TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Multi-Physics and Multi-Fidelity Approaches for Digital Twin Integration

PhD in Design, Manufacturing and Operations Engineering

PhD Cycle XXXVII

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Coordinator: Prof. Francesco Vivio

PhD Candidate: Andrea Lopez

Main Activities

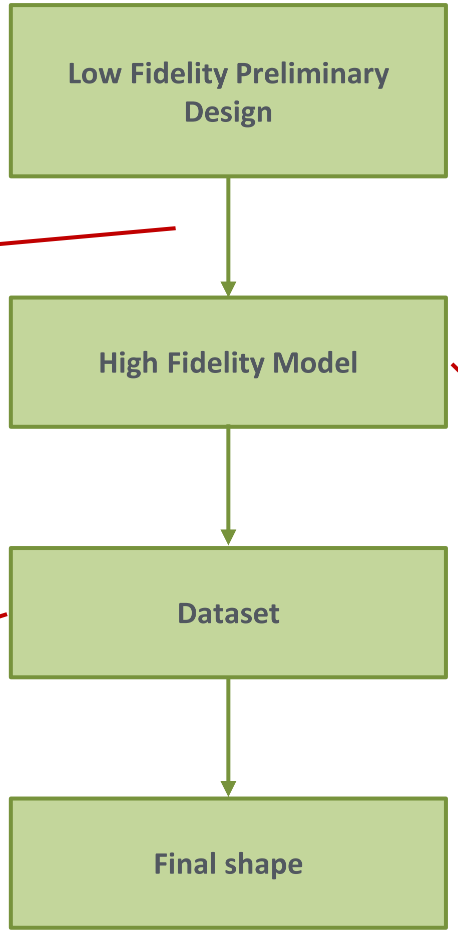
- PhD focus on CAE methodologies for interactive design dashboards
- Conducted in collaboration with Leonardo Labs, Turin, with on-site internship periods
- Some Other Collaborations:
  - University of Padova
  - University of Napoli
  - INAF
  - RBF Morph
  - Avio
  - Dallara

Summary

- Overview
- Radial Basis Functions (RBF)
- Multi-fidelity workflows
- Multi-physics analysis
- Shape parameters definition
- Real Time Design Dashboards:
  - Adjoint
  - Reduced Order Model (ROM)

Overview

- How **to connect the two models**?
- How to switch from one to the other?



- How to connect the **different physical domains** involved? (each will have a different model)
- How to define **shape parameters**?

- How to **interact** with the parametric space **in real time**?

RADIAL BASIS FUNCTIONS (RBF)

Radial Basis Functions (RBF)

- Given two heterogeneous domains Ω_1 and Ω_2, RBFs are used to interpolate quantities from Ω_1 to Ω_2 using a proximity criterion;
- If m is the number of source points, the interpolation function can be expressed as:

$$f(x) = \sum_{i=1}^{m} \gamma_i \phi(\|c_i - x\|) + p(x)$$

Where:

$$p(x) = \beta_1 + \beta_2 x_1 + \cdots + \beta_{n+1} x_n$$

The unknowns of the system are the polynomial coefficients β_i and the weights γ_i of the radial basis functions. These can be determined by enforcing the following conditions:

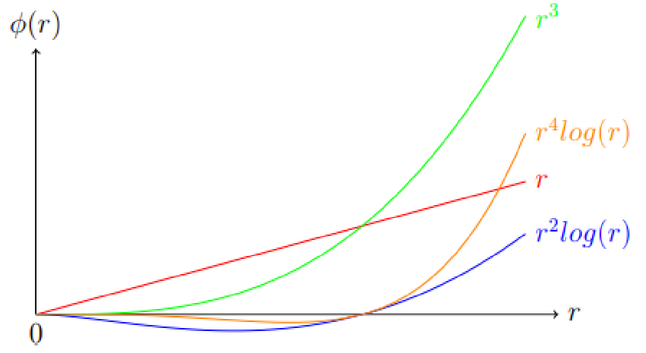
$$f(c_i) = g_i$$

$$\sum_{i=1}^{m} \gamma_i p(c_i) = 0$$

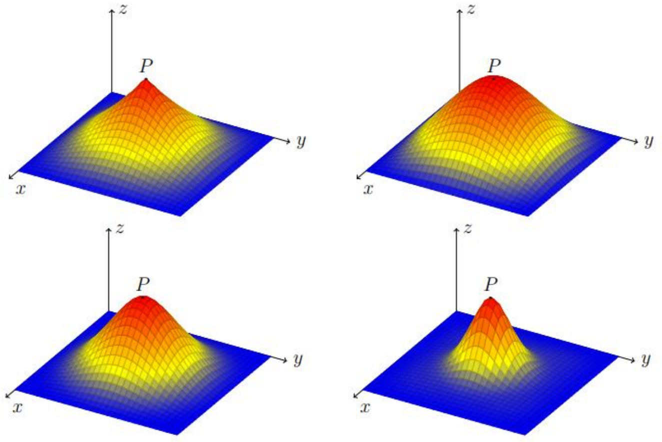
In matrix form: $\begin{bmatrix} M & P \\ P^T & 0 \end{bmatrix} \begin{Bmatrix} \gamma \\ \beta \end{Bmatrix} = \begin{Bmatrix} g \\ 0 \end{Bmatrix}$

RBF	$\boldsymbol{\phi(r)}$
Spline type	$\lvert r \rvert^n$
Multiquadric	$\sqrt{1+r^2}$
Inverse multiquadric	$\frac{1}{\sqrt{1+r^2}}$
Inverse quadratic	$\frac{1}{1+r^2}$
Gaussian	e^{-r^2}

Typical radial functions



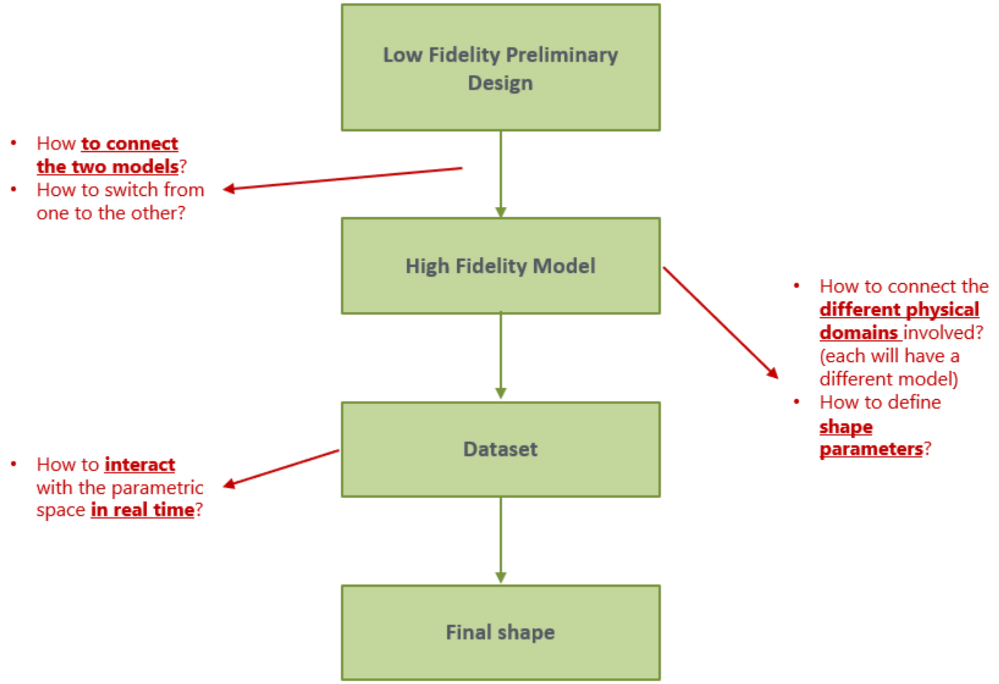
The most commonly used poly-harmonic functions, $r = \|c_i - x\|$



Interpolation using a linear poly-harmonic spline $\phi(r) = r$ (top left) and a cubic poly-harmonic spline $\phi(r) = r^3$ (top right). Interpolation using C2 Wendland functions with r=0.7 (bottom left) and r=0.4 (bottom right).

Radial Basis Functions (RBF)

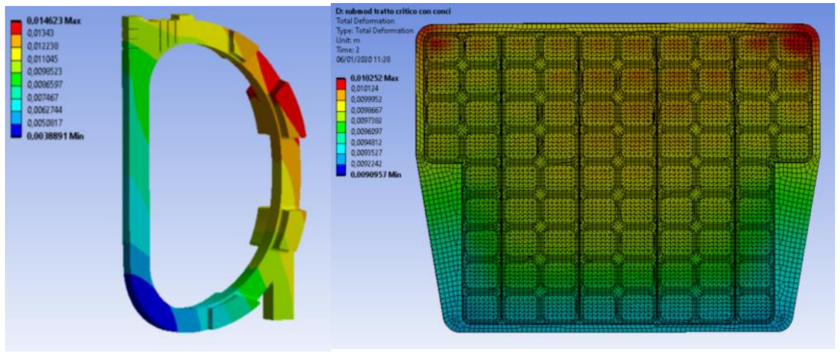
- Mapping FSI
- Shape parameters definition (Mesh Morphing)
- Response Surface Interpolation
- Connect multi-fidelity analysis



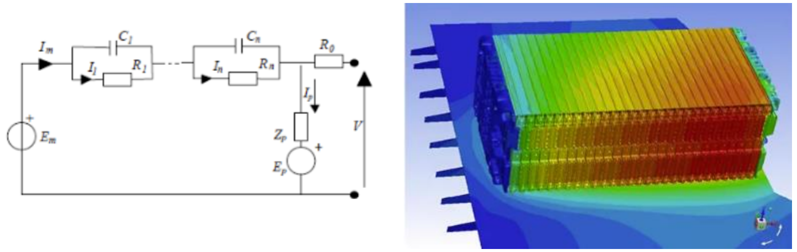
MULTI-FIDELITY WORKFLOWS

Multi-Fidelity Workflows

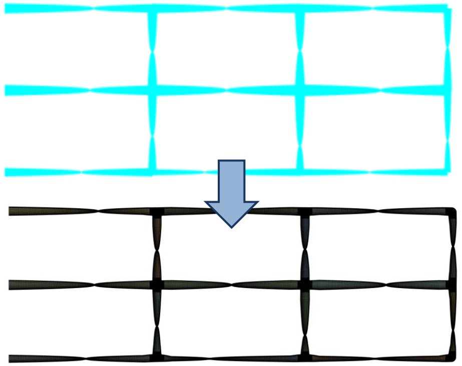
- Multi-fidelity approaches enable the connection of models with varying levels of accuracy. The objectives of these approaches can be manifold:
  - To model in detail only specific areas of interest (sub-modelling, homogenization).
  - To connect different physical phenomena that require varying degrees of accuracy.
  - To link low-fidelity tools and analyses for preliminary design with high-fidelity numerical tools. For instance, combining analytical and numerical approaches to optimize the design process



Sub-Modelling example



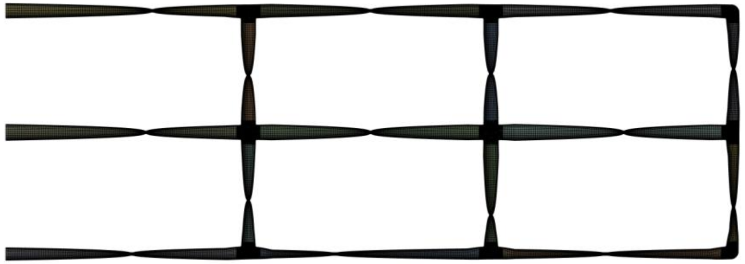
CFD - ECM Coupling for electrical and thermal analysis

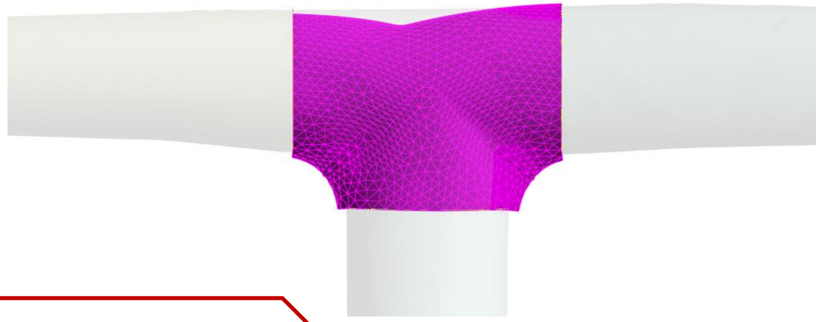


From analytic to FEM

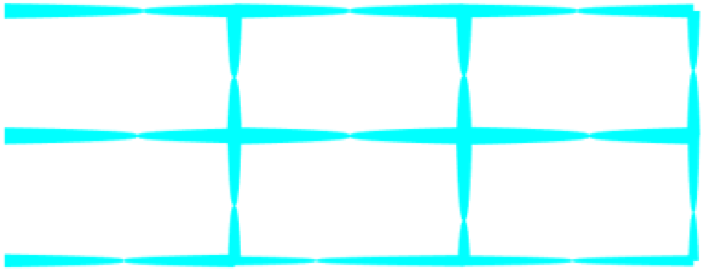
Multi-Fidelity Workflows

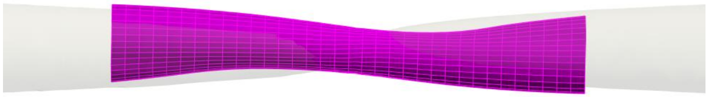
- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Workflow





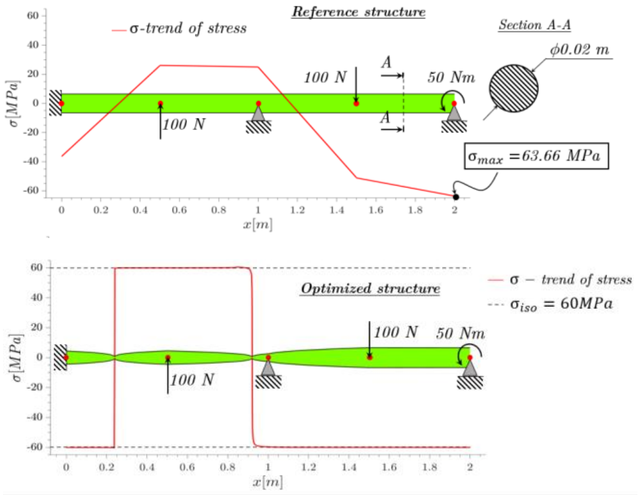
Step 1: Analytical Optimization - Uniform Strength → Automatic Creation of FEM Model → Step2: Numerical Optimization - BGM





Multi-Fidelity Workflows

- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Step 1: Analytical Optimization - Uniform Strength



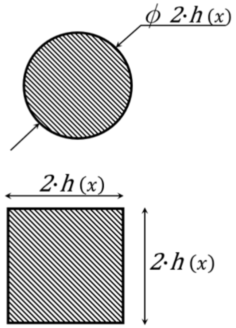
Why the Uniform Strength? ⟶ *Maximum mechanical efficiency*

$$\mathscr{L} = \frac{\textit{Elastic Strain Energy}}{\textit{maximum energy that can be accumulated}} = \frac{1}{(\sigma_{max})^2\, V}\int_L \frac{M^2(x)}{I(x)}\,dx = \begin{cases} \frac{1}{9} & \textit{for constant section} \\ \frac{1}{3} & \textit{for Uniform Strength beams (variable sections)} \end{cases}$$

How to obtain the cross-section shape to guarantee the Uniform Strength?

$$\sigma_x(x,y) = \frac{N(x)}{A(x)} - \frac{M(x)}{I(x)}\,y$$

$$max\big(\sigma_x(x, \pm h(x)/2)\big) = \sigma_{iso} = const \longrightarrow \sigma_{iso} = \frac{|N(x)|}{A(x)} + \frac{|M(x)|}{I(x)}\frac{h(x)}{2}$$



$$h(F_x^I, F_y^I, M_z^I, x) = \sqrt[3]{\frac{q}{2}}\left[\sqrt[3]{-1+\sqrt{\Delta}} + \sqrt[3]{-1-\sqrt{\Delta}}\right]$$

$$\Delta = 1 + \frac{4}{27}\frac{p^3}{q^2} \quad ; \quad p(F_x^I, x) = -\frac{|N(x)|}{c_A\,\sigma_{iso}} \quad ; \quad q(F_y^I, M_z^I, x) = -\frac{|M(x)|}{c_I\,\sigma_{iso}}$$

Circular cross-section: $c_A = \pi \;\; , \;\; c_I = \pi/4$

Square cross-section: $c_A = 1 \;\; , \;\; c_I = 1/12$

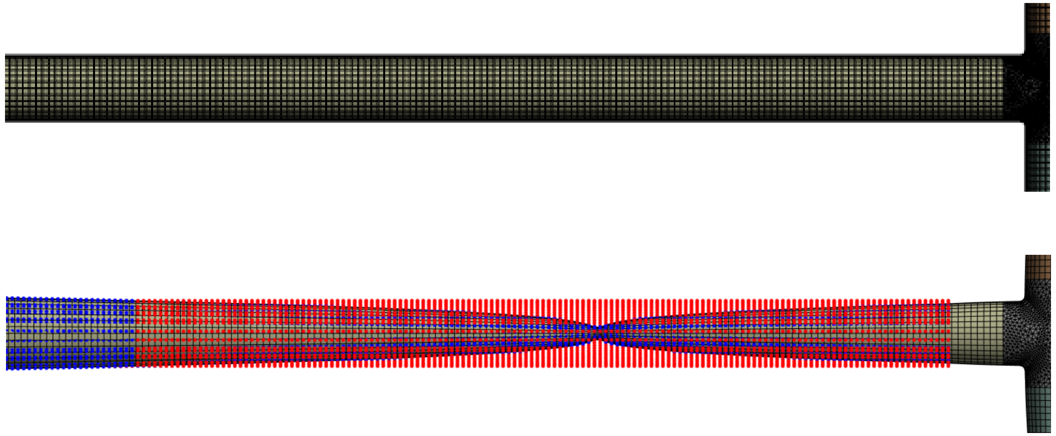
If the stress contributes due to normal force is neglected and the distributed loads are nulls, it is possible to integrate the kinematic equations:

$$h(F_y^I, M_z^I, x) \cong \left[c_M\; s(x) \cdot M(F_y^I, M_z^I, x)\right]^{\frac{1}{3}}$$

Multi-Fidelity Workflows

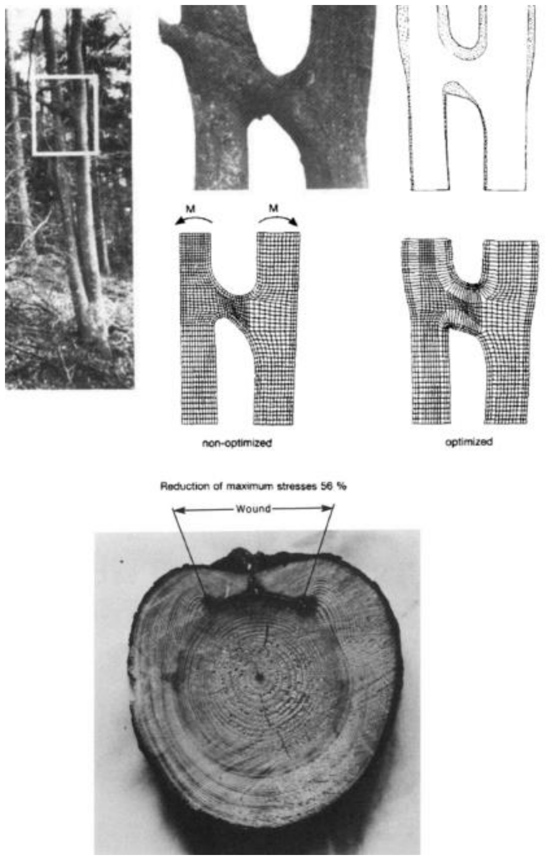
- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
    - Automatic Creation of FEM Model

RBF Mesh Morphing



Multi-Fidelity Workflows

- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Step 2: Numerical Optimization - BGM



- BGM approach is based on the observation that biological structures growth is driven by local level of stress.
- Bones and trees' trunks are able to adapt the shape to mitigate the stress level due to external loads.
- The process is driven by stress value at surfaces. Material can be added or removed according to local values.
- Was proposed by Mattheck & Burkhardt in 1990.
- Automatic optimization is accoplished connecting adjoint and BGM data from numerical simulation to mesh morphing tool.
- Offset Surface shape modification allow to define for each node a displacement according to the local normal direction.
- When using BGM data, the direction and amplitude of displacement is defined according to BGM stress data, considering the threshold stress value σ_{th} and the d maximum displacement:

$$S_{node} = \frac{\sigma_{node} - \sigma_{th}}{\sigma_{max} - \sigma_{min}} \cdot d$$

Multi-Fidelity Workflows

- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Performance Factors:

Surface exploitation factor: $f_1 = \frac{\sqrt{\sum_{i=1}^{n_S} (\sigma_{ISO} - \sigma_{VM})^2}}{n_S} \frac{1}{\sigma_{ISO}}$

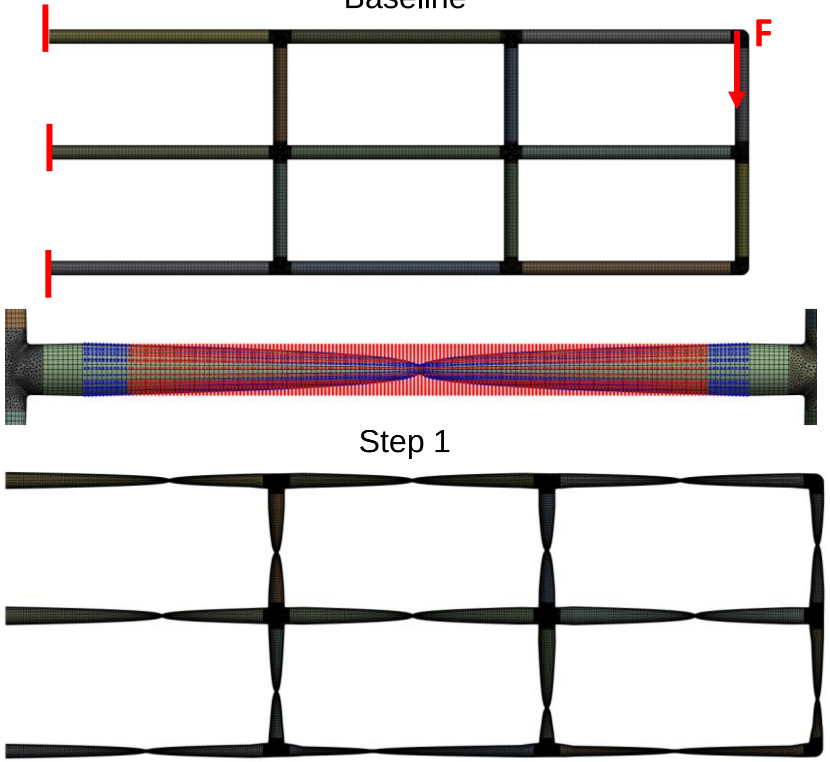
Volume exploitation factor: $f_2 = \frac{\sqrt{\sum_{i=1}^{n_V} (\sigma_{ISO} - \sigma_{VM})^2}}{n_V} \frac{1}{\sigma_{ISO}}$

Energy factor: $f_3 = \frac{E_d * 2E}{{\sigma_{ISO}}^2 V}$

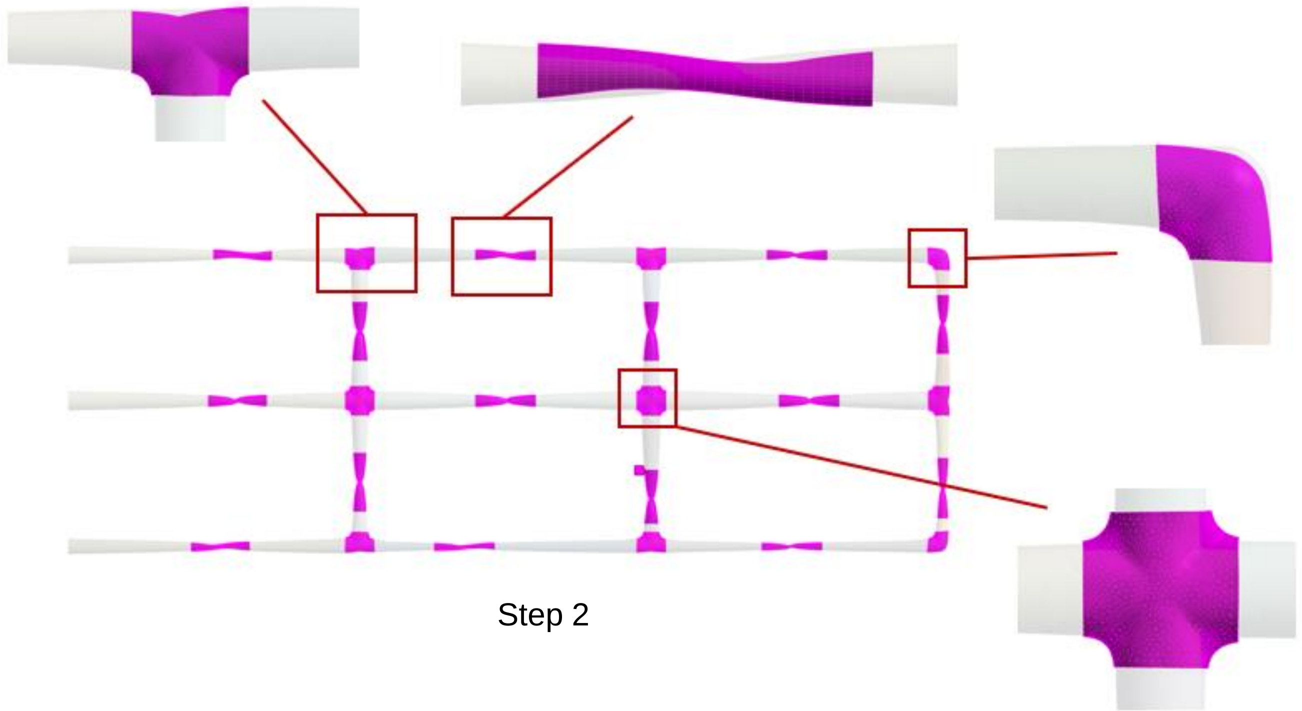
Multi-Fidelity Workflows

- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Testcase 1:
    - Fixed constraints, F = 7kN, $\sigma_{ISO} = 2.5\text{e}^{8}$ Pa, $R(x) = \sqrt[3]{-\frac{2|M(x)|}{\pi\sigma_{iso}}}\left[\sqrt[3]{-1+\sqrt{\Delta(x)}}+\sqrt[3]{-1-\sqrt{\Delta(x)}}\right]$

Baseline



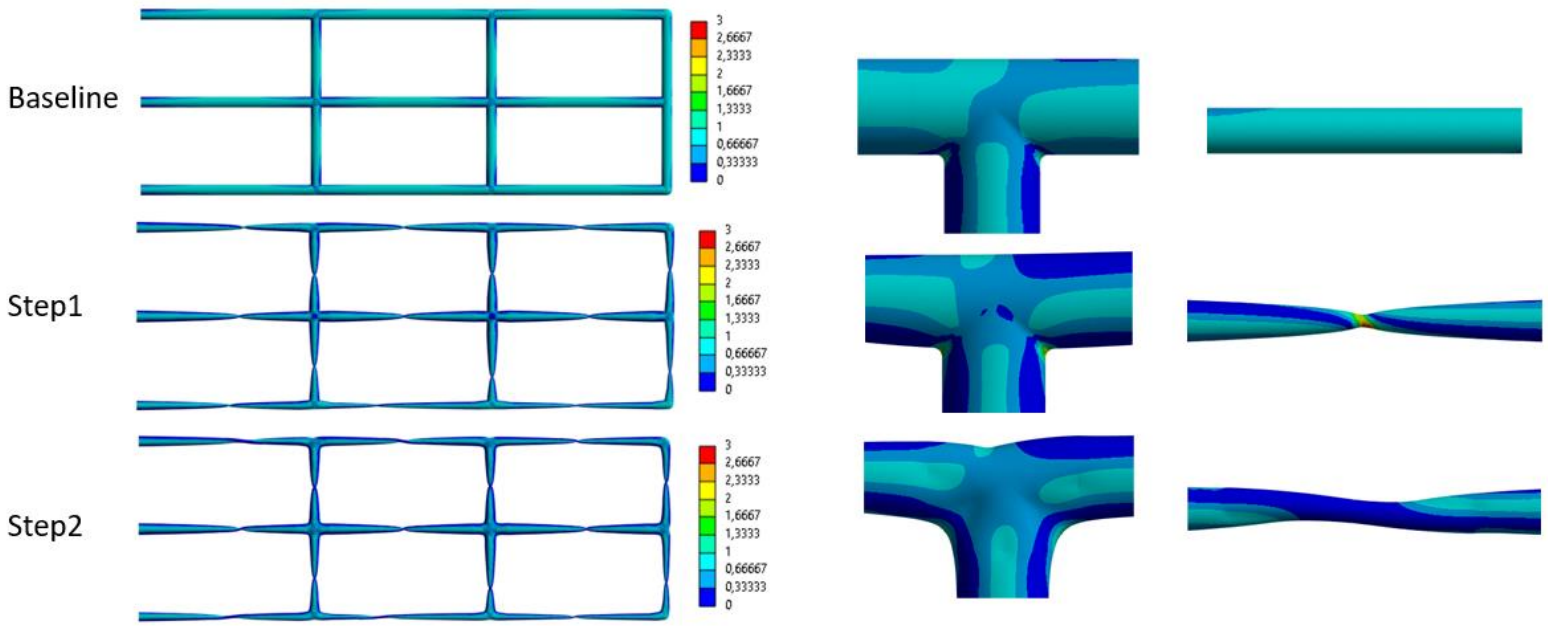
Step 1



Step 2

Multi-Fidelity Workflows

- Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach
  - Testcase 1:
    - Results



Surface exploitation factor

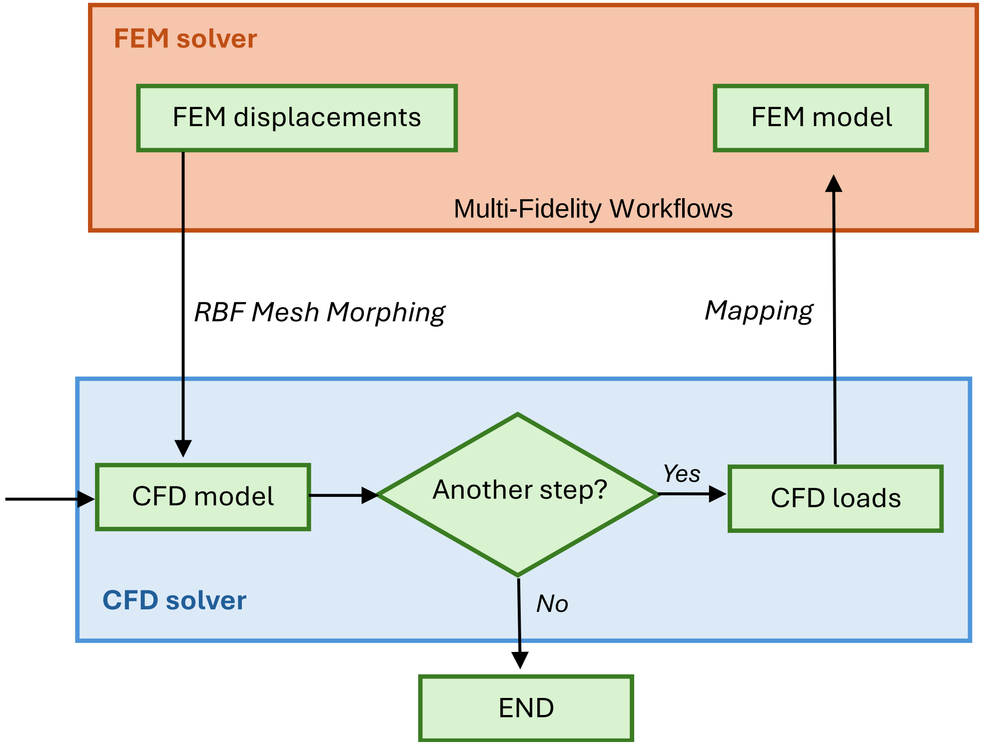
	VM_max [Pa]	Vol [m^3]	Surface exploitation factor	Volume exploitation factor
Base	6,9e8	4,16e-003	0,72	0,8
Step1	1e9	2,24 e-003	0,53	0,64
Step2	5,7e8	1,95 e-003	0,48	0,612

	Strain energy	Energy factor
Baseline	48,221 J	0,075
Step1	98,108 J	0,28
Step2	102,23 J	0,335

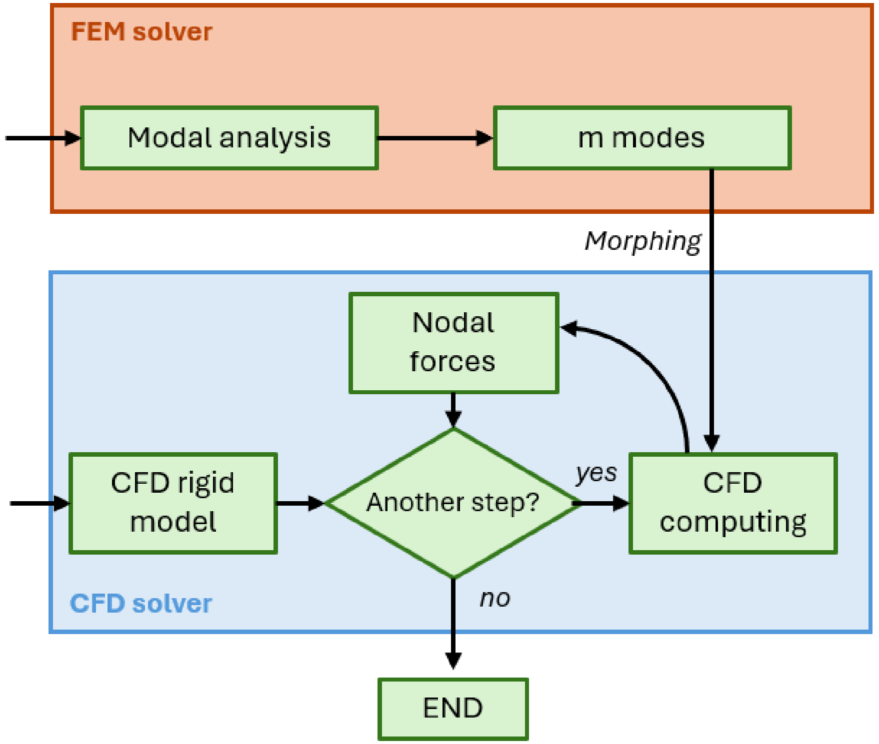
MULTI-PHYSICS ANALYSIS : FSI

Multi-Physics Analysis : FSI

- Modal superposition vs two-way



Two-way FSI workflow

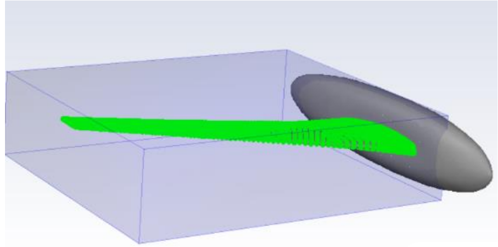


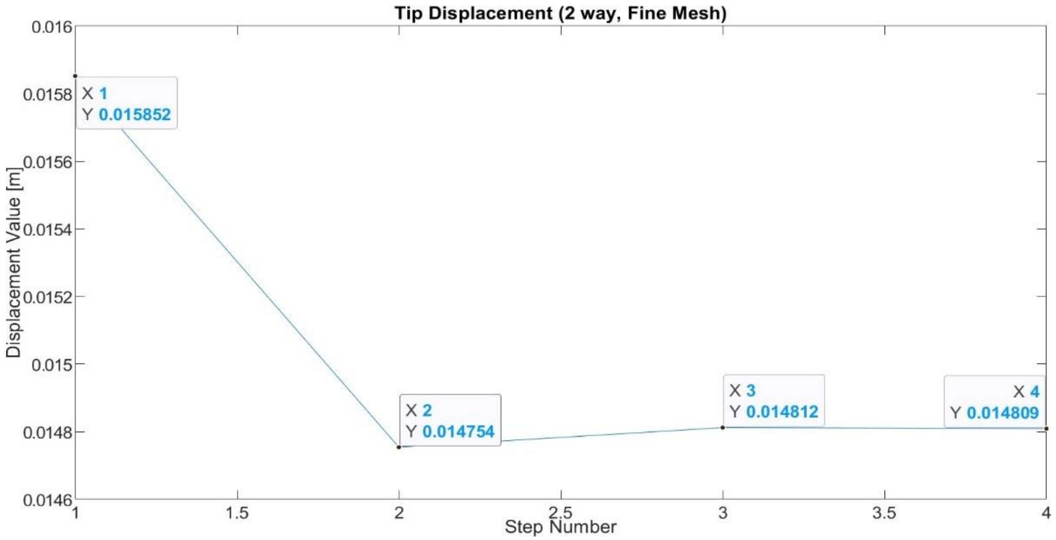
Modal superposition workflow

Multi-Physics Analysis : FSI

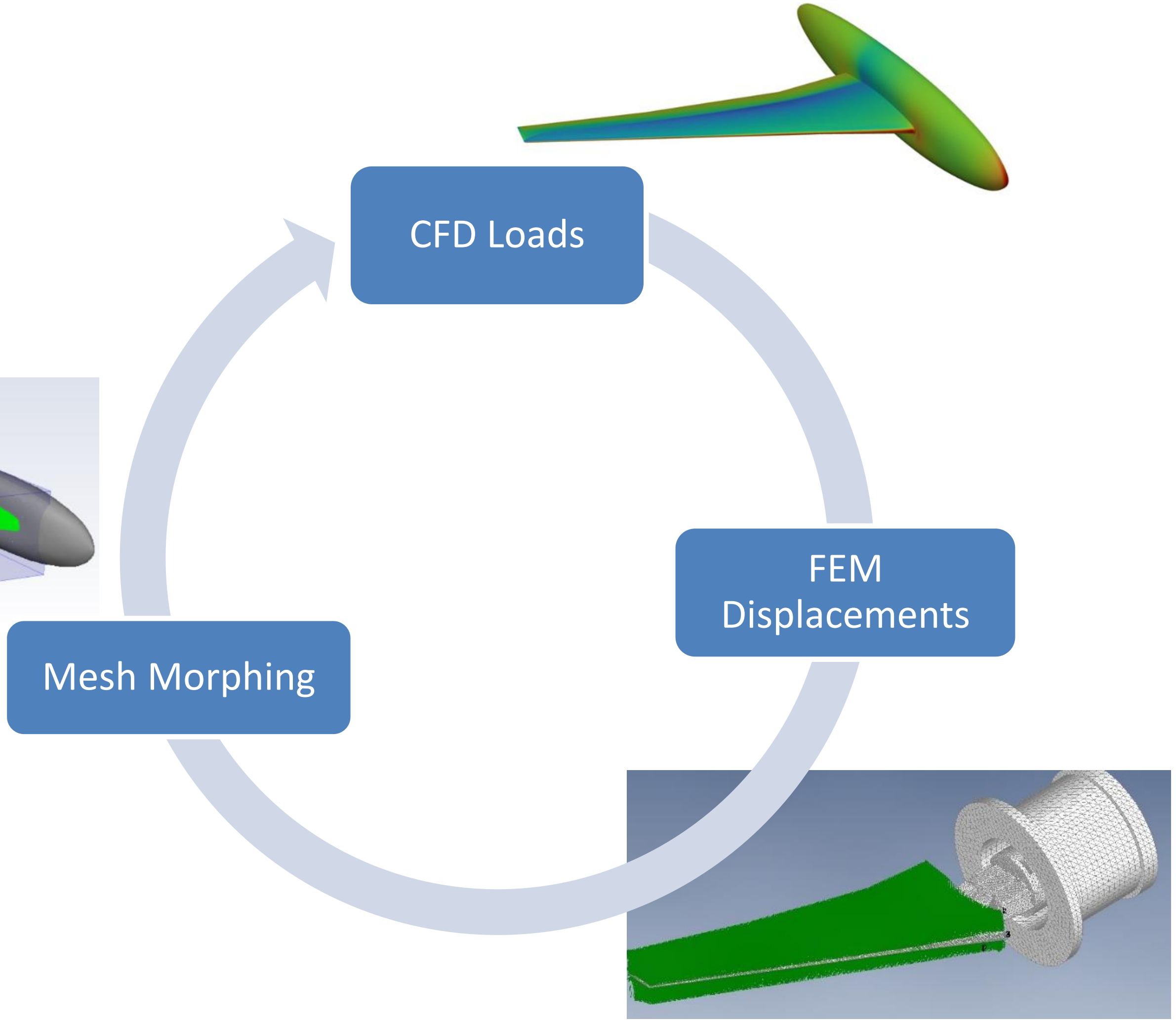
- Modal superposition vs two-way
  - HIRENASD testcase: Two-Way
    - Mach 0.8 and an AoA of 1.5°

	Baseline	Two-Way	Δ%
C_L	0.3568	0.3395	-4.85%
C_D	0.0137	0.0144	+5.11%





Tip Displacements convergence



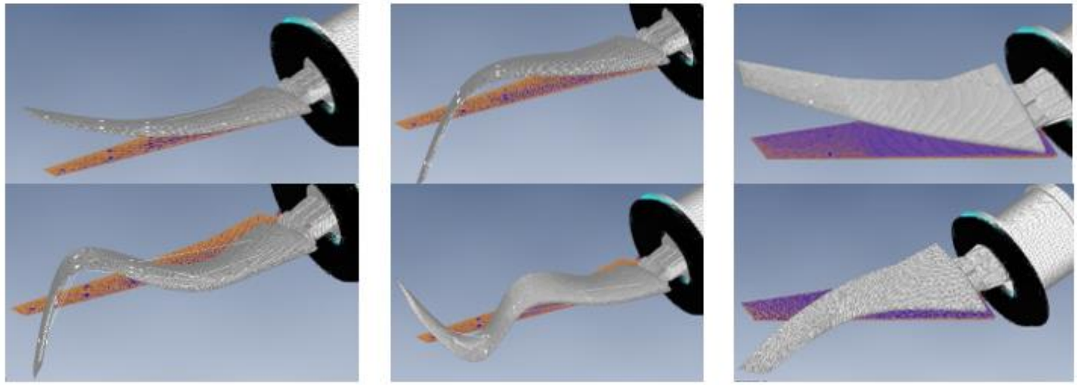
Multi-Physics Analysis : FSI

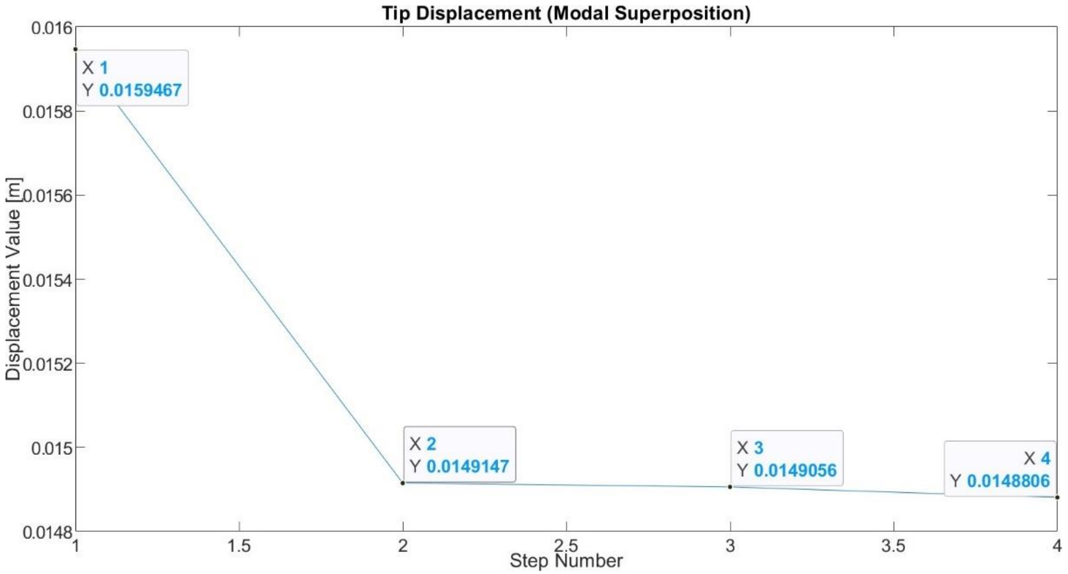
- Modal superposition vs two-way
  - HIRENASD testcase: Modal Superposition
    - Phase 1: The vibration modes of the deformable parts, normalized with respect to mass, are computed through a FEM analysis.
    - Phase 2: The vibration modes are imported into the CFD model. This requires the introduction of a mesh morphing technique and a mapping algorithm to deform the CFD mesh according to the linear combination of the extracted modes.
    - Phase 3: The weights of each mode are estimated based on equilibrium considerations. The mesh is then deformed, and the aerodynamic variation is evaluated.
    - Mesh displacements: $x_{CFD} = x_{CFD0} + \sum_m \boldsymbol{X}_m q_m$,

Modal force: $f_m = \sum_{i=1}^{n} \boldsymbol{X}_{m,i} \cdot F_{CFD_i}$

Modal weight: $q_m = \frac{f_m}{\omega_m^2}$

First six vibration modes

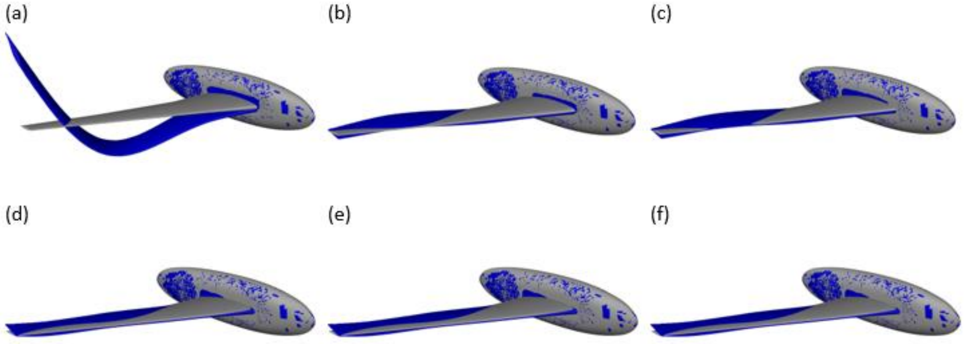




	Two-Way	Modal
C_L	0.3395	0.3395
C_D	0.0144	0.0144

Multi-Physics Analysis : FSI

- Modal superposition vs two-way
  - HIRENASD testcase
    - Number of modes selection



Displacements error for increasing number of modes

Tip displacements obtained as the number of modes considered varies, along with the percentage difference compared to the displacement obtained with two-way

# Modes	**Displacements [mm]**	**Δ%**
1 mode	15.94	/
2 modes	14.79	-7.21%
3 modes	14.81	-7.09%
4 modes	14.89	-6.59%
5 modes	14.88	-6.65%
6 modes	14.88	-6.65%

    - Comparison

C_L, C_d comparison

	Two-Way	Modal
C_L	0.3395	0.3395
C_D	0.0144	0.0144

Tip Displacements comparison

	Two-Way	Modal
Disp [mm]	14.81	14.88

Time required

	Two-Ways	Modal
Time	4h 15min	59min

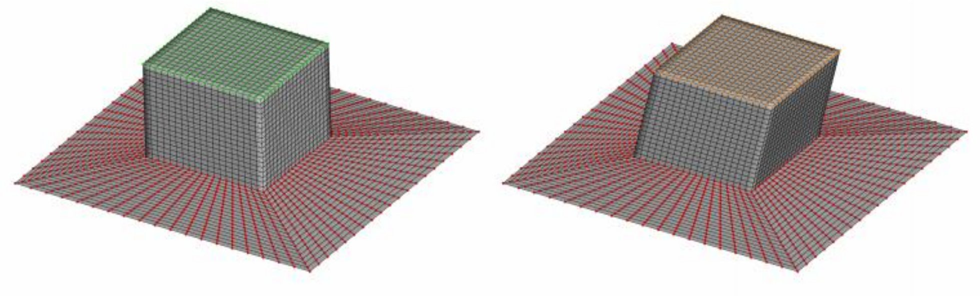
SHAPE PARAMETERS DEFINITION

Shape Parameters Definition

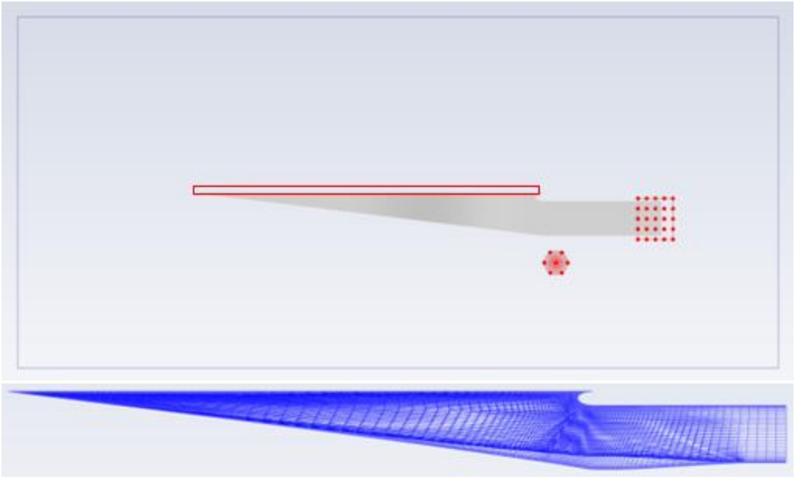
- Two main approaches can be used in numerical simulations to define shape parameters:
  - Parametric CAD

OpenVSP CAD Example

  - Mesh morphing



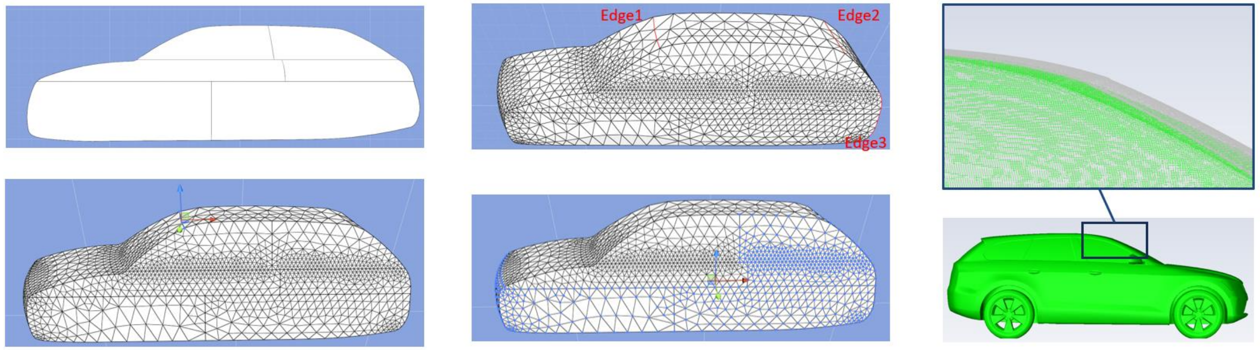
RBF Mesh Morphing example on a cube



RBF Mesh Morphing example on NACA air intake

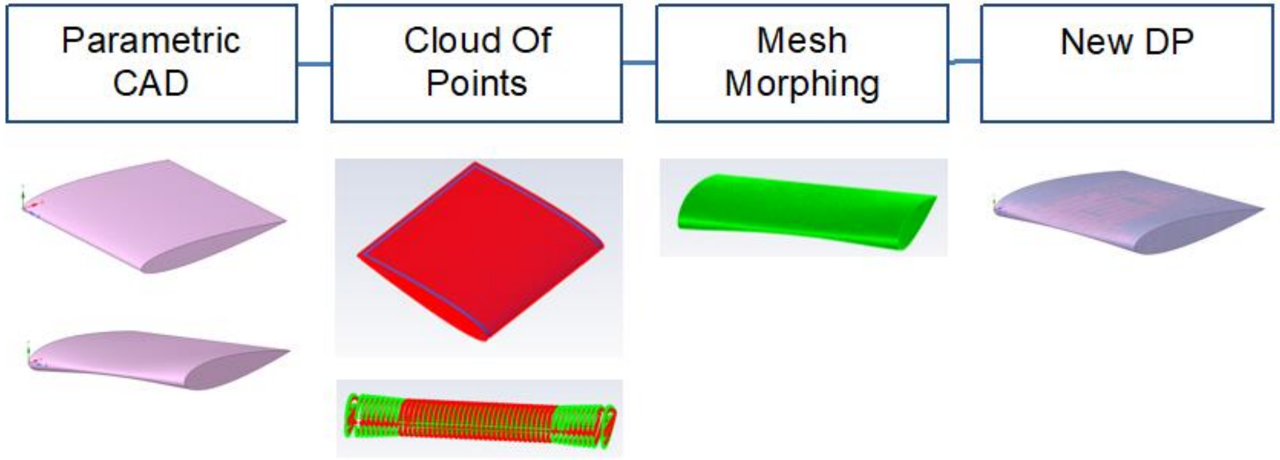
Shape Parameters Definition

- Hybrid methods
  - AeroSUV Method



Wrapper CAD and support mesh · *Source points defined on CAD entities* · *Morphed Mesh*

  - OPAM method



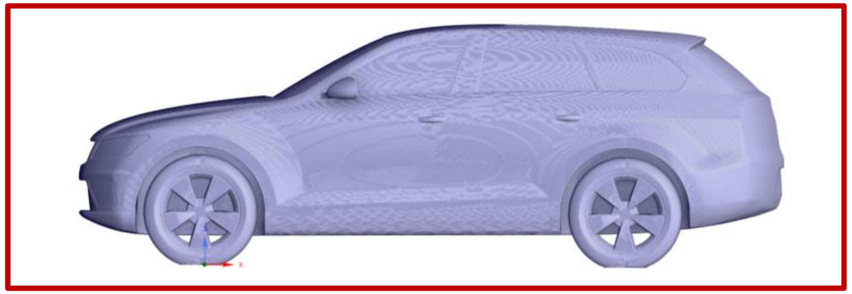
REAL TIME DESIGN DASHBOARD

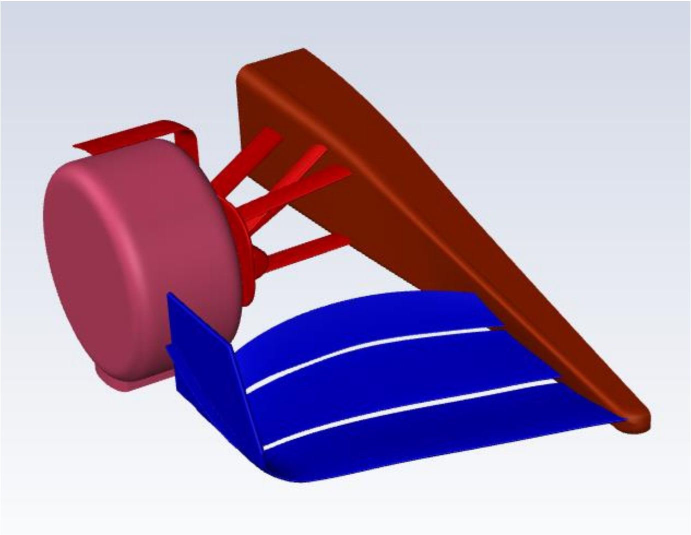
ADJOINT-BASED

ROM-BASED

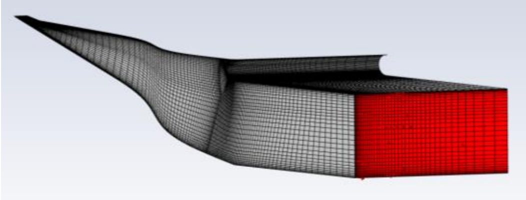
Real Time Design Dashboard

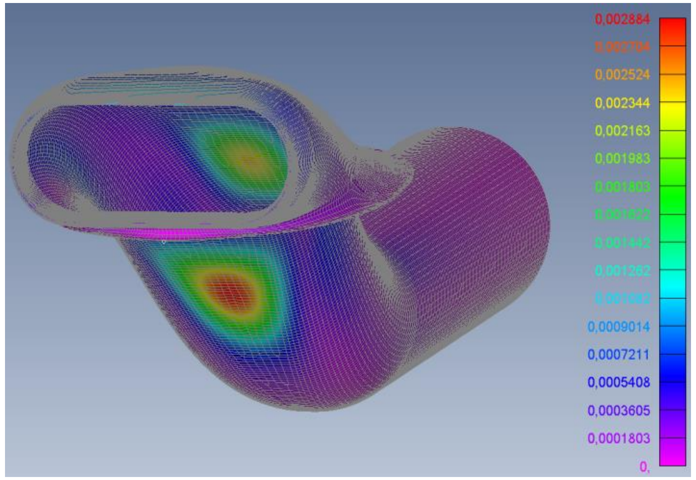
- **Adjoint-based**

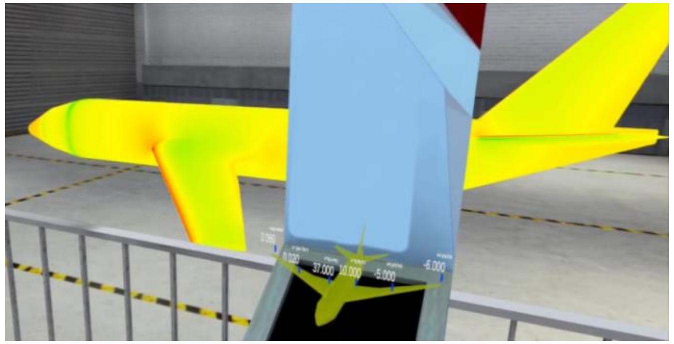




- **ROM-based**







Adjoint Method Background

- In general, the derivative of a function is defined using the concept of the limit of the incremental ratio:

$$\frac{df}{dx} = \lim_{h\to 0}\frac{f(x+h)-f(x)}{h}$$

- This definition cannot be used in a numerical code, it must be discretized.
- The simplest technique for sensitivity calculation is finite differences. The method used in this thesis is the adjoint method.
- Let f be the objective function, which generally depends on both physical variables x and design variables α:

$$f = f(x,\alpha) \ \to \delta f_i = \frac{\partial f_i}{\partial x_j}\delta x_j + \frac{\partial f_i}{\partial \alpha_k}\delta \alpha_k$$

- Considering the residuals of the governing equations, it must be verified that $R(x,\alpha(x)) = 0$

$$\delta R = \left[\frac{\partial R}{\partial x}\right]\delta x + \left[\frac{\partial R}{\partial \alpha}\right]\delta\alpha = 0$$

- The problem can thus be reduced to a constrained optimization problem, where the goal is to minimize the objective function f, with the function R serving as the constraint. By introducing Lagrange multipliers and differentiating the auxiliary function, we obtain:

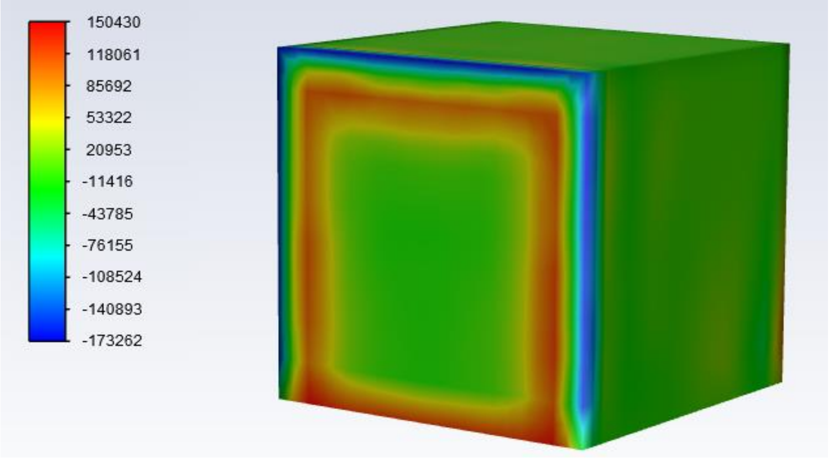
$$\delta f = \frac{\partial f}{\partial x}\delta x + \frac{\partial f}{\partial \alpha}\delta\alpha - \lambda^T\left\{\left[\frac{\partial R}{\partial x}\right]\delta x + \left[\frac{\partial R}{\partial \alpha}\right]\delta\alpha\right\} = \left[\frac{\partial f}{\partial x} - \lambda^T\frac{\partial R}{\partial x}\right]\delta x + \left[\frac{\partial f}{\partial \alpha} - \lambda^T\frac{\partial R}{\partial \alpha}\right]\delta\alpha$$

- λ is the added vector, and the values of its components are arbitrary. Therefore, a vector is chosen in such a way that the terms related to δx are cancelled, making the observable function dependent only on the external parameters:

$$\left[\frac{\partial R}{\partial x}\right]^T\lambda = \frac{\partial f}{\partial x}$$

- This equation depends only on the derivatives with respect to the fluid dynamics variables. The solution to the adjoint problem, therefore, allows the calculation of the adjoint variables λ. Once these variables are known, it is then possible to construct the gradient using expression, which can be reformulated as follows:

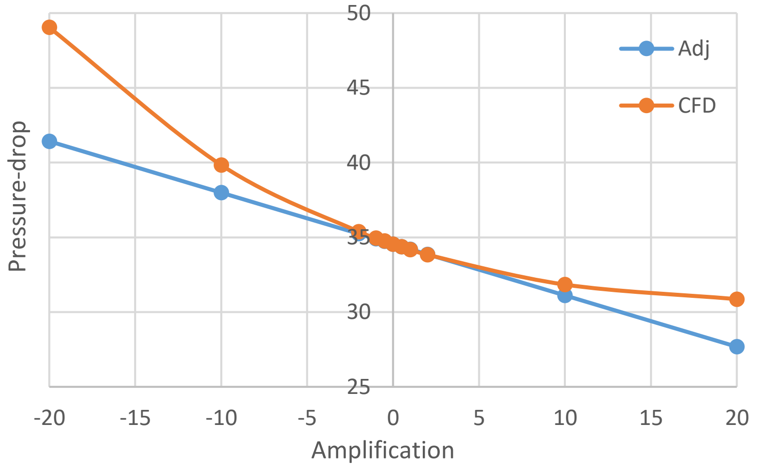
$\delta f = G\ \delta\alpha$, with $G = \frac{\partial f}{\partial \alpha} - \lambda^T\frac{\partial R}{\partial \alpha}$



Shape sensitivity map for a cube for drag

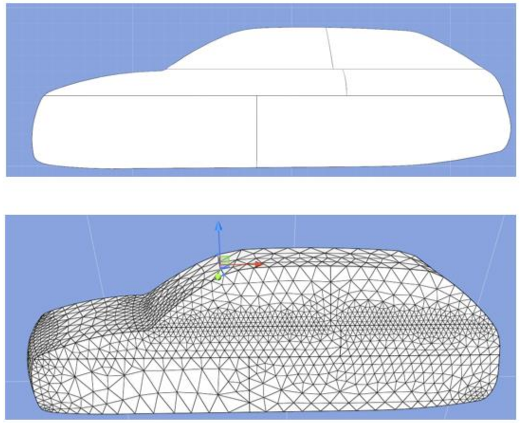
Real Time Design Dashboard

- **Adjoint**
  - The goal of this work is to create a **real-time adjoint-based** design procedure that enables the definition of any shape parameter and provides a prediction of the variation in the monitored observable
  - Adjoint Method can be used to estimate effects of shape variations on observables.
  - Figure:
    - Orange Curve: Vary parameter amplification, modify mesh, evaluate observable via CFD analysis.
    - Blue Curve: Same amplifications, use adjoint method.
    - Observation: Blue curve is tangent to the objective function at the origin, representing the rate of mesh deformation as the parameter varies.
  - Sensitivity: $\frac{\delta\Psi}{\delta a} = \frac{\delta\Psi}{\delta x} \cdot \frac{\delta x}{\delta a}$

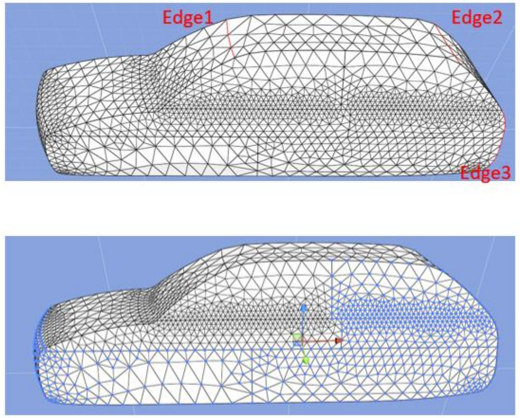


Real Time Design Dashboard

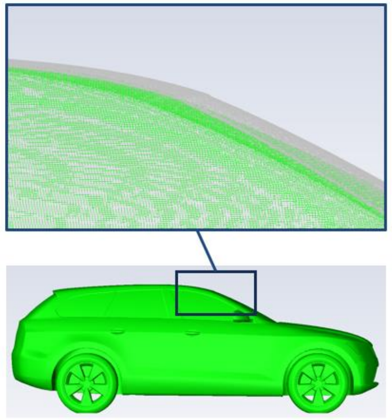
- **Adjoint**
  - AeroSUV Workflow



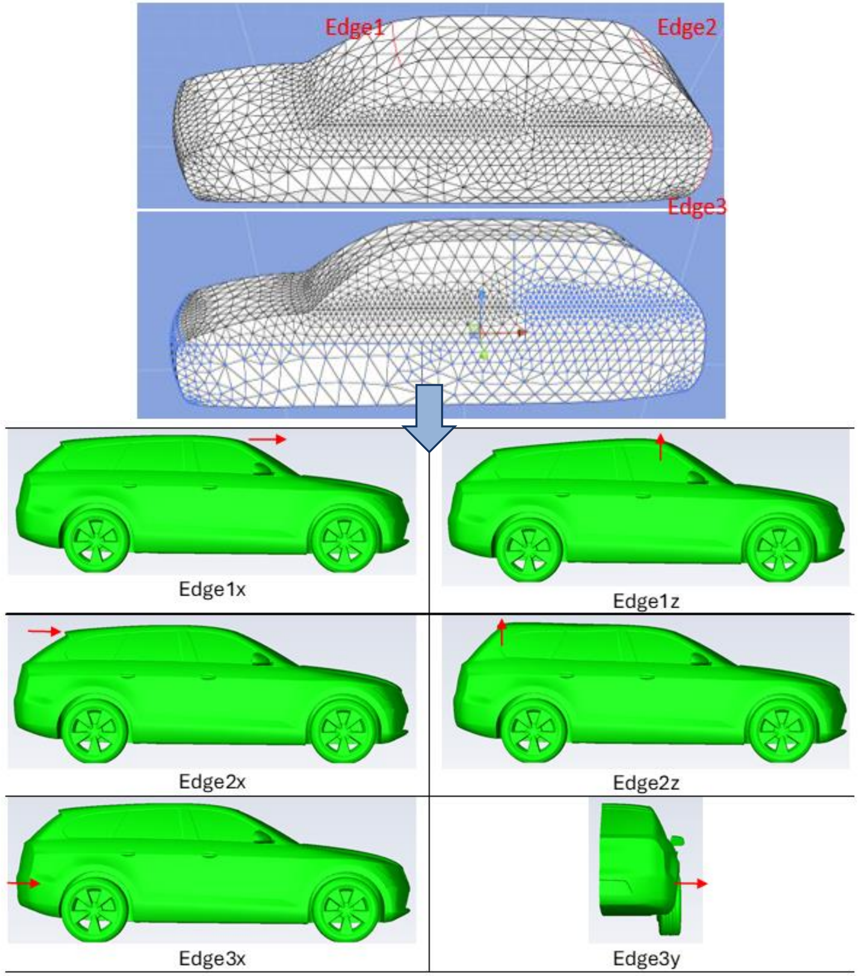
Wrapper CAD and support mesh



Source points defined on CAD entities



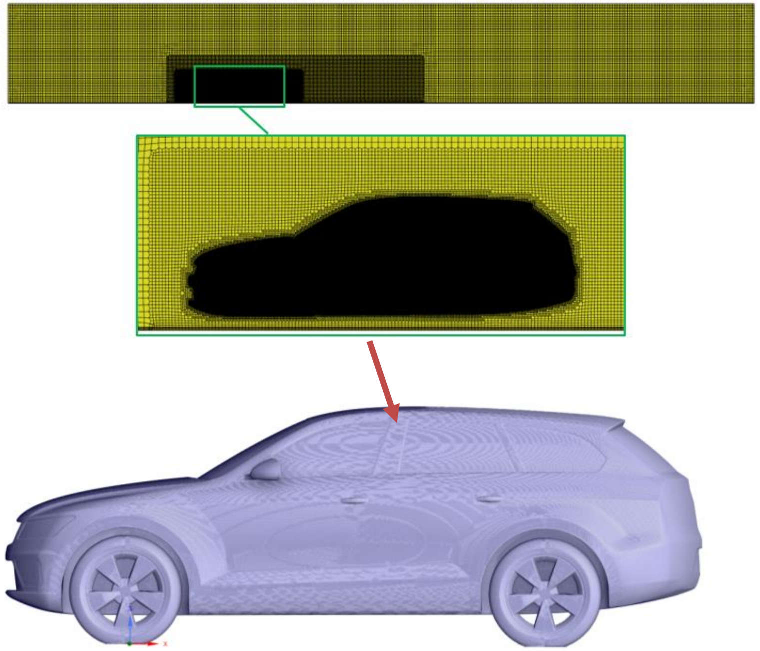
Morphed Mesh



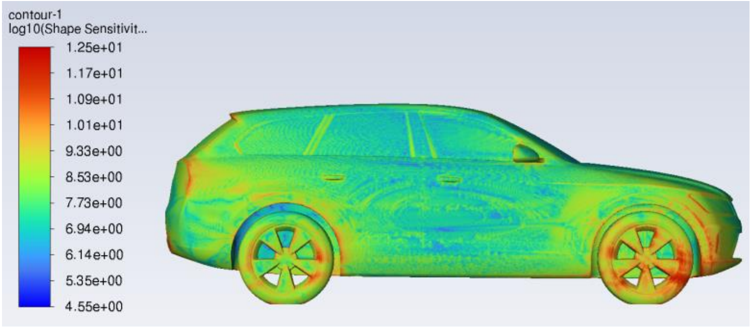
Shape parameters definition

Real Time Design Dashboard

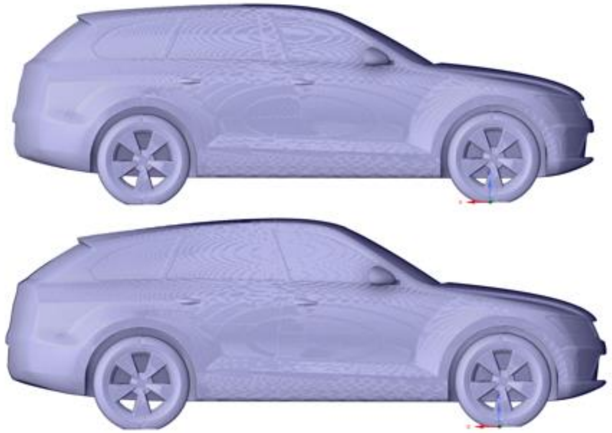
- **Adjoint**
  - AeroSUV Testcase
    - Velocity inlet: 50 m/s
    - 6 shape parameters



CFD Mesh



Adjoint shape sensitivity



Comparison of baseline and optimized shape

	Cd
Baseline	0.3
Optimized	0.29 (-3.33%)

	Edge 1x	Edge 1z	Edge 2x	Edge 2z	Edge 3x	Edge 3z
Range	-1 ÷ 1	-1 ÷ 1	-1 ÷ 1	-1 ÷ 1	-1 ÷ 1	-1 ÷ 1
Sensitivity	0.04	-0.33	0.54	-0.9	0.2	0.1
Final Value	-0.12	1	-1	1	-0.6	-0.3

Reduced Order Model (ROM)

- Proper Orthogonal Decomposition (POD) is a dimensionality reduction technique used to analyse complex data and identify the main modes of variation
- One of the most effective methods used alongside POD is SVD:

$$M = \begin{bmatrix} \vdots & \cdots & \vdots \\ s_1 & \cdots & s_n \\ \vdots & \cdots & \vdots \end{bmatrix} = \begin{bmatrix} \vdots & \cdots & \vdots \\ u_1 & \cdots & u_n \\ \vdots & \cdots & \vdots \end{bmatrix} \text{x} \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \cdots & \sigma_n \end{bmatrix} \text{x} \begin{bmatrix} \vdots & \cdots & \vdots \\ v_1 & \cdots & v_n \\ \vdots & \cdots & \vdots \end{bmatrix}^T = U\Sigma V^T$$

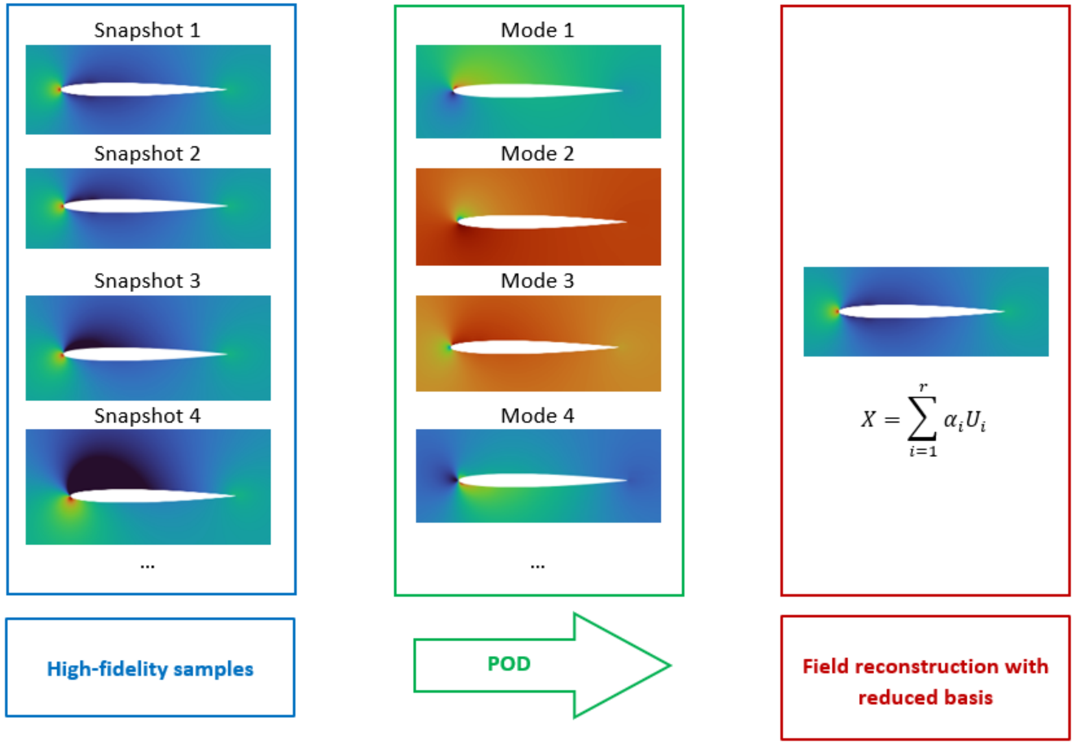
- The field solution X in the design space can then be approximated as a linear combination of r modes:

$$X = \sum_{i=1}^{r} v_i \sigma_i U_i$$

- r is a critical parameter that balances accuracy and compression while excluding noise. Generally, an energetic approach is used to select the number of modes, which corresponds to imposing the condition:

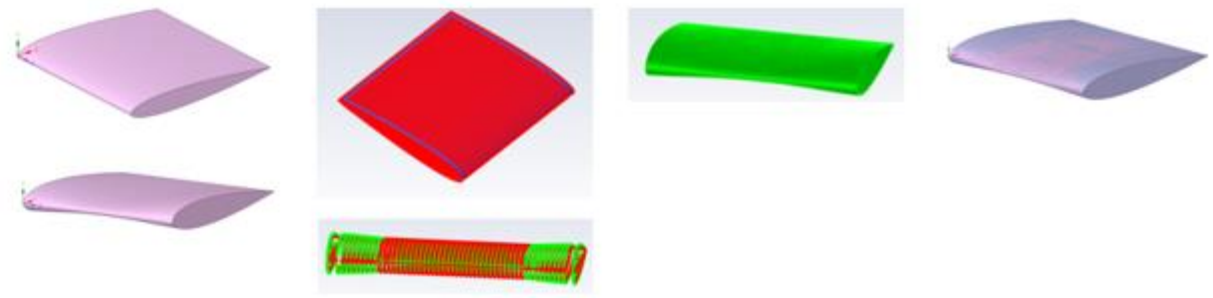
$$\frac{\sum_{i=1}^{r} \sigma_i{}^2}{\sum_{i=1}^{n} \sigma_i{}^2} = 0.99$$

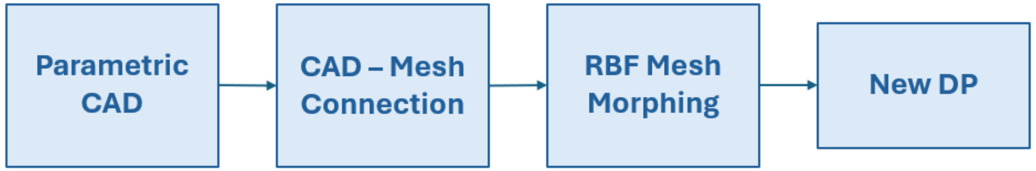
- Once the modes have been extracted and the optimal number of modes r has been selected, it is necessary to identify a correlation between the model's input parameters and the mode weights. The main methods used in literature are:
  - Genetic Aggregation Response surface (GARS)
  - Neural Network (NN)
  - Gaussian Regression
  - RBF network



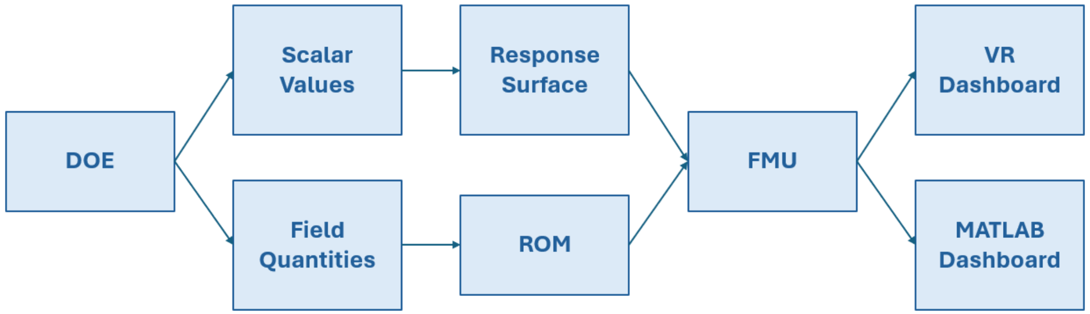
Real Time Design Dashboard

- **ROM**
  - **Open Parametric Aircraft Model (OPAM)**
  - Workflow Proposal: Creation of **advanced aerodynamics design dashboards.**
  - CAD modeler linked to CFD simulation results, real-time exploration of shape parameters' effects on aerodynamics.
  - Case Study: **OPAM** (Open Parametric Aircraft Model), a simplified Boeing 787 model.
  - **Hybrid workflow**: Combination of CAD parameterization and mesh morphing to generate DPs.
  - **ROM** Development: Linking CFD analysis results to chosen parameterization.
  - **RSM** for scalar quantities
  - Exported as **FMUs** for easy management in any environment.
  - **VR Design Dashboard** created in Unity environment, enables interaction with geometric model in an immersive and intuitive environment, MetaQuest 3 headset selected for tests.





Hybrid workflow



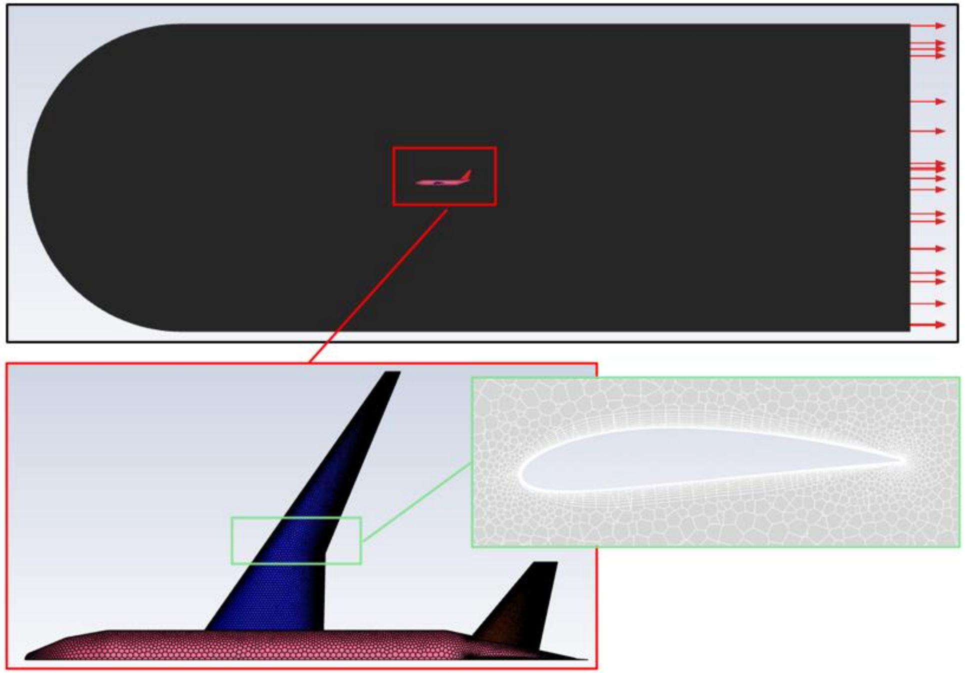
Design Dashboard

Real Time Design Dashboard

- **ROM**
  - **Open Parametric Aircraft Model (OPAM): CFD Baseline**

The following main options are configured:

- Steady-state simulation;
- Density-based solver;
- k-omega SST turbulence model;
- Air as an ideal gas with the Sutherland viscosity law;
- Inlet [pressure-far-field]: Mach equal to 0.7 inclined by $\alpha = 0°$
- Outlet [pressure-outlet]: Pressure and temperature standard (101325 Pa, 298 K)
- Side [pressure-far-field]: Same conditions as the Inlet.
- Symmetry [symmetry]: Symmetry plane.
- Plane [wall].
- The implicit Roe-FDS formulation with second-order discretization was em-ployed.



CFD Mesh

Number of faces	4,979,888
Number of cells	957,205
Number of nodes	3,366,691
Min. Orthogonal Quality	1.50172e-01
Max. Aspect Ratio	1.38865e+02
y+	<10

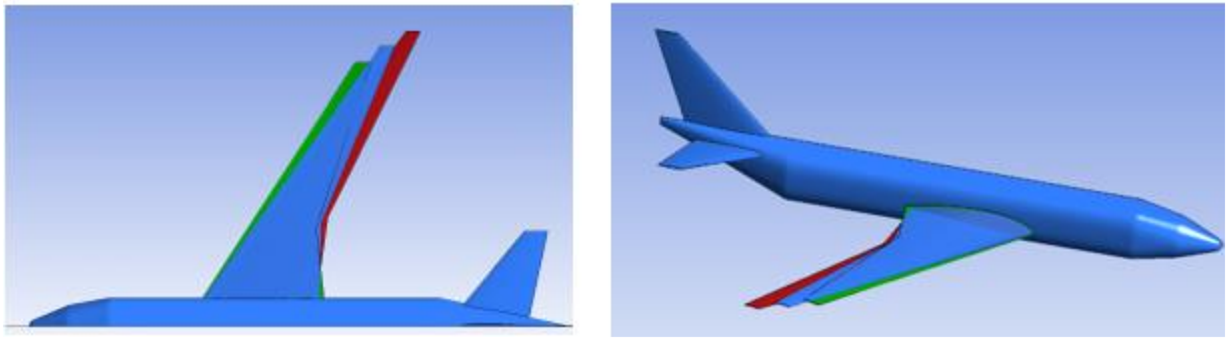
Mesh Properties

Real Time Design Dashboard

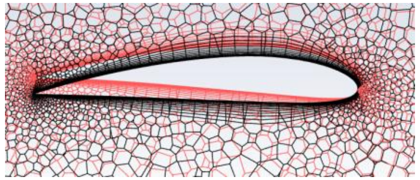
- **ROM**
  - **Open Parametric Aircraft Model (OPAM): DOE**
    - Out of the 53 model parameters, the 6 parameters are chosen
    - A DOE consisting of 66 DPs was generated using the LHS

	Aspect R	Sweep	Alpha B	Camber B	Alpha T	Camber T
Range	8 ÷ 10	33 ÷ 37	−5 ÷ −1	0.02 ÷ 0.06	−10 ÷ −6	0.02 ÷ 0.06
Baseline	9	35	−3	0.04	−8	0.04

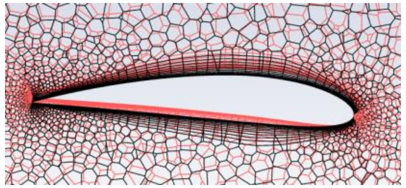
Min Orthogonal Quality	DP
1.45437e- 01	baseline
8.80044e-02	1
9.94842e-02	10
9.51205e-02	20
1.02042e-01	30
1.02038e-01	40
9.15076e-02	50
9.12111e-02	60
5.18119e-02	65
9.16307e-02	66



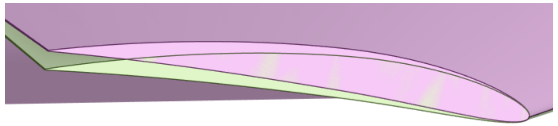
Effect of aspect ratio and sweep



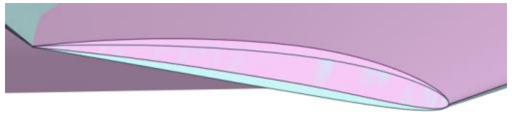
Effect of alpha_b



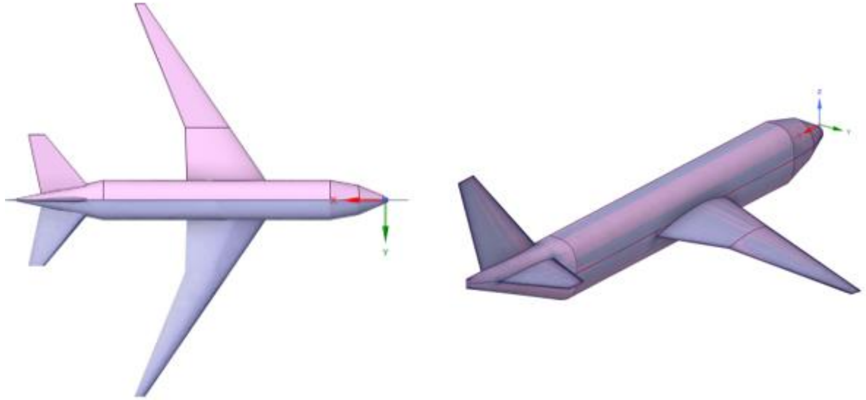
Effect of camber_b



Effect of alpha_t



Effect of cambert_t



Comparison of CAD and mesh for DP 65

Real Time Design Dashboard

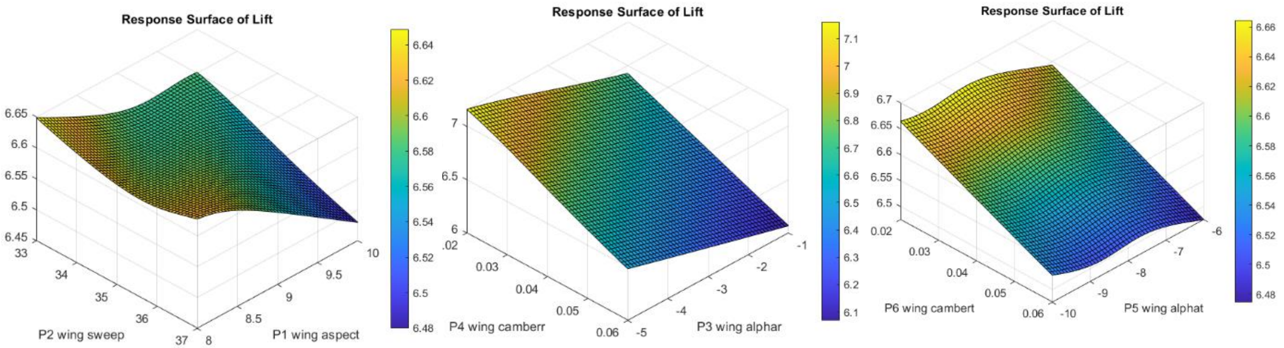
- **ROM**
  - **Open Parametric Aircraft Model (OPAM): RSM**

	Observations	MSE	R
Train	40 (60%)	0.0001	0.9989
Validation	13 (20%)	0.0013	0.9829

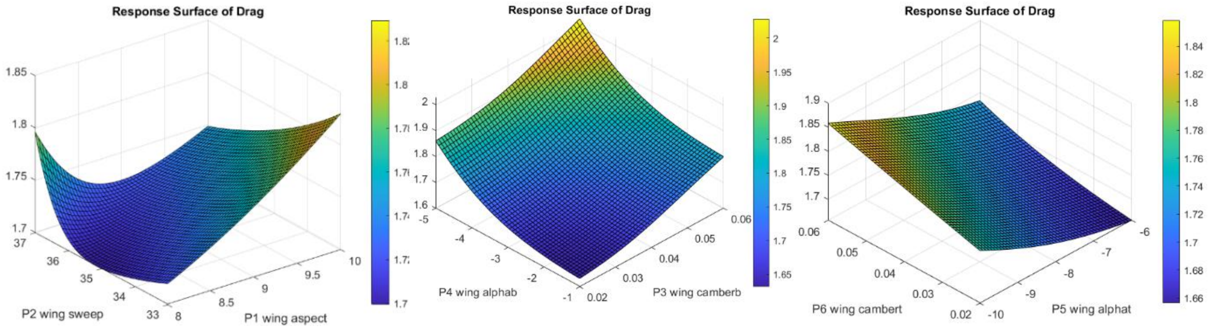
Performance of RS for lift evaluation

	Observations	MSE	R
Train	40 (60%)	2.15×10^{-5}	0.9989
Validation	13 (20%)	5.37×10^{-4}	0.9765

Performance of RS for drag evaluation



RS for lift evaluation



RS for drag evaluation

Real Time Design Dashboard

- **ROM**
  - **Open Parametric Aircraft Model (OPAM): ROM**
    - **Mesh ROM**

      50% of the DPs were used for training

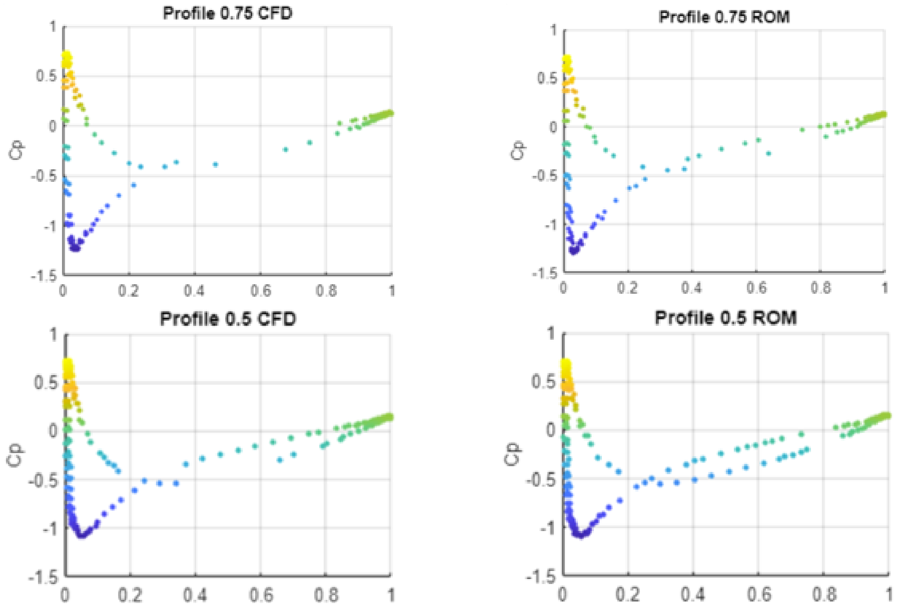
      Six modes were selected

      The error of the ROM evaluated by the software is less than 1%
    - **Static Pressure ROM**

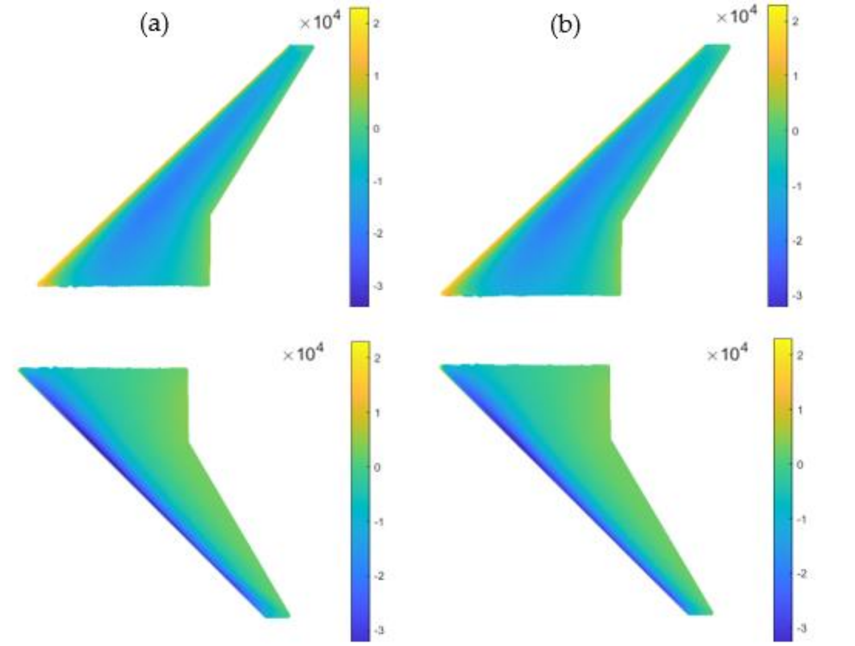
      50% of the DPs were used for training

      Five modes were selected

      The error of the ROM evaluated by the software is less than 5.1%.



CP profile on the chord at 0.75 and 0.5; comparison between CFD and ROM for the DP in the test set with maximum error



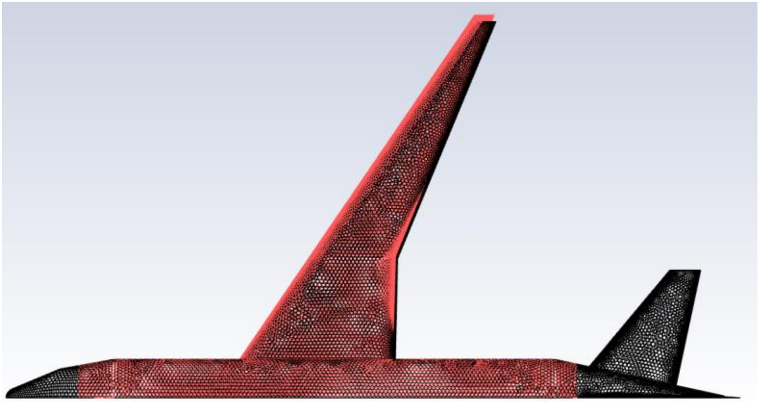
Comparison of pressure: CFD (**a**) vs. ROM (**b**) for the DP with max error in the test set [Pa].

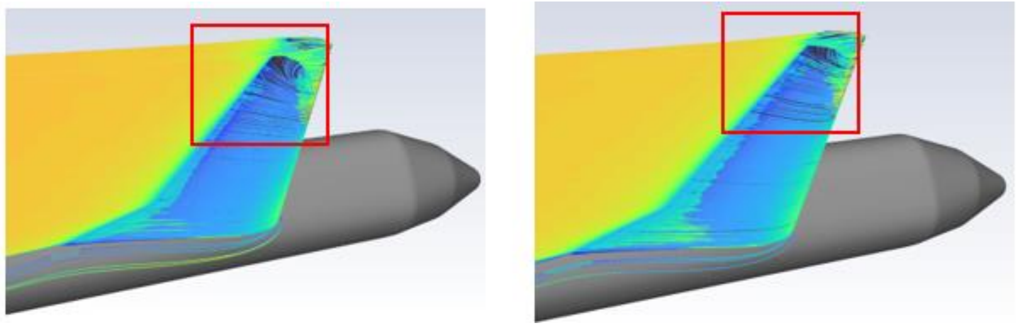
Real Time Design Dashboard

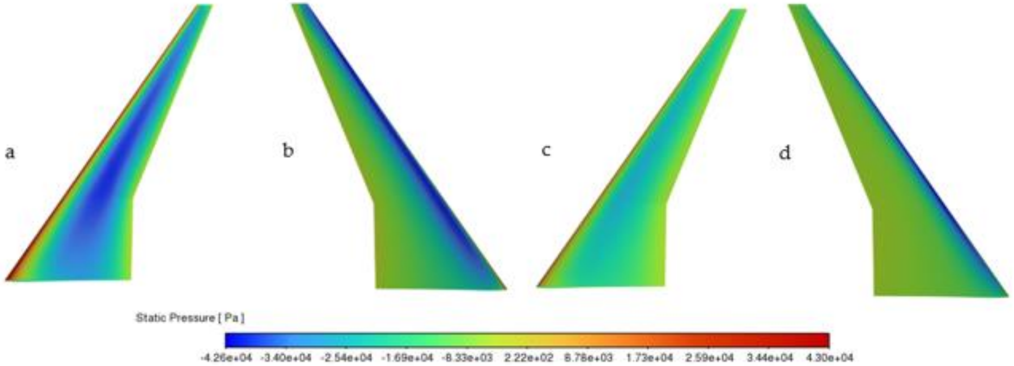
- **ROM**
  - **Open Parametric Aircraft Model (OPAM): Optimization results**
    - Better guided flow.
    - Reduced separation at the trailing edge.
    - Increased pressure on the lower surface enhances efficiency.
    - Reduced separation on the upper surface lowers drag.

	Aspect R	Sweep	Alpha B	Camber B	Alpha T	Camber T
Range	8 ÷ 10	33 ÷ 37	−5 ÷ −1	0.02 ÷ 0.06	−10 ÷ −6	0.02 ÷ 0.06
Optimized	9.31	34.39	−2.93	0.025	−6.2	0.027

	Cl	Cd	Eff
Baseline	0.505	0.134	3.77
Optimized	0.535 (+6%)	0.129 (−4%)	4.15 (+10%)


Comparison of baseline (black) and optimized shape (red)

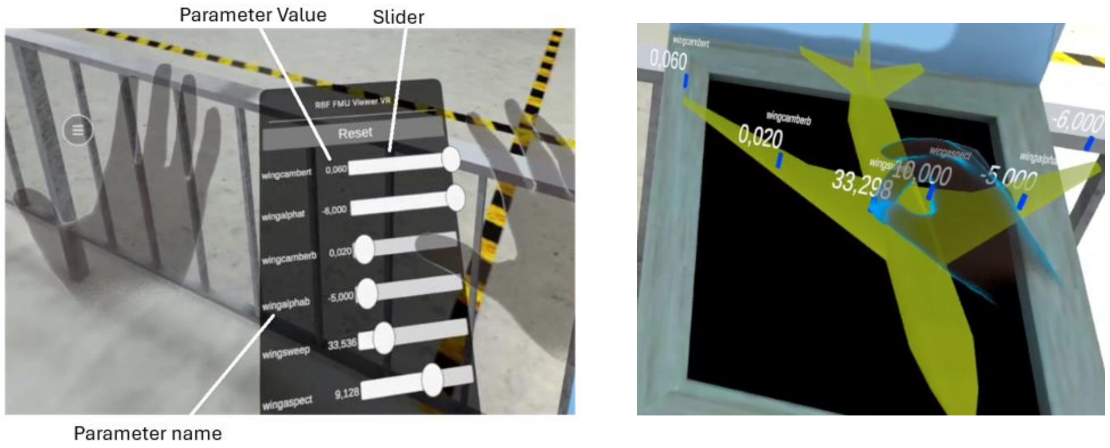

Comparison of baseline (left) and optimized shape (right)



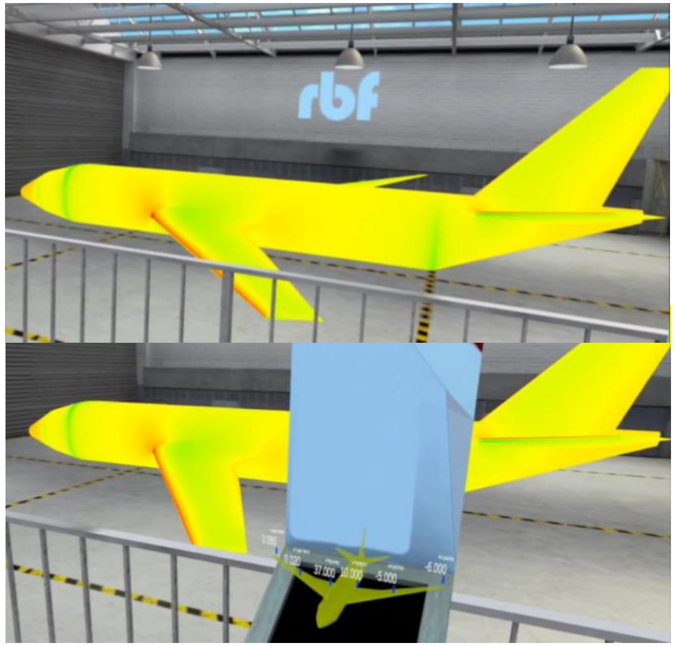
Comparison of pressure contours: baseline-upper (a), baseline-lower (b), optimized-upper (c) and optimized lower surface (d)

Real Time Design Dashboard

- **ROM**
  - **Open Parametric Aircraft Model (OPAM): VR Dashboard**
    - ROMs loaded into interactive VR dashboard.
    - Meta Quest 3 headset used for real-time exploration of CAD-based parameters.
    - Geometry and pressure modes loaded into GPU memory at initialization.
    - FMUs loaded into CPU for real-time updates of mode weights.
    - Visualization Performance: stable at 60 frames per second.
    - Parameter Menu activated by facing left-hand palm towards the camera.
    - Sliders: Interacted with using index finger. Grabbing and dragging updates parameter values, geometry, and pressure field.
    - Smaller Model: Manipulated by dragging with index finger and thumb.
    - Updates both smaller and larger models with pressure field.



Slider interface (left) and Three-dimensional interactive handles (right)



Full plane in the hangar with CFD results

Conclusions And Next Steps

- Solid framework for integrating multi-physics and multi-fidelity analyses were developed and tested
- Hybrid workflows to link CAD and mesh were developed
- Design processes were studied to improve real-time data accessibility.
- Advanced techniques (ROMs, adjoint methods) and automated workflows enhance engineering design efficiency.

- Transfer these workflows to industrial cases

Publications And Conferences

- **Journal papers:**
  - **Development of a ROM-Based Workflow for Integrating CAD Editors with Aerodynamics in a Virtual Reality Dashboard: OPAM-1 testcase**, Andrea Lopez, Marco E. Biancolini, Applied Sciences, Published, https://doi.org/10.3390/app15020846. **Q1**
  - **Advanced RBFs methods for mapping aerodynamic loads onto structures in high-fidelity FSI simulations**, Andrea Chiappa, Andrea Lopez, Corrado Groth, Fluids, https://doi.org/10.3390/fluids9060137, Published. **Q2**
  - **Reduced-Order Model of a Time-Trial Cyclist Helmet for Aerodynamic Optimization through Mesh Morphing and Real-Time Interactive Visualization**, Emanuele Di Meo, Andrea Lopez, Corrado Groth, Pier Paolo Valentini, Marco E. Biancolini, Fluids, Published. **Q2**
- **Book Chapters:**
  - **An interactive design tool for NACA intakes based on high fidelity CFD simulations and Reduced Order Models**, Andrea Lopez, Viola Rossano, Ubaldo Cella, Corrado Groth, Marco E. Biancolini, Springer, Accepted for publication.
  - **Human Body Models customization by advanced mesh morphing: parametric THUMS**, Emanuele Di Meo, Emanuele Lombardi, Andrea Lopez, and Marco Evangelos Biancolini, Springer, https://doi.org/10.1007/978-3-031-63755-1_22, Published.
  - **The role of high-fidelity Computer-Aided Engineering (CAE) multi-physics design within the research institutes of the National Institute for Astrophysics (INAF),** Springer, Accepted for publication.
- **Conference Proceedings:**
  - **EFFICIENT SHAPE OPTIMIZATION IN AERONAUTICS: INTEGRATING PARAMETRIC CAD AND MESH MORPHING FOR ENHANCED AERODYNAMIC PERFORMANCE**, Andrea Lopez, Gianluca Magri, Ubaldo Cella, Giorgio Urso, Federico Della Barba & Marco E. Biancolini, ICAS 2024, Published, icas2024_0824_paper.pdf.
  - **Design And Optimization Of Aeronautical Components And Digital Twins Development**, Andrea Lopez, Ubaldo Cella, Corrado Groth, and Marco E. Biancolini, AIAS 2023, 10.1088/1757 899X/1306/1/012025, Published.
  - **Shape Optimization of Frame Structures through a Hybrid Analytical-2D and Numerical-3D Approach**, Andrea Lopez, Christian Iandiorio, Daniele Milani, Pietro Salvini, and Marco E. Biancolini, AIAS 2024, Published
  - **The multi-physics analysis and design of CUSP, a two CubeSat constellation for space weather and solar flares X-ray polarimetry**, https://doi.org/10.1117/12.3018369, Published.
  - **The payload design of the CubeSat Solar Polarimeter (CUSP), for Space Weather and Solar flares X-ray polarimetry**, AIAS 2024, Published
- **Industrial Magazines**
  - **Revolutionizing aerodynamic design with a VR-enabled workflow**, Enginsoft
- **Workshops and Conferences:**
  - 4-month internship at **Leonardo S.p.A**.
  - **MISE workshop on Advanced Product Design**.
  - **Workshop Digital Twin for Industry** at BI-REX in Bologna.
  - **Workshop Simulation**: Driving the Convergence to Electrification, an Automotive Perspective.
  - **HxGN Live Conference**, Las Vegas.
  - **AIAS 2023** Conference, Genoa.
  - **AIAS 2024** Conference, Naples.
  - **ICAS 2024** Conference, Florence.

Thank you for your attention

PhD in Design, Manufacturing and Operations Engineering

PhD Cycle XXXVII

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