AVT-331, L2 Problem (Sea Vehicle): DTMB 5415 Hull-shape Optimization for Resistance Minimization in Calm Water

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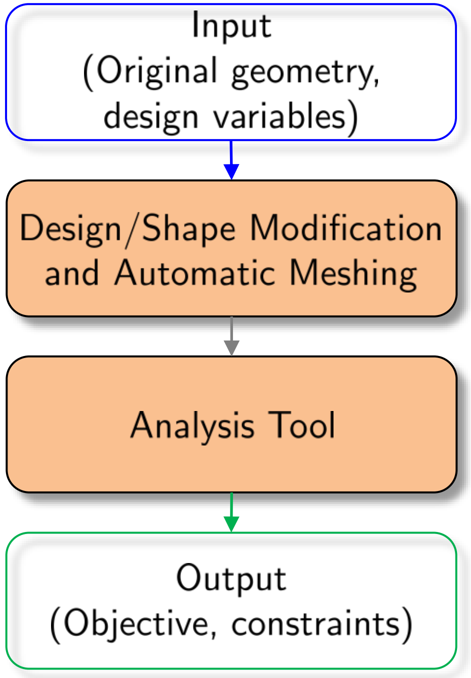
The Tool and the L2 Benchmark

❑ Tool components:

- Numerical solver based on linear potential flow
- Geometry modification
- Automatic meshing
- Variable-fidelity capability given by
  - Variable computational grid
  - Variable coupling (between hydro loads and rigid body equations of motion, 2DoFs)



❑ L2 problem:

- Hull: DTMB 5415
- Objective: Resistance reduction in calm water at Fr=0.28
  - Even keel
- Constraints: geometrical equalities and inequalities

L2 problem: DTMB 5415 Hull-shape Optimization

Objective

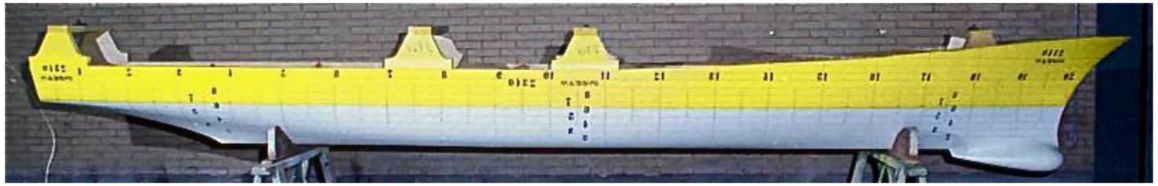
- Model-scale resistance reduction in calm water at Fr=0.28 (20kn in full scale)

Constraints

- Fixed length between perpendiculars (L_{pp})
- Fixed displacement (∇)
- ±5% variation of beam (B) and draft (T)
- Reserved volume (V) for the sonar in the dome

$$
\begin{array}{rll}
\text{minimize} & R_\mathrm{T}(\mathbf{x}) & \text{with } \mathbf{x} \in \mathbb{R}^N \\
\text{subject to} & L_\mathrm{pp}(\mathbf{x}) = L_{\mathrm{pp}_0} & \\
\text{and to} & \nabla(\mathbf{x}) = \nabla_0, & \\
& |\Delta B(\mathbf{x})| \leq 0.05 B_0, & \\
& |\Delta T(\mathbf{x})| \leq 0.05 T_0, & \\
& V(\mathbf{x}) \geq V_0, & \\
& -1 \leq x_i \leq 1 & \forall i = 1, \ldots, N
\end{array}
$$

Arleigh Burke-class destroyer (from military.com)



Arleigh Burke-class destroyer model: DTMB 5415

Hull-shape Modification

- Shape modification based on an original design space composed by M=27 global modification functions
- Optimization on a reduced design space based on **physics-informed/augmented dimensionality reduction** providing ***N*=14** orthogonal basis functions (ψ)

Modified geometry

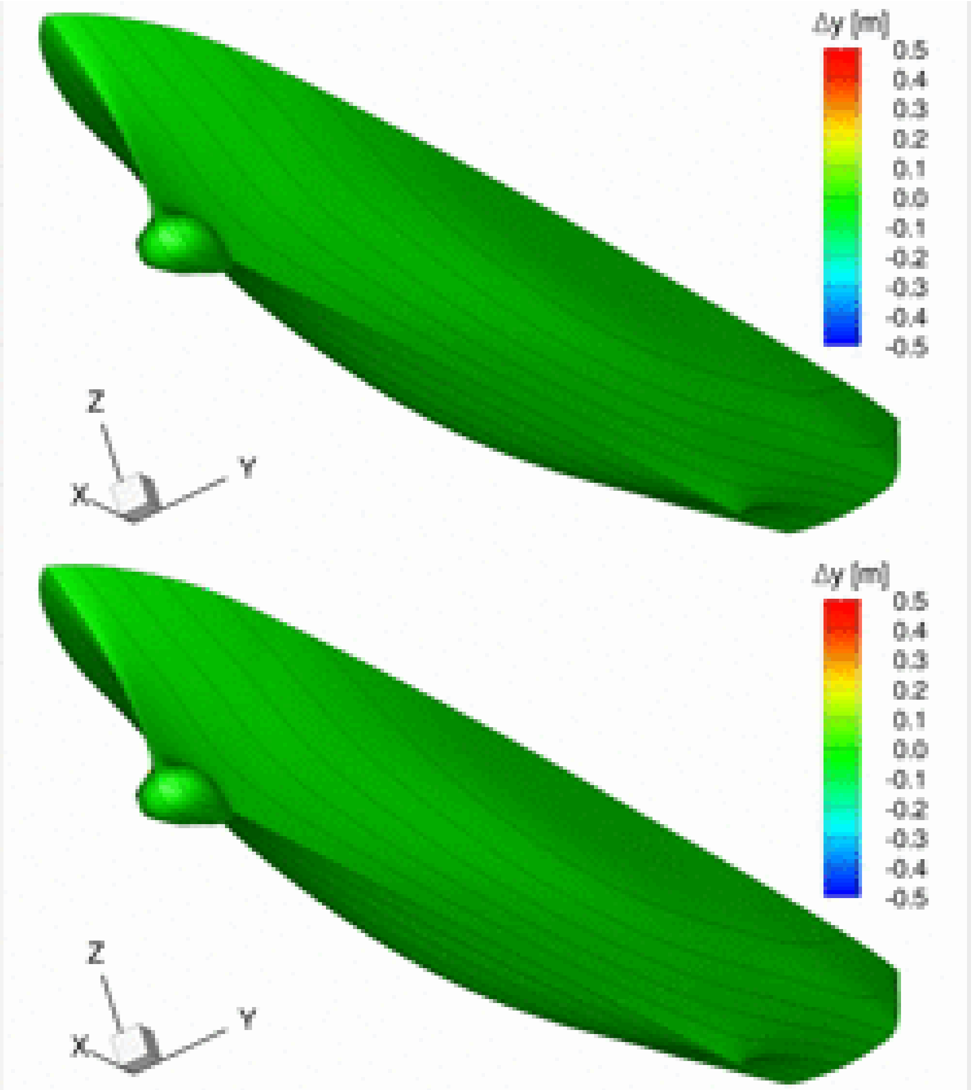
Shape modification vector

Physics-informed dimensionality reduction

$$\mathbf{g}(\mathbf{u},\mathbf{x}) = \mathbf{g}_0 + \boldsymbol{\delta}(\mathbf{u},\mathbf{x}) \longrightarrow \boldsymbol{\delta}(\mathbf{u},\mathbf{x}) = \sum_{i=1}^{N} x_i \boldsymbol{\psi}_i(\mathbf{u})$$

Original geometry

Shape modification examples

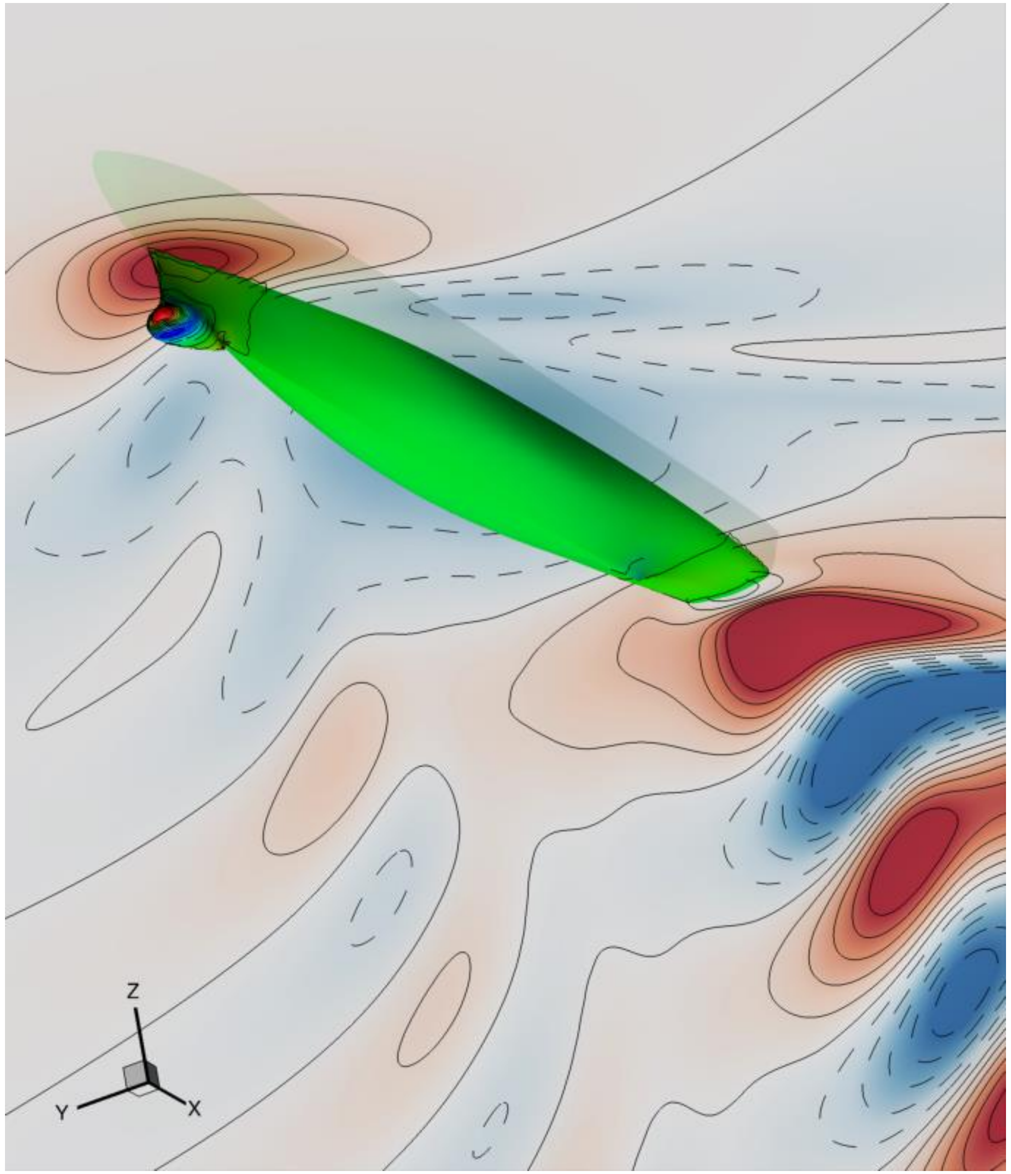


- Serani, A., Diez, M., Wackers, J., Visonneau, M., & Stern, F. (2019). Stochastic shape optimization via design-space augmented dimensionality reduction and RANS computations. In AIAA Scitech 2019 Forum (p. 2218).
- Serani, A., Stern, F., Campana, E. F., & Diez, M. (2021). Hull-form stochastic optimization via computational-cost reduction methods. *Engineering with Computers*, 1-25.

Hydrodynamic Solver

Wave Resistance Program (WARP)

- ❑ Developed at CNR-INM (former CNR-INSEAN)
- ❑ Linear potential flow
- ❑ Dawson (double-model) linearization
- ❑ Pressure integral for wave resistance
- ❑ Flat-plate approximation for frictional resistance, based on local Reynolds number
- ❑ Coupling with body equation of motions (2 DoF) given a fixed tolerance

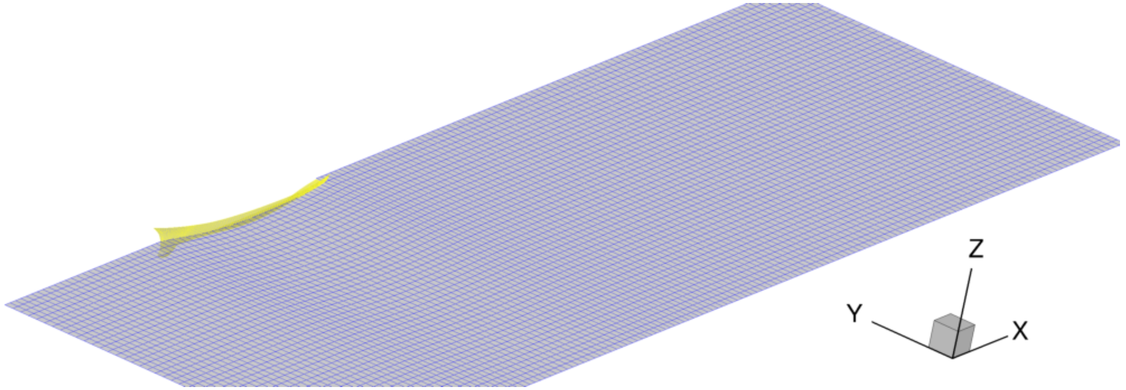


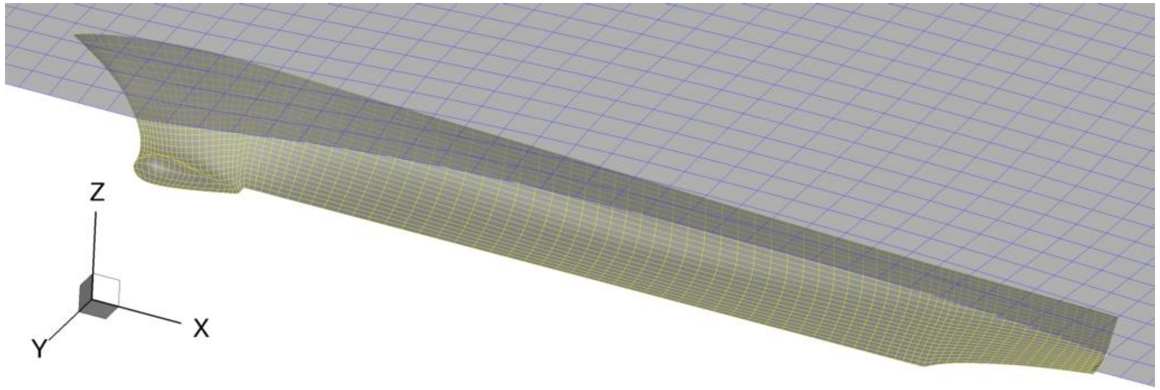
❖ Bassanini, P., Bulgarelli, U., Campana, E. F., and Lalli, F., "The wave resistance problem in a boundary integral formulation," Surveys on Mathematics for Industry, Vol. 4, 1994, pp. 151–194.

Numerical Grids

Free-surface and hull discretization

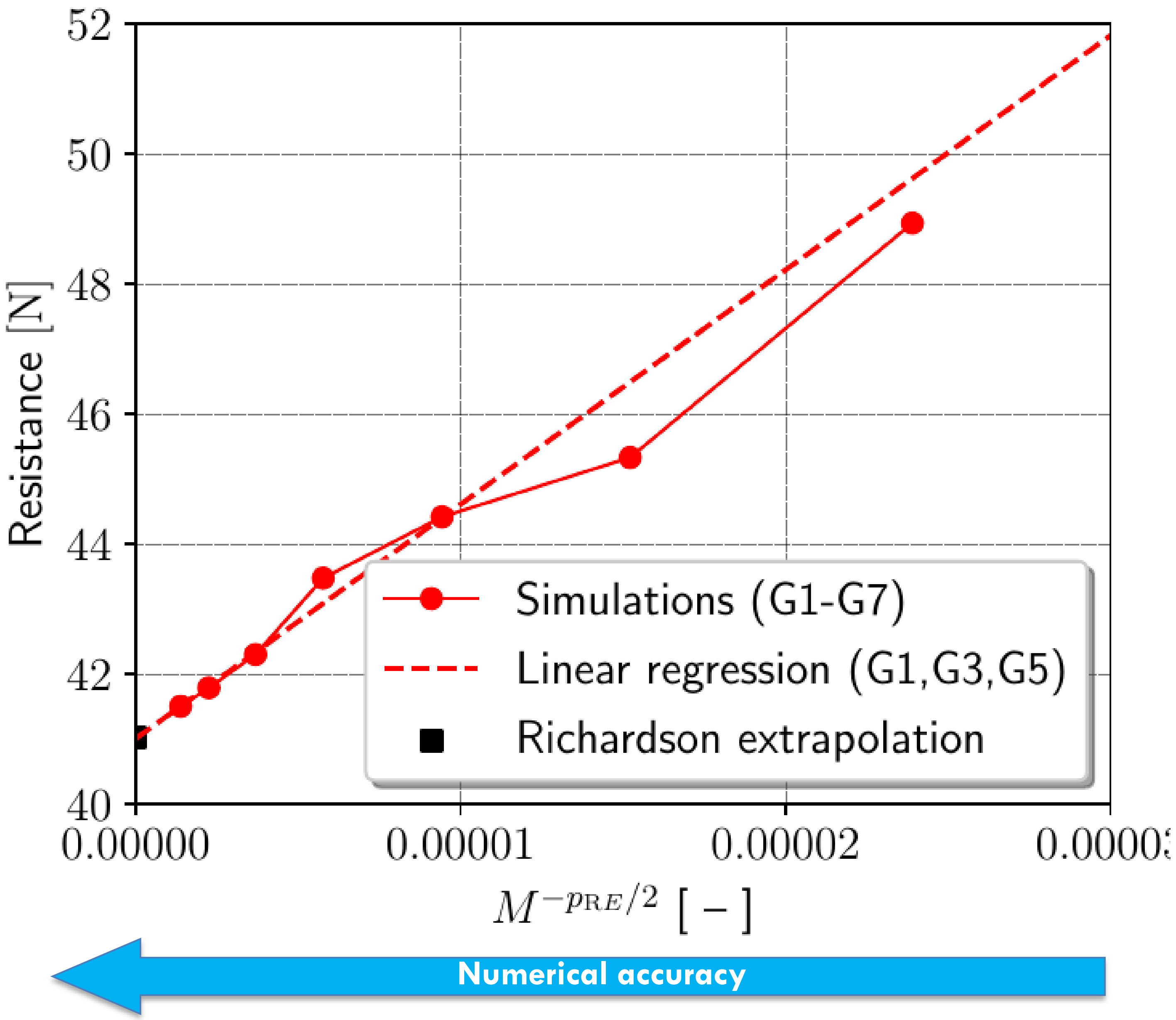
Grid/fidelity level	Refinement ratio	Free-surface	Hull	Number of elements (N)
G1	$2^{0.25}$	150 x 50	180 x 50	16.5k
G2		126 x 42	151 x 42	11.6k
G3		106 x 35	127 x 35	8.2k
G4		89 x 29	107 x 29	5.7k
G5		76 x 25	90 x 25	4.2k
G6		64 x 21	76 x 21	2.9k
G7		54 x 18	64 x 18	2.1k





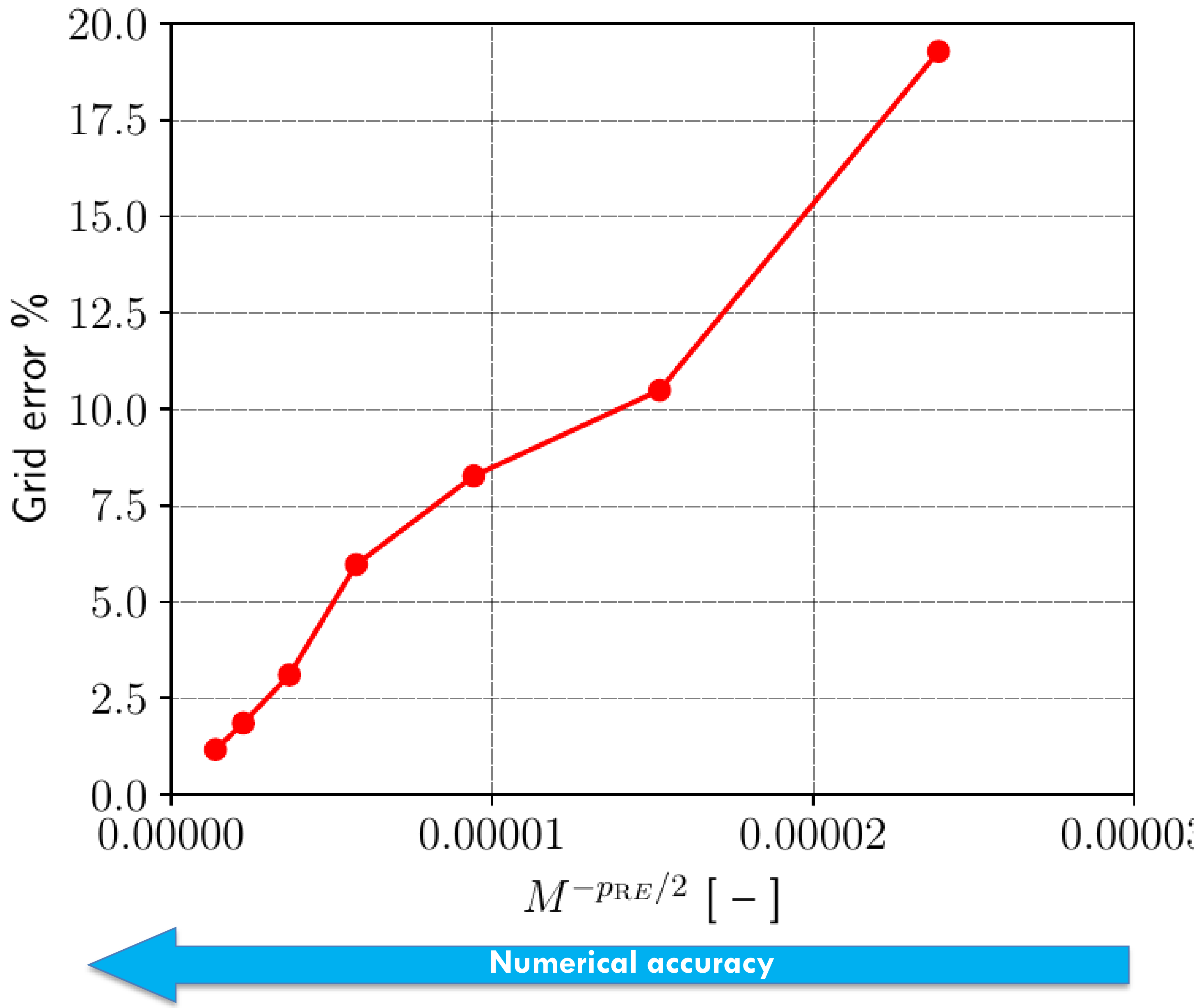
Numerical Grids – Resistance Grid Convergence

- Grid convergence is in the asymptotic range
- Coarser grids (G6, G7) are far from the linear regression
- The use of extra-coarse grids have to be done carefully



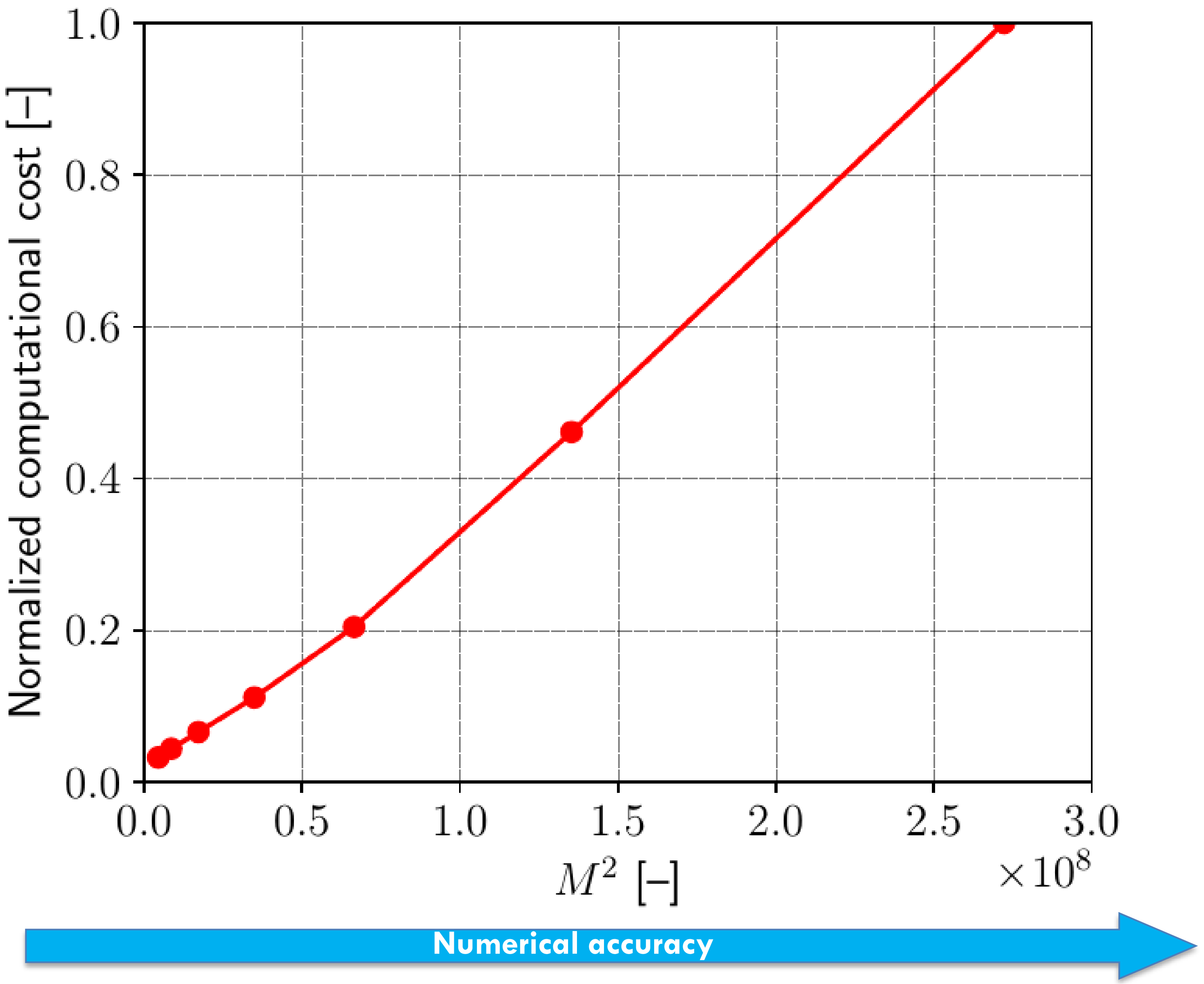
Numerical Grids – Resistance Grid Error

- Reference solution is estimate via Richardson extrapolation (RE) of G1, G3, G5 triplet
- Grid levels error are evaluated with respect to RE
- Grid errors go from 20 (G7, coarsest) to 1% (G1, finest)

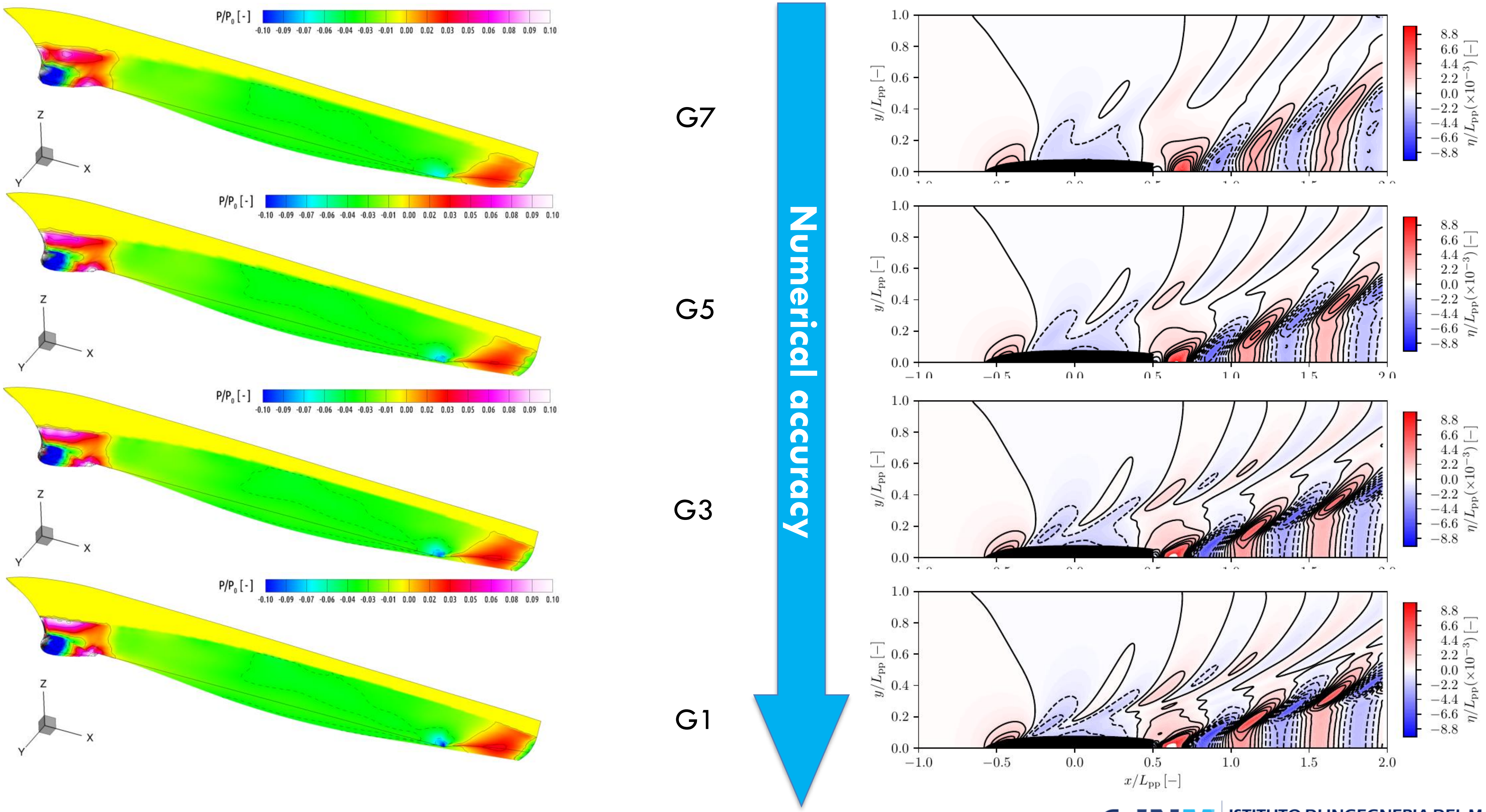


Numerical Grids – Normalized CPU Time Convergence

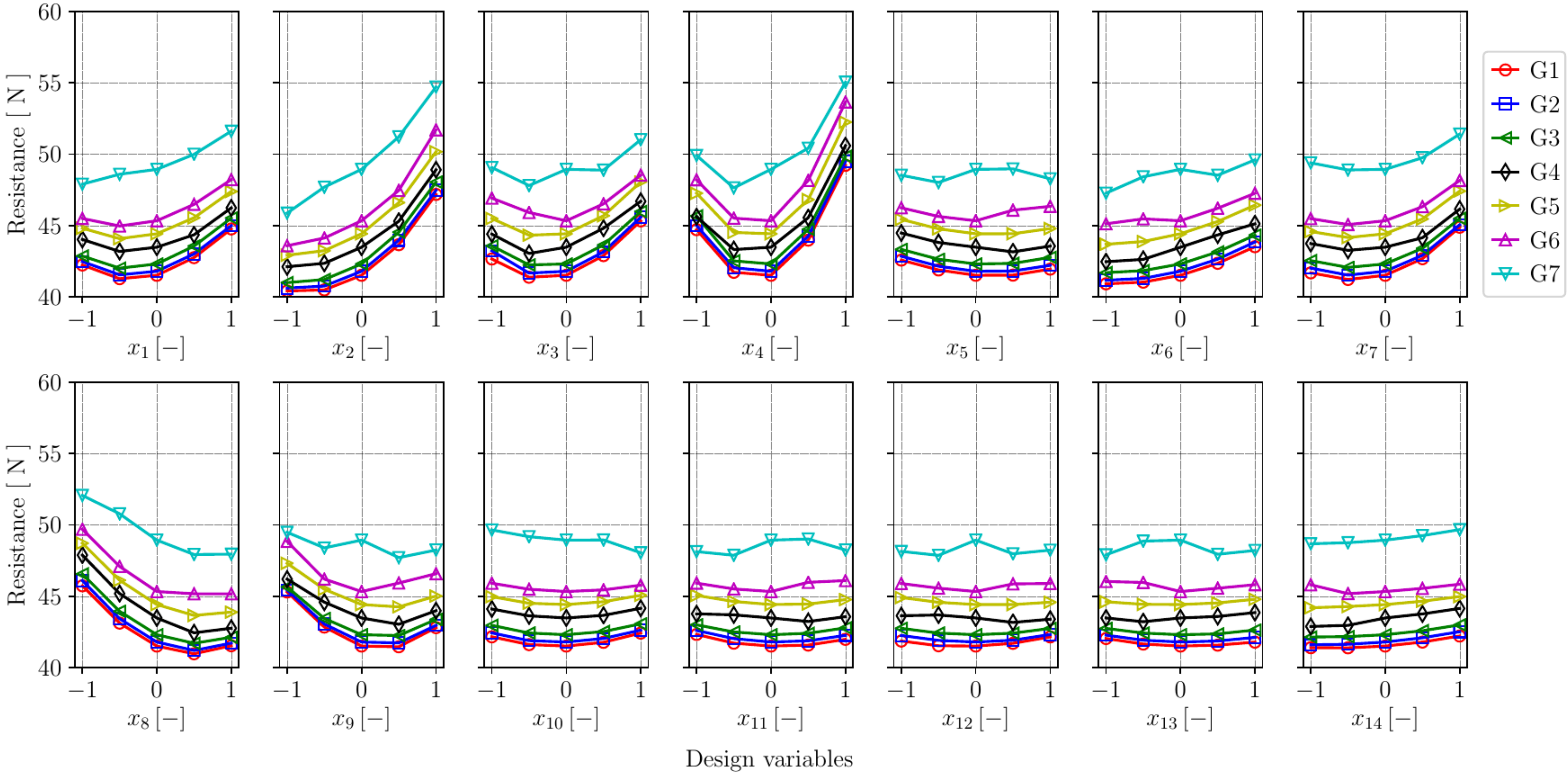
- CPU time normalized by the highest-fidelity (G1) CPU time cost
- Computational cost increase with a quadratic trend
- Computational cost ratio:
  - 1.00, 0.46, 0.20, 0.11, 0.07, 0.04, 0.03



Numerical Grids – Hull Pressure Field and Wave Elevation Patterns



Sensitivity Analysis – 0 DoF



Distributed Package

- ❑ Compiled fortran code (tested on Linux and Windows Linux Subsytem)
  - ➢ Compiled with both *gfortran* and *ifort*
  - ➢ External libraries needed:
    - *lapack* and *blas* (for GNU compiler)
    - *mkl* or *lapack* and *blas* (for Intel compiler)
    - *openMP* (not mandatory)

- ❑ Source code with makefile

- ❑ For use:
  - ➢ Input namelist (SBDF.nml) needs to be edited
    - Fidelity level can be defined selecting the grid level and/or the coupling accuracy
  - ➢ Design variables file (variables.inp)

Package to be Distributed and Timeline

- **Package uploaded on GitLab repository**
  - https://gitlab.com/qudo046/avt-331-benchmarks/-/tree/master/sea