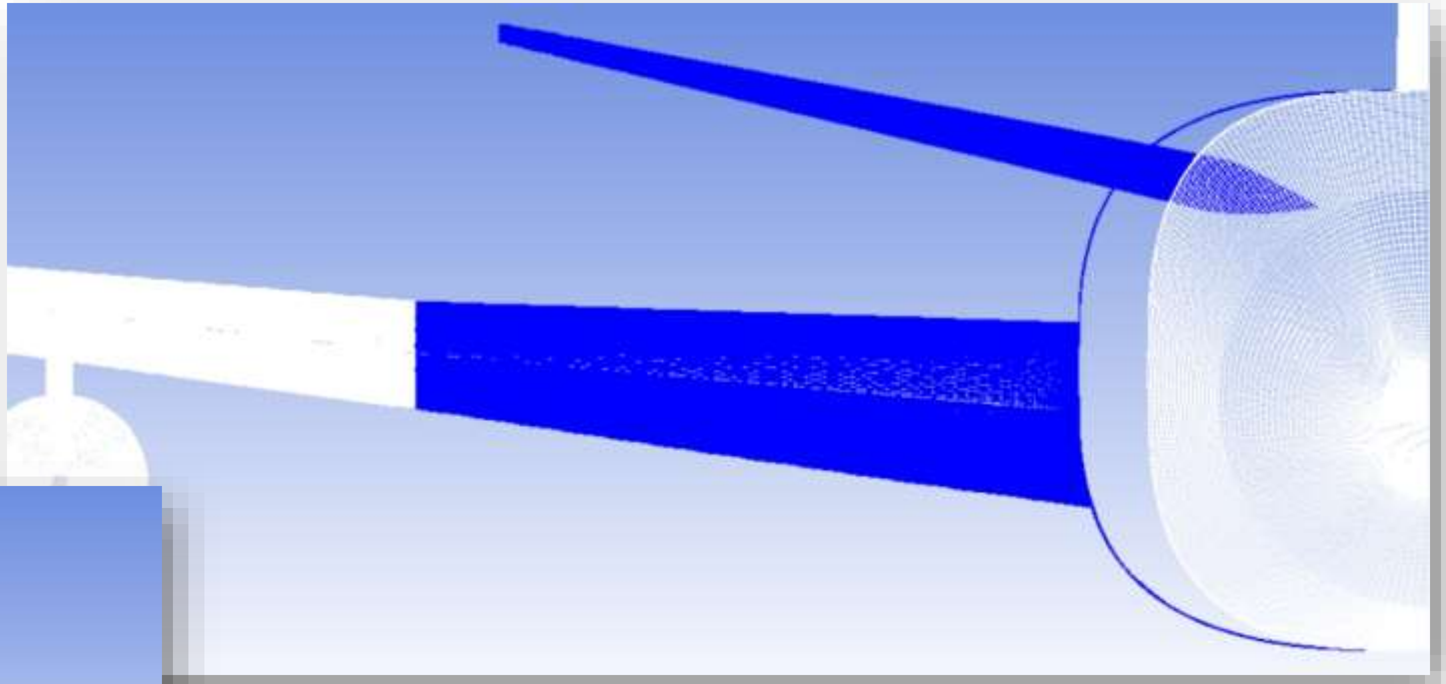
# Baseline mesh

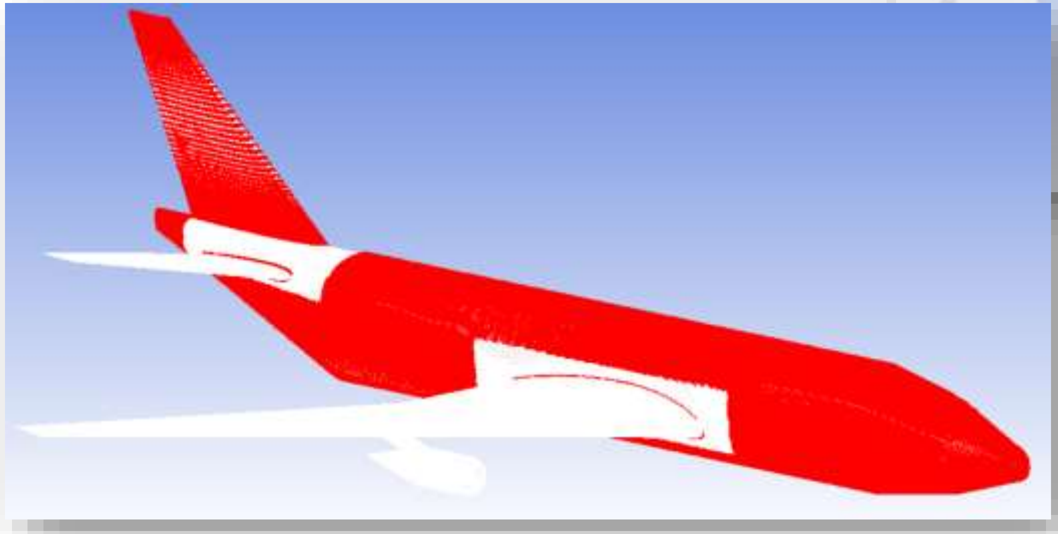


# Fuselage width

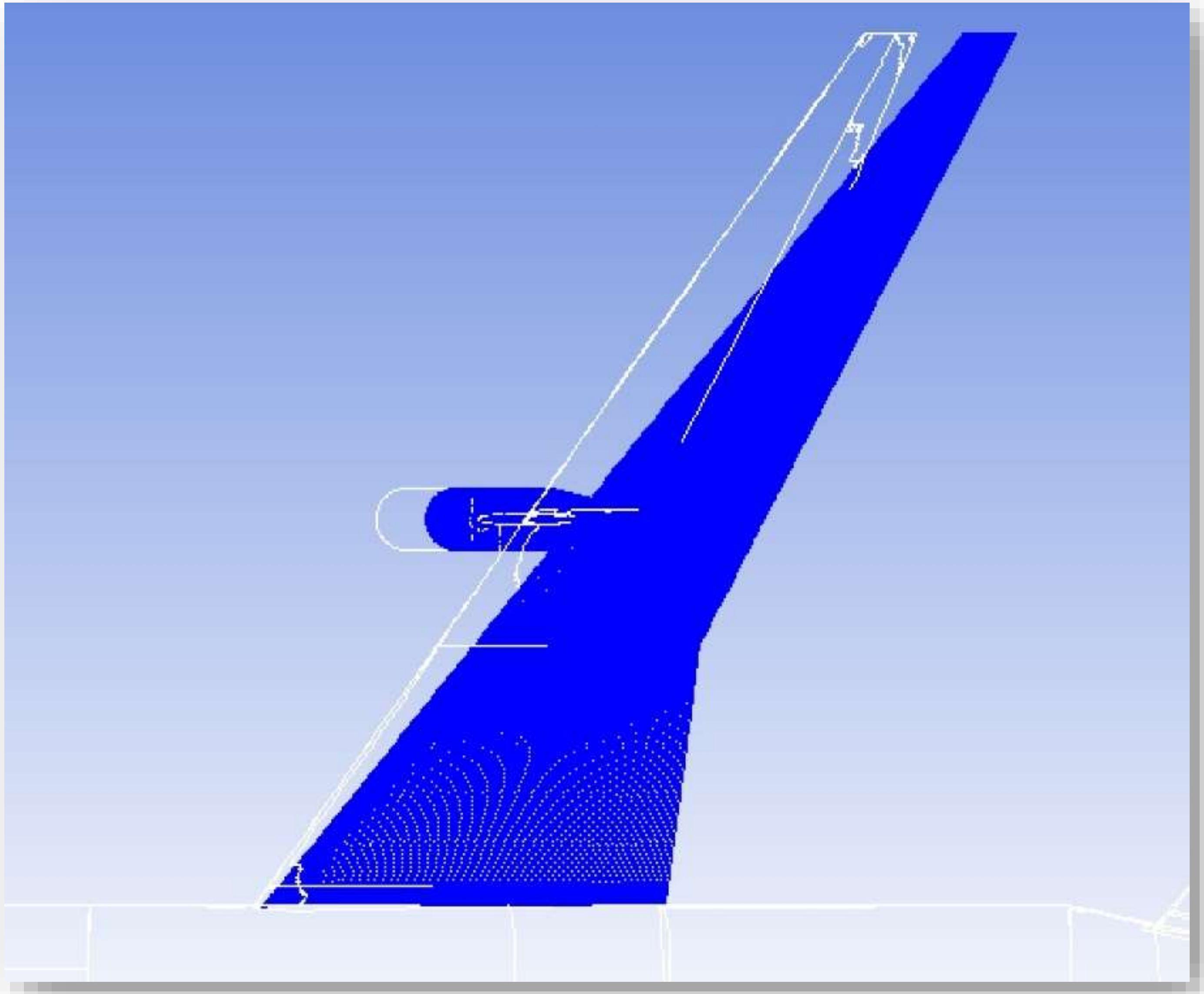
- Two morphing actions applied in sequence:
  - Two step fuselage scaling
  - Restoring the inner wing shape by STL target tecnique





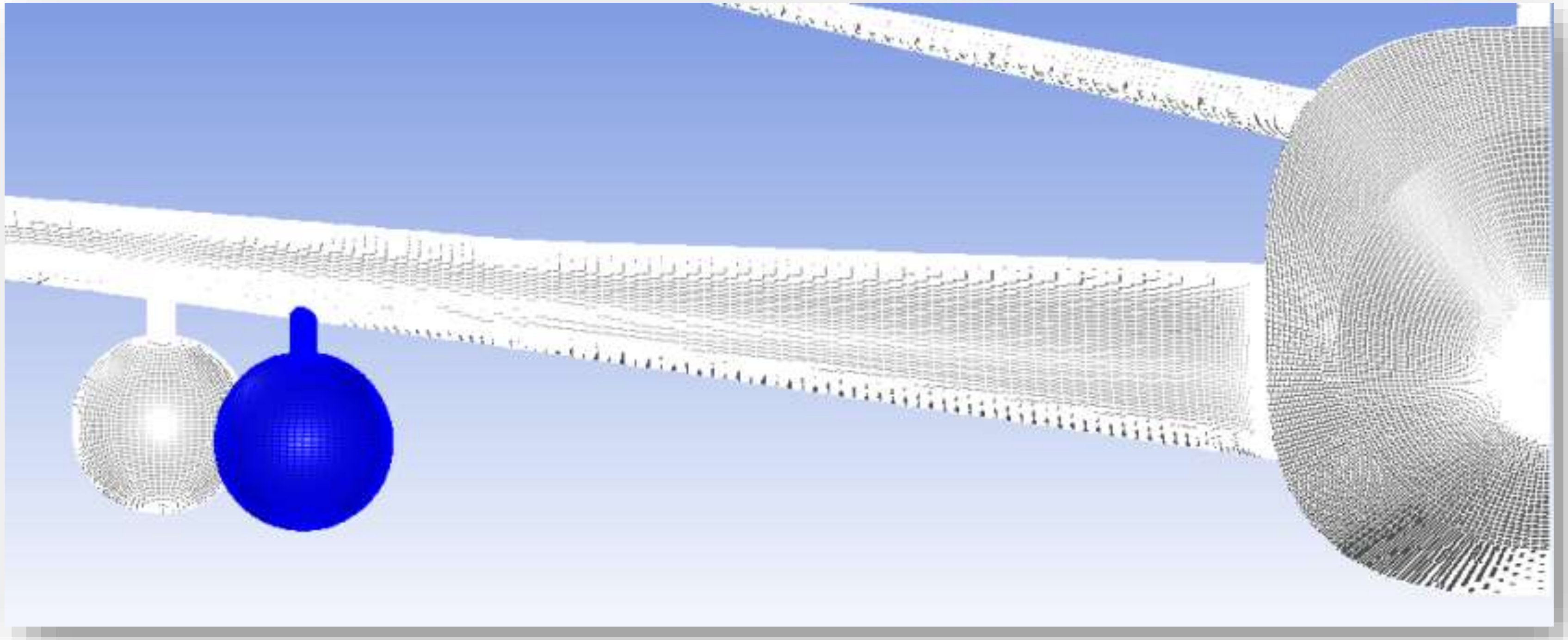
# Wing sweep

- Two-step procedure
  - Streamwise displacement of a set of wing sections.
  - Smoothing applying the stored RBF solution to the wing and rigidly shifting the fuselage/pod.



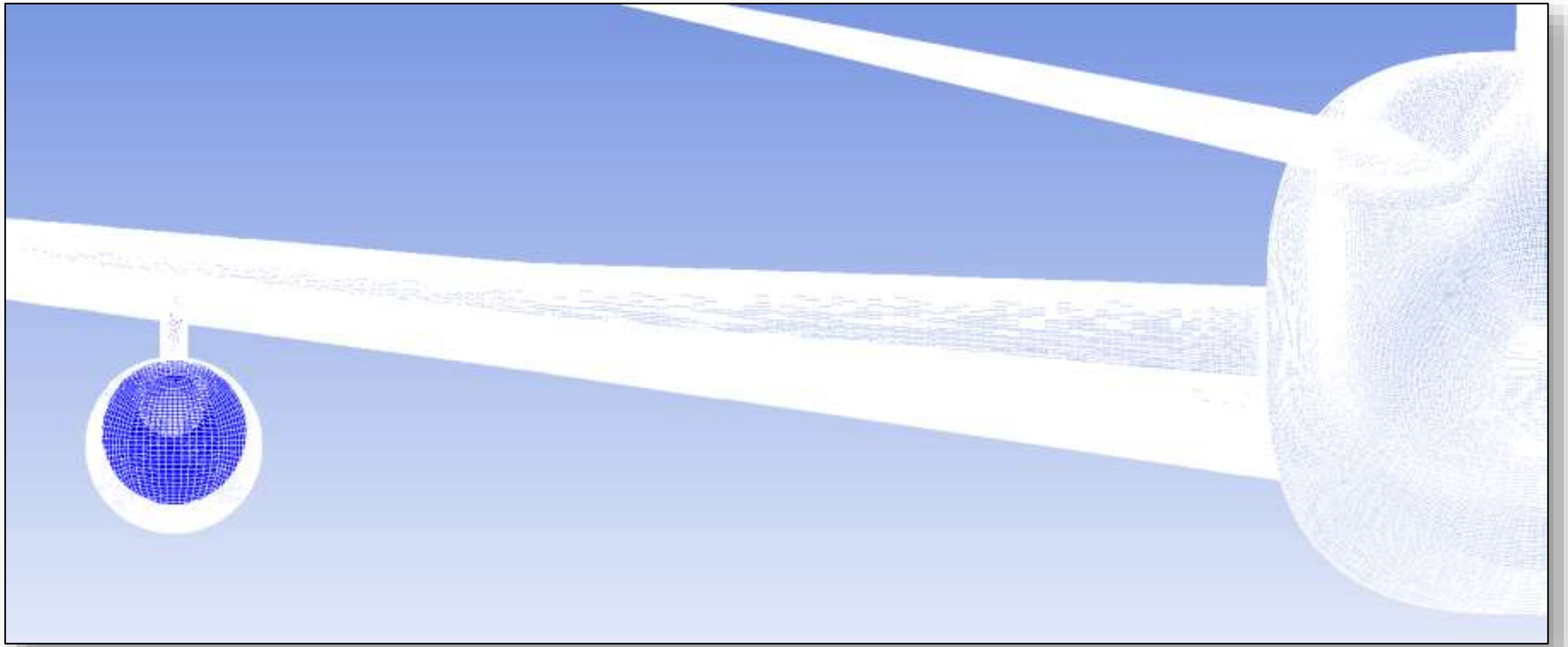
# Pylon/pod position

- Two morphing actions applied in sequence:
  - Displacement of the group pod/pylon.
  - Recovering of the wing shape by STL target technique.



# Pod size

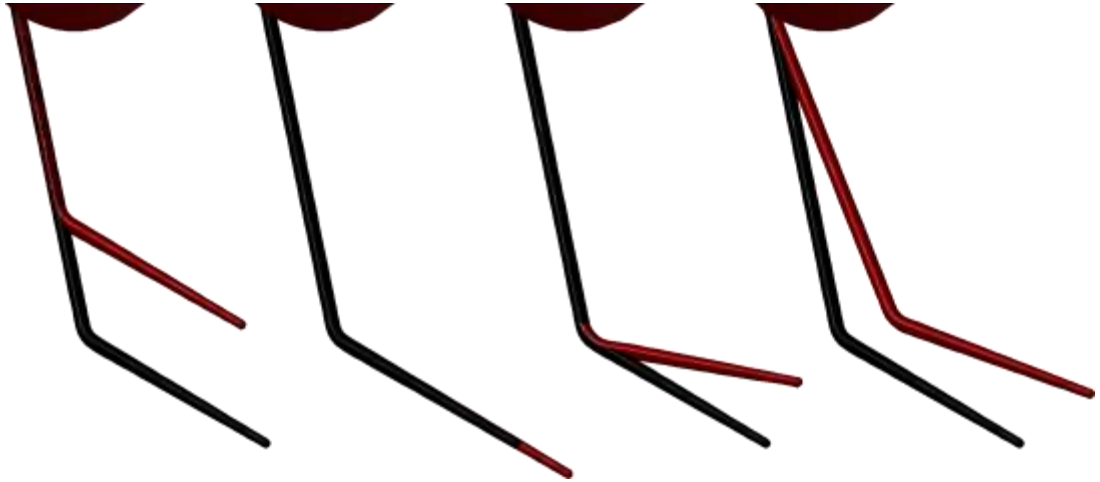
- Simple scaling applied to the mesh nodes on the pod surface.

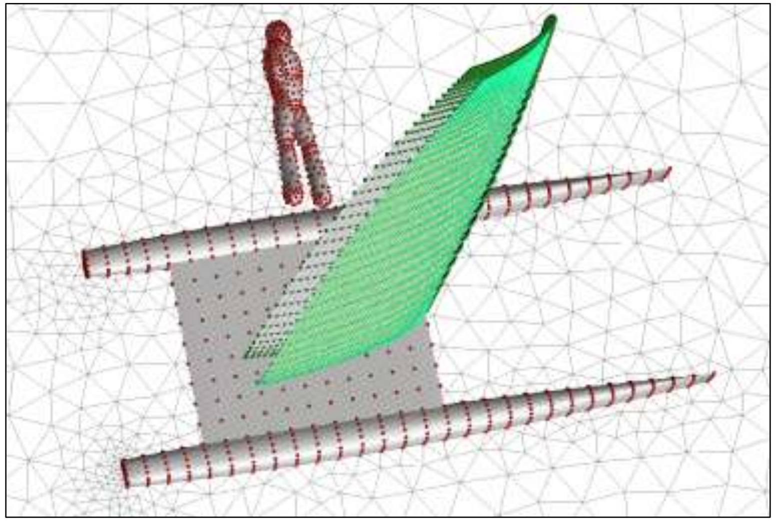


# Computational resources required

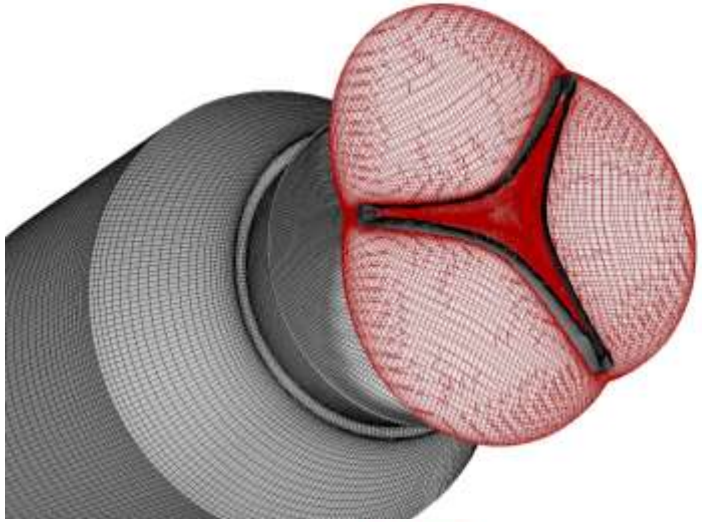
| |
|---|
| **Widen fuselage** |
| Mesh Morphing performed in 405 + 235 = 10 minutes and 40 seconds (84 cores, 200 GB RAM) |
| **Wing sweep** |
| Mesh Morphing performed in 9 minutes and 30 seconds (84 cores, 200 GB RAM) |
| **Move pylon/pod** |
| Mesh Morphing performed in 103 + 75 = 2 minutes and 58 seconds (84 cores, 200 GB RAM) |
| **Narrow pod** |
| Mesh Morphing performed in 50 seconds (84 cores, 200 GB RAM) |

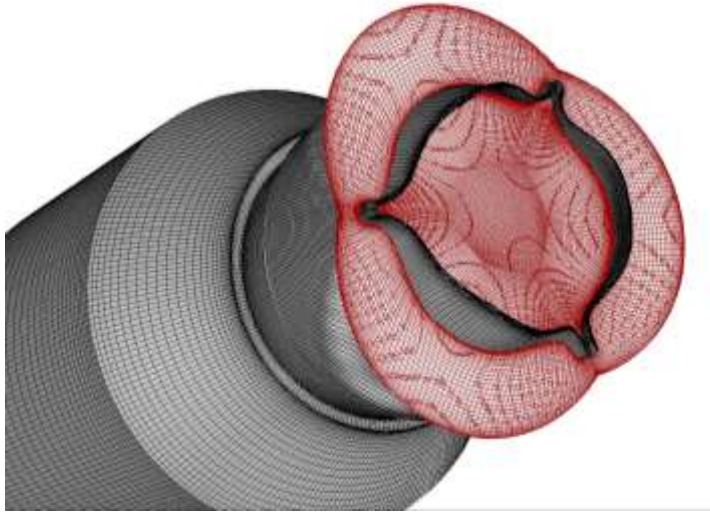
# Nautical application

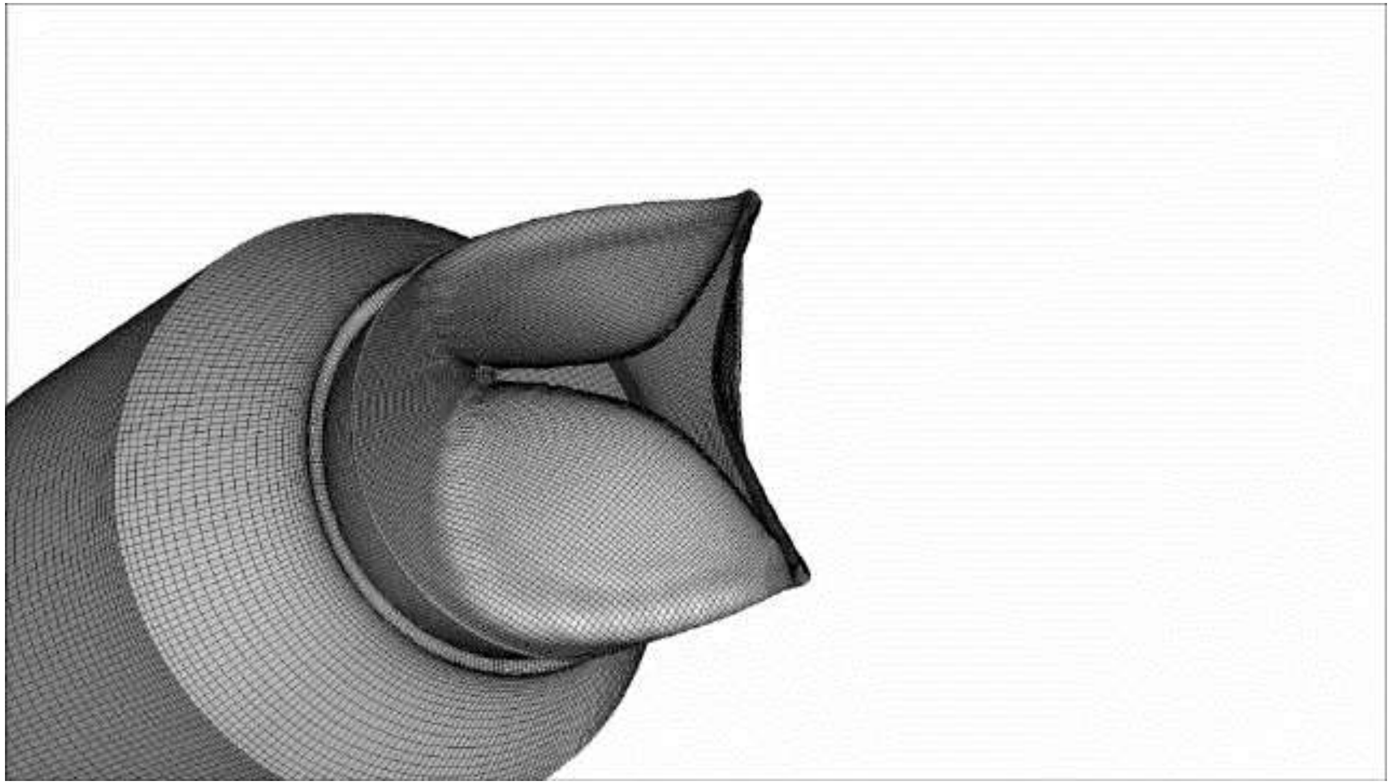





# Hemodynamic application







Collaboration with **BioCardioLab**
Bioengineering dept. Monasterio Fundation

# Conclusions

## Challenge

- drawbacks of RBF mesh morphing approach:
    1. *Limitation in the deformation amplitude*
    2. *Computationally expensive (HPC for large grids)*
    3. *Back to CAD procedure required*
    4. *Uncertainness in the capability to setup complex parameterizations*
- .. what are the real limits?

## Solution

- Study **complex** and **challenging** cases to provide a realistic quantification of the limits when faced adopting *RBF Morph*.

## Results

1. *RBF Morph* showed good performance also in case of extreme morphing
2. *RBF Morph* solver offers performances that make mesh morphing competitive with remeshing approach
3. *RBF Morph* is capable to apply the RBF solutions to the starting CAD model
4. *RBF Morph* offer several tools that allow to setup very complex constrained parameterizations

# Many thanks for your kind attention

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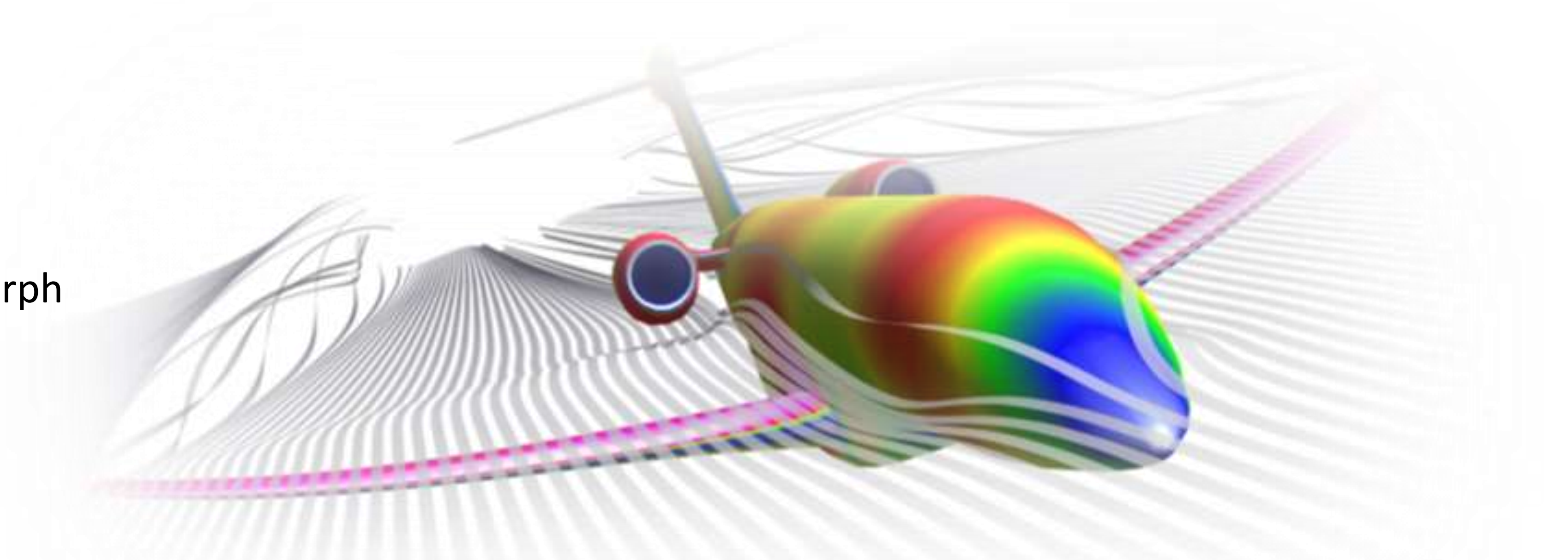
youtube.com/user/RbfMorph

rbf-morph.com



(rbf-morph)™

Welcome to the World of Fast Morphing!

**Ubaldo Cella** - ubaldo.cella@rbf-morph.com