FLEXI/GALÆXI

Code of the Month — Okt. 2024

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CEEC

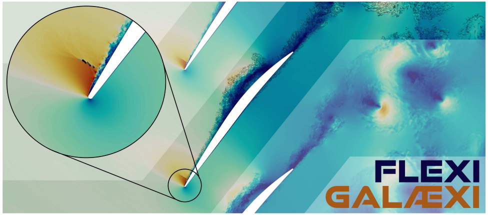
Centre of Excellence in Exascale CFD

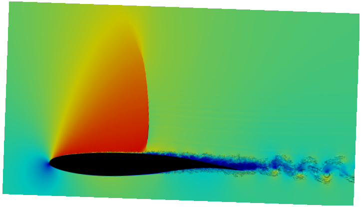
CFD Software Framework FLEXI/GALÆXI

Developed by the Numerics Research Group - Prof. Dr. Andrea Beck

- **OpenSource** HPC solver for the **unsteady compressible** Navier–Stokes equations
- **High order Discontinuous Galerkin** Spectral Element Method (DGSEM)
- FLEXI is part of the Center of Excellence for CFD (CEEC)

FLEXI/GALÆXI





https://numericsresearchgroup.org/flexi_index.html

CFD Software Framework FLEXI/GALÆXI

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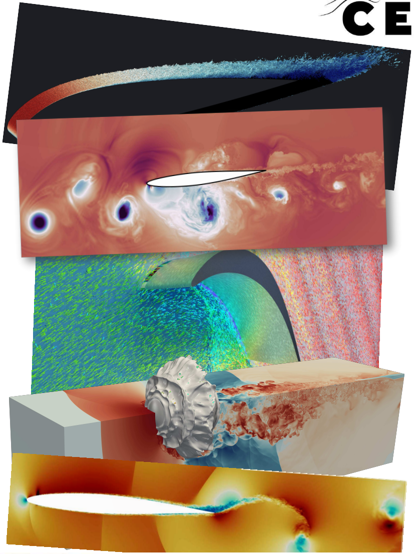
- Focus on LES/DNS of **compressible multiscale** and multiphysics flows



CFD Software Framework FLEXI/GALÆXI

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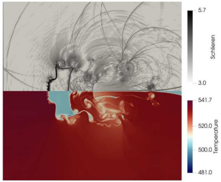
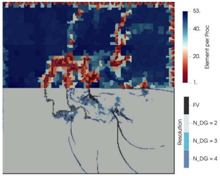
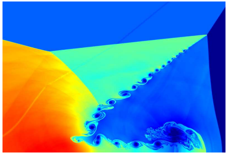
- Focus on LES/DNS of **compressible multiscale** and multiphysics flows
- Support of **complex geometries**: unstructured, non-conforming, moving meshes, hp-refinement
- **Shock capturing** based on FV subcells
- Multiphase and particle-laden flow



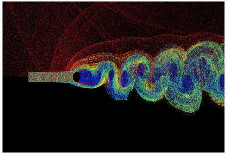
Shock-drop interaction



hp-refinement with DBL



FV subcell shock capturing



Euler–Lagrange particle tracking

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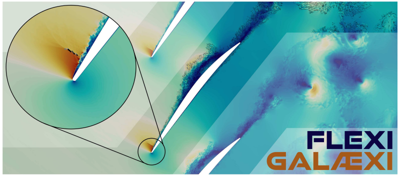
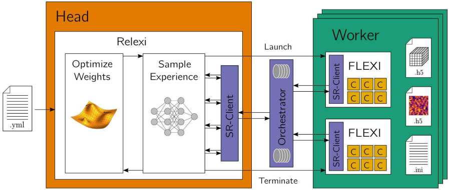
- Support of **complex geometries**: unstructured, non-conforming, moving meshes, hp-refinement
- **Shock capturing** based on FV subcells
- Multiphase and particle-laden flow
- GALÆXI: **GPU accelerated** using CUDA aware MPI
- Relexi: HPC reinforcement learning framework
- **Excellent scaling** on various European Supercomputers
- Performs comparable to other CFD codes, e.g., CODA [J.B. Chapelier, A. Beck et al., Physics of Fluids, 2024.]



M. Kurz, A. Beck, et al. GALÆXI [...], Comput. Phys. Commun., 2024.

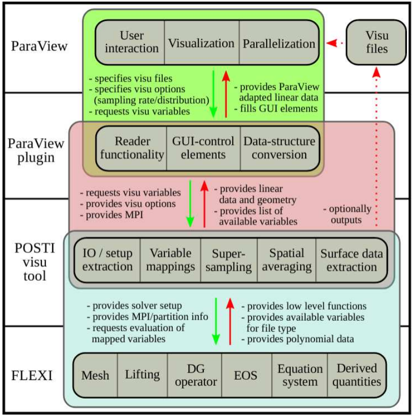


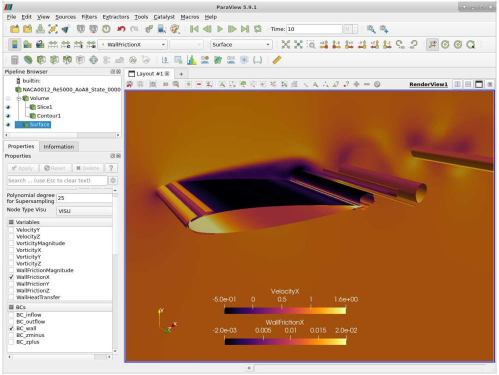
M. Kurz, A. Beck, et al., Relexi [...], Software Impacts, 2022.

CFD Software Framework FLEXI/GALÆXI

Complete High-Order Toolchain Including Pre- and Post-Processing

Open source mesh generator **HOPR** for unstructured, high-order meshes: `https://github.com/hopr-framework/hopr`

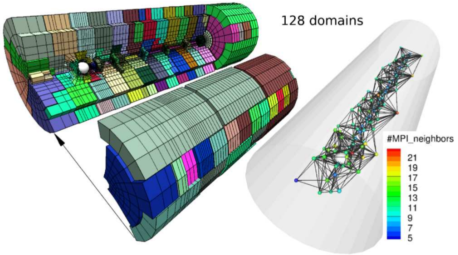


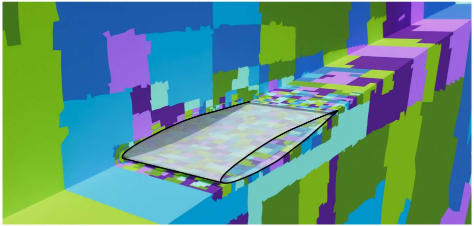


Parallel Performance

- Parallelization with the MPI paradigm
  - **Domain decomposition** using a space-filling curve
  - Communication latency hiding by local work
  - DGSEM operator requires only communication of surface fluxes

    ⇒**Small communication stencil**
- **Parallel I/O**, small memory footprint
- **Efficient cache usage** at about 4000 DOF/core
- Efficiency still intact for combined FV/DG calculations

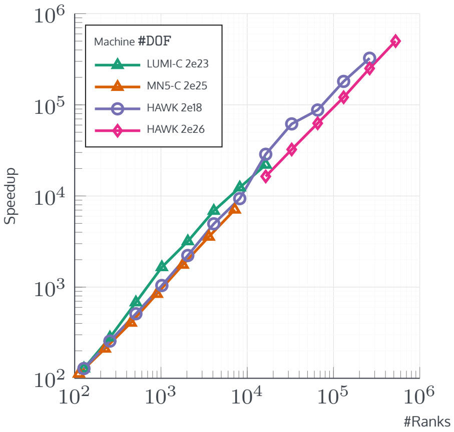




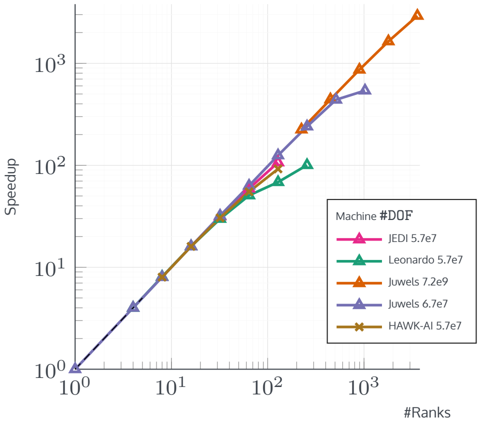
Parallel Performance

FLEXI CPU / GALÆXI GPU

FLEXI CPU



GALÆXI NVIDIA GPU

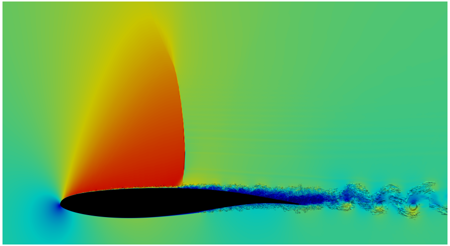


Applications

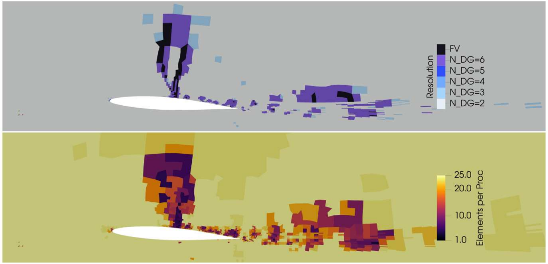
Wall-Modeled LES of Shock Buffet around NACA airfoil

Transonic NACA airfoil at $M = 0.73$ and $Re = 930000$ using 118 Mio DOFs

using **hp-refinement, dynamic load balancing** and FV subcell shock capturing



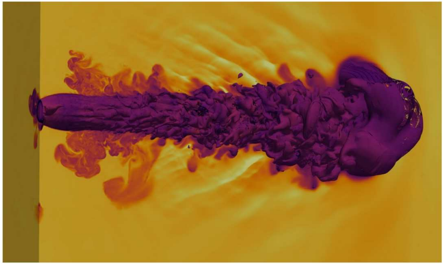
M. Blind, A. Beck, et al. Numerical and Experimental Investigation of a NACA 64A-110 Airfoil in Transonic Flow Regime, 2023.



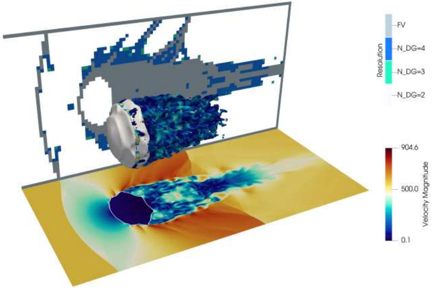
Applications

Multiphase Flow: Diffuse and Sharp Interface

Hydrogen injection at a nozzle pressure ratio of 10 using a mixture model



3D shock-drop interaction using the hp-adaptive level-set ghost fluid method

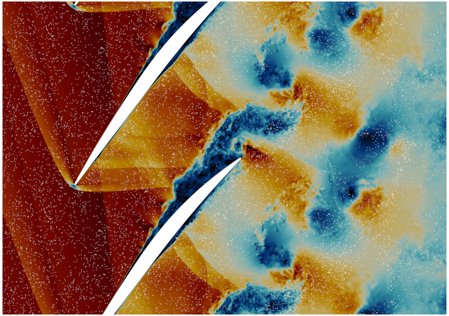


P. Mossier, A. Beck, et al. An Efficient hp-Adaptive Strategy for a Level-Set Ghost-Fluid Method, JSC, 2023.

Applications

Particle-Laden Flow: 4-way Coupled Euler–Lagrange Method

Particle-laden flow around a compressor cascade with $M = 1.4$ and $Re = 1.4e6$



A. Schwarz, High-fidelity particle tracking and impact-induced deformations, Thesis, 2024.

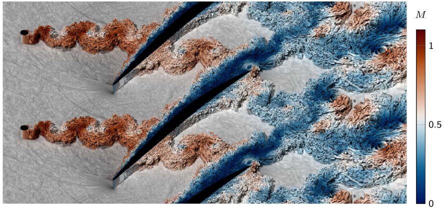
Particle-laden flow around a wall-mounted cylinder at $M = 0.7$ and $Re = 32000$

P. Kopper, An Euler–Lagrange Method for Compressible Dispersed Multiscale Flow, Thesis, 2024.

Applications

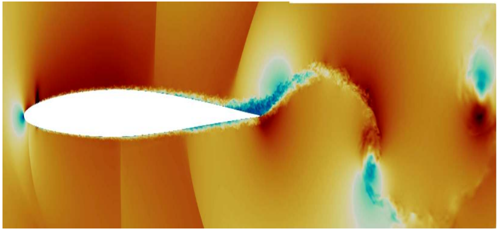
Moving Mesh Methods: Sliding Mesh and Arbitrary Lagrangian-Eulerian (ALE)

Transonic compressor cascade with wake generator using the **sliding mesh method**



P. Kopper, An Euler–Lagrange Method for Compressible Dispersed Multiscale Flow, Thesis, 2024.

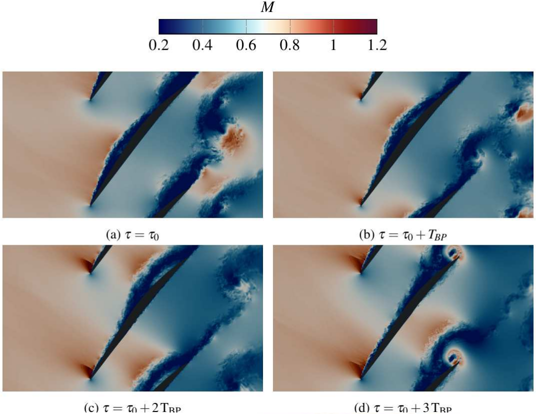
Plunging airfoil with $M = 0.72$ and $Re = 9.3e5$ using **ALE**



Applications

Transonic Compressor Cascade

NASA Rotor 37 with $M = 0.758$ and $Re = 972550$ for the comparison of FLEXI with GALÆXI



Applications

Transonic Compressor Cascade

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Performance index:

$$\text{PID} = \frac{\text{total runtime x \#procs}}{\text{\#DOFs x \#time steps x \#RK-stages}}$$

Energy-normalized PID (EPID):

$$\text{EPID} = \frac{\text{Walltime x Power}}{\text{\#RK-stages x \#DOF}} = \frac{\text{Power}}{\text{\#Ranks}} \text{x PID}$$

	Ranks	DOF/Rank	P_{rank} [W]	PID [s]	EPID [J]	Walltime/t^* [s]	Energy/t^* [kWh]
GPU	128	2.03×10^6	448	4.58×10^{-9}	2.05×10^{-6}	9209	147
CPU	32 768	7.93×10^3	4.94	1.02×10^{-6}	5.06×10^{-6}	7538	339
Savings					59.5 %		56.8 %

M. Kurz, A. Beck, et al. GALÆXI: Solving complex compressible flows with high-order discontinuous Galerkin methods on accelerator-based systems, Comput. Phys. Commun., 2024.

$\Rightarrow$ **GALÆXI is able of reducing the carbon emission of large-scale flow simulations by more than** 55%

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EuroHPC Joint Undertaking

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DFG Deutsche Forschungsgemeinschaft

HLRS

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Thank you for your attention!