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ESTECO INTERNATIONAL **USERS'** MEETING

Numerical simulation of aerospace propulsion systems: research and teaching

Andrea Ferrero
Associate Professor
Politecnico di Torino

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Agenda

CFD and Multi-fidelity model for nozzle optimization
Master thesis and course training in collaboration with ESTECO

Multi-Fidelity Modeling of Hydrogen Burner
Conference paper at AIAA Scitech 2025

Multidisciplinary and ROM for Optimization of a Jet Fighter
Master thesis and conference paper in collaboration with ESTECO

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CFD Analysis and Multifidelity Modeling for the Parametric Study of the Performance of a Convergent-Divergent Nozzle

Master Thesis by Linda Ennio in collaboration with ESTECO
(Thanks to C. La Guardia, F. Carlini and S. Genovese for support)

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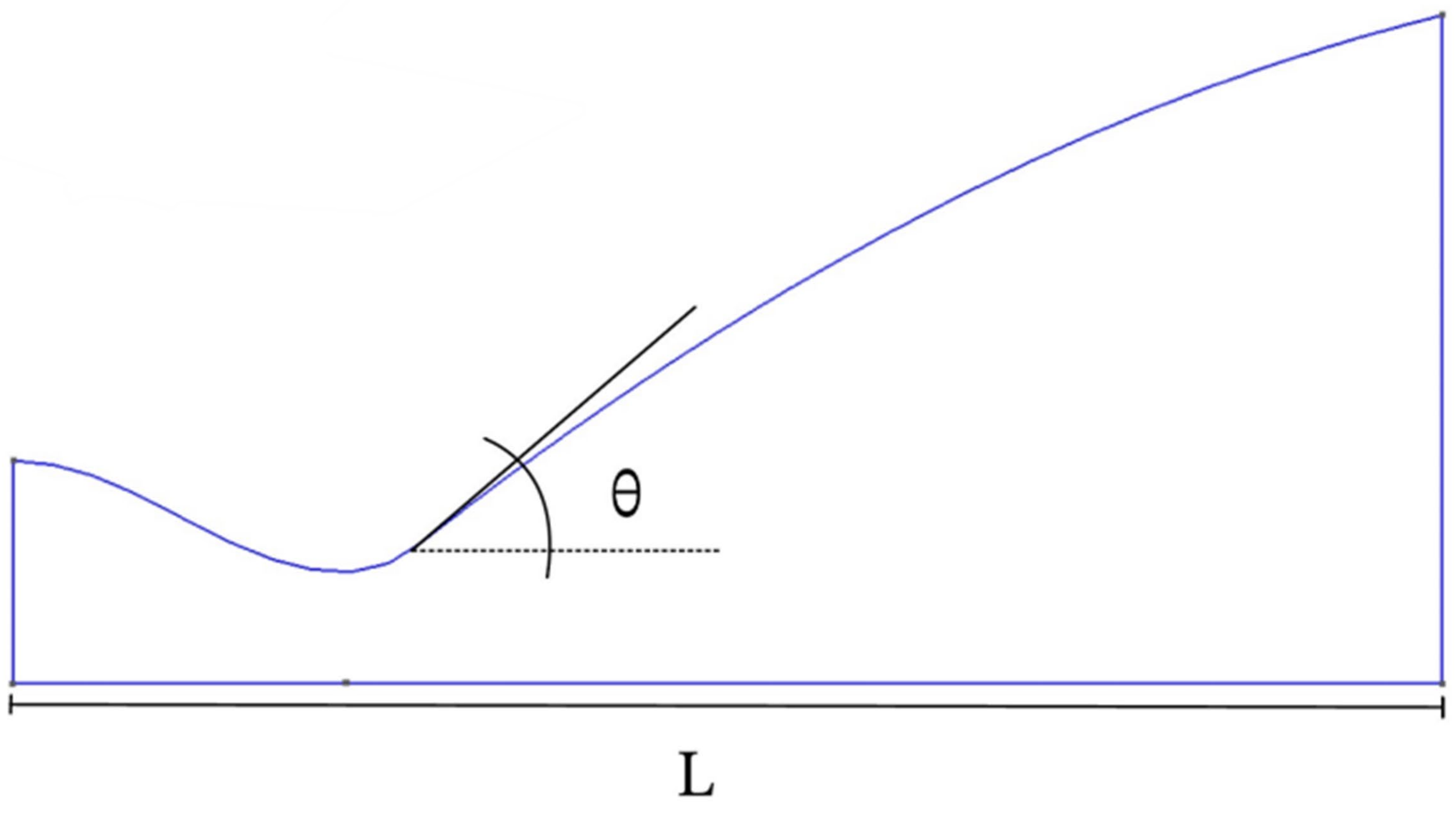
Problem definition

- 2D axysymmetric supersonic nozzle
- Preliminary design with quasi-1D model: area ratio is fixed
- **Two design parameters: angle θ and length L**
- **Two goal functions: thrust coefficient C_F**(to be maximized) and **nozzle surface S** (to be minimized)



- Multiobjective optimization problem
- Multifidelity approach:
  - Student-developed Euler Solver (low-fidelity)
  - Fluent solver for RANS simulations (high-fidelity)

$$L \in [9.5R, 10.5R]$$
$$\theta \in [38°, 42°]$$

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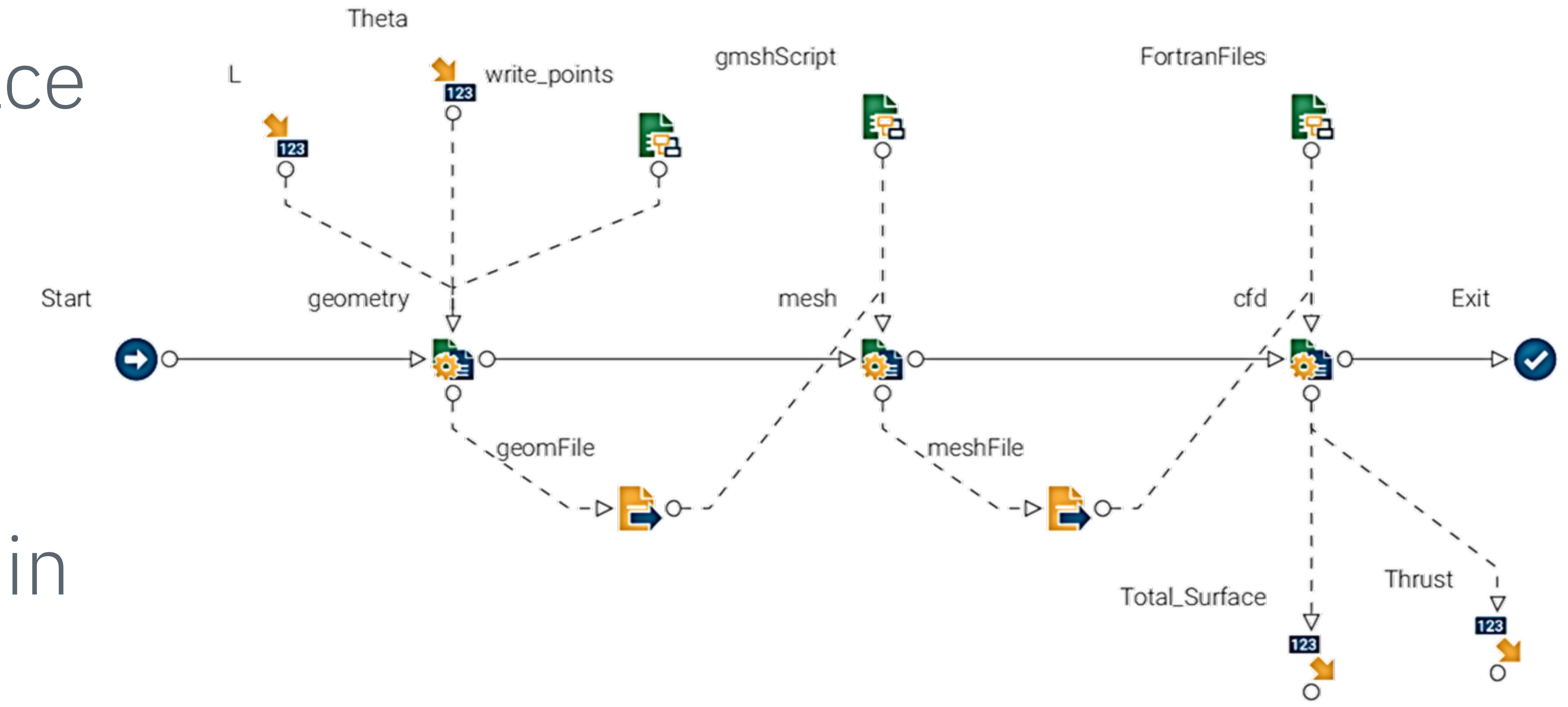
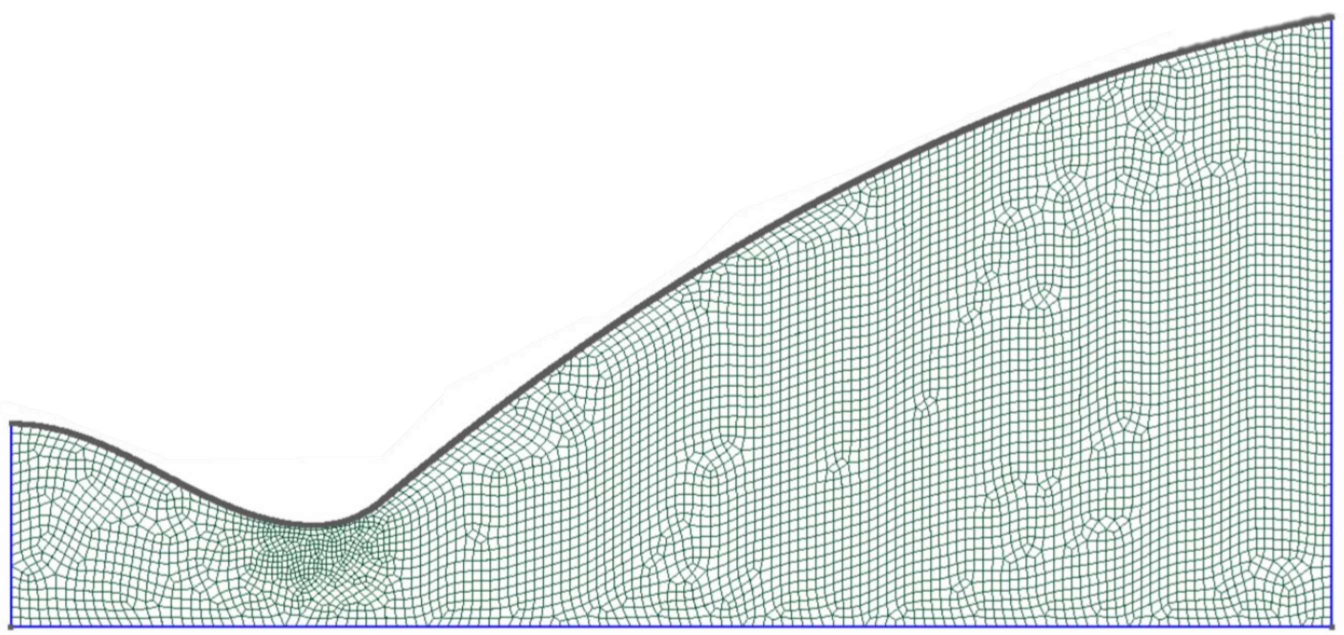
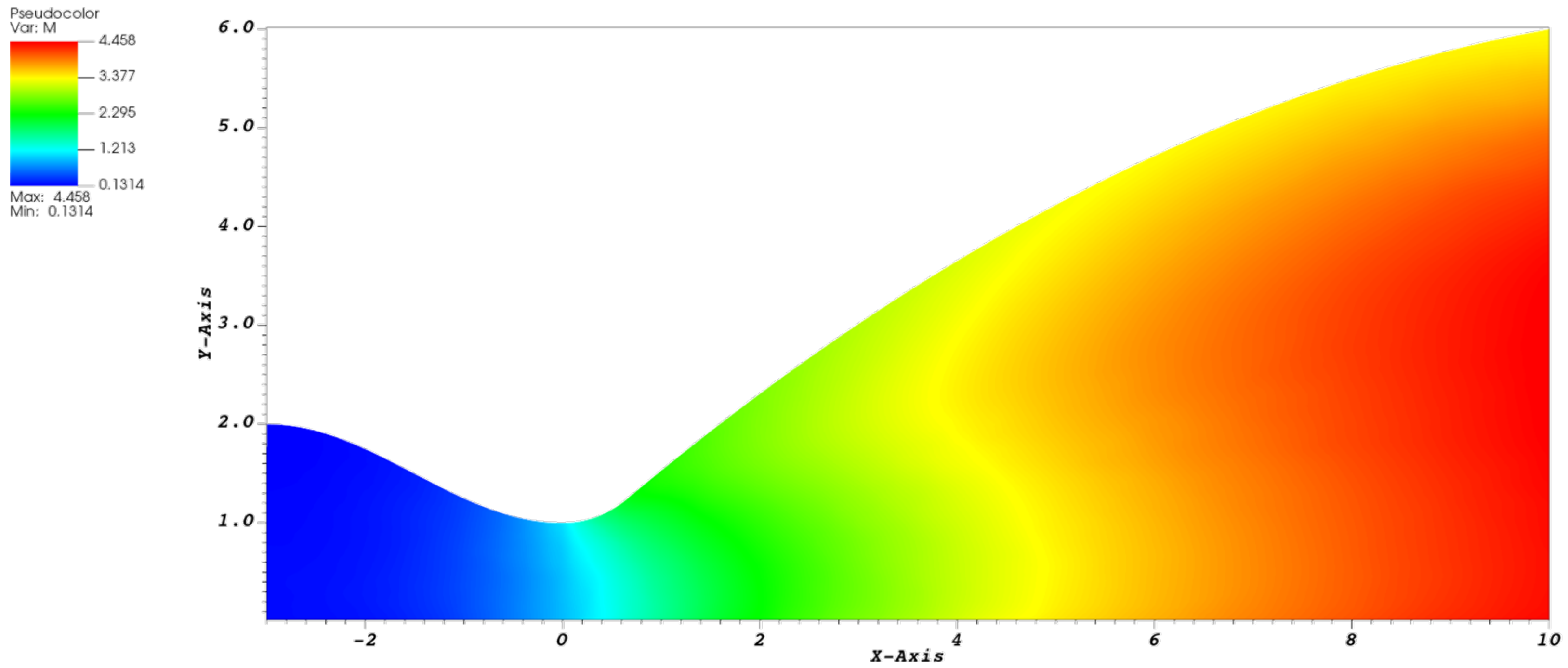
Low-fidelity design space exploration

- **modeFRONTIER** workflow to explore design space
- Unstructured mesh generated by Gmsh
- Euler CFD in-house solver allow to evaluate **divergence losses**
- DoE with approx. 100 simulations
- Each simulation is very fast (one or two minutes in serial)







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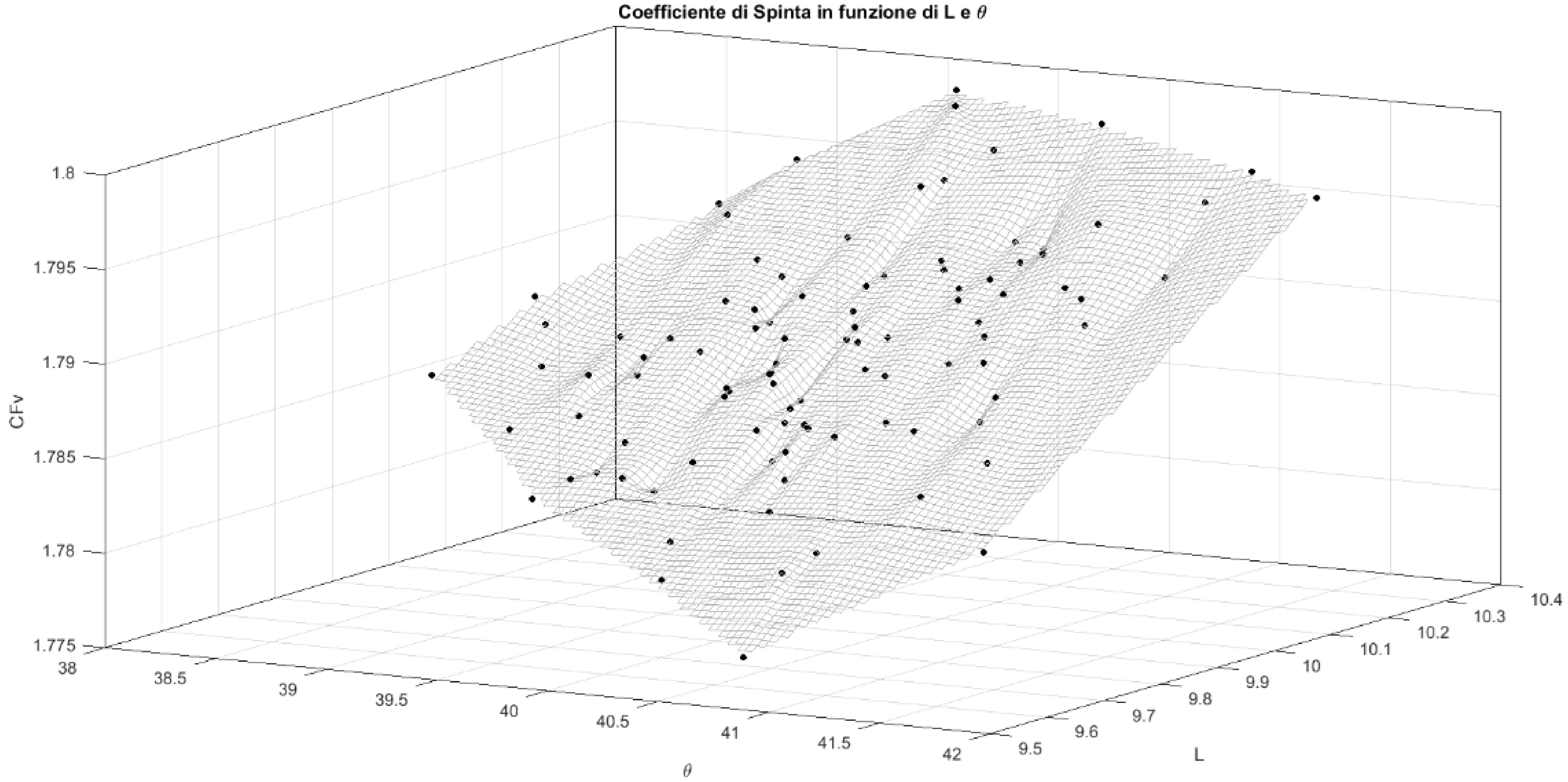
Low-fidelity results: thrust coefficient



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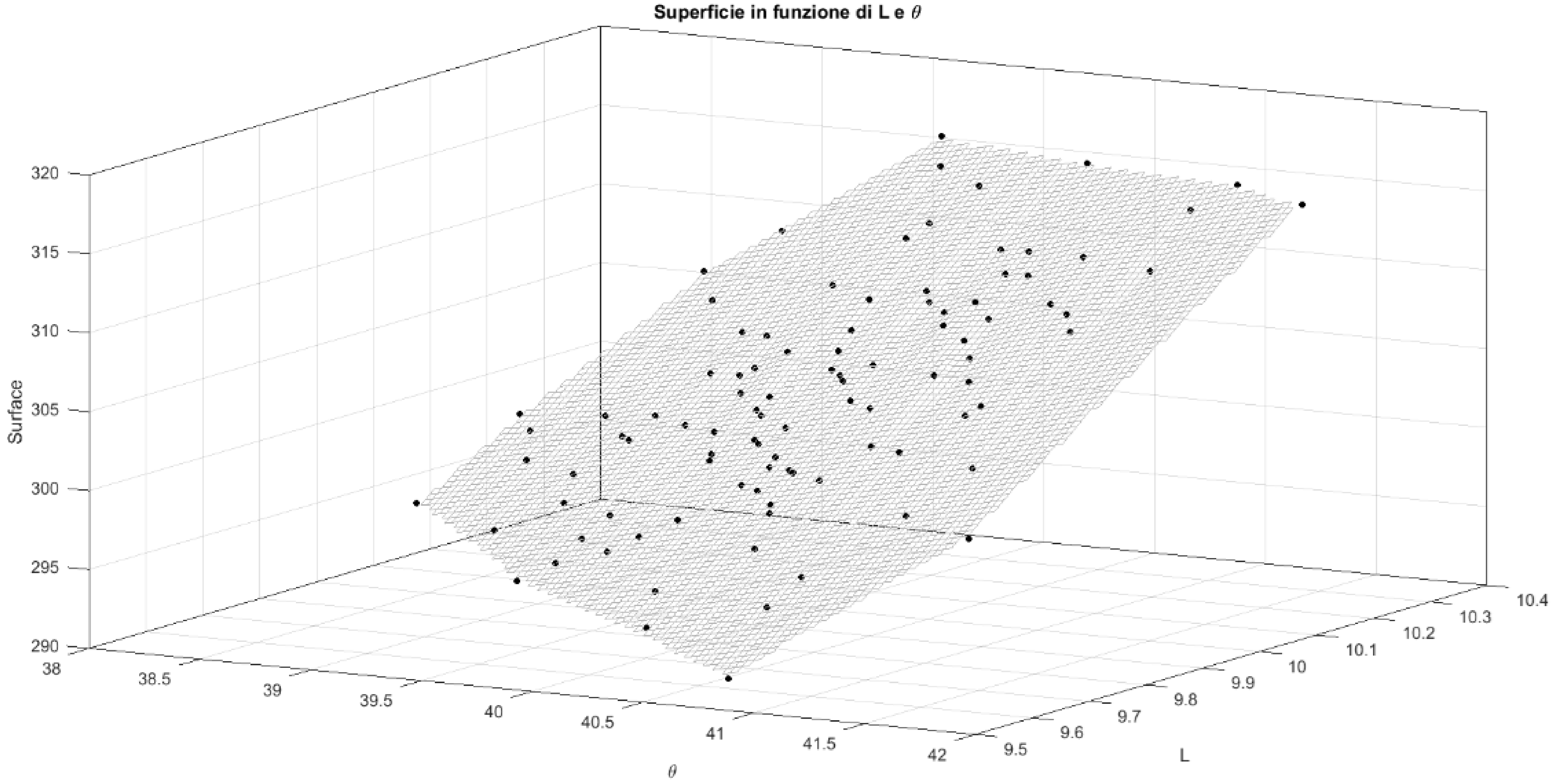
Low-fidelity results: surface



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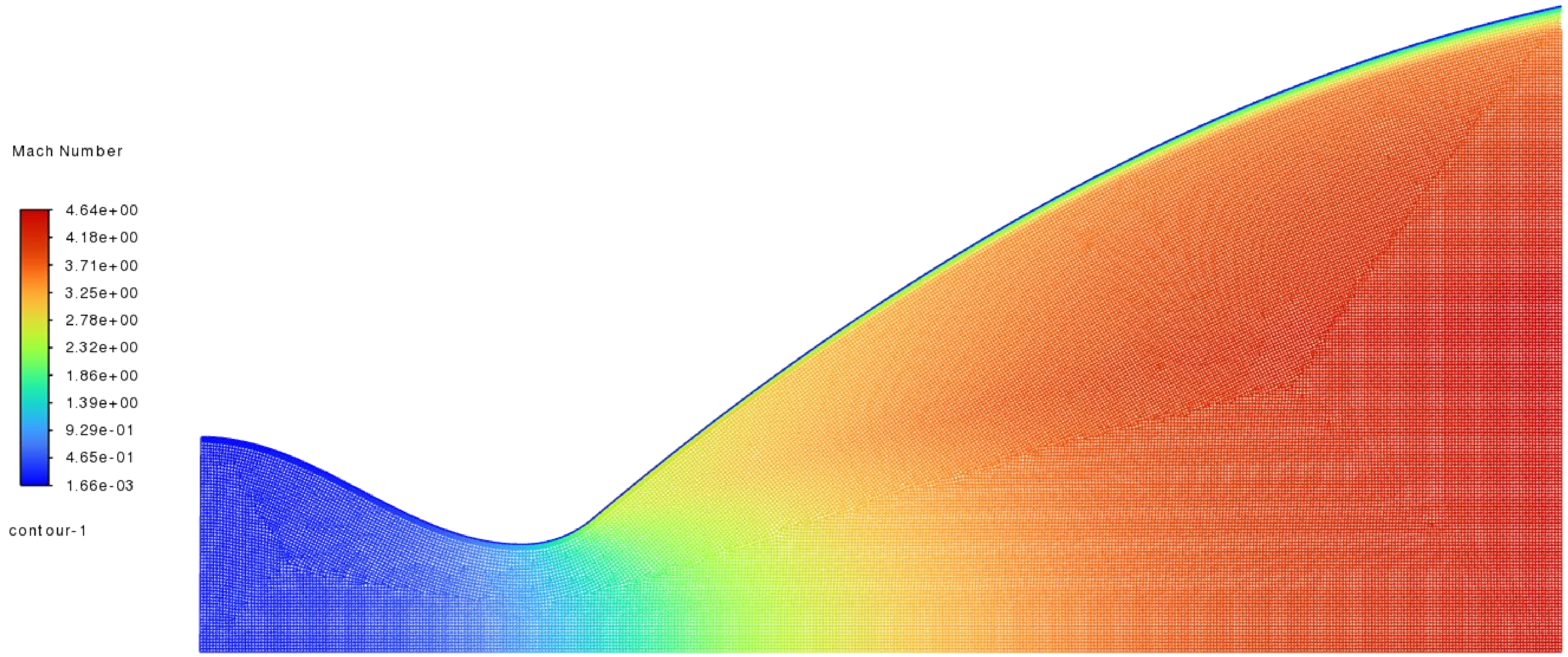
High-fidelity design space exploration

- **modeFRONTIER** workflow to explore design space
- Unstructured mesh with boundarygenerated by Gmsh
- RANS (Spalart-Allmaras) CFD simulations with Fluent allow to evaluate **divergence losses and boundary layer losses**
- DoE with 20 simulations
- Each simulation is very fast (one or two minutes in serial)



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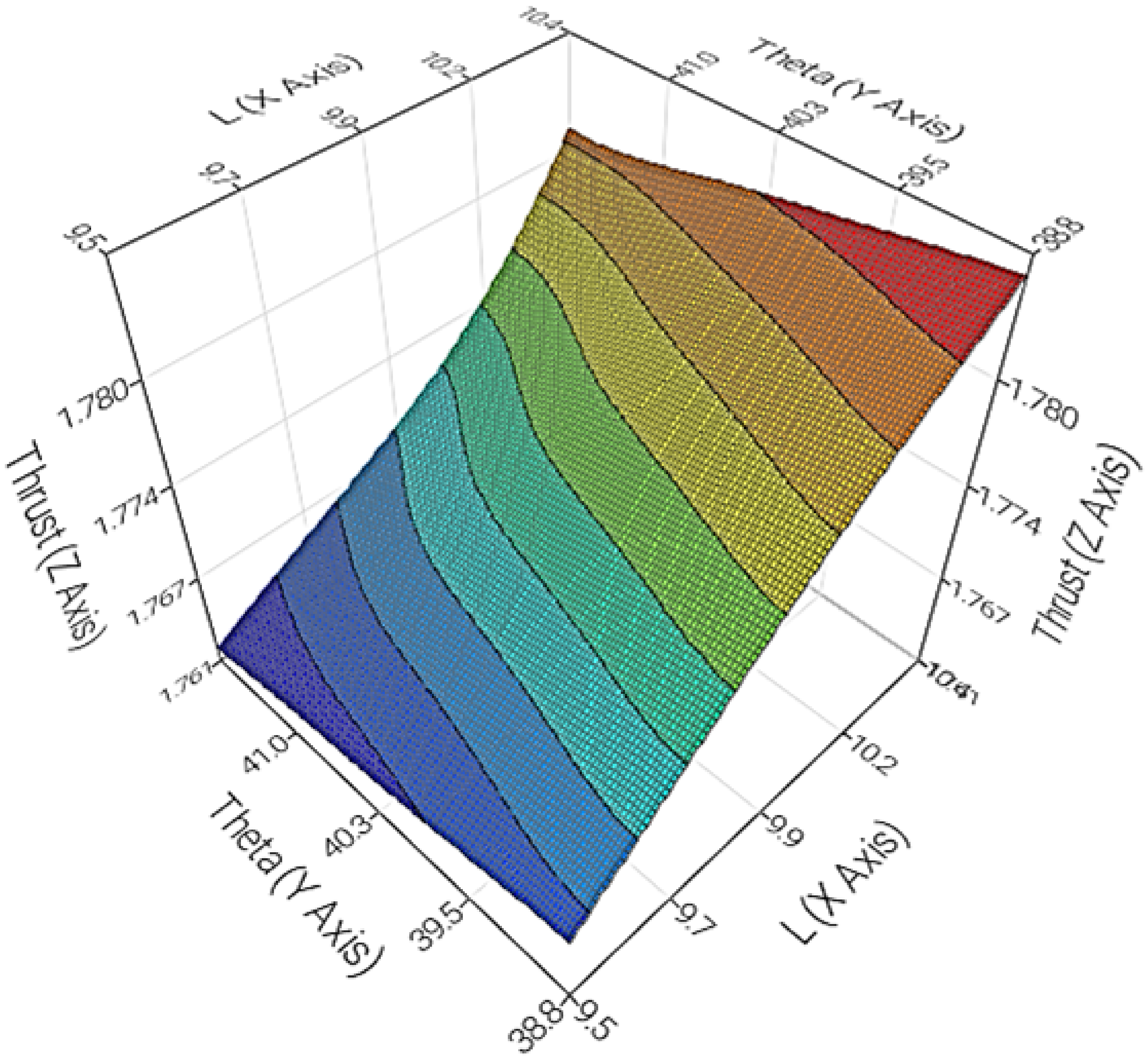
Multi-fidelity modeling of thrust coefficient

- Inviscid simulations see **only divergence losses**
- RANS simulations see **also boundary layer losses**



- Thrust coefficient prediction with **Correction-Based Multi-Fidelity (CBMF)** Model

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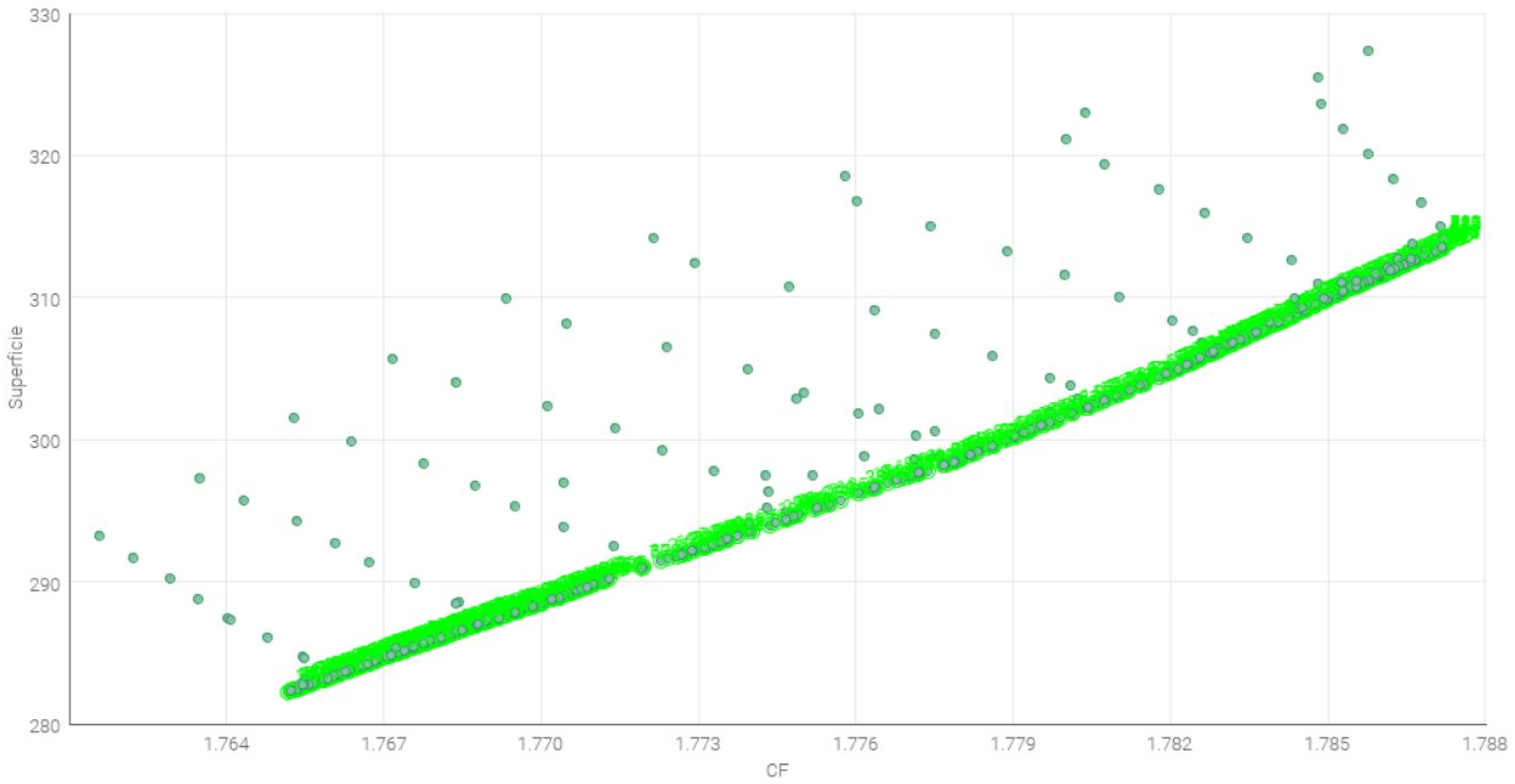
Optimization and Pareto front



Optimization with multi-fidelity surrogate model and check with high-fidelity model

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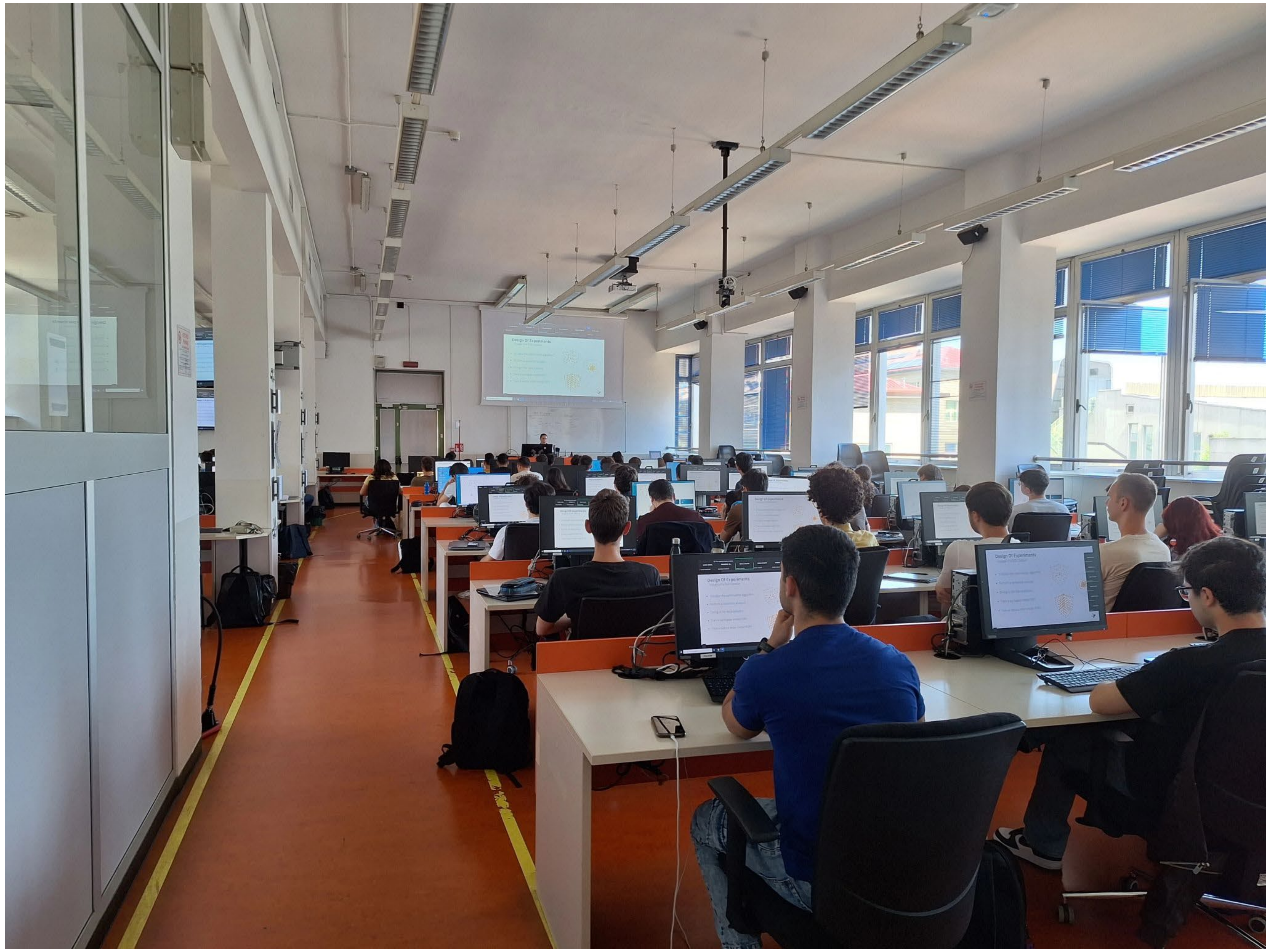
Similar test case used for modeFRONTIER training in the course "CFD for aerospace propulsion systems" at PoliTo



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Multi-Fidelity Modeling of a Lean Premixed Swirl-Stabilized Hydrogen Burner With Axial Air Injection

L. Folcarelli, A. Spagnolo, F. Dicech, A. Ferrero, F. Masseni and D. Pastrone

AIAA SCITECH 2025 Forum, 6-10 January 2025, Orlando, FL

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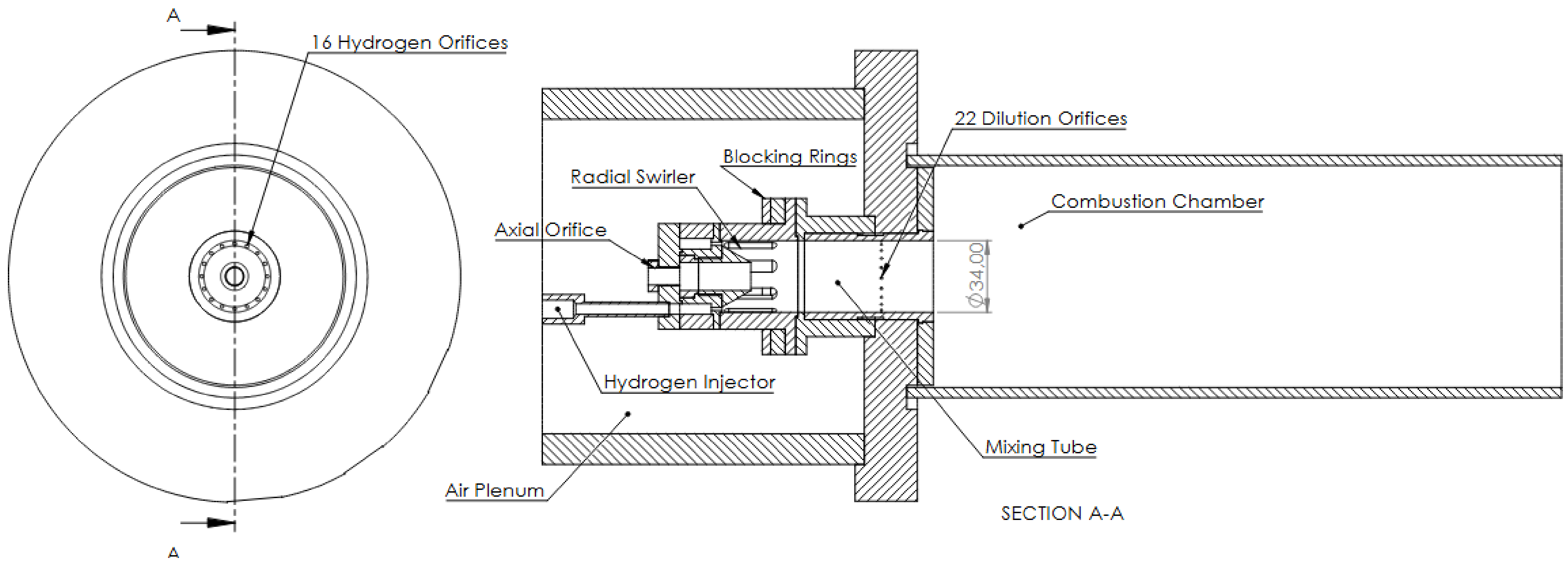
Problem definition

- AHEAD lean premixed swirl-stabilized **hydrogen burner**
- Operating conditions: inlet air temperature from 313K to 693K, inlet air mass flow rate from 80 kg/h to 255 kg/h, and equivalence ratios from (0.2) to 1
- Flame distance from the mixing nozzle is considered a marker of the safety margin of flashback -> **Focus on flame distance prediction**



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Multi-fidelity modeling

- Low-fidelity: **2D axisymmetric RANS simulations with Fluent** (SST+Eddy Dissipation Concept)
- High-fidelity: **experimental results from literature**
- Simple and efficient multi-fidelity approach (experimental feature in nDAI):

$y^*_{HF}(x) = a \cdot y_{LF}(x) + b$	To be solved for a and b in the mean-squares sense
$\delta^i = y^i_{HF} - y^*_{HF}(x^i_{HF}) \quad \forall\, i = 1, \ldots, n$	Correction to recover full accuracy in high-fidelity points
$y_{HF}(x) \sim y^*_{HF}(x) + \delta(x)$	Final reconstruction

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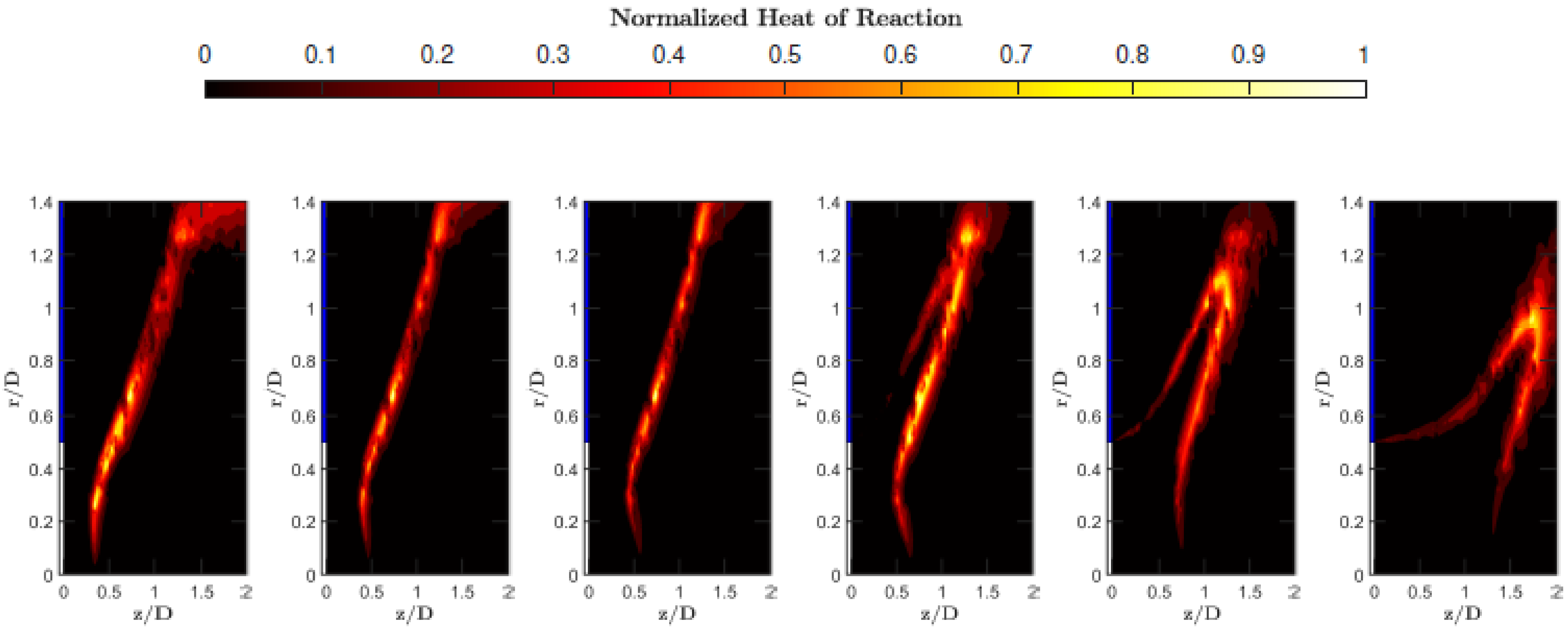
Flame position: CFD results



(a) $\phi = 0.3$ (b) $\phi = 0.4$ (c) $\phi = 0.5$ (d) $\phi = 0.6$ (e) $\phi = 0.8$ (f) $\phi = 1.0$

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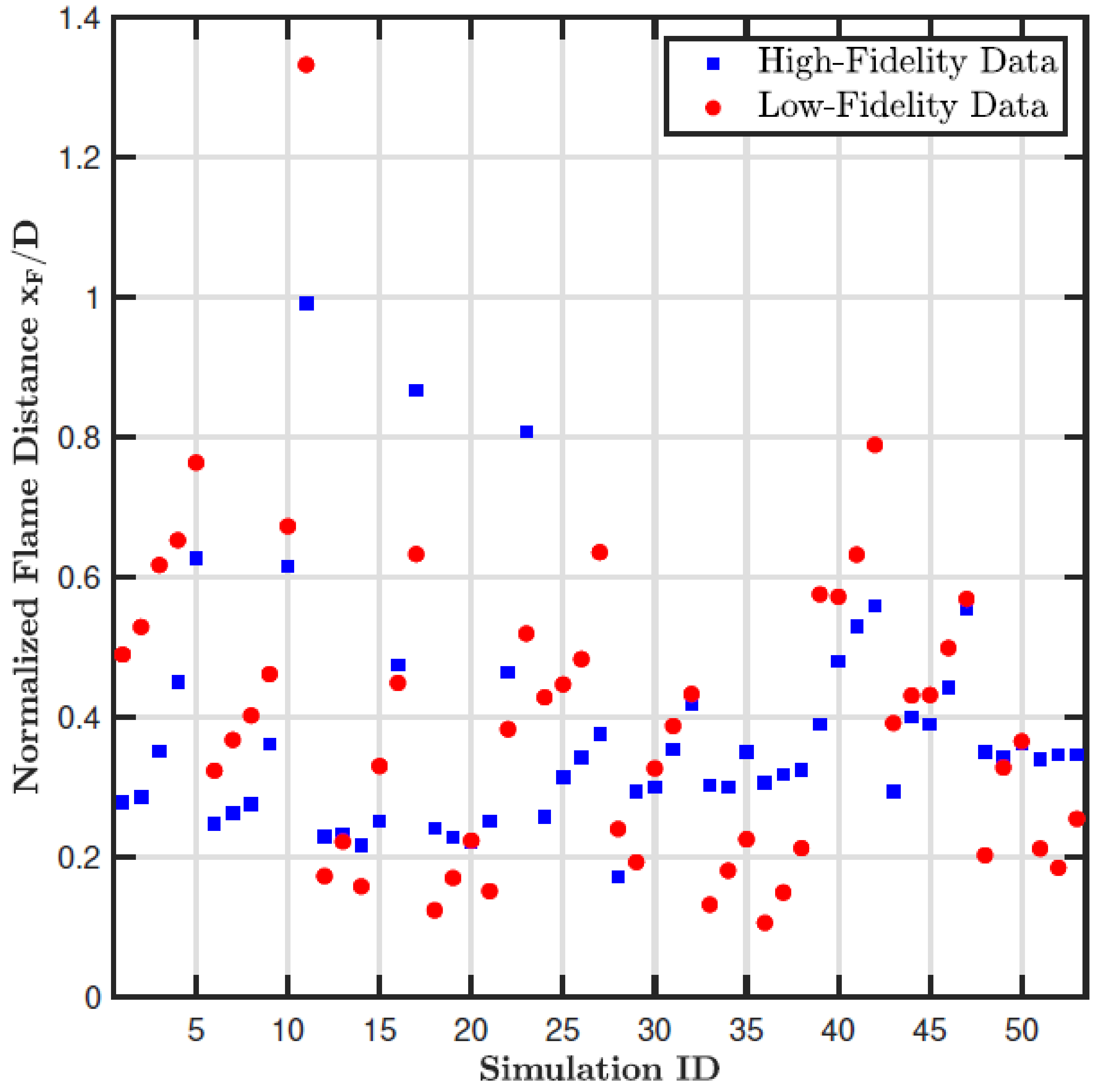
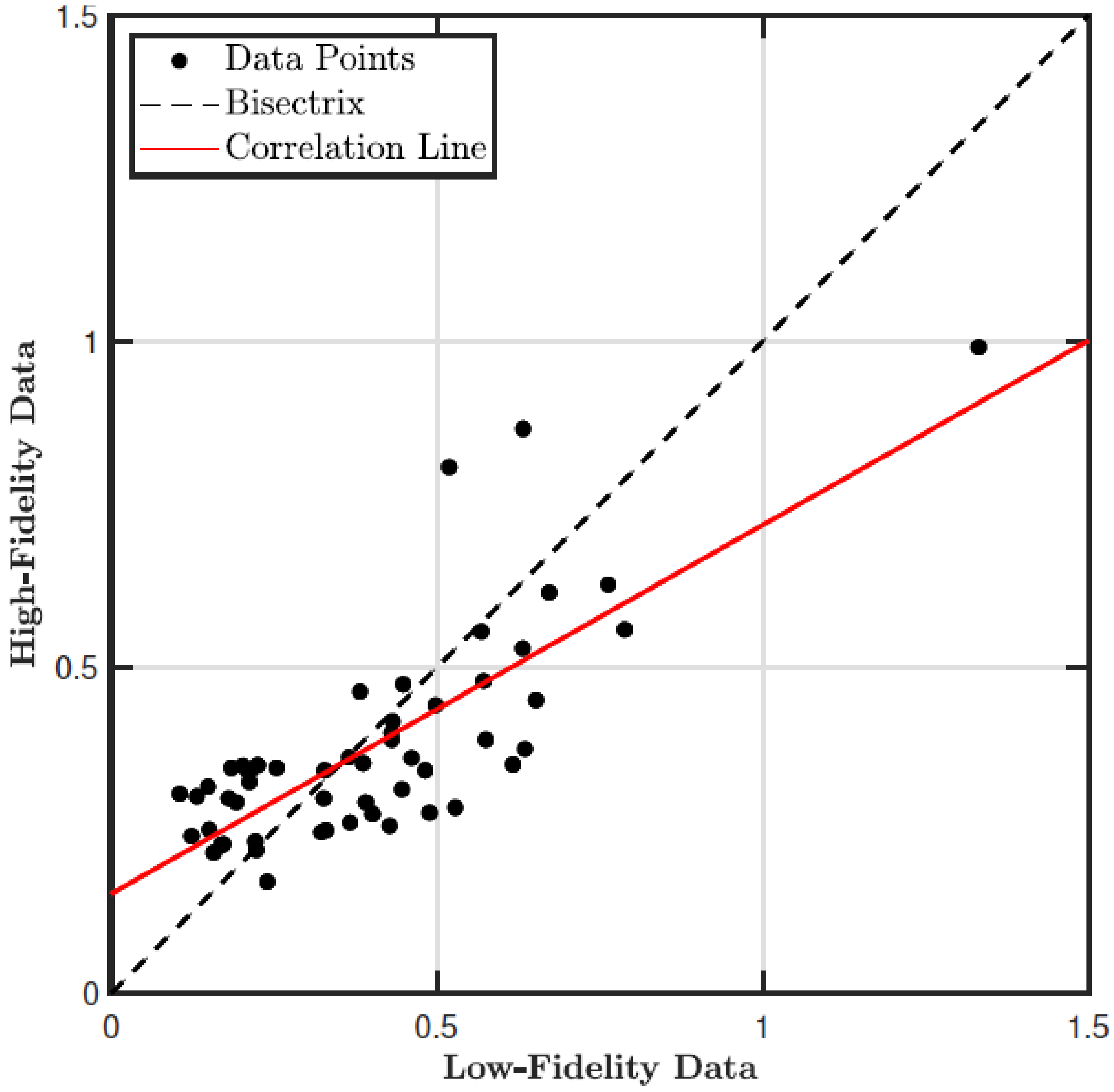
Flame position: CFD vs experiments





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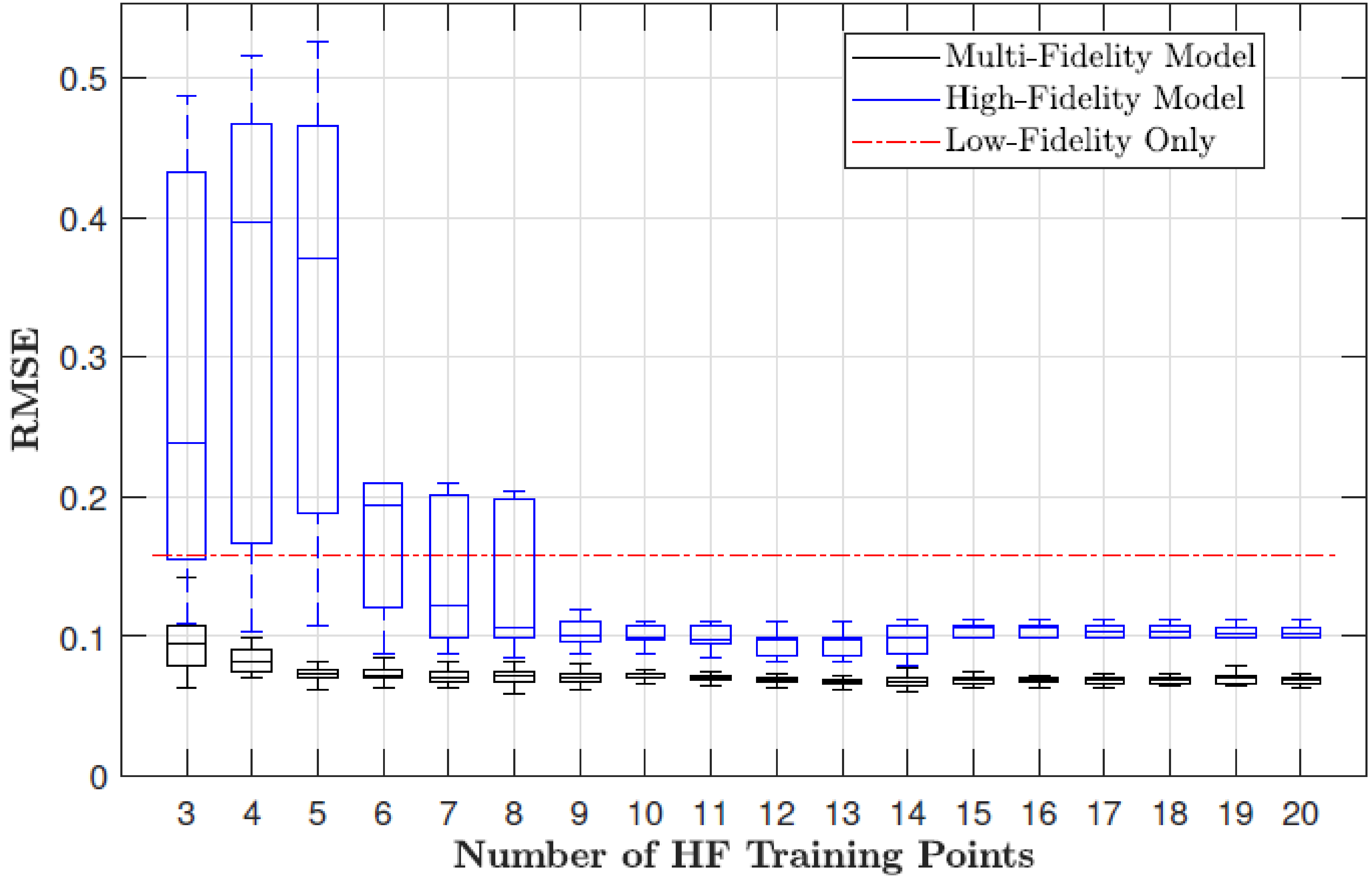
Multi-fidelity accuracy vs training points



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Multidisciplinary Shape Optimization of a Supersonic Jet by Reduced Order Models

Master Thesis and paper by Leonardo De Maio in collaboration with ESTECO
(Thanks to A. Clarich, H. Telib, A. Scardigli, R. Russo, C. Poloni, S. Genovese for support and collaboration)

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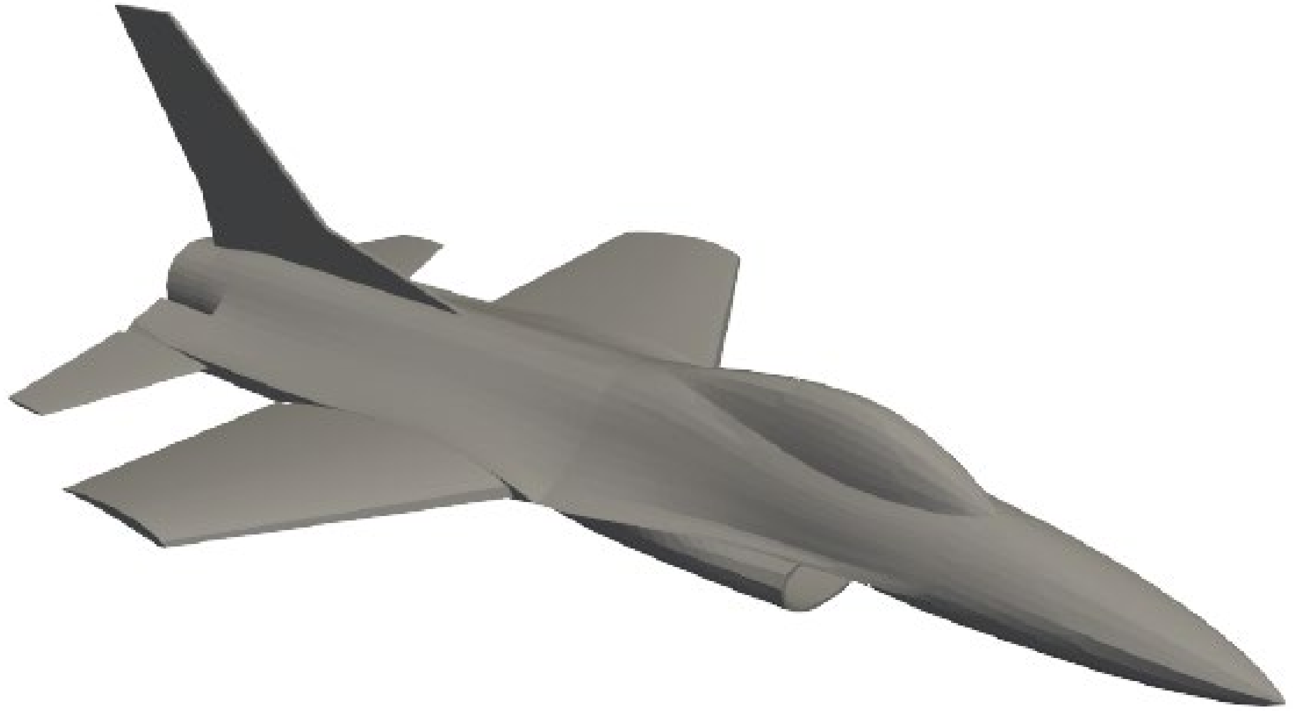
Multi-objective optimization of a jet fighter (F-16-like)

- Multi-objective optimization: **drag coefficient and radar cross section (RCS)**
- Constraint: preserve lift, negative pitch moment
- Design space exploration with modeFRONTIER
- Development of **ROM** with nDAI for both aerodynamics and RCS



- **Goal of the thesis: evaluate ROM accuracy for a wide range of design parameters**

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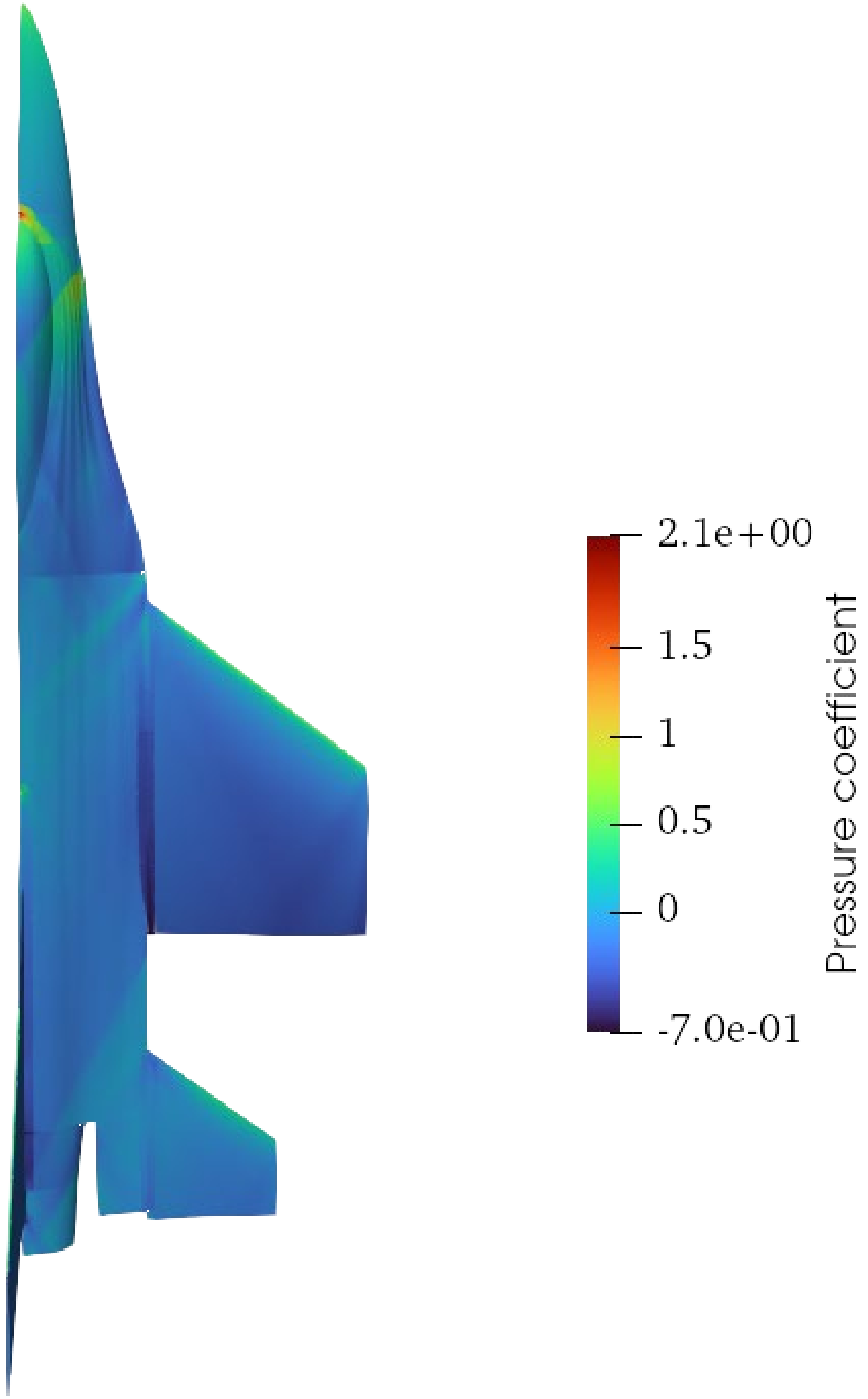
Aerodynamics

- CFD simulations with Fluent
- Euler equations
- Flight Mach number = 1.6
- CFD used to evaluate wall pressure distribution
- Implementation of engine 1D model with suitable BCs



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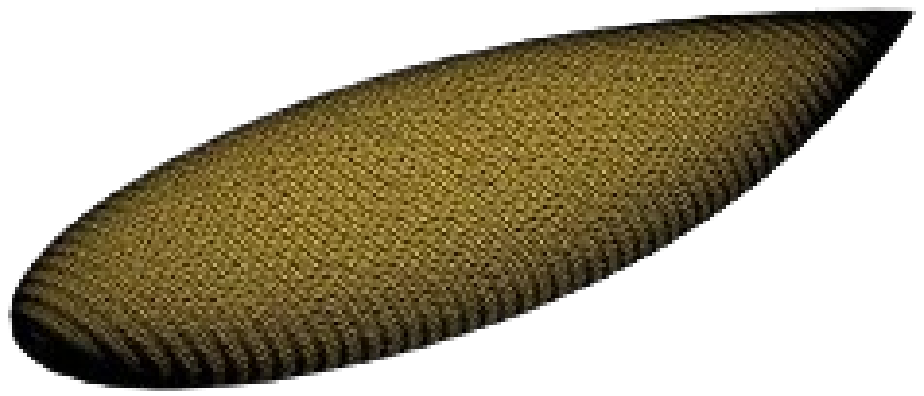
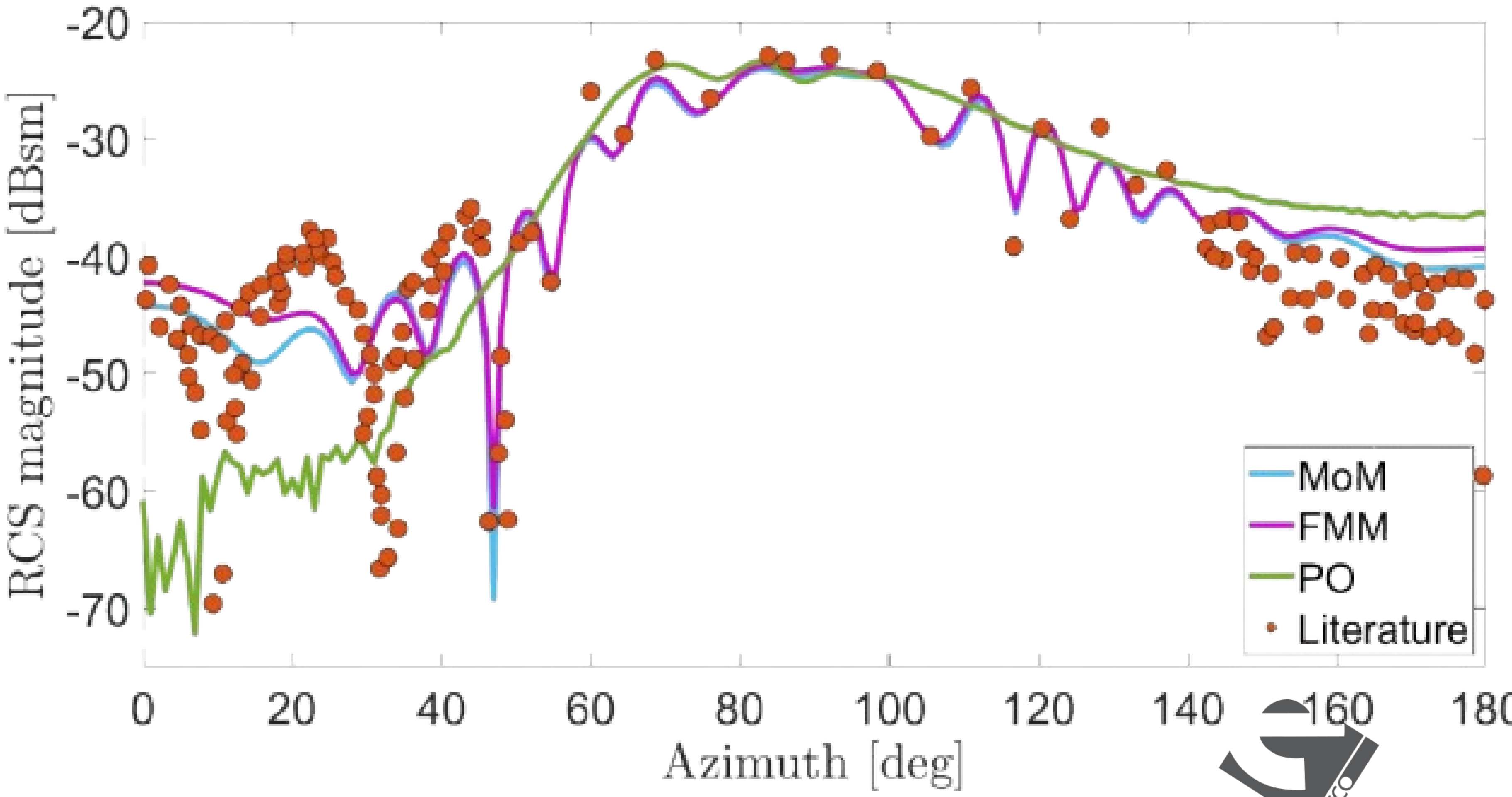
Radar Cross Section



- Methods benchmark on NASA almond test case
- Comparison between Physical Optics (PO), Fast Multipole Method (FMM) and Method of Momentum (MoM)
- Significant differences in computational cost (1200s vs 200s vs 50s)
- PO method (cheaper) chosen for this study



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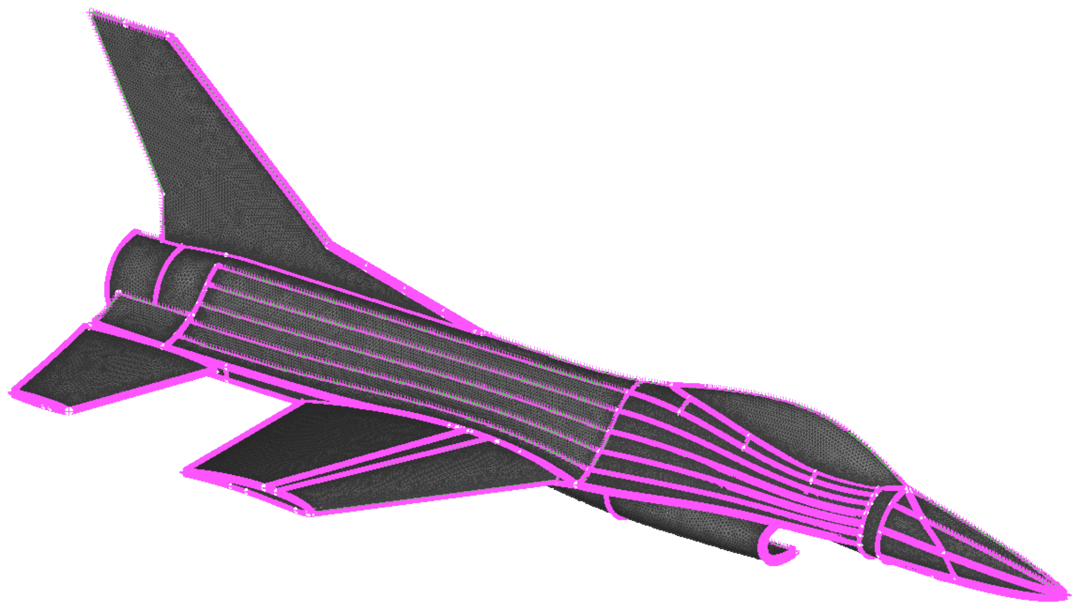
Design space exploration with modeFRONTIER



Baseline geometry

Parameters	Baseline	Min	Max
Wing half span	2679.2 mm	2500 mm	7775.0 mm
Wing dihedral angle	0.0°	-60.0°	60.0°
Wing sweepback angle	0.0°	-60.0°	50.0°
HTP half span	1636.1 mm	1275.0 mm	6000.0 mm
HTP dihedral angle	-7.0°	-80.0°	0.0°
HTP sweepback angle	0.0°	-45°	80°

- Identification of the main parameters influencing drag and RCS according to literature
- Definition of a **wide range** for each parameter to **challenge ROMs**
- Generation of a training database with 62 geometries

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ROMs for Aerodynamics and RCS in nDAI

- Proper Orthogonal Decompositon (POD) to reconstruct wall pressure distribution (for drag calculation) and RCS angular distribution

- Aerodynamics:
  - POD coefficient predicted with Radial Basis Function interpolation based on thin-plate spline kernel
  - 18 POD modes out of 62 selected, as they express 99.0% of the global energy
  - Single CFD = 25 h on 16 cores; ROM = 80 s

- RCS:
  - Gaussian Processes interpolation with rational-quadratic kernel
  - 16 POD modes out of 62 selected, as they express 99.0% of the global energy
  - Single RCS = 15 min with GPU on laptop; ROM = 10 s

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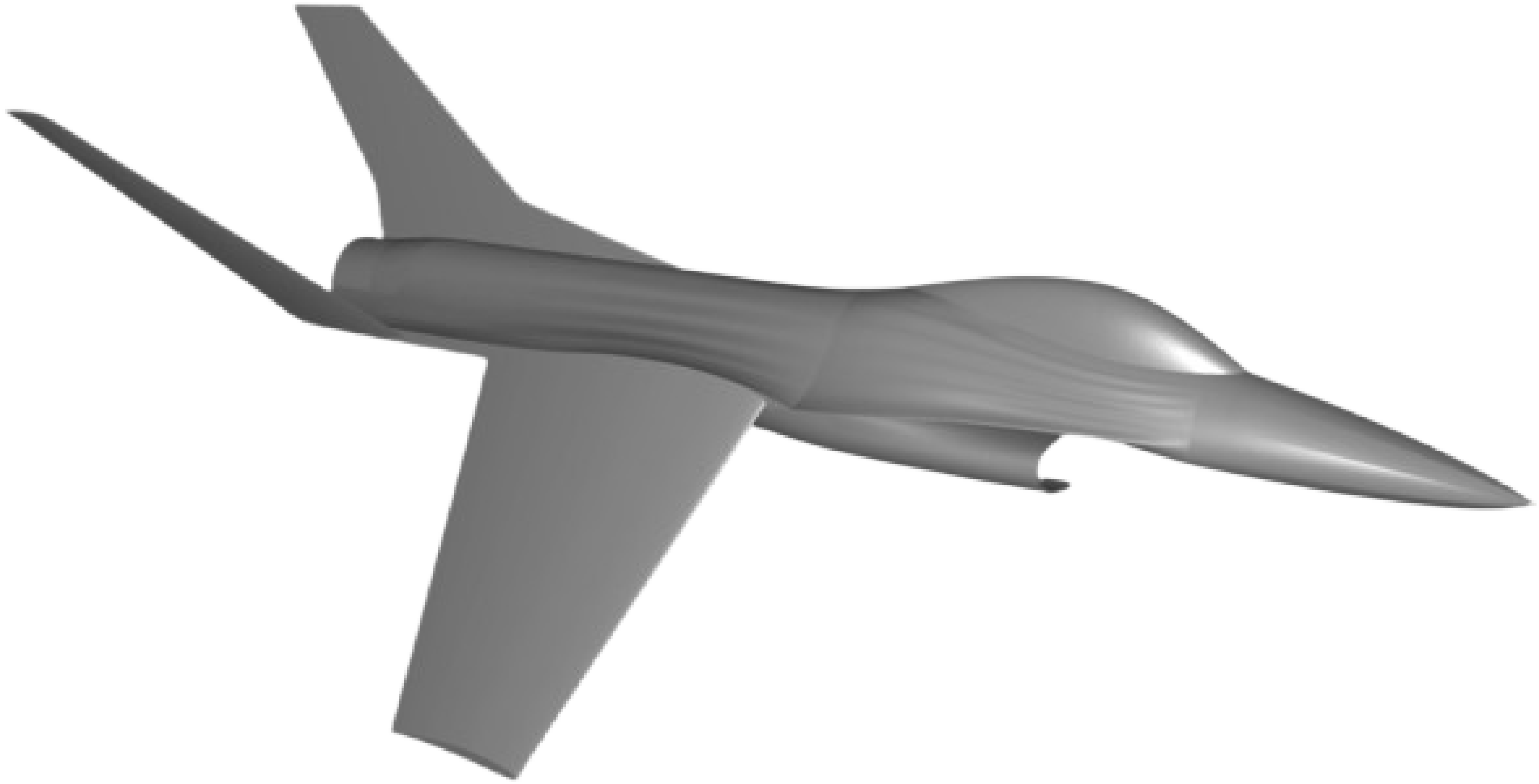
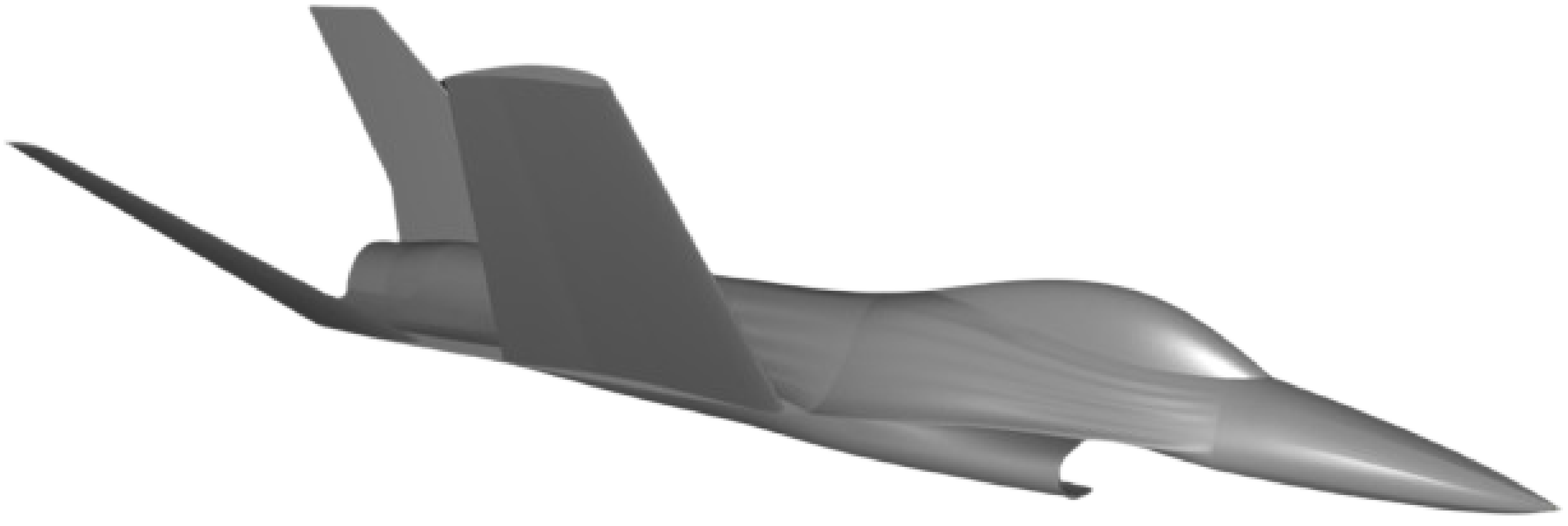
Optimization results with ROMs and modeFRONTIER



Minimum drag design



Minimum RCS design

Example of optimized geometries very different with respect to the baseline

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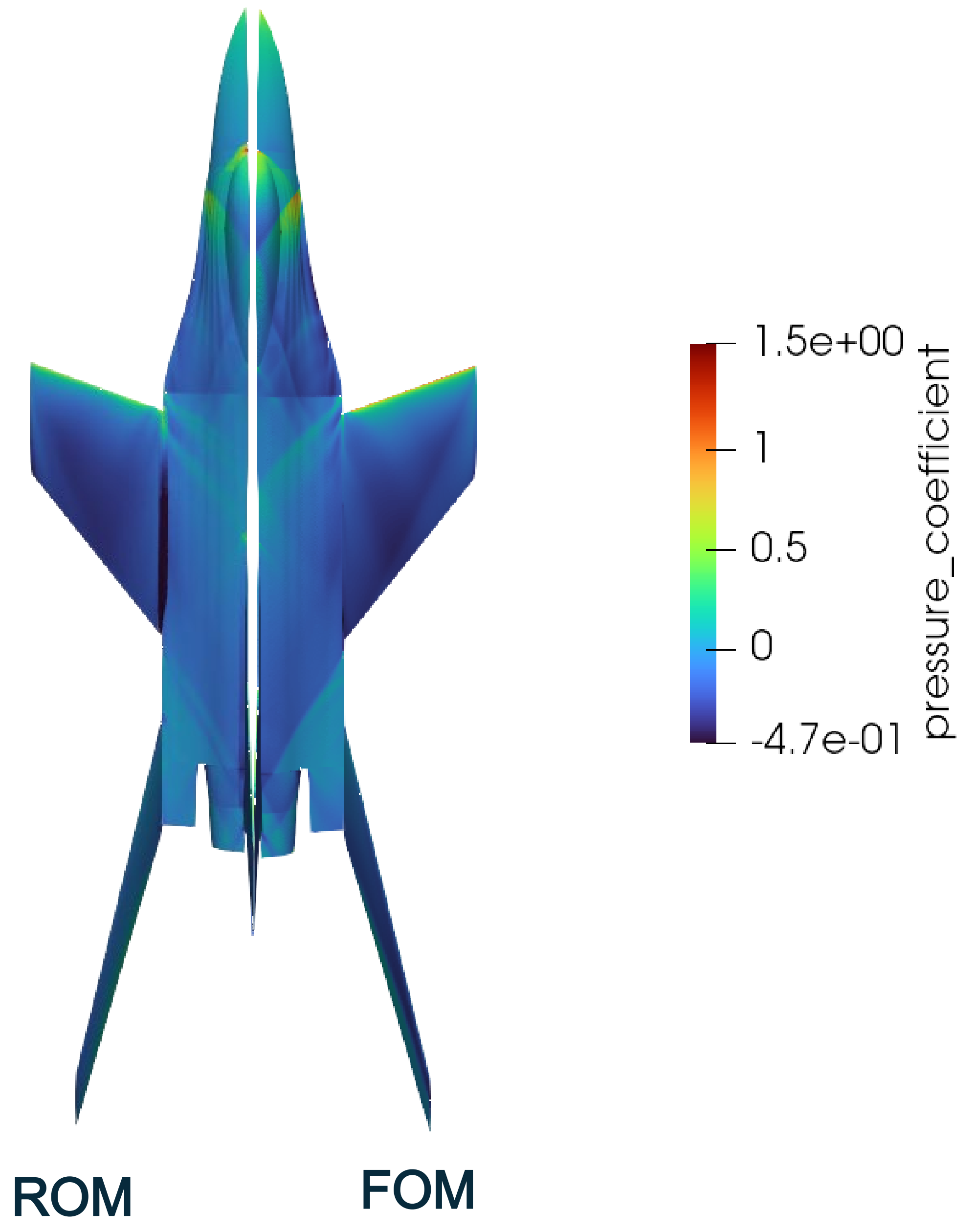
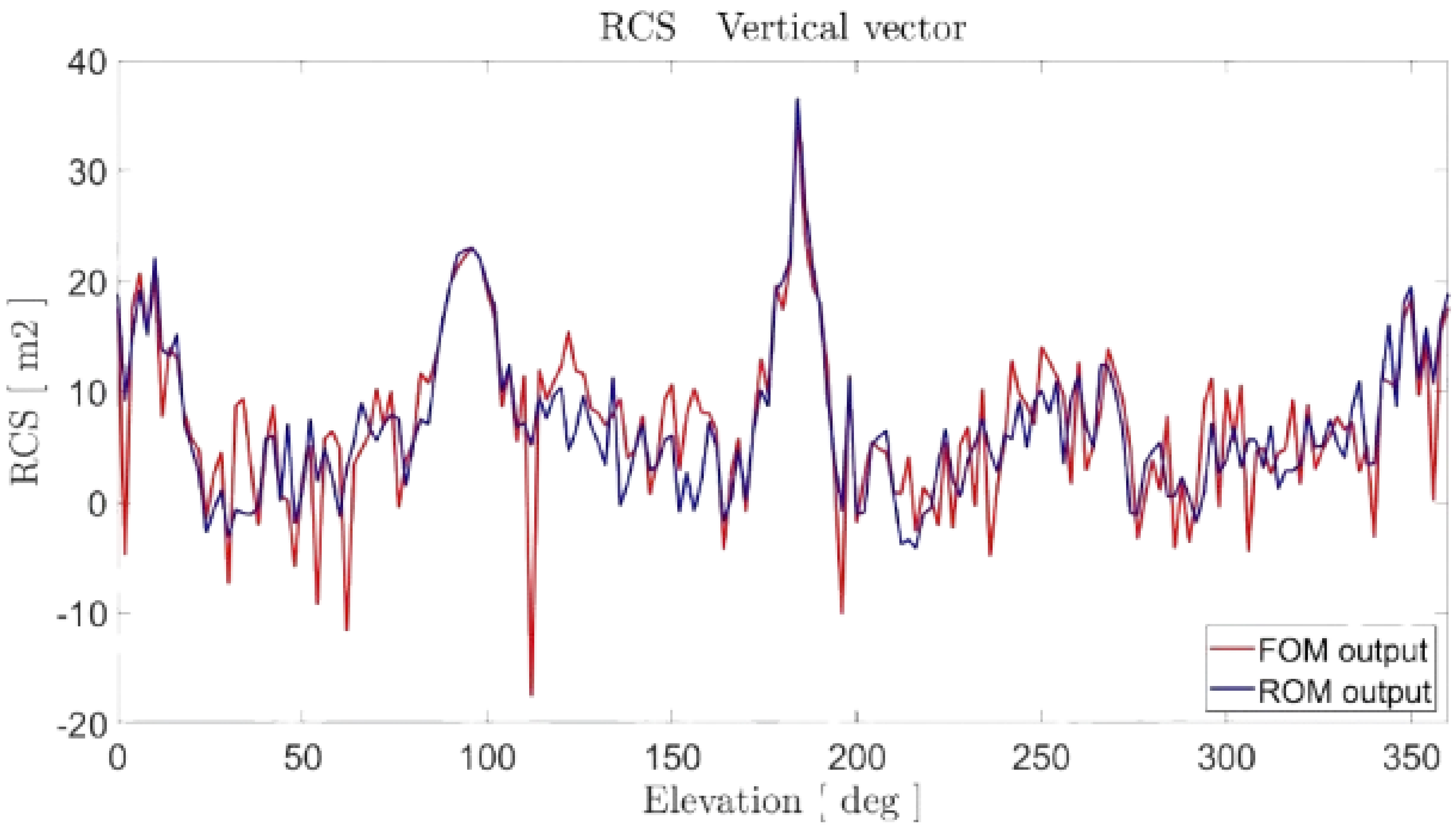
ROMs accuracy for wall pressure and RCS





- **Good accuracy on pressure** even on geometries **very far from baseline.**
- **Excellent prediction of peaks in RCS distribution**

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