Design And Optimization Of Aeronautical Components And Digital Twins Development

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Summary

Introduction

Design And Optimization

Results

Introduction: Case Study

First task:

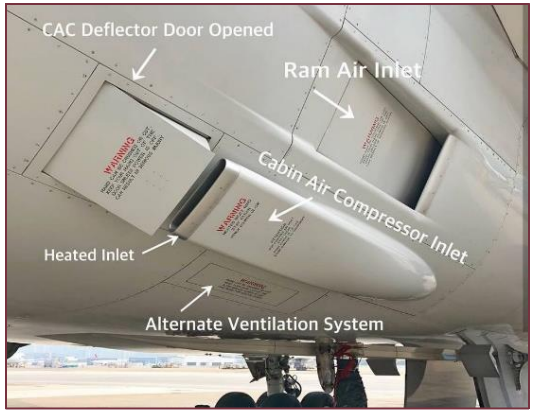
- Design and optimization of scoop air intake

Second task:

- Digital twin development of scoop air intake

Objective:

- The aim is to create an accurate and reliable model that allows to evaluate in real time both scalar quantities and field quantities;
- The generated model can be integrated with the rest of the aircraft;



Introduction: Methods

Mesh Morphing
RBF (Radial Basis Function))

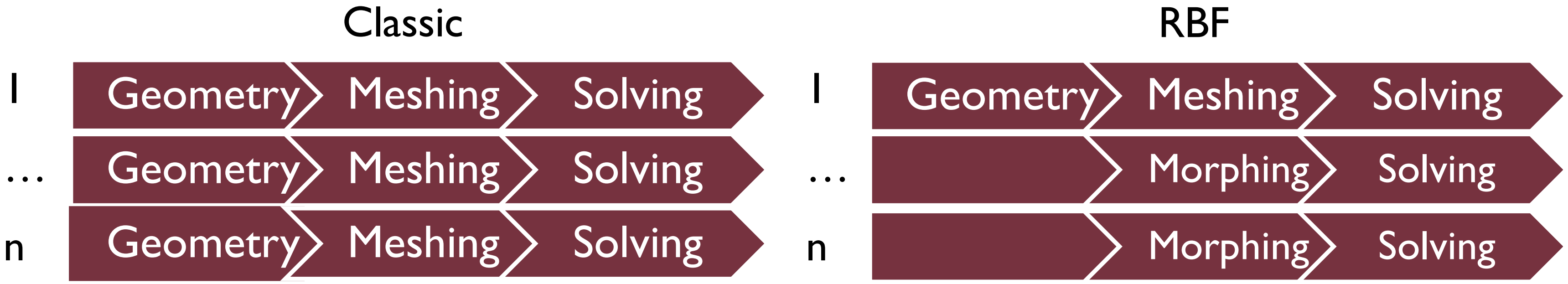
$$f^x(x) = \sum_{i=1}^{m} \gamma_i^x \phi(\|c_i - x\|) + \beta_1^x + \beta_2^x x_1 + \beta_3^x x_2 + \beta_4^x x_3$$
$$f^y(x) = \sum_{i=1}^{m} \gamma_i^y \phi(\|c_i - x\|) + \beta_1^y + \beta_2^y x_1 + \beta_3^y x_2 + \beta_4^y x_3$$
$$f^z(x) = \sum_{i=1}^{m} \gamma_i^z \phi(\|c_i - x\|) + \beta_1^z + \beta_2^z x_1 + \beta_3^z x_2 + \beta_4^z x_3$$

Weight and radial function

Polynomial term

$$\begin{bmatrix} M & P \\ P^T & 0 \end{bmatrix} \begin{Bmatrix} \gamma \\ \beta \end{Bmatrix} = \begin{Bmatrix} g \\ 0 \end{Bmatrix}$$
$$With \quad M = \phi(\|c_i - c_j\|)$$
$$P_j = [1 \; x_1 \; x_2 \; \dots \; x_n]$$

Boundary conditions

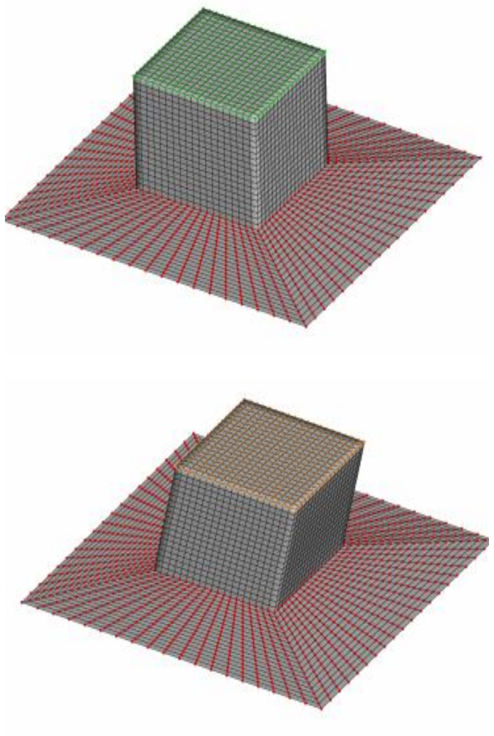


Classic

I	Geometry	Meshing	Solving
…	Geometry	Meshing	Solving
n	Geometry	Meshing	Solving

RBF

I	Geometry	Meshing	Solving
…		Morphing	Solving
n		Morphing	Solving



Introduction: Methods

Optimization workflow
Response surface

Baseline › Parameters › DOE › RS › Optimum

- Linear Regression:

$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i$$

$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1}^3 + \beta_4 X_{i2}^2 + \varepsilon_i$$

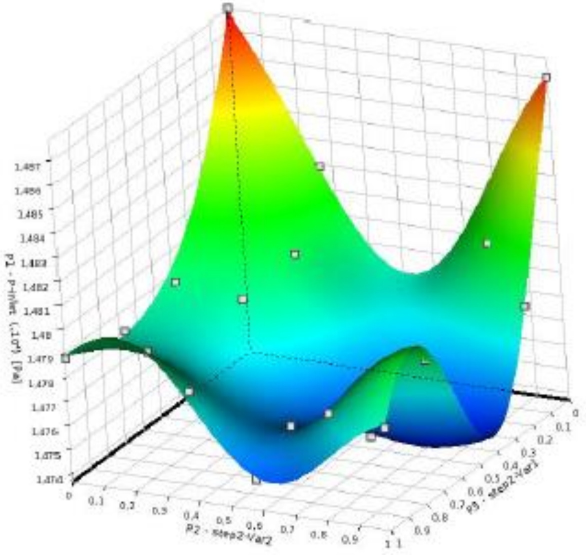
$$y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1} X_{i2} + \beta_4 \log X_{i3} + \varepsilon_i$$

- A weighted linear combination of RBF functions

$$f(x) = \sum_{1}^{n} \omega_i \phi(\|x - c_i\|)$$

- Neural network
- …

Fitting

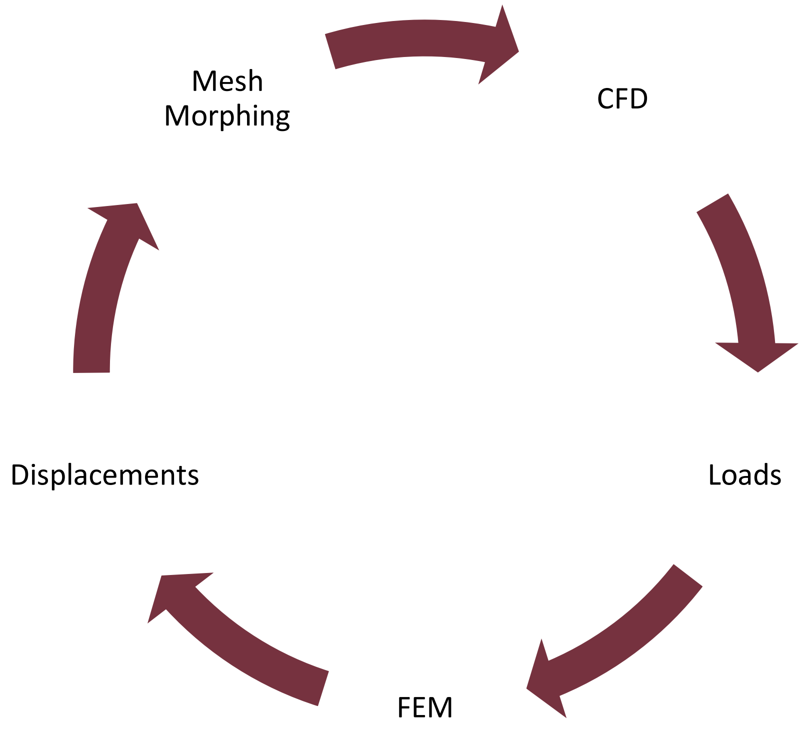


Introduction: Methods

Fluid-Structure-Interaction (FSI)

- To study fluid-structure interaction with high-fidelity analysis there are generally two approaches:
    - 1 way
    - 2 ways
    - Modal Superposition

- In this study, the focus is on the two-way method:
    - From the CFD analysis, the aerodynamic loads are calculated and exported;
    - The loads are imported into the FEM model and the displacements are estimated;
    - The displacements are used to deform the CFD mesh and have a more accurate estimate of the loads.
    - The workflow is iterated until forces and displacements converge



Mesh Morphing

CFD

Loads

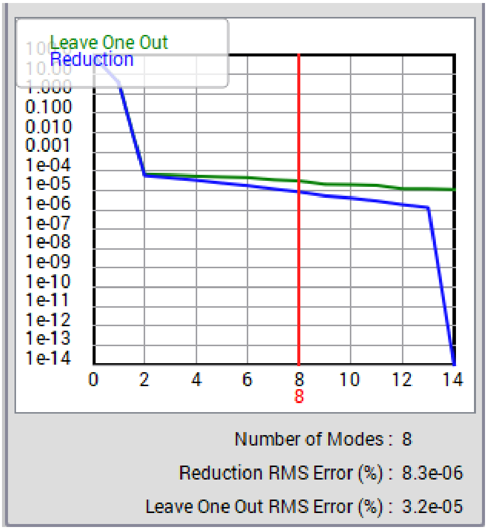
FEM

Displacements

Introduction: Methods

Digital twin development: SVD + ROM

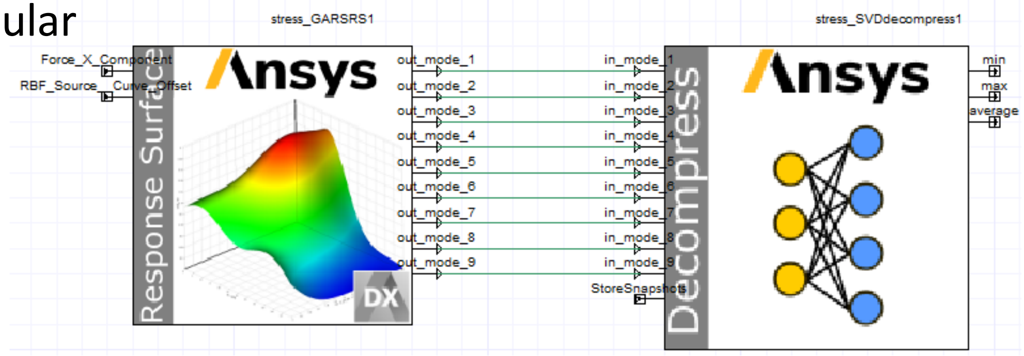
- One of the best-known applications of SVD is Principal Component Analysis (PCA);
- Given a matrix $A \in R\ m \times n$ and given $p = \min(m, n)$, a singular value decomposition (SVD) of A is a factorization of the form:
  $A = U\Sigma^t V$
- $U = (u_1 \dots u_m) \in R\ m \times m$ and $V = (v_1 \dots v_n) \in R\ n \times n$ are orthogonal and $\Sigma \in R\ m \times n$ is (pseudo)diagonal with diagonal elements $\sigma_1 \geq \dots \geq \sigma_p \geq 0$
- $\sigma_1, \dots, \sigma_p$ are the singular values of A
- A can be rewritten as: $A = \sum_1^k \alpha_i U_i$, where k are the principal singular values
- Finally, to construct the ROM it is necessary to find a correlation between input parameters and mode weights, and several interpolation methods can be used (RBF, Polynomial/Gaussian Regression, neural networks)



Number of Modes : 8

Reduction RMS Error (%) : 8.3e-06

Leave One Out RMS Error (%) : 3.2e-05



Design And Optimization

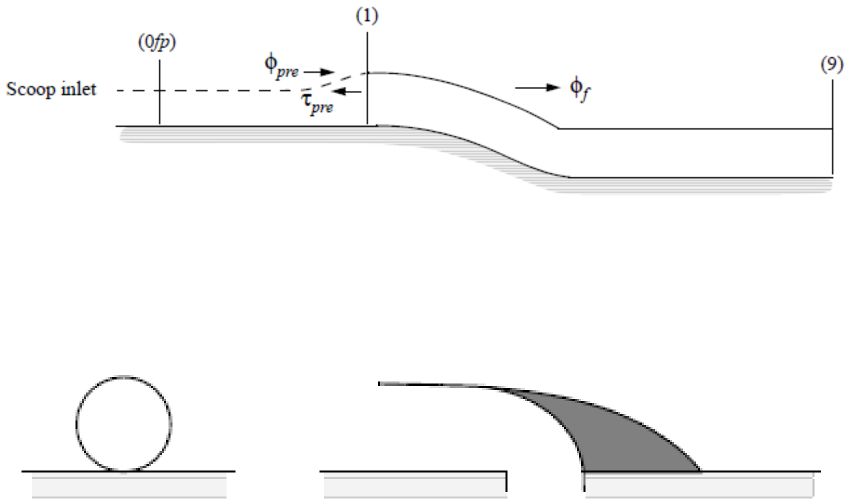
Design baseline: ESDU 86002

Input:

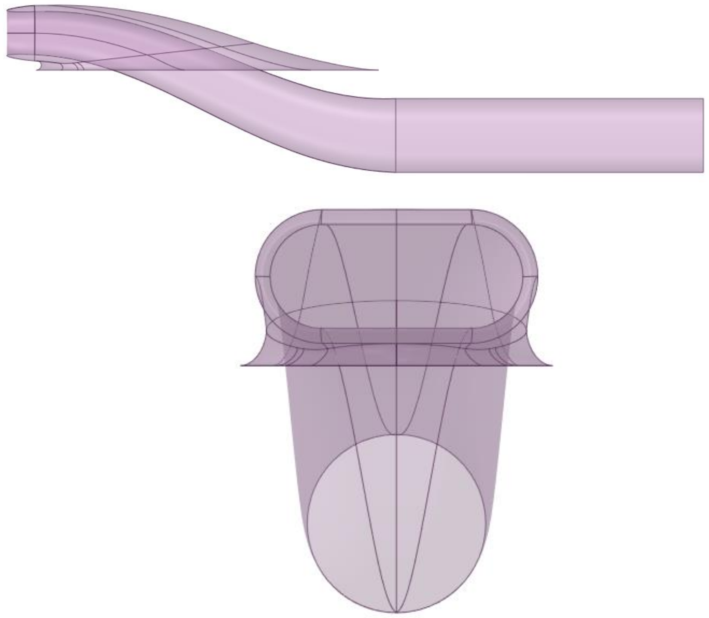
- Required massflow
- Momentum thickness
- Boundary layer thickness
- Mach number

Output:

- Sizing



Some images extracted from the standard

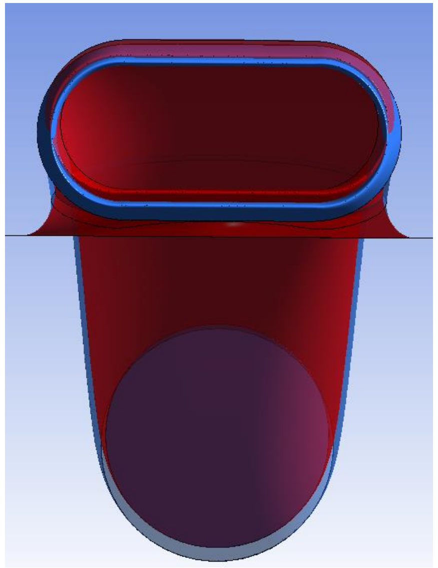


CAD baseline

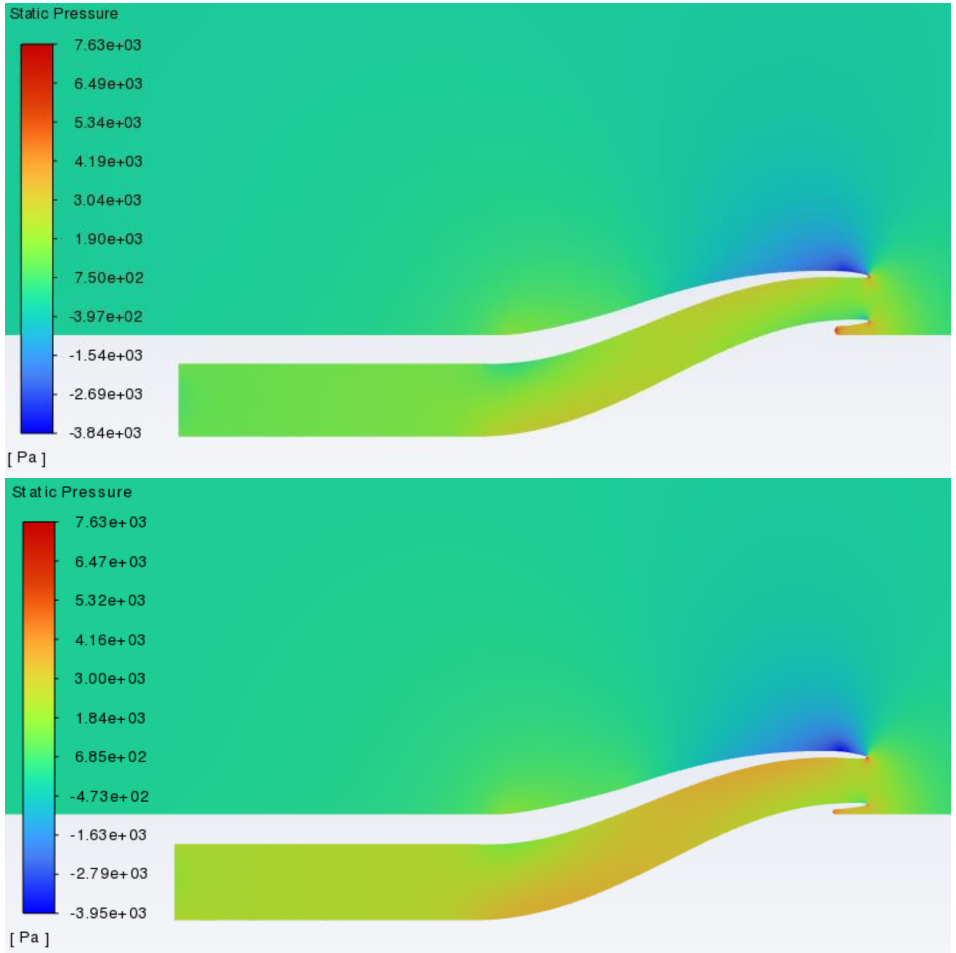
Design And Optimization

CFD Optimization

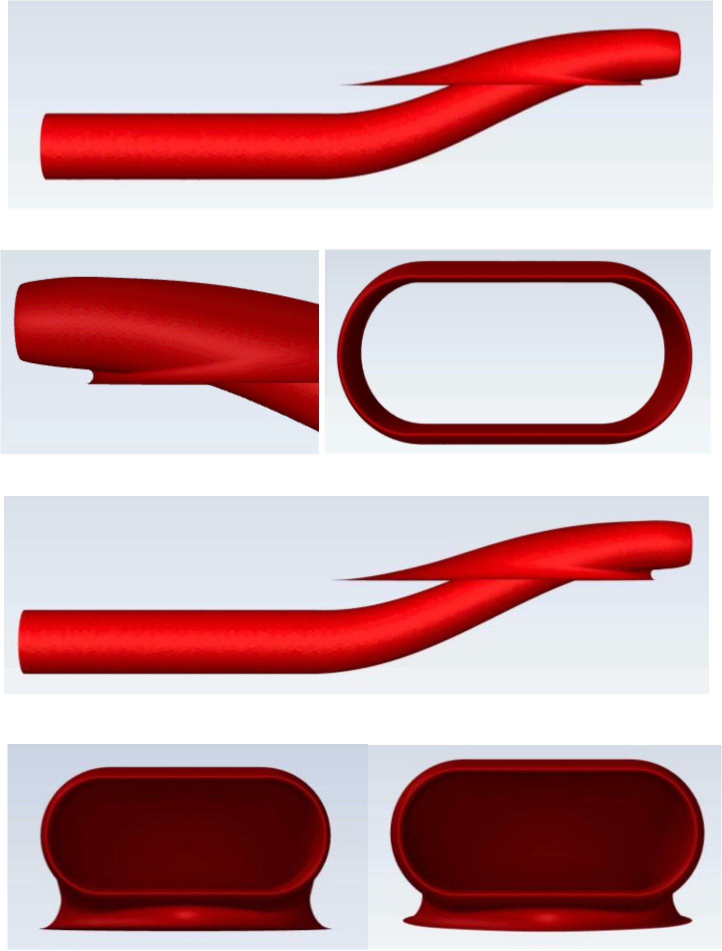
- Drag -32%
- Outlet pressure +86%



Comparison of baseline (red) and optimized (blue)



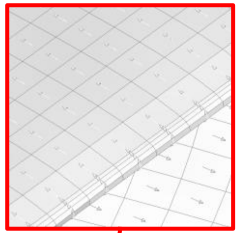
Pressure on symmetric plane baseline (above) and optimized (below)

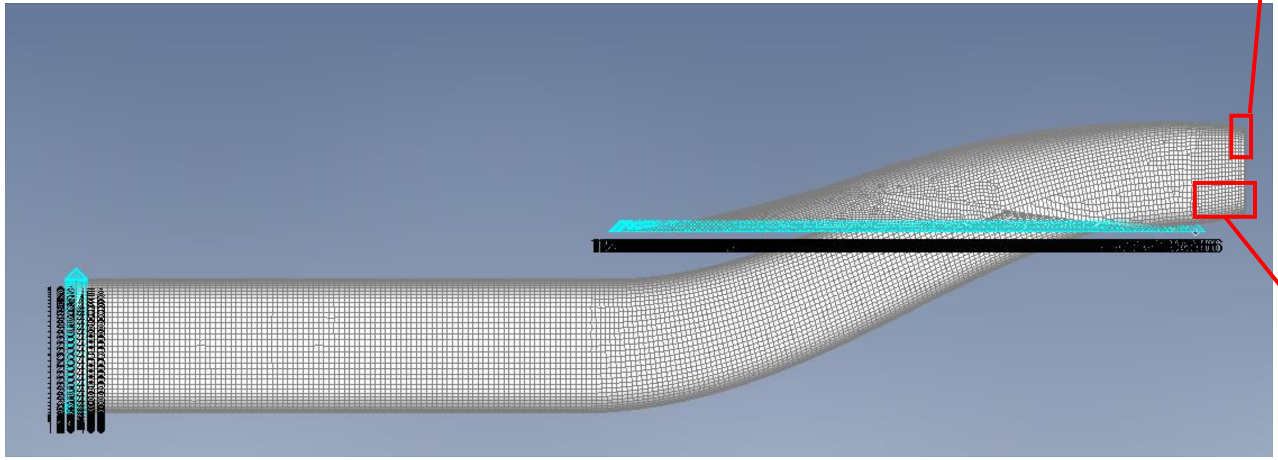


6 shape parameters

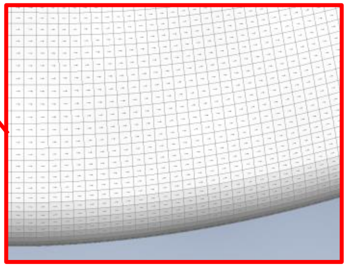
FEM Analysis: Mesh and parameters

- Laminate Plate, Linear elements: 48874
- Tsai-Wu Failure Theory
- Constraints: Fixed curves
- Loads: Pressure field of the most critical point (FSI)
- Parameters: Number and angle of plies





Morphed mesh



Material orientation

Density [kg/m^3]	*1530*
E11 [Pa]	*1.83 E+11*
E22 [Pa]	*9 E+9*
G12 [Pa]	*8 E+9*
G1z [Pa]	*8 E+9*
G2z [Pa]	*4 E+9*
X1t [Pa]	*1.5 E+9*
X2t [Pa]	*9.5 E+8*
X1c [Pa]	*7 E+7*
X2c [Pa]	*2 E+8*
S12 [Pa]	*8 E+7*
nu	*0.35*

Material property

Design And Optimization

FEM Analysis: Number of plies

Baseline:

- 24 Plies of 0.25 mm
- Lamination sequence: [45/-45/02/90/02/45/-45/02]s

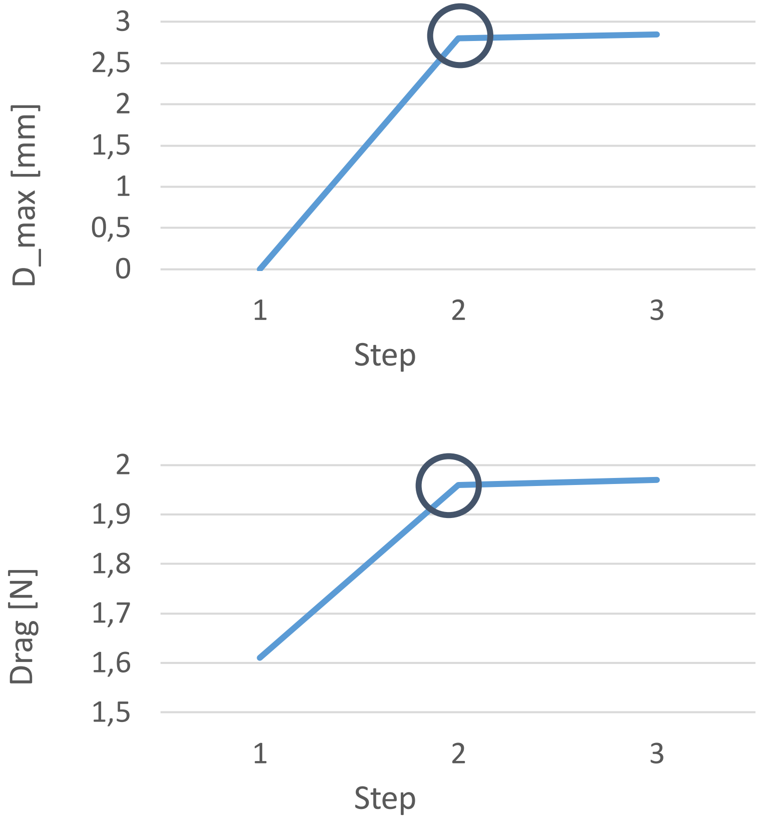
Optimized number of plies:

- 4 Plies of 0.125 mm
- Lamination sequence: [0/90]s

Mass reduction: -92%

	Delta
Drag	+0.3 N
P_Out	+0.3%

Variation of CFD performances



Convergence of FSI workflow

Results: Digital Twin

FEM ROM: Commercial software

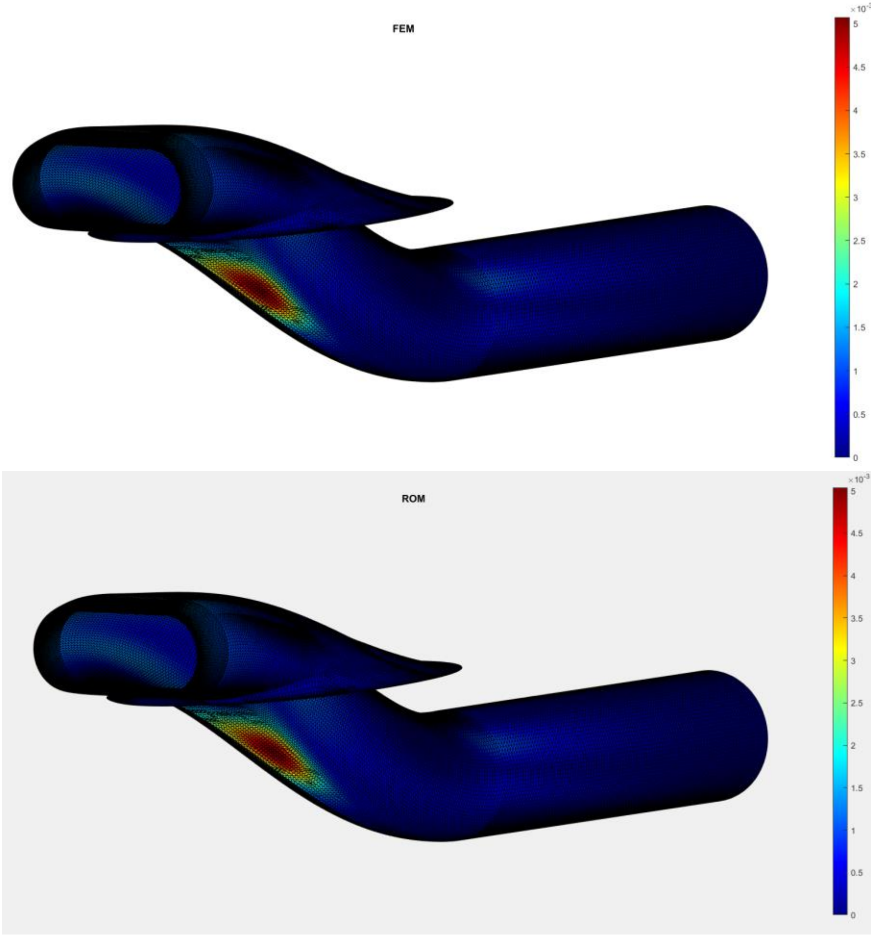
Input:
- 2 angle value

Output:
- Displacements field

Ansys Twin Builder was used to identify the relationship between input parameters and mode weights

ROM Relative error < 5%

Exported as .fmu



Comparison of FEM (left) and ROM (right) displacements for a random point of the test set

Results: Digital Twin

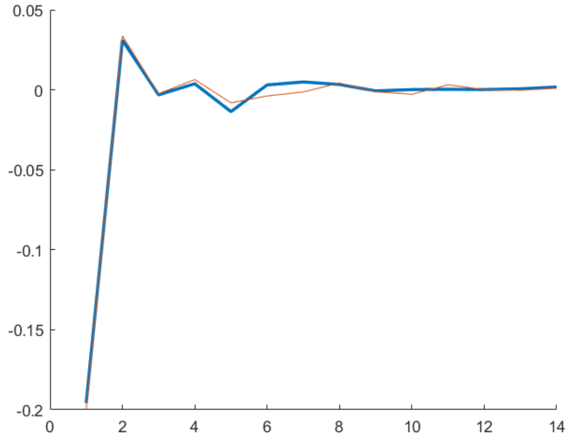
FEM ROM:
Matlab code

Input:
- 2 angle value

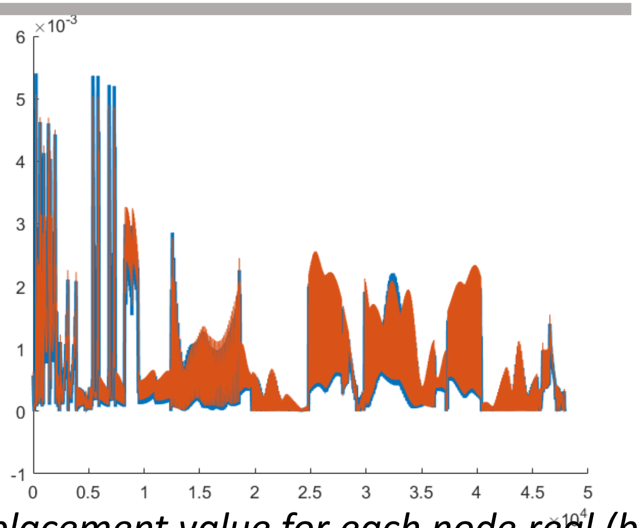
Output:
- Displacements field

A neural network was trained to identify the relationship between input parameters and mode weights

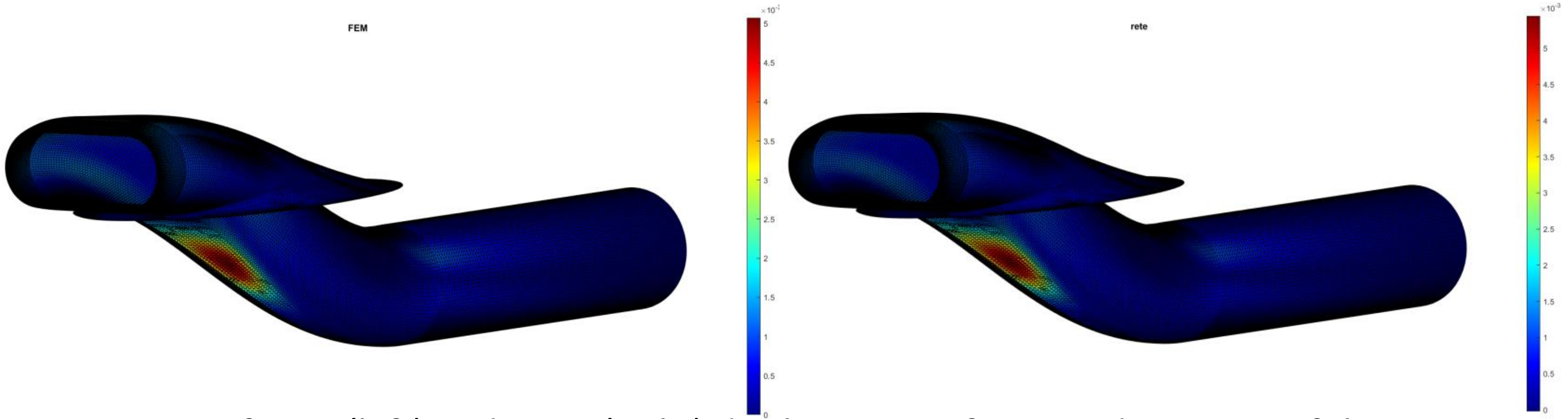
ROM Relative error < 6%



Weight of modes real (blue) and calculated by the neural network (orange)



Displacement value for each node real (blue) and calculated by the neural network (orange)



Comparison of FEM (left) and ROM (right) displacements for a random point of the test set

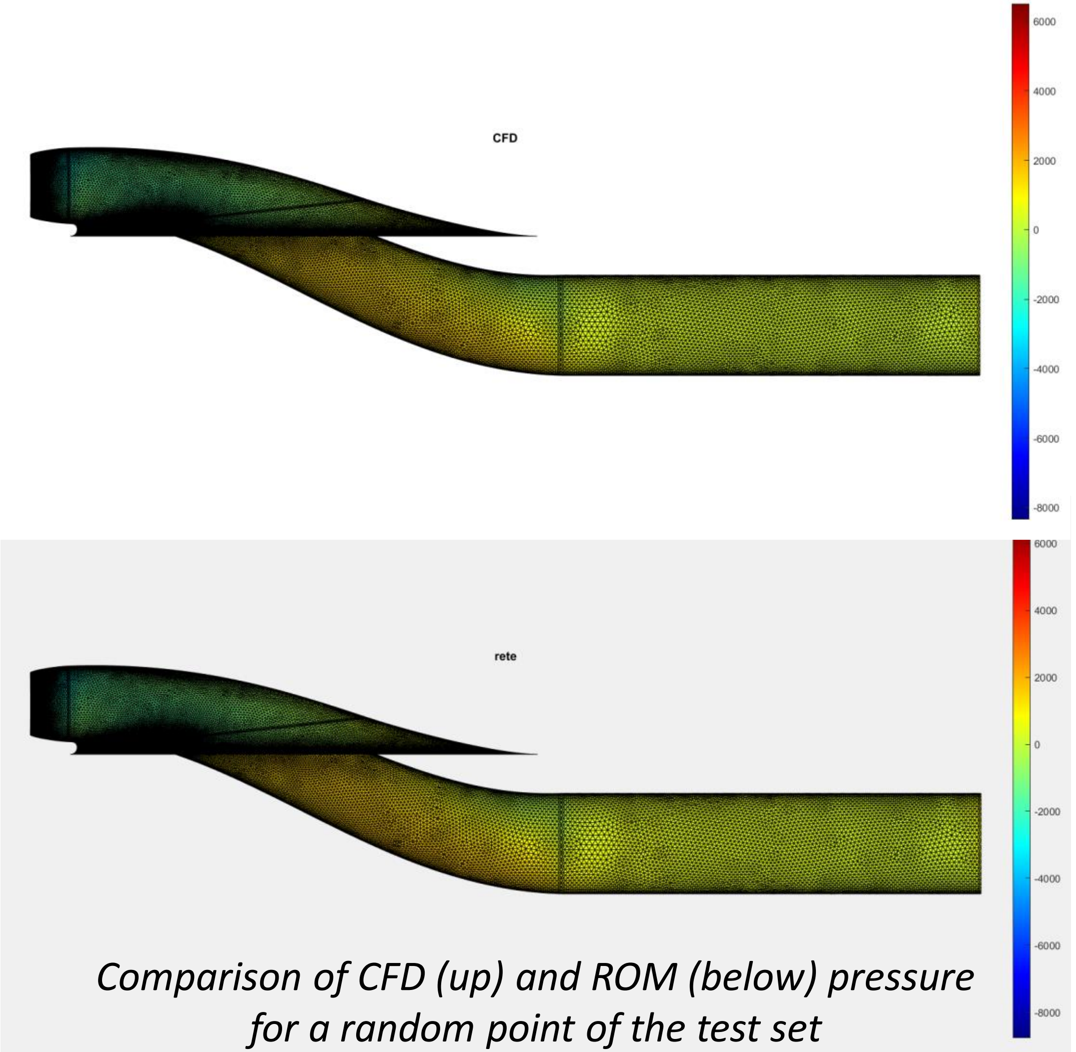
Results: Digital Twin

CFD ROM

Input:
- 6 shape parameters
- Velocity
- Outlet massflow

Output:
- Pressure field

ROM Relative error < 6%

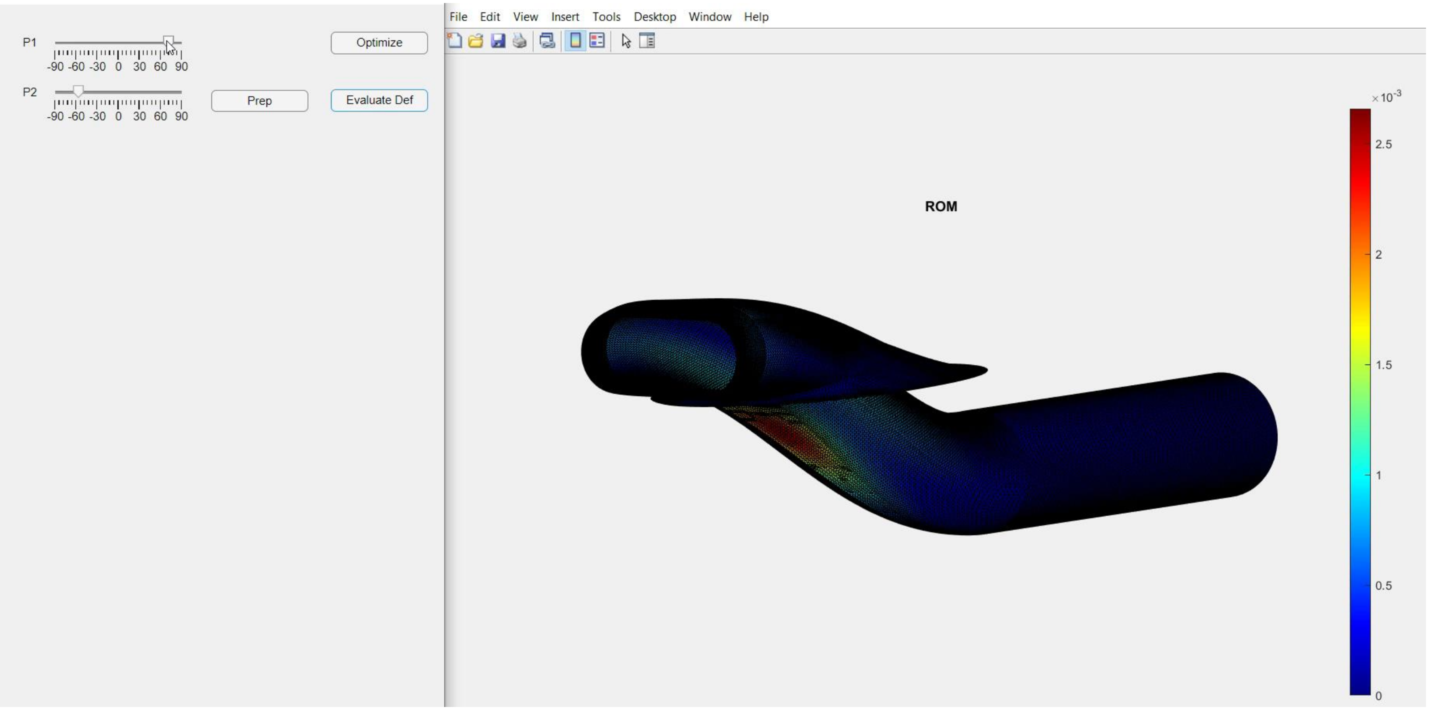


Comparison of CFD (up) and ROM (below) pressure for a random point of the test set

Results: Digital Twin

Optimization dashboard

- Physical parameters are set and the optimum is identified;
- Field quantities can also be evaluated in real time;
- Accurate and reliable;
- Understanding of the physics of the problem.



Results

FEM Optimization: Angle of plies

Baseline:

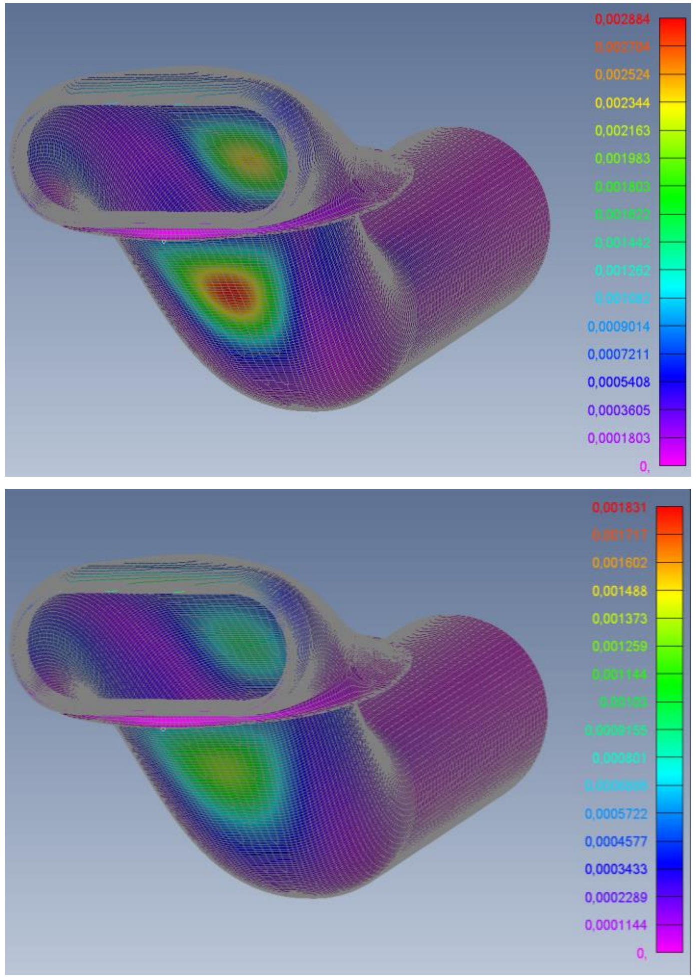
- Lamination sequence: [0/90]s

Optimized angle:

- Lamination sequence: [-90/0]s

Max Displacements reduction: -36%

	Max Displamets [mm]
Baseline	2.88
Optimized	1.83



Displacements baseline (above) and optimized (below)

Conclusions

- CFD optimization: Drag -32% ; P_out +86%
- Mass reduction: Mass -92%
- FEM optimization: Max_displ -36%
- ROM development: ROM Realtive Error < 6%

- The workflow presented enables improved fluid dynamic and structural performance.
- The extracted ROMs allow real-time evaluation of the quantities of interest and can be used to create an optimization dashboard or can be integrated with visualization tool

Thank You For Your Attention

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