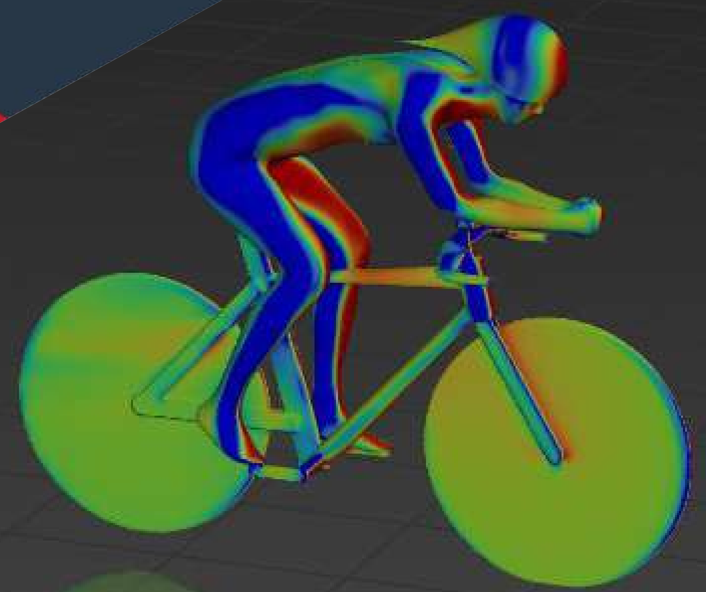
NAFEMS

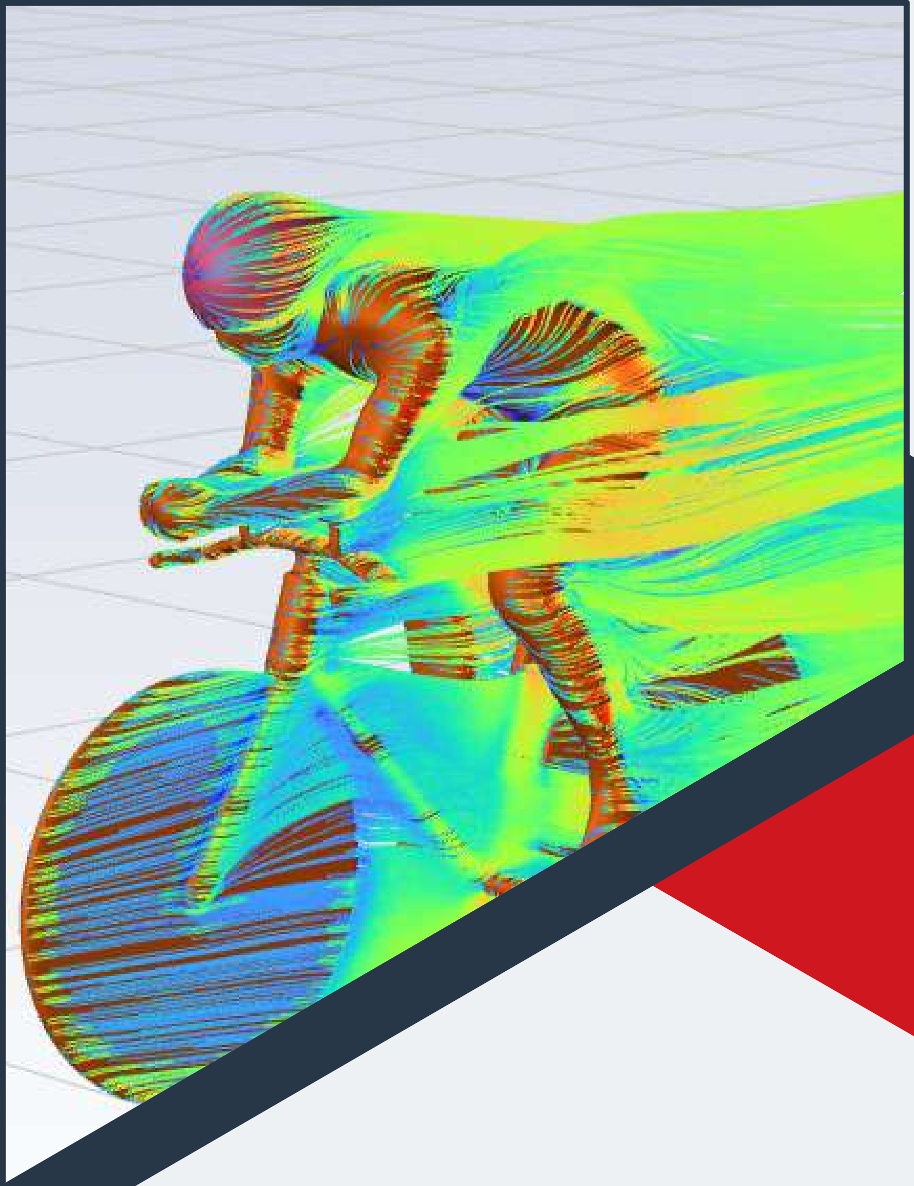
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

rbf™



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, Marco Evangelos Biancolini, Pier Paolo Valentini
University of Rome "Tor Vergata"
Department of Enterprise Engineering "Mario Lucertini"
emanuele.di.meo@uniroma2.it



Summary

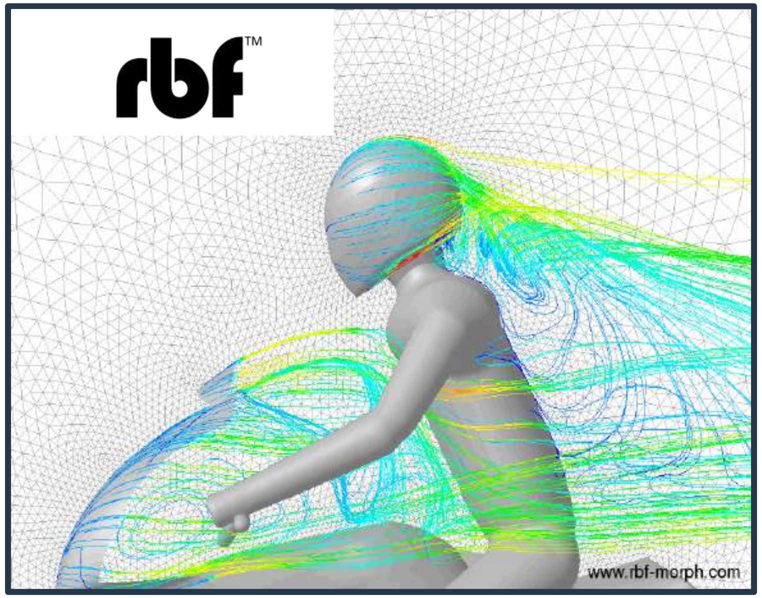
Who are we? Tor Vergata University

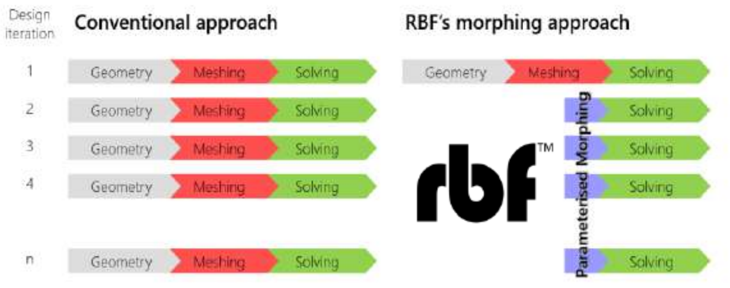
- **Department of Enterprise Engineering "Mario Lucertini",** Machine Design Group, involved in national and international research projects

- Authors details:
  - **Emanuele Di Meo**, Research Fellow in Novel CAE-based Digital Twin Technologies
  - **Andrea Lopez**, PhD Student in Digital Twin Technologies
  - **Corrado Groth**, Tenure-track Assistant Professor of Machine Design
  - **Marco Evangelos Biancolini**, Associate Professor of Machine Design
  - **Pier Paolo Valentini**, Full Professor of Computer-Aided Design and Virtual Prototyping

Who are we? RBF Morph

- **RBF Morph** is an ISV, pioneer and world-leading provider of numerical morphing techniques and CAE solutions
- **rbf-morph.com**
- **Technical Partner of Ansys Inc. since 2009** (OEM since 2012) with solutions for structures and fluids
- **Partnership with University of Rome 'Tor Vergata'** academic and industrial synergy
- **Multi-sectorial CAE** analysts, focused on high fidelity multi-physics problems
- Cutting-edge technologies and **academic research driven by industrial needs**
- Clear idea of the direction taken by industry, deep knowledge of the **technologies available now** and in the near **future**

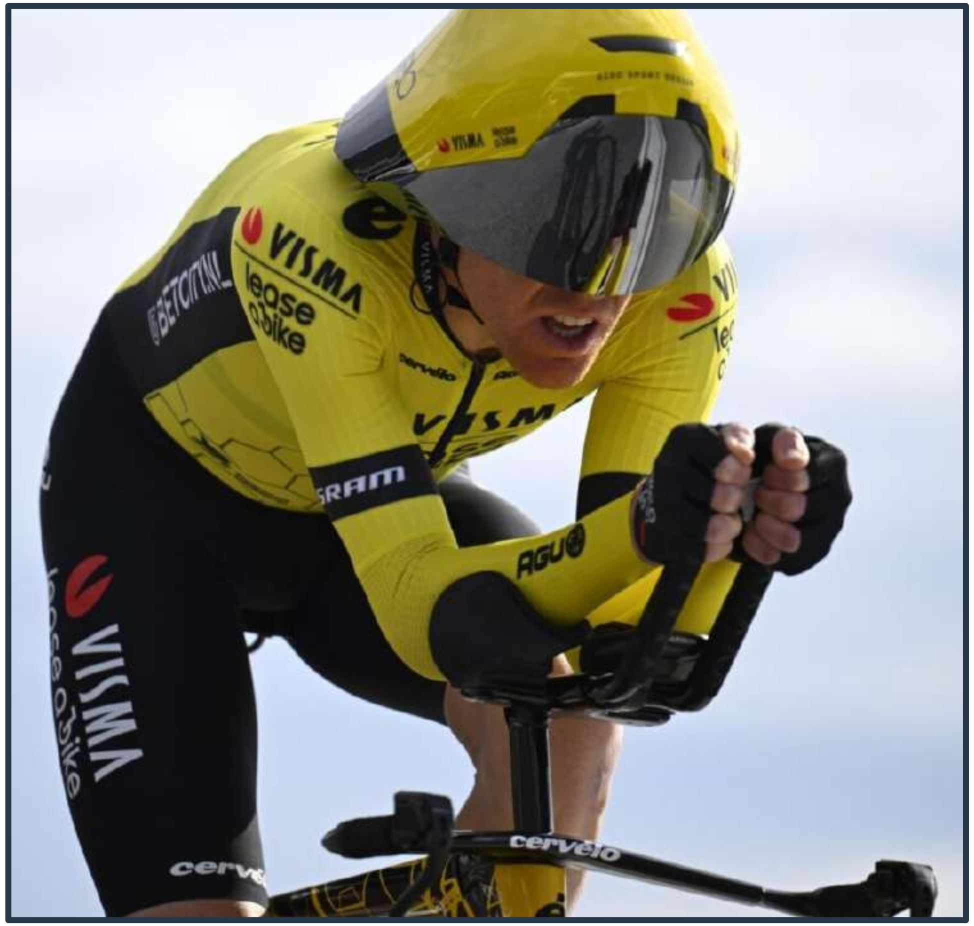




Reduced-Order Model of a Time-Trial Cyclist Helmet for Aerodynamic Optimization through Mesh Morphing and Real-Time Interactive Visualization
Emanuele Di Meo, Andrea Lopez, Corrado Groth, Marco Evangelos Biancolini, Pier Paolo Valentini

Introduction

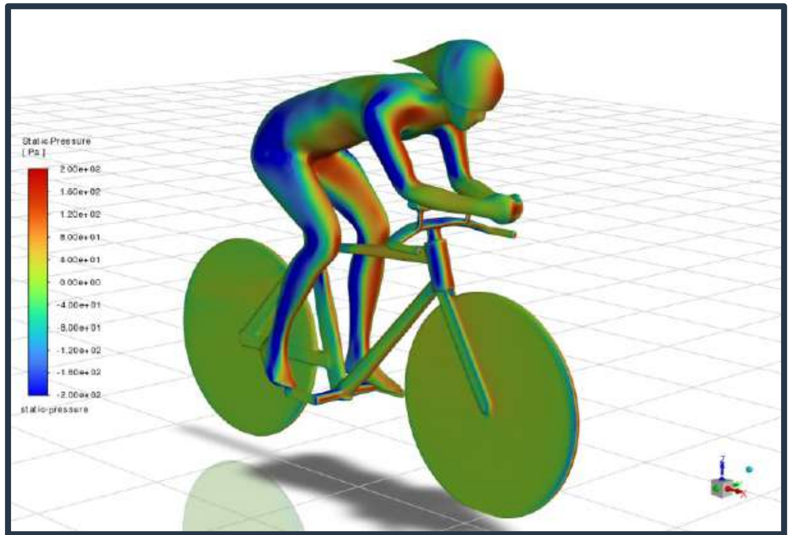
- **Time-trial** cycling races against the clock require **optimal aerodynamics**
- Research emphasizes **positioning**, **attire**, and **helmet** choices to minimize drag for efficiency
- Reducing aerodynamic drag in cycling was crucial in **Greg Lemond's victory** over Laurent Fignon in the 1989 Tour de France
- Recent helmets aerodynamics development led to **innovative helmet** design **shapes**

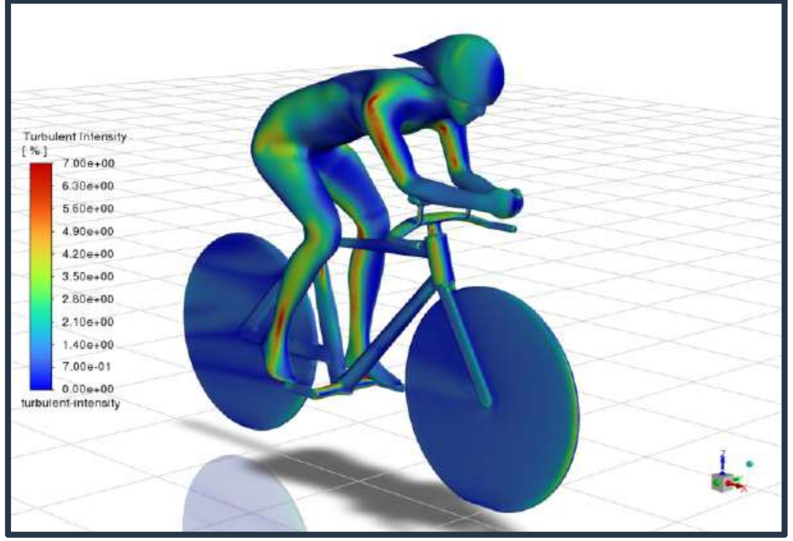


Credits: Team Visma | Lease a Bike

Introduction

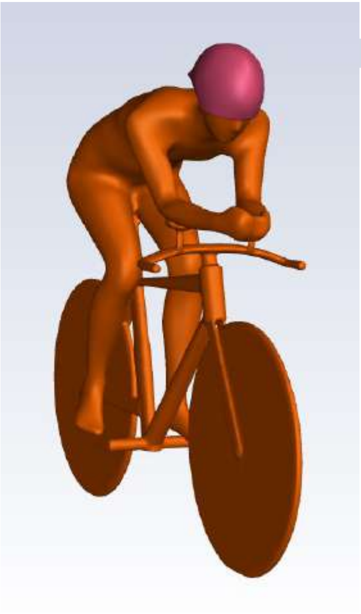
- The aim of the study is to create an **accurate and reliable model** that allows to evaluate in **real-time** both **scalar** and **field quantities** such as:
  - Drag Force
  - Static Pressure
  - Turbulent Intensity
  - Wall Shear Stress
  - …
- A procedure has been developed for optimizing the helmet shape using **mesh morphing** and **response surface** techniques





Introduction

- **Workflow**



CAE Model

↓

Parametrization

↓

Simulations for dataset creation

↓

Machine Learning Algorithms

↓

Reduced-Order Model (ROM)

→

Methods

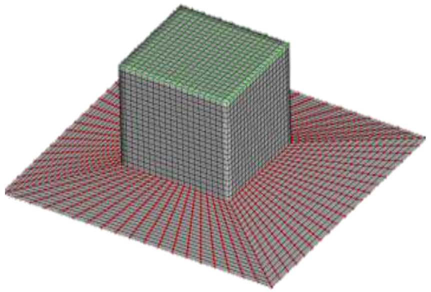
- **RBF Mesh Morphing**

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

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

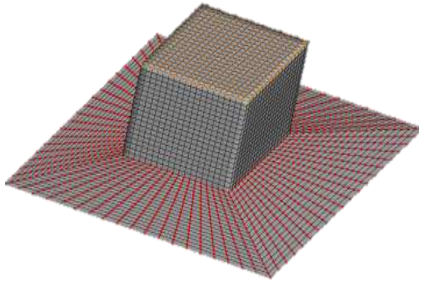


Classic

1	Geometry	Meshing	Solving
…	Geometry	Meshing	Solving
n	Geometry	Meshing	Solving

RBF

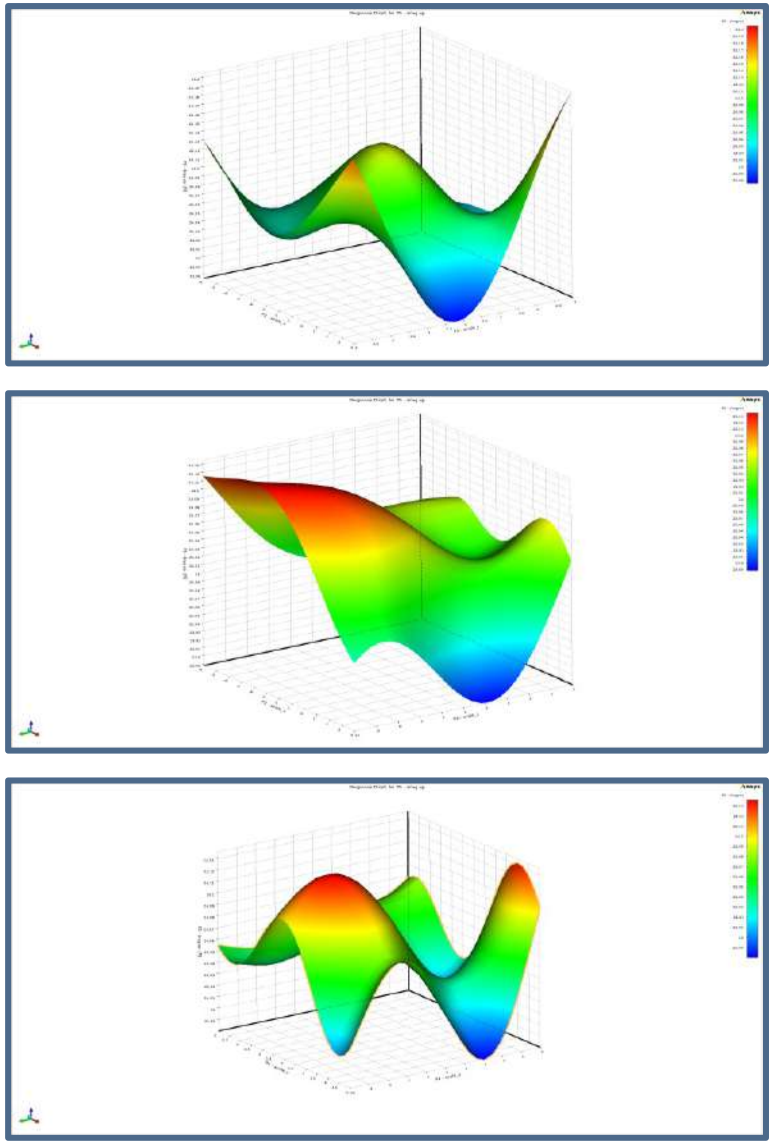
1	Geometry	Meshing	Solving
…		Morphing	Solving
n		Morphing	Solving



Methods

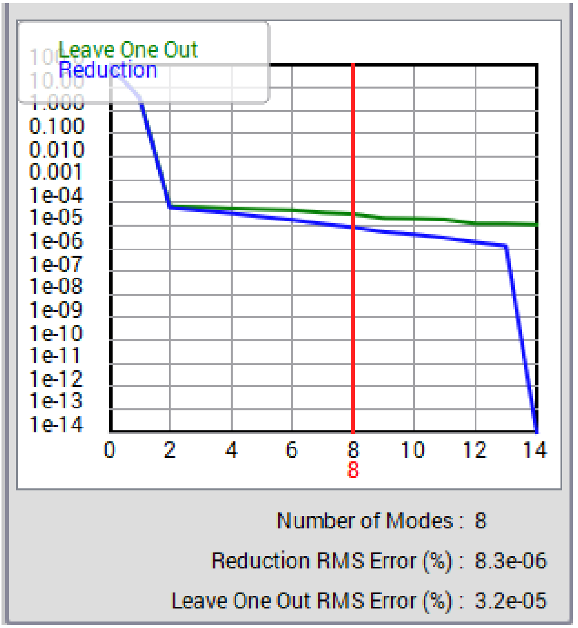
• Response Surface Optimization

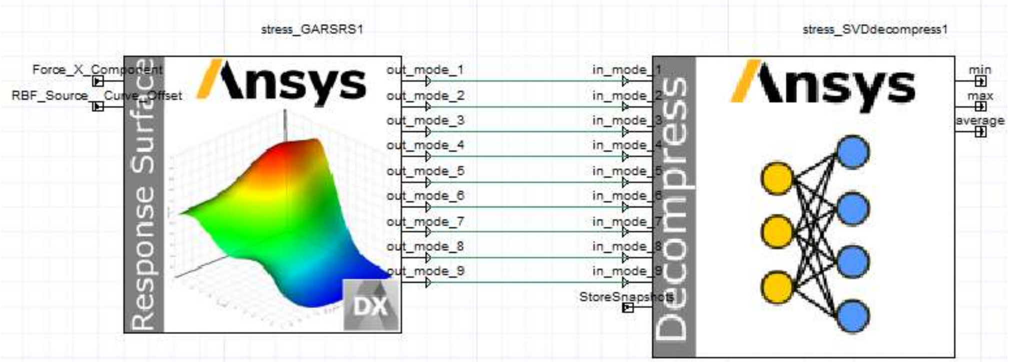
- **A Design of Experiments** (DoE) is performed using a **Latin Hypercube** sampling technique
- A candidate point is selected through **Response Surface Optimization** methods
- The generated dataset is used to build a **Reduced Order Model** (ROM)
- This approach enables efficient exploration of the design space, facilitating the **identification of optimal configurations while minimizing computational resources** and time



Methods

- **Reduced Order Models development**
  - The numerical approximation of parametrized partial differential equations (PDEs) for **multiple parameter values**, or for solving them in real-time, requires **high computational resources** for **full-order models**
  - **Reduced order modelling (ROM)** techniques can be employed to reduce the computational cost associated with high-fidelity simulations while maintaining acceptable accuracy
  - **Real-time simulations** can be implemented on portable devices supporting **virtual and augmented reality**





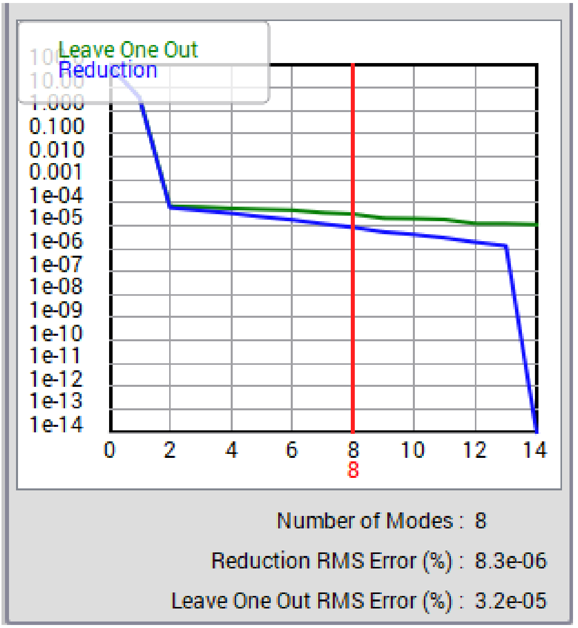
Methods

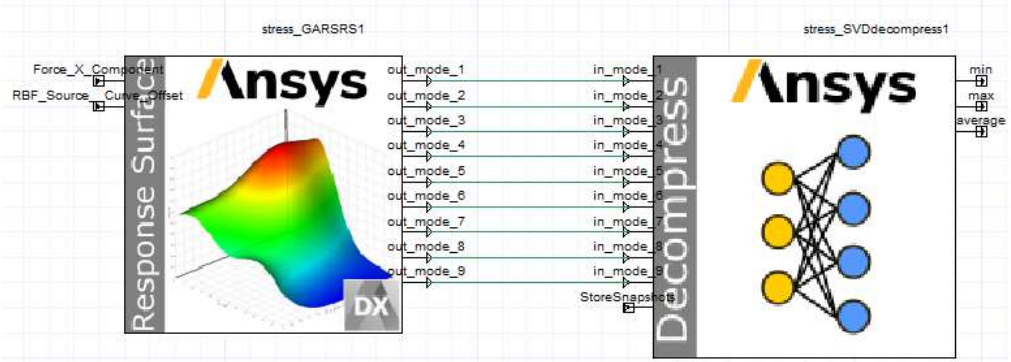
• Reduced Order Models development

- A common approach for model order reduction is the use of **Proper Orthogonal Decomposition (POD)** based on the **Singular Value Decomposition (SVD)** algorithm
- Given a matrix $A \in R\ m\ x\ n$, an SVD of A is a **factorization** in the form:

$$A = U\Sigma^t V$$

- A can be rewritten as: $A = \sum_1^k \alpha_i U_i$, where k are the **principal singular values**
- A **correlation** between input parameters and mode weights must be established to build the ROM
- Several **interpolation methods** can be used (RBF, Polynomial/Gaussian regression, neural networks)

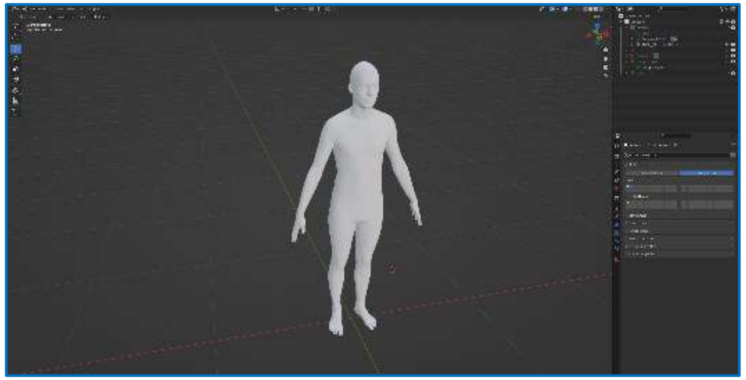


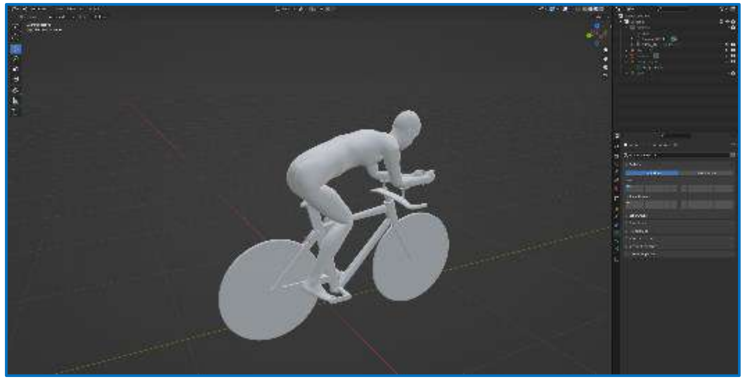


Case study

• Cyclist modelling and positioning

- A human body model was imported from the **DINED** anthropometric database of TU Delft, specifically an **adult male** with a height of **180 cm**
- The model was refined and a **bicycle model** was added using the Blender software
- The **helmet geometry** was reconstructed using 3D CAD software, referencing actual **product datasheets** and **images** for accuracy and detail, ensuring a realistic representation of the whole assembly
- A **computational domain** with dimensions of **10 x 3.5 x 3 m** was modelled for the computational fluid dynamics analysis

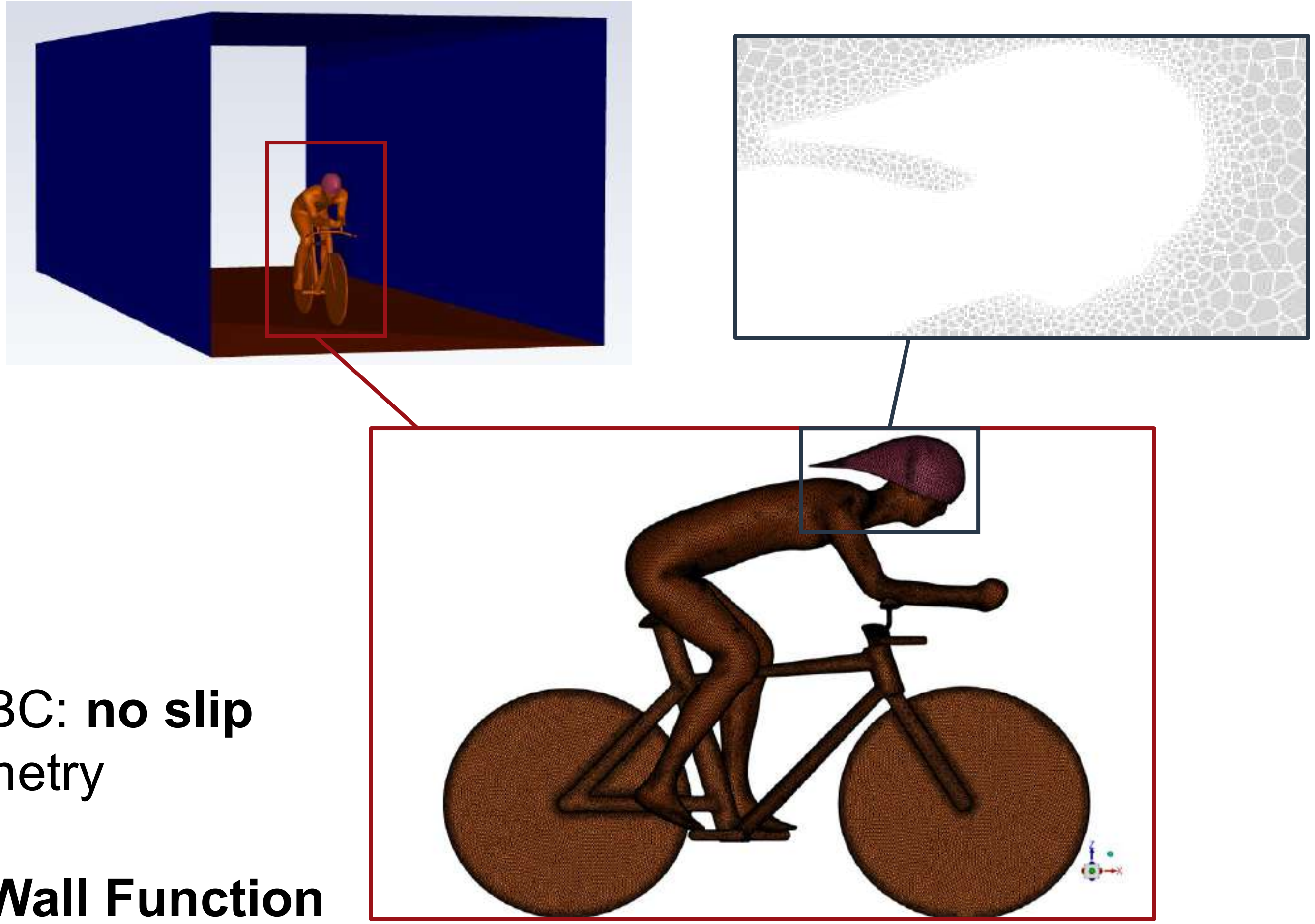




rbf™ TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA NAFEMS

Case study

- **Mesh**
  - **Polyhedral elements**
  - **4.08 millions cells**
  - 20.5 millions facets
  - 13.4 millions nodes
- **CFD settings**
  - Software: Ansys Fluent
  - **Inlet Velocity: 15 m/s**
  - Turbulent Intensity: 1%
  - Helmet, cyclist and ground surfaces BC: **no slip**
  - Lateral and upper surfaces BC: symmetry
  - Outlet Pressure: 0 Pa (relative)
  - **Turbulence model: k-ε, Enhanced Wall Function**



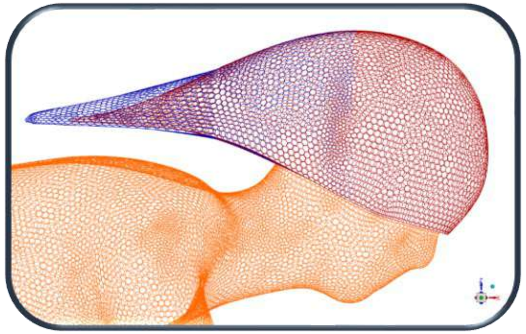
Case study

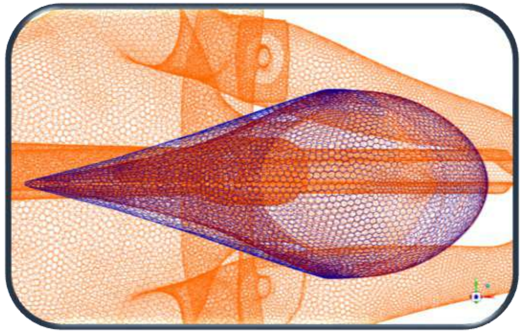
• Mesh Morphing, DoE and ROM setup

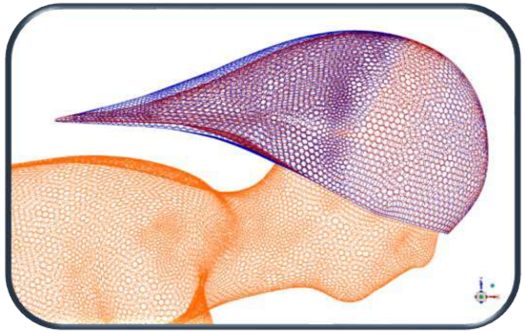
- The **mesh morphing** setup was performed through the RBF Morph software, targeting the backside of the helmet
- Three **scaling parameters** were defined along x, y, and z axes
- Parameters range: **scale x (-8;4), scale y (-1;5), scale z (0;10)**

- The **Design of Experiments** was implemented choosing **100 design points** (DPs)
- **Latin Hypercube Sampling** was used for generating the DPs

- The **Reduced Order Model** was configured in the Ansys Twin Builder platform, utilizing a total of **100 snapshots**
- Of the total number of snapshots, **50** were designated for **model training** and **50** for **model validation**, incorporating **10 modes**

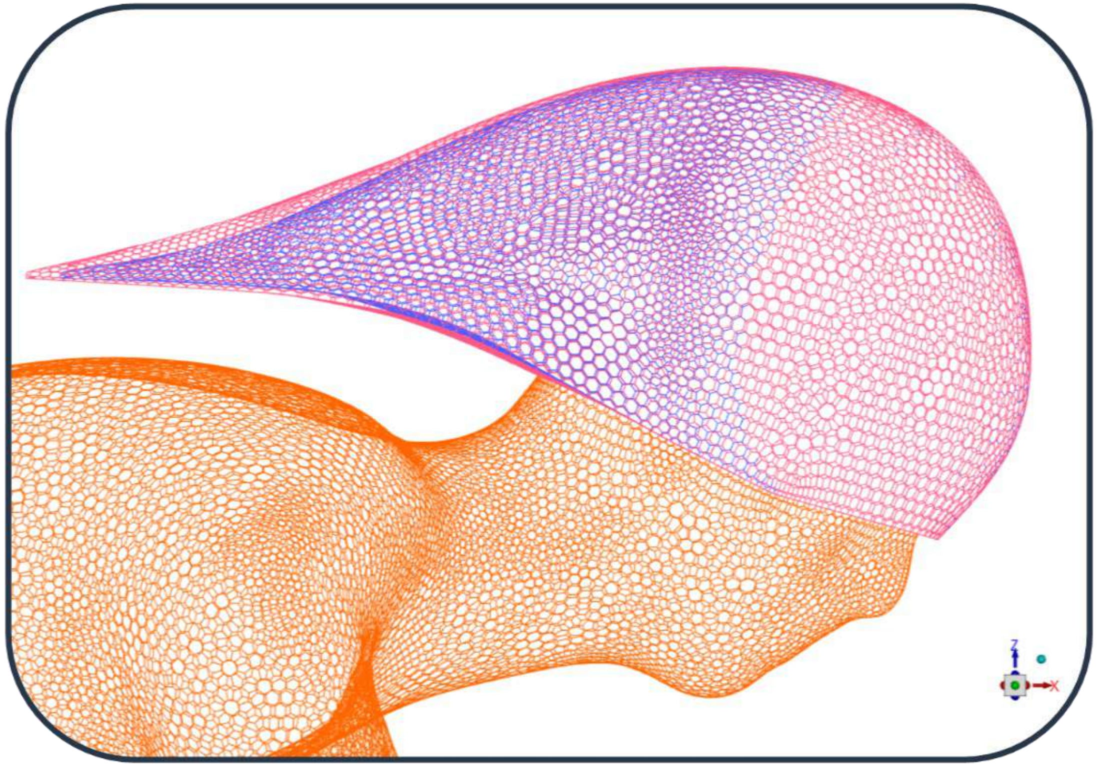






Results

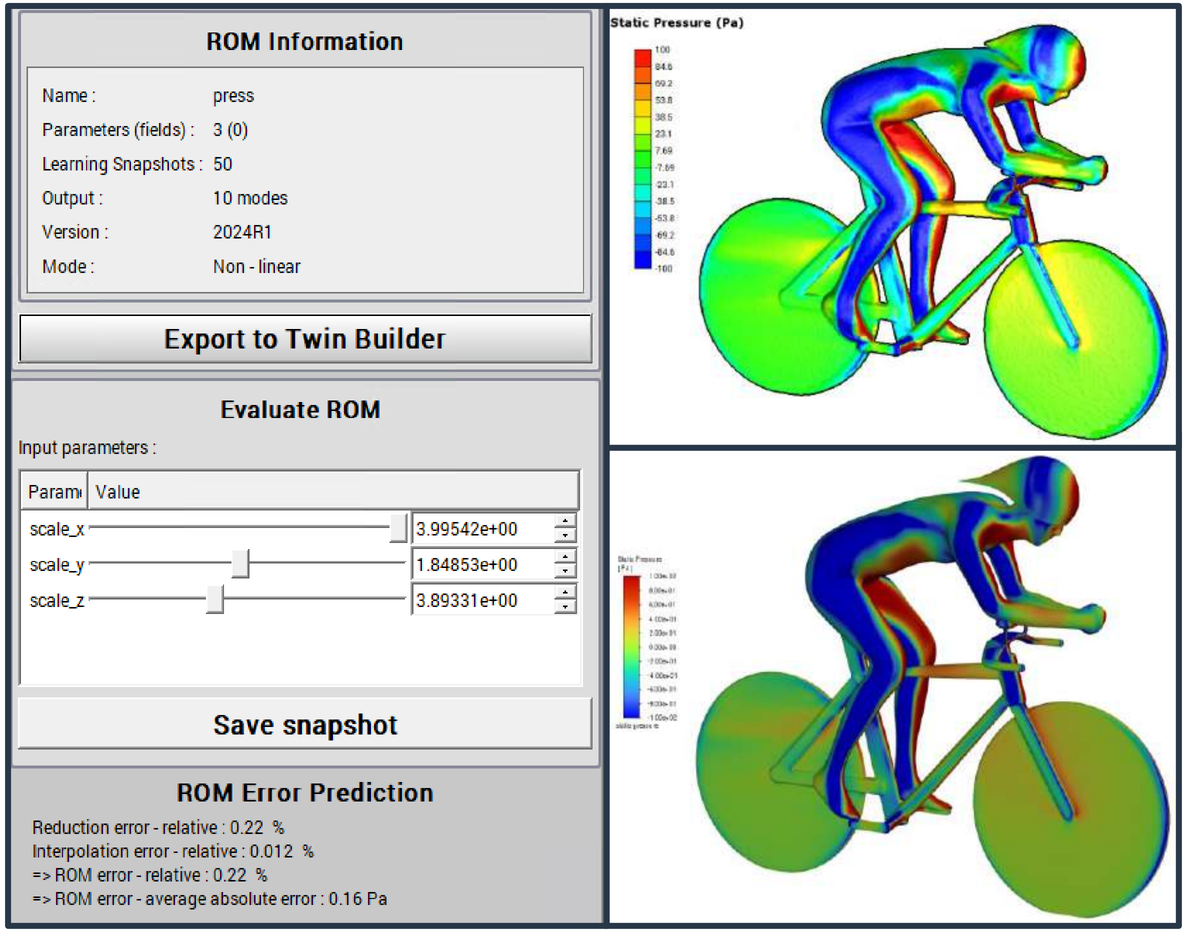
- ## Optimization
  - **Response Surface Optimization** results in a **4.56% drag reduction** on the **helmet** only
  - The helmet shape optimization has also a **positive impact** on the overall assembly, reducing drag on the **cyclist** by **0.77%**
  - **Total drag decreased** by **0.91%,** dropping from 24.239 to 24.019 N
  - The optimal candidate point is characterized by respective values of **3.99, 1.85, and 3.89** for the **scaling** parameters along **axes x, y, and z,** obtaining the shape shown in figure



DRAG	Baseline [N]	Morphed [N]	Gap
Helmet	0.8866	0.8462	-4.56%
Cyclist	23.3528	23.1729	-0.77%
Overall	24.2394	24.0191	-0.91%

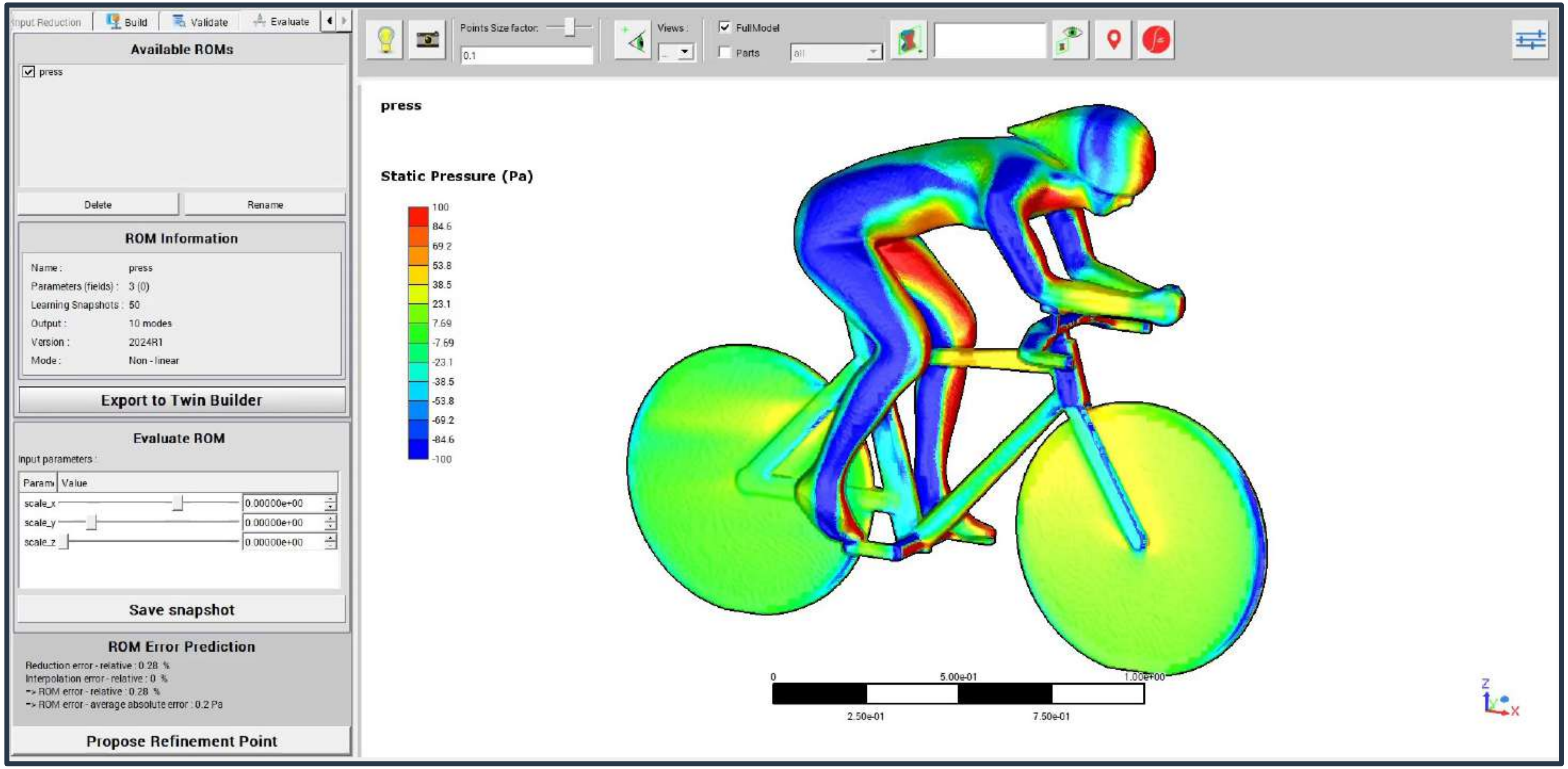
Results

- **ROM**
  - The **Reduced Order Model** allows **real-time evaluation** of shape changes, static pressure, turbulence intensity, and wall shear stress results
  - The **optimum design point** has a **ROM error** of **0.22%**, equivalent to **0.16 Pa**
  - The **maximum** ROM error in the DPs used for model building is **1.14% (13 Pa)**
  - Maximum model **reduction error** is **0.298%**
  - Pressure contours show an excellent **matching** between **full** and **reduced model**



Results

- **ROM**
  - **Real-time evaluation** of static pressure through the use of **ROM** is demonstrated in this video
  - Pressure level **varies** in both **helmet and back areas**



Results

• Implementation in Virtual and Augmented Reality

- **FMU** standard translated to **ARM**
- Headset model: **Meta Quest 3**
- Input parameters controlled **by hands**
- **Custom UI** developed tailoring specific application

- **ROM case studies** application delivered
- **Cyclist ROM** implementation (ongoing)

Live demonstration available

Conclusions

- The study provides a methodology for **improving aerodynamic design** by taking into account both **scalar and field quantities** in the optimization procedure
- In addition to classical methods as response surface optimization, innovative methods such as **ROMs have been implemented**, providing **real-time evaluation** of fluid dynamics quantities
- This detailed examination aims to provide a **better understanding of the physics** of the problem, helping designers in **optimizing the helmet shape** for improving cyclist performance
- Not only drag or pressure field but also **turbulence-related quantities** can be easily evaluated during the design process
- **Future developments** involve:
  - Investigation of **additional shape parameters**, particularly in the front and side areas of the helmet and on the bicycle
  - Results **verification with experimental data** from pressure sensors attached to the cyclist
  - Personalization of the **inside of the helmet** using a 3D scanner to create a customized design to fit the head
  - Implementation of the model in **virtual and augmented reality** environments and devices

NAFEMS

THANK YOU FOR YOUR ATTENTION

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, Marco Evangelos Biancolini, Pier Paolo Valentini
University of Rome "Tor Vergata"
Department of Enterprise Engineering "Mario Lucertini"
emanuele.di.meo@uniroma2.it

rbf™ TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

The authors wish to acknowledge the support of the National Center for HPC, Big Data and Quantum Computing, Project CN_00000013 – CUP E83C22003230001, Mission 4 Component 2 Investment 1.4, funded by the European Union – NextGenerationEU