Interactive Reduced Order Models for Ship Hull Design and Optimization Coupling an Open-Source CFD Tool with Advanced RBF Mesh Morphing

E. Costa, B. Di Paolo, A. Krassas, **P. Geremia,** *ENGYS*

C. Growth, M. E. Biancolini, *University of Rome "Tor Vergata"*

M. Camponeschi, U. Cella, E. Di Meo, *RBF Morph*

Outline

1. About ENGYS
2. Methodology
3. Results
4. Conclusions

About ENGYS

Founded in 2010 (UK)

Global providers of open-source CFD products and services

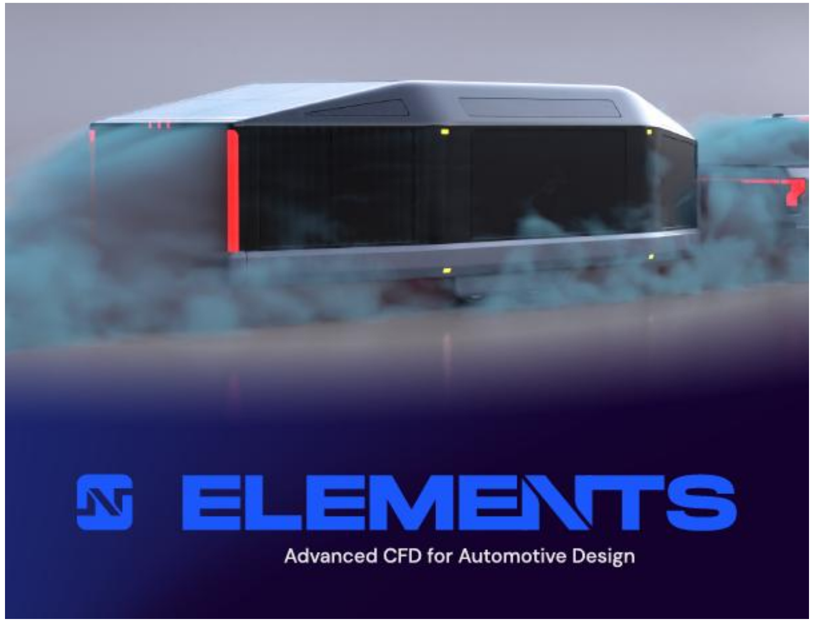
CFD Enterprise software products HELYX and ELEMENTS

8 local offices

UK, Germany, Italy, USA, Australia, Brazil, RSA, Greece

Well established resellers network

Spain & Portugal, Netherlands, Japan, South Korea, USA...



Methodology

Methodology

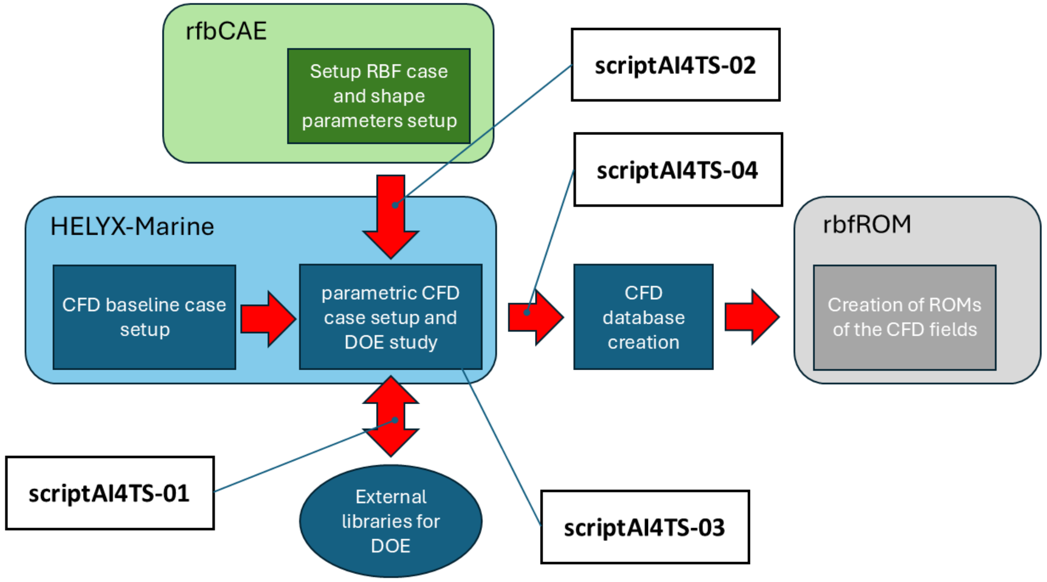
Introduction > *AI4TwinShip* Proof of Concept (PoC)

- Traditional CFD-based optimization is accurate but computationally expensive
- Reduced Order Models (ROM) offer fast, accurate alternatives using limited high-fidelity CFD data
- ROMs allow near real-time hydrodynamic predictions
- This PoC demonstrates a streamlined ROM-based optimization process using RBF morphing
- Software stack:
  - **HELYX-Marine** → CFD simulations
  - **rbfCAE** → Morphing
  - **rbfROM** → ROM

Methodology

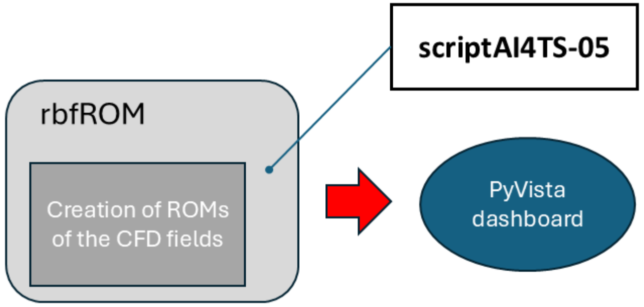
Off-line Stage

- Definition of the CFD baseline case
- Parametrization of the reference CAD model of the hull
- Generation of the CFD database
- ROMs generation and validation



On-line Stage

- Real-time prediction using ROMs
- Interactive dashboard for 3D visualisation

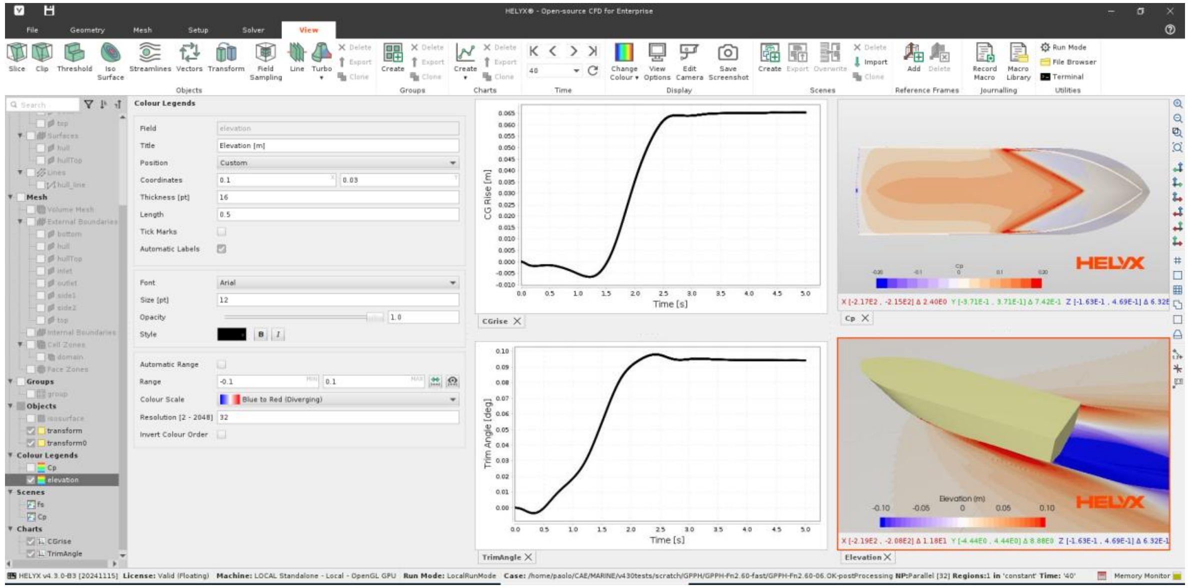


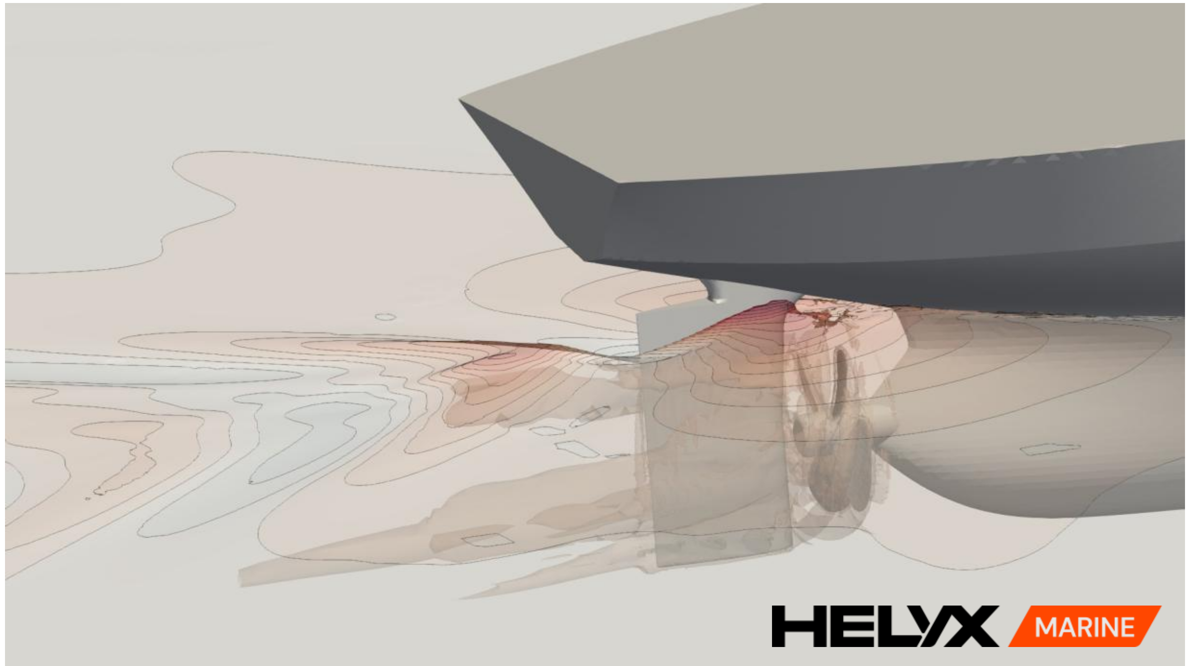
Python scripts to automate the process

Methodology

Introducing HELYX-Marine

- VOF and linearized free-surface (LFS) solvers
- Unique earth-fixed reference frame 6DoF rigid-body formulation
- Adaptive Mesh Refinement (AMR) approach
- Extensive wave library
- Advanced rudder/propeller models for self-propulsion and maneuvering



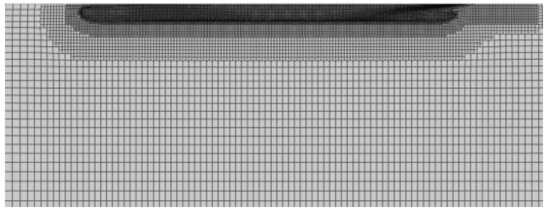
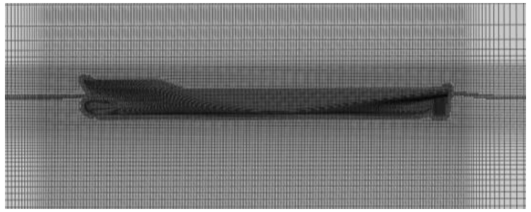
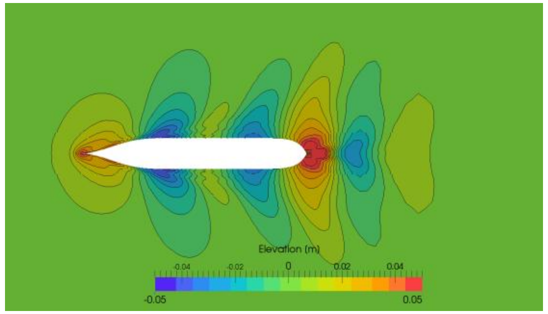


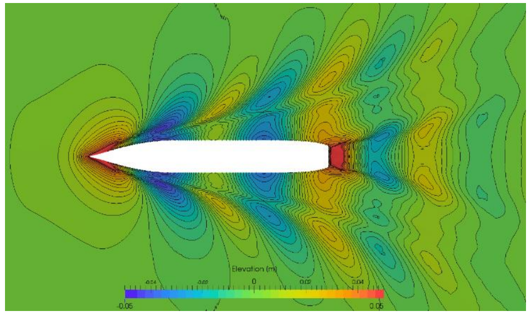
Methodology

HELYX-Marine > CFD Validation

Gothenburg 2010 Case 2.2b

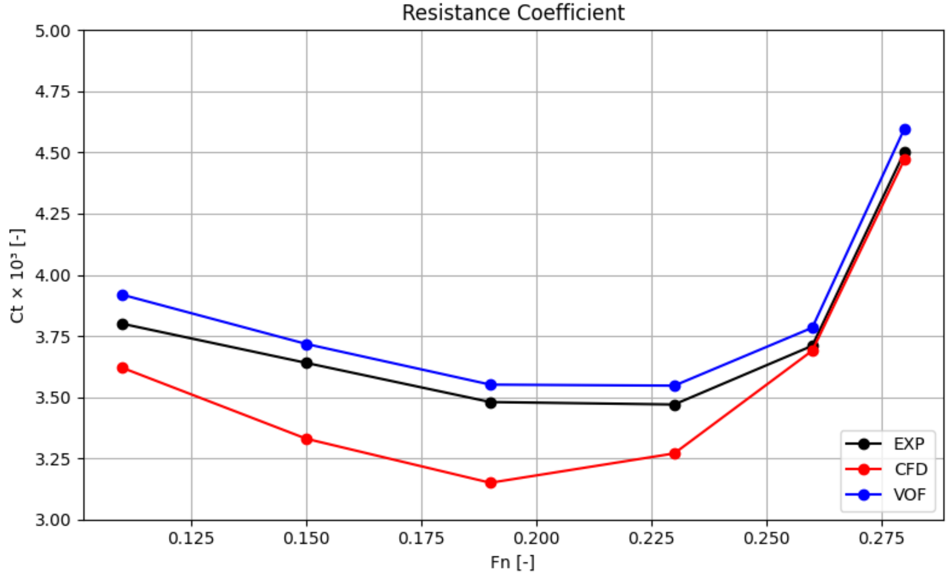
- Fn → 0.11, 0.15, 0.19, 0.23, 0.26, 0.28
- Scale → 1:31.6
- VOF vs. LFS RANS solver
- Turbulence Model → k-ω SST
- Mesh size → 1.2M cells LFS vs. 3.1M cells VOF
- CPU time → 20mins LFS vs. 5.6hrs VOF on 64 processors AMD Genoa



LFS Solver

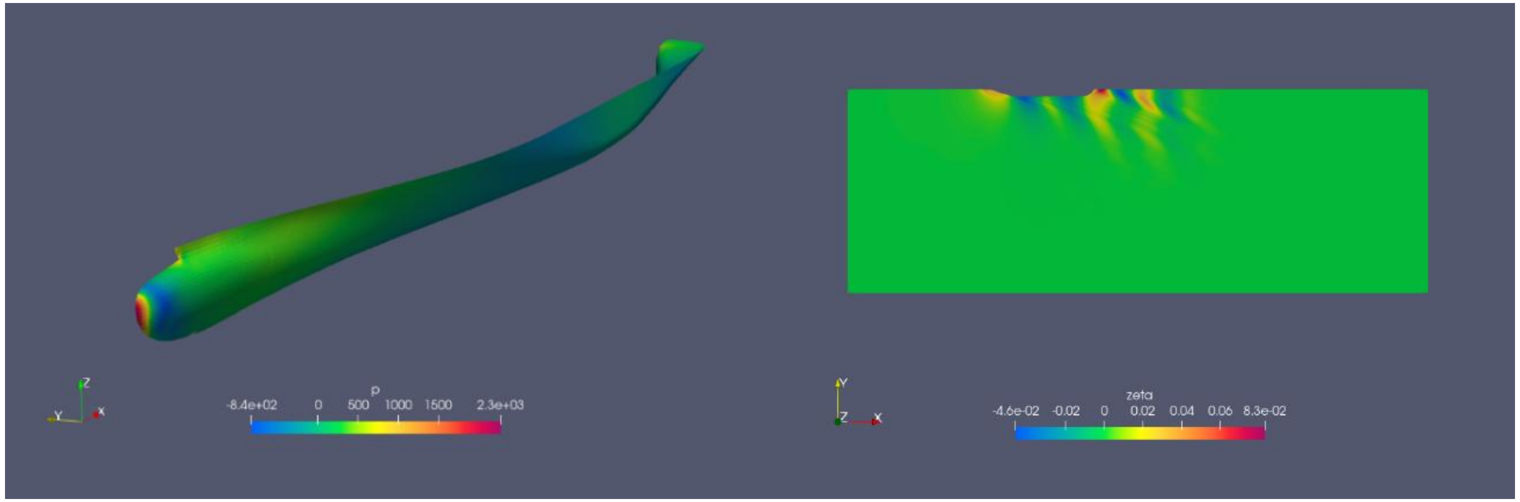
VOF Solver

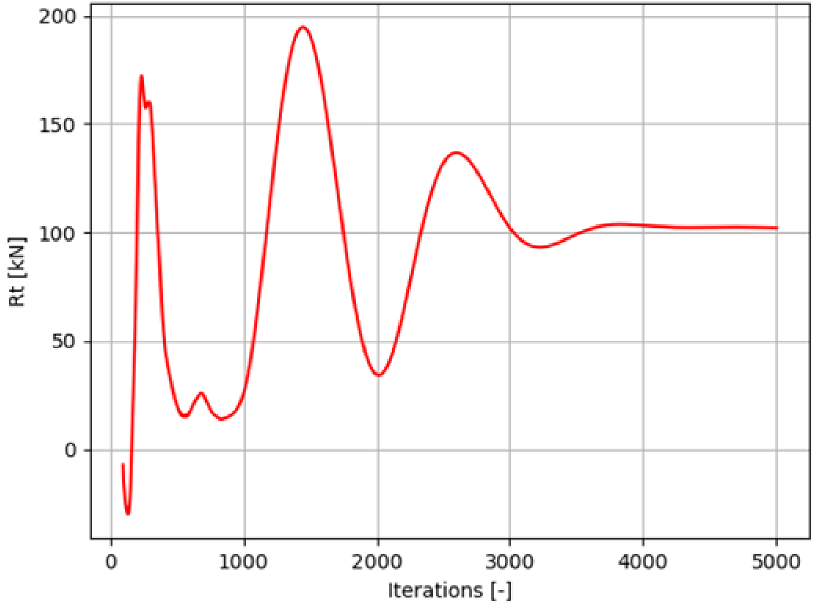


Methodology

HELYX-Marine > Baseline Case

- KCS hull form
- Fn → 0.26
- Scale → 1:1
- Mesh size → 2.5M cells
- LFS solver, steady-state RANS
- Turbulence Model → k-ω SST
- Results
  - Pressure and free-surface elevation surface fields (VTK format)
  - Resistance force



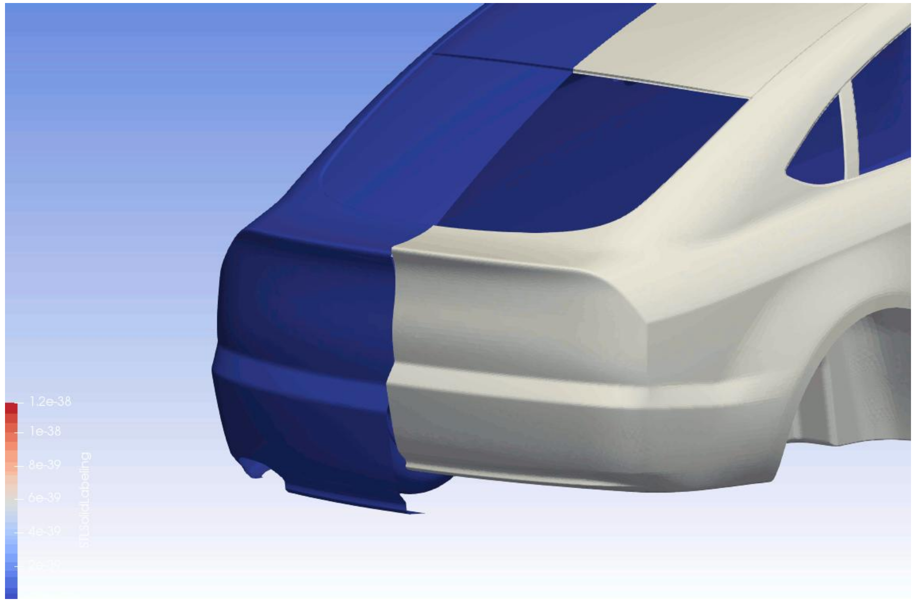


engys

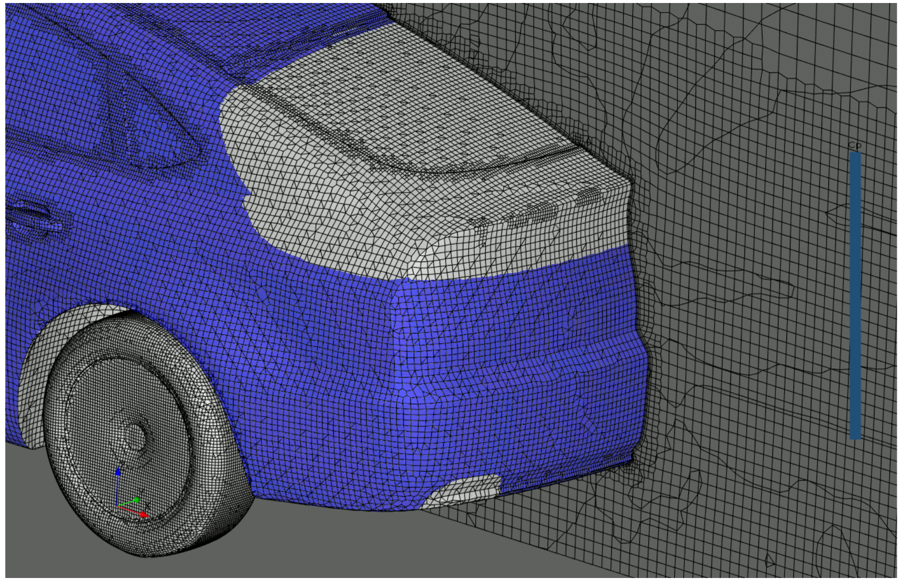
Methodology

rbfCAE > Morphing Approaches

- Morphing options in **rbfCAE**:
  - Surface morphing → Robust
  - Volume morphing → Consistent topology
- **Volume morphing** approach used in this work to ensure consistent mesh for ROM



Surface Morphing

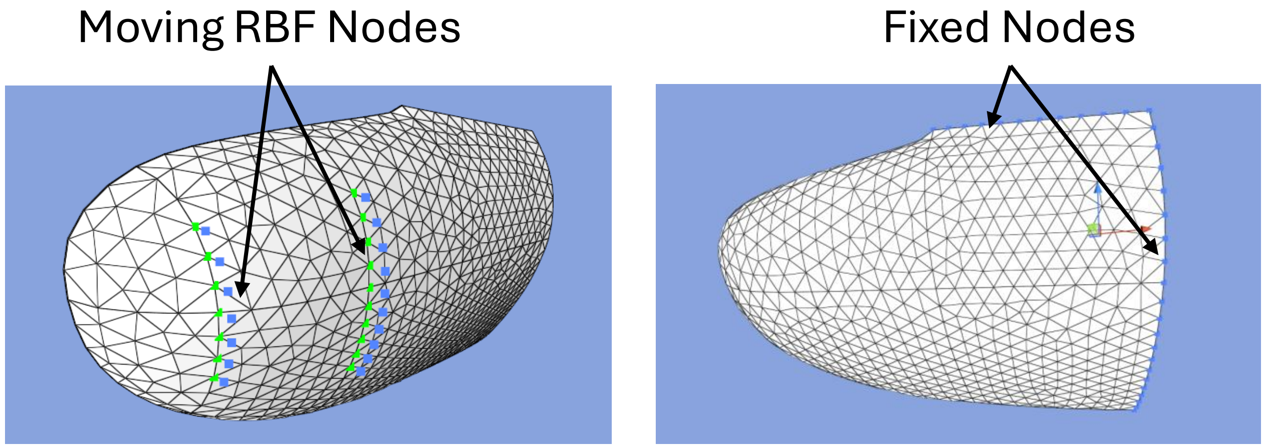


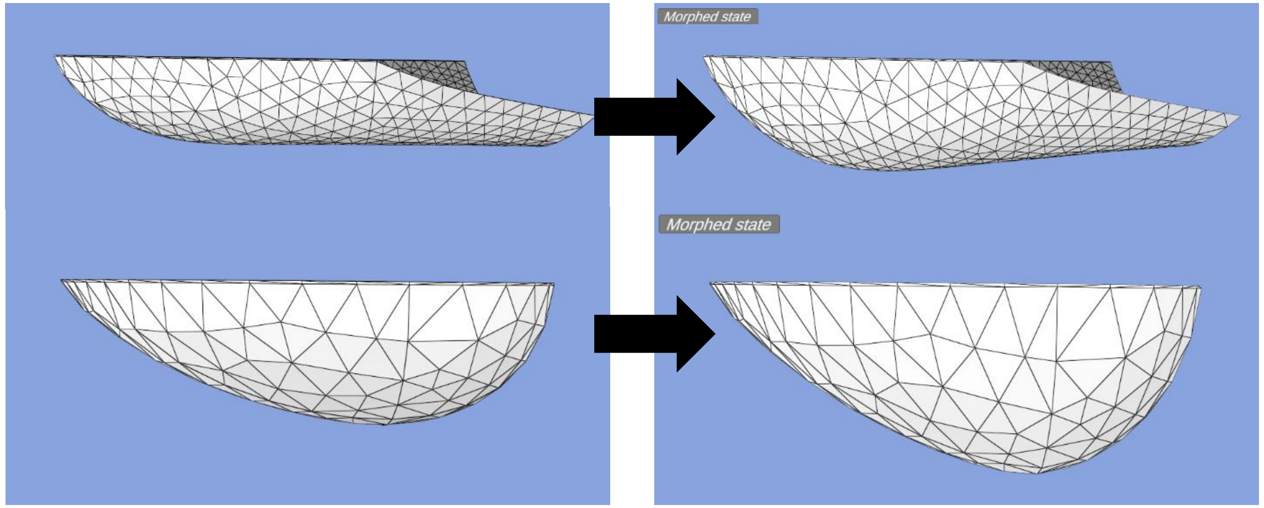
Volume Morphing

Methodology

rbfCAE > Morphing Parameters

- **RBF shape modifiers** set:
  - Bulbous bow → 3 shape modifications (2 in-plane and 1 out-of-plane)
  - Stern → 2 shape modifications (1in-plane and 1out-of-plane)



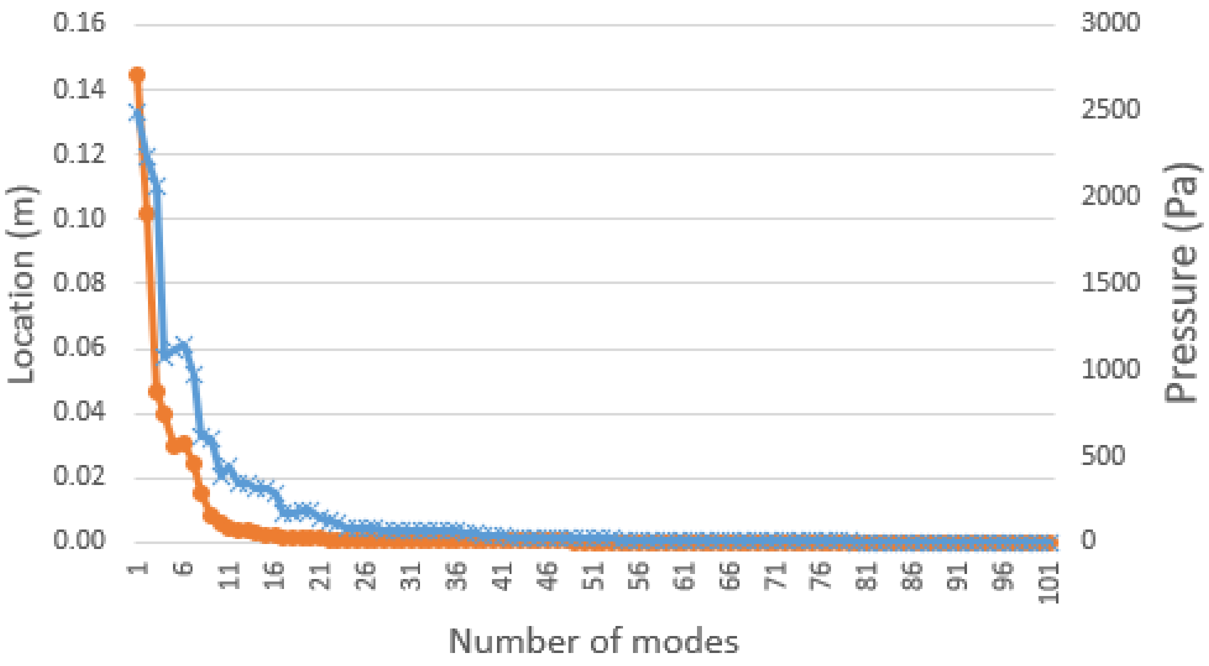


Bow Morphing Preview from Top and Front View

Methodology

rbfROM > CFD Database and Creation of ROMs

- DOE generated using **Latin Hypercube Sampling** → 101 design points
- ROM creation:
  - CFD fields structured into arrays for POD
  - Full SVD retained (no truncation) for maximum accuracy.
- ROMs created for mesh, resistance, pressure, and wave elevation



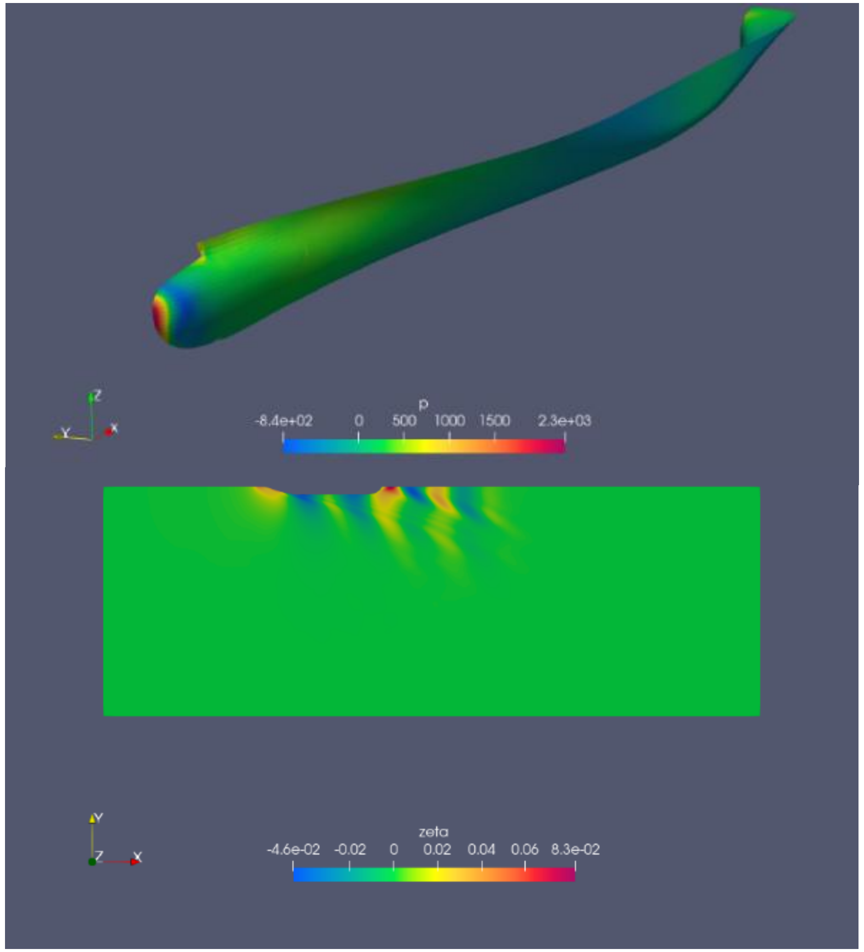
Maximum error vs # modes

Results

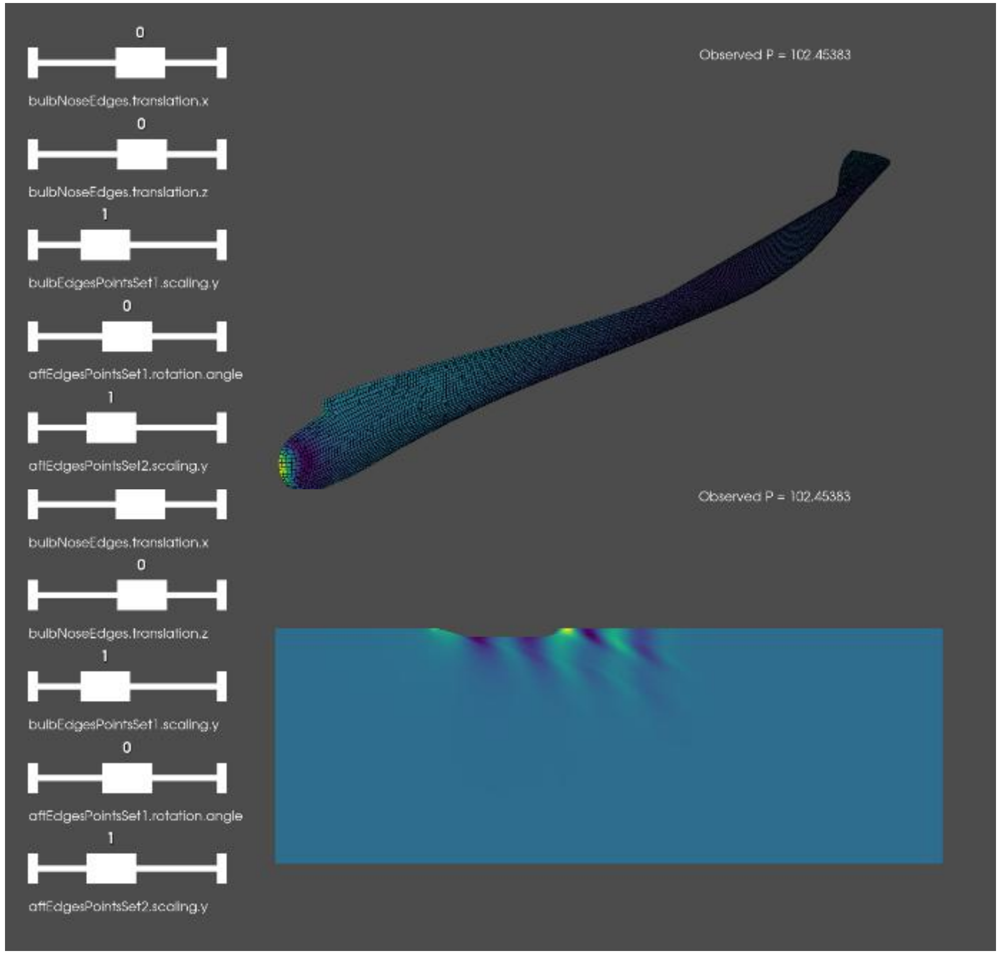
Results

Validation inside DOE

ID 0



CFD



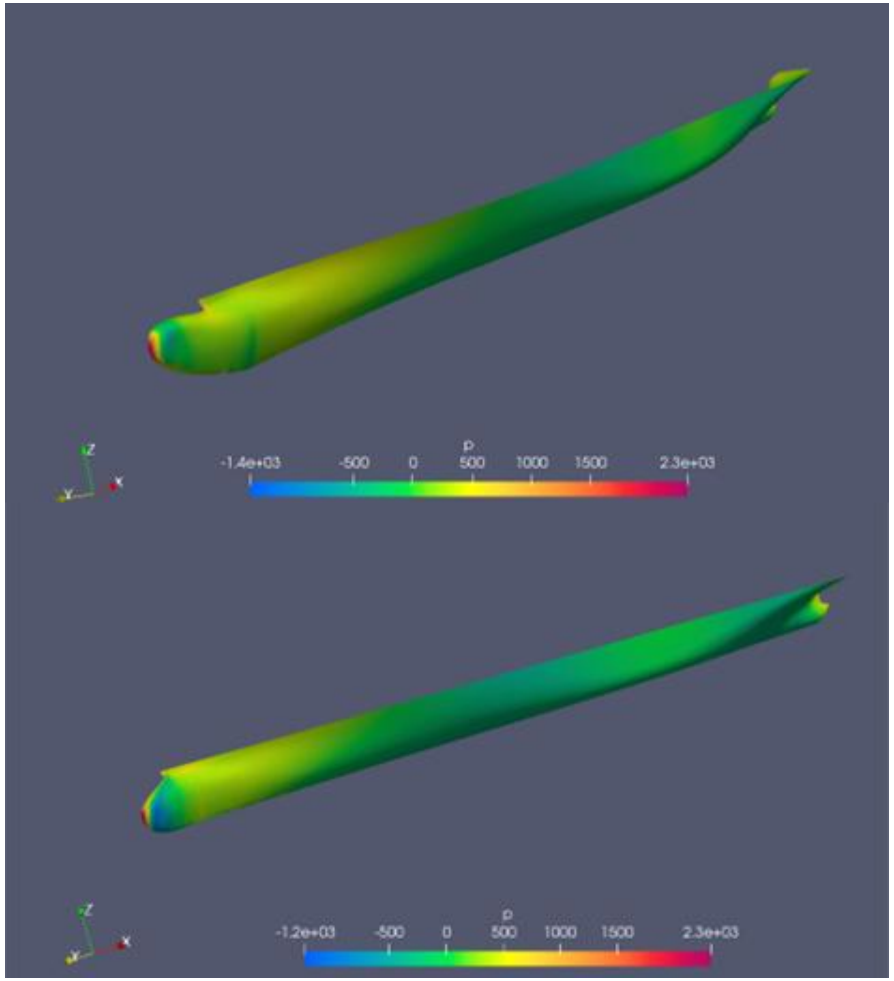
ROM

Results

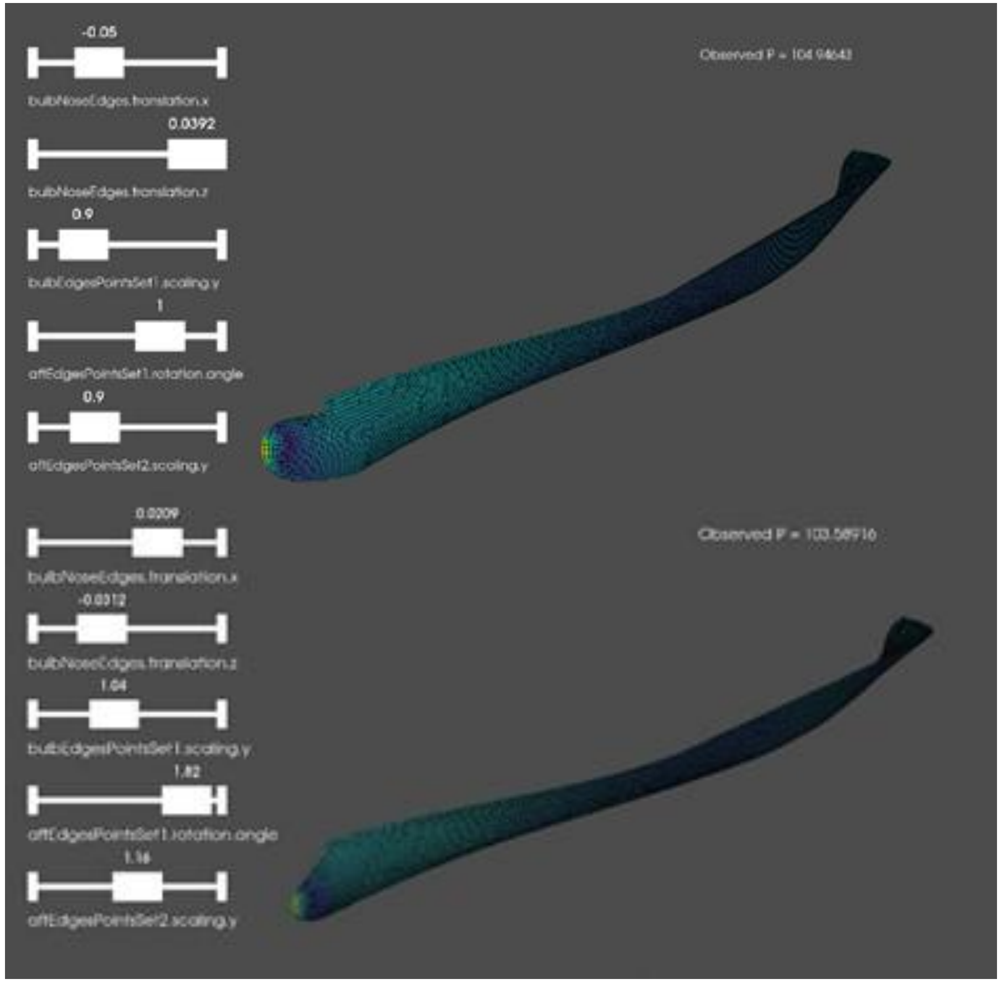
Validation outside DOE

ID 1

ID 2



CFD



ROM

Results

ROM Total Resistance Validation Errors

- In-DOE

ID	RBF Parameters Combination	$R_{t,CFD}$ [N]	$R_{t,CFD}$ [N]	Error %
0	0, 0, 1, 0, 1	102.45	102.45	0.00
21	-0.0347, 0.0327, 1.19, 1.6, 1.25	108.52	108.52	-1.38E-06

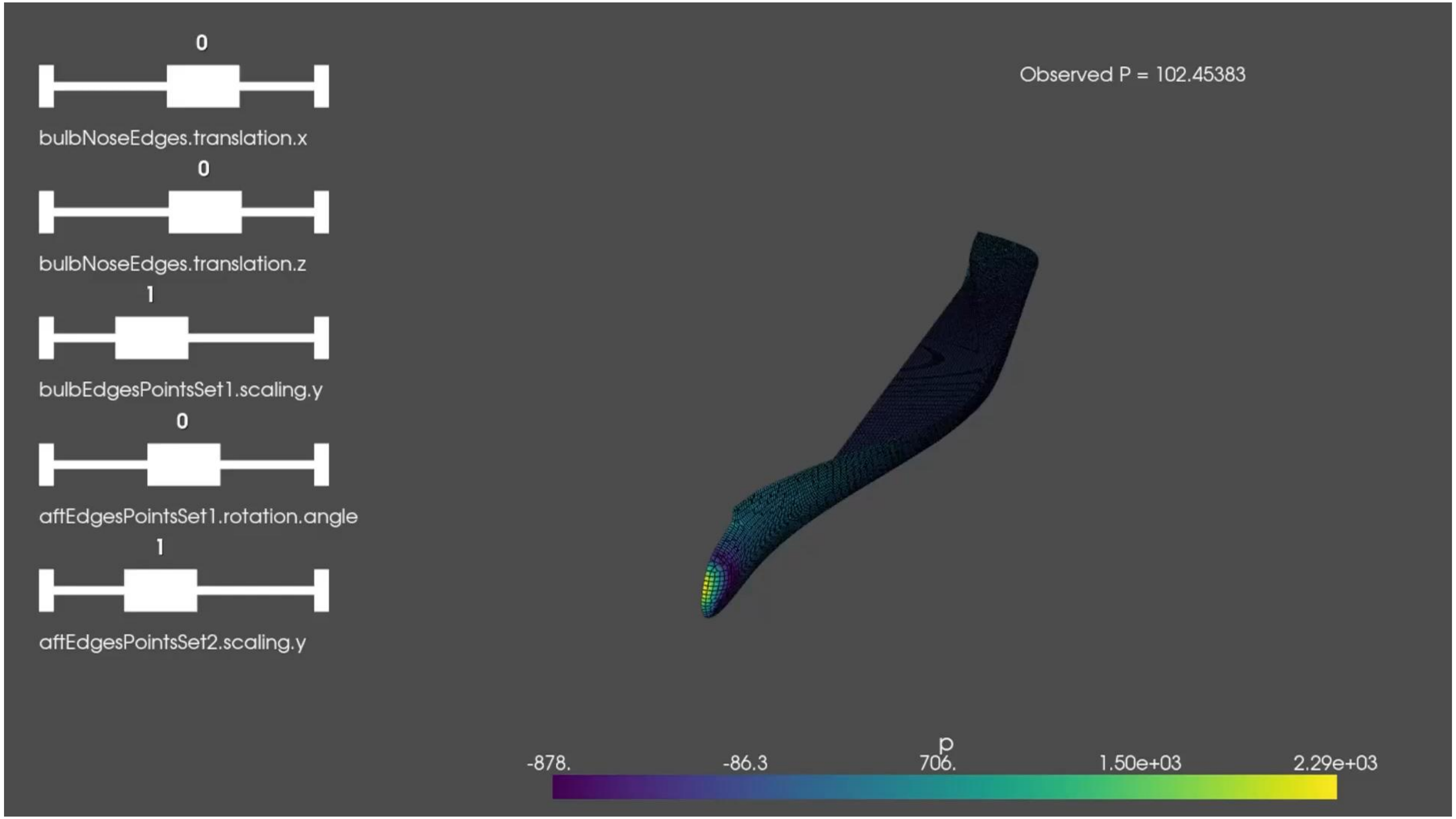
- Off-DOE

ID	RBF Parameters Combination	$\Delta R_{t,CFD}$ * [N]	$\Delta R_{t,ROM}$ * [N]	Error %
1	-0.05, 0.0392, 0.9, 1, 0.9	2.58	2.49	3.48
2	0.0209, -0.0312, 1.04, 1.82, 1.16	1.14	1.14	0.03

(*) vs. baseline

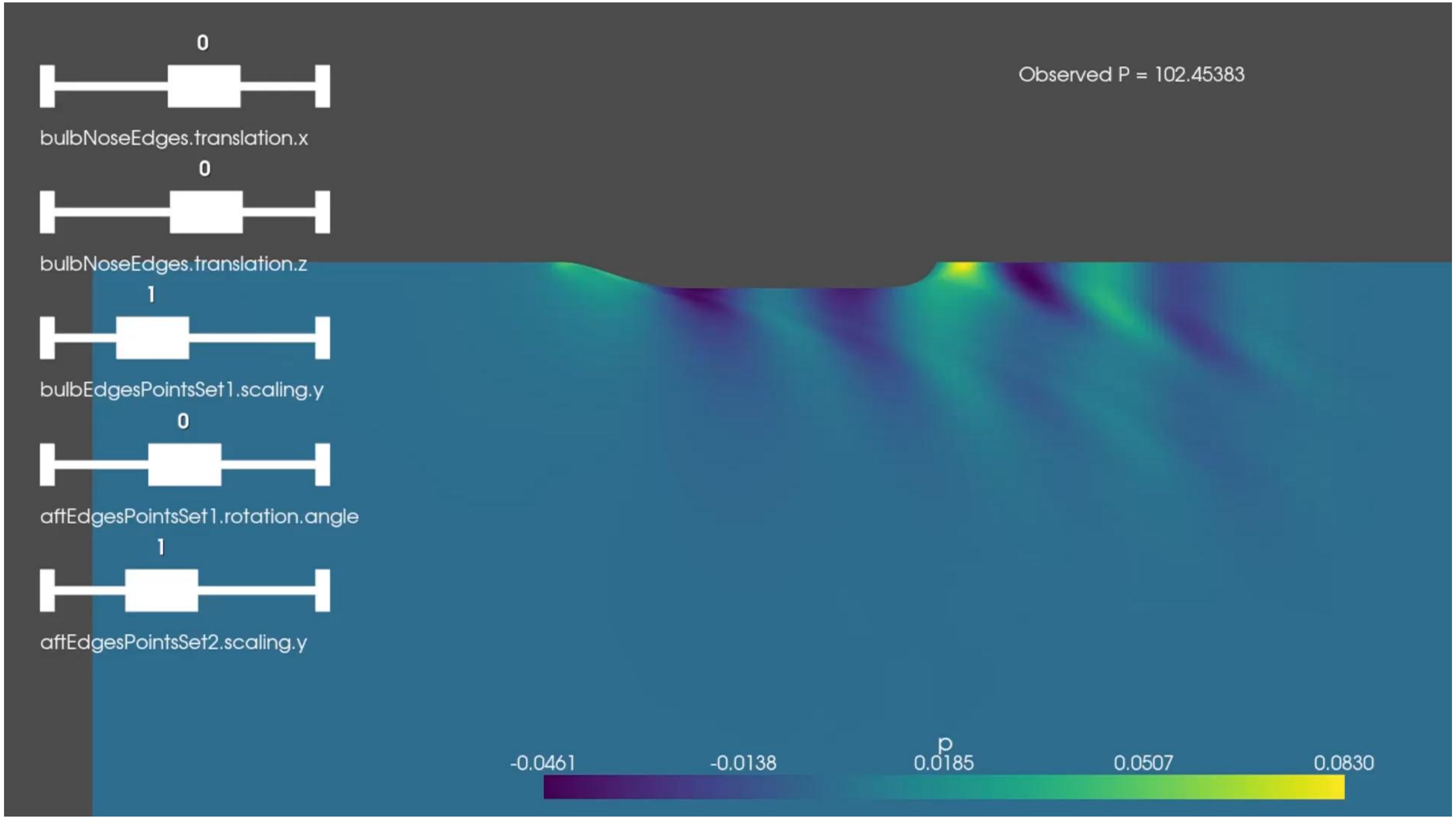
Results

Real-time Dashboard > Mesh, Pressure and Total Resistance



Results

Real-time Dashboard > Mesh, Wave Elevation and Total Resistance



Conclusions

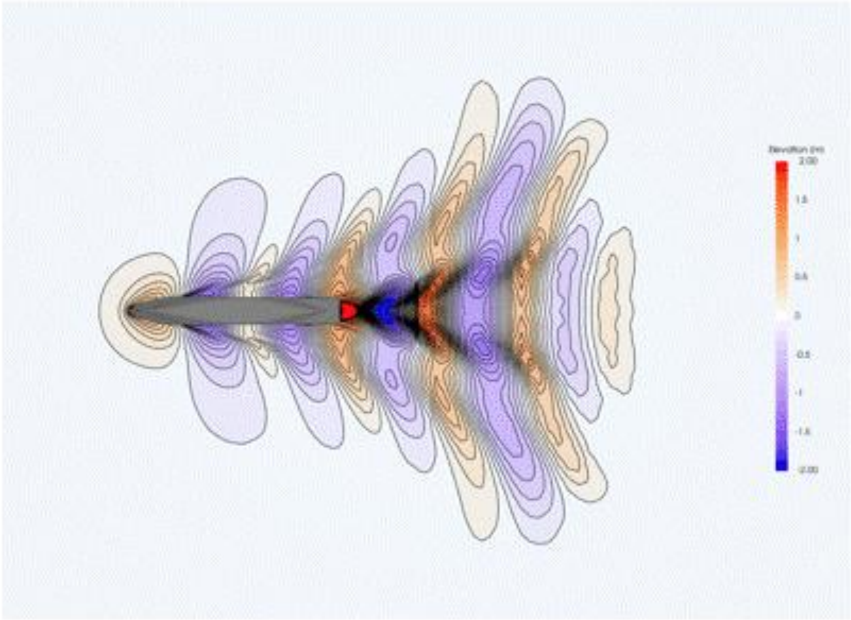
Conclusions

- A fast, accurate, and automated procedure to generate interactive ROMs to design and optimize ship hulls was presented
- RBF morphing and POD enable efficient shape parameterization and prediction
- ROMs demonstrated a maximum percentage error on prediction < 3.5% for total resistance
- Open-source tools and automation make the approach cost-effective and scalable
- ROMs support real-time design exploration and Digital Twin development

engys

Future Work

- Extend PoC to a larger dataset and different hull forms
- Employ deep learning to learn NN prediction models with a variety of different displacement hull-forms (in-progress)
- Investigate different design variation methods not limited to morphing



Acknowledgements

This work was developed within the framework of the Italian research project *AI4TwinShip*, that was co-funded by the European Union, the Italian government and the Friuli Venezia Giulia region in the context of the PR FESR 2021-2027 program

Funding: 149.545,06 € (of which 40% European Union, 42% Italy and 18% Friuli Venezia Giulia Region)

Thanks for your Attention! Questions?