Universität Rostock Traditio et Innovatio

Application of the Overset Grid Library Bellerophon

NOFUN 2016
29. September 2016 - Braunschweig, Germany

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Outline

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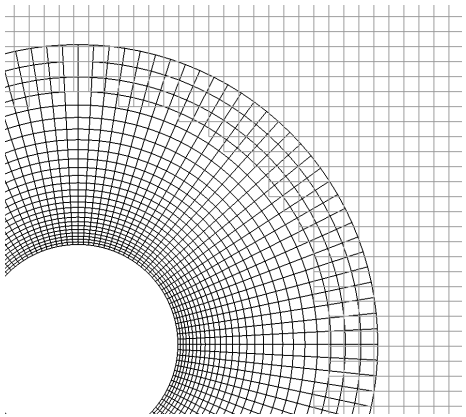
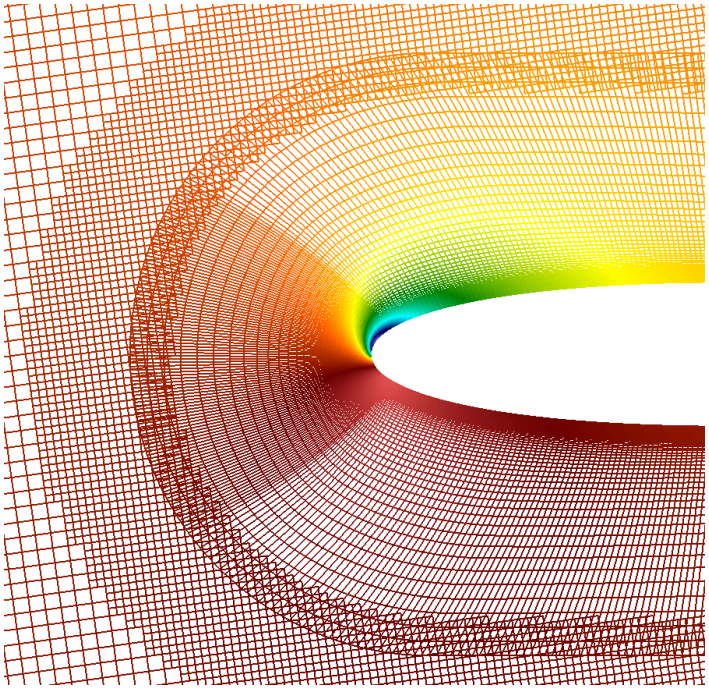
Introduction

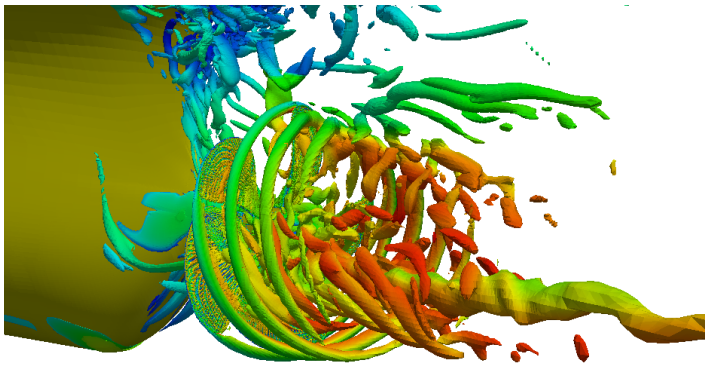


- Spacial discretisation yields simulation quality
- Meshing for complex geometries may be challenging
- Further problems when geometries move
- Idea: separate meshes for each feature
- Interpolation between grids accounts for coupling of the solution

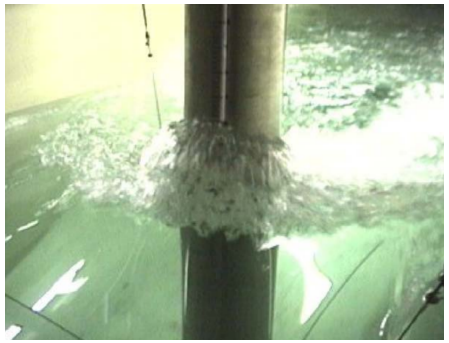
Introduction

- Traditional Overset Grid Codes
  e.g. Code TAU, OVERFLOW, INS3D:
  - Blockstructured Meshes
  - Finite-Difference-/Finite-Element-Method
  - Limited to special applications, i.e. aerodynamics
- OpenFOAM
  - Structured and unstructured Meshes
  - Finite-Volume-Method
  - Fully featured
  - Open Source
- Overset libraries commercial solvers
  e.g. StarCCM+, Suggar++, DirtLIB:
  - Structured and unstructured Meshes
  - Finite-Volume-Method
  - Fully featured
  - Closed Source $\rightsquigarrow$ Black Box
  - May become expensive (at least for massive parallelisation)





Mathematical Modelling



[Chaplin et al. (2003)]

- Navier-Stokes-Equations:

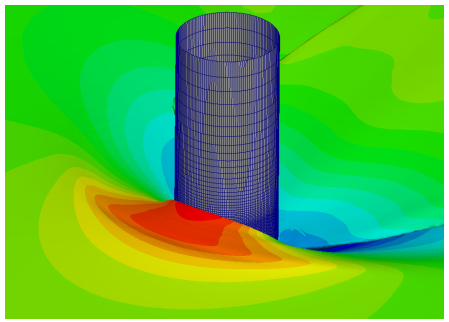
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U U) = \nabla \cdot T + \rho b$$

- Transport of a scalar Φ:

$$\frac{\partial \rho \Phi}{\partial t} + \nabla \cdot (\rho U \Phi) = \nabla \cdot (\Gamma \nabla \Phi) + q_\Phi$$

- Numerical models like RANS-models or VOF are special forms of the transport equation



Mathematical Modelling

- Discretisation of equations, e. g. convective term:

$$\nabla \cdot (\rho U \Phi) = \sum_f \vec{S}_f \cdot (\rho_f \vec{U}_f) \Phi_f$$

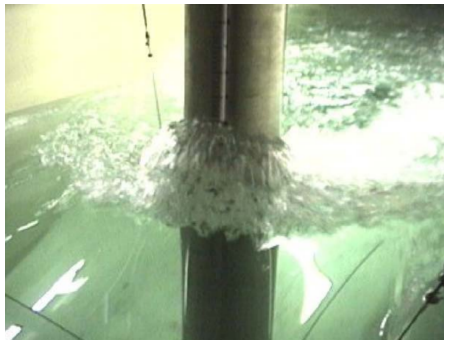
with $\Phi_f = \delta_f \Phi_p + (1 - \delta_f) \Phi_{n(f)}$

- Implicit connection of field values $\rightsquigarrow$ SLE

$$a_i \Phi_i + \sum_{j \neq i} a_j \Phi_j = b_i$$

- Solution of resulting matrix yields flow field

$$\Phi = A^{-1} b$$



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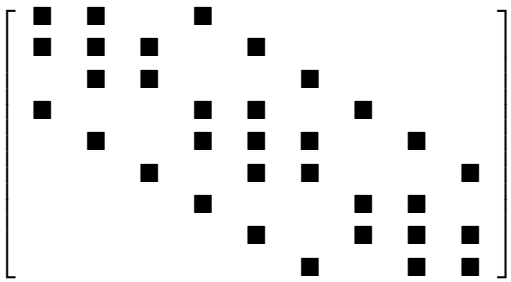
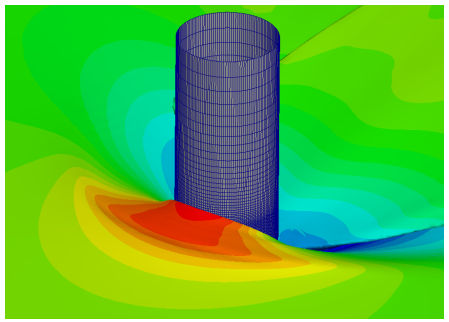
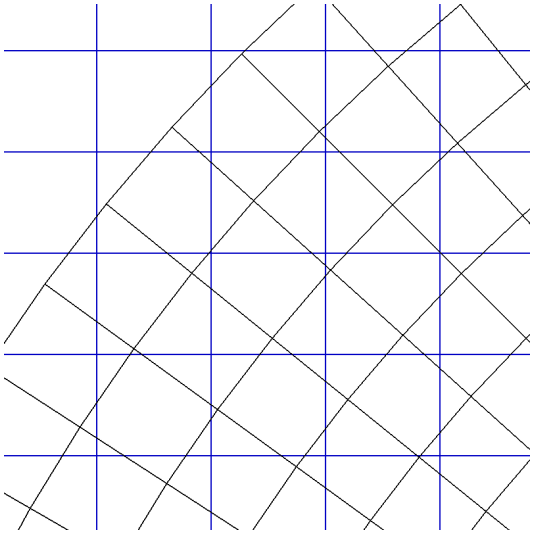
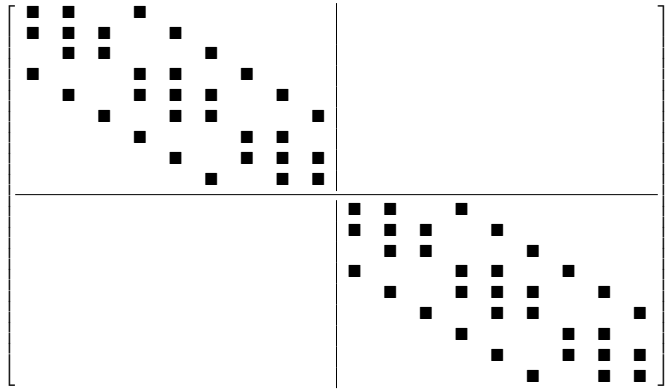




Overset Grid Methodology





- Overset zones do not share faces
- No linkage between cells
- Overset grid scheme has to provide Overset Interpolation Information
- Identification Acceptors and Donors
- Hole cutting

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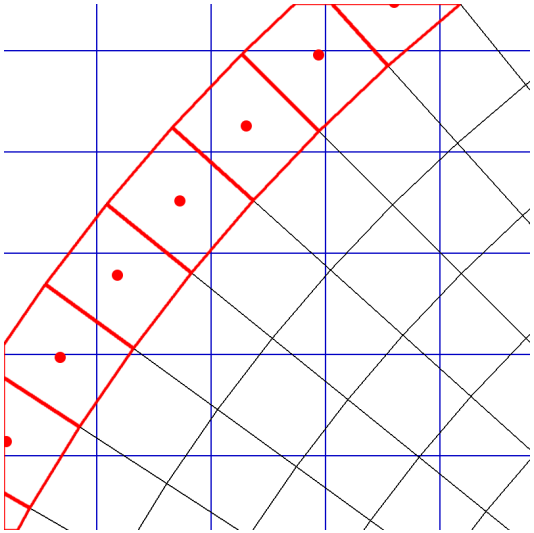

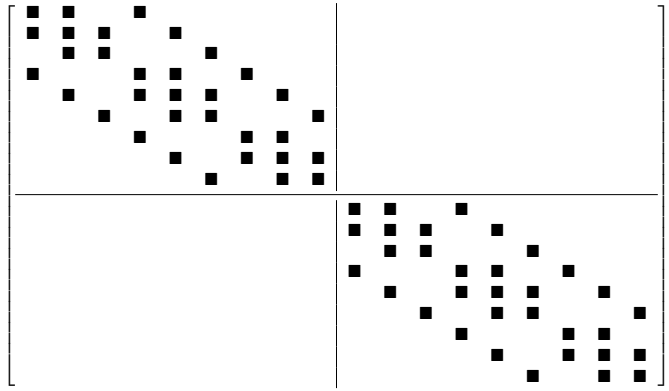

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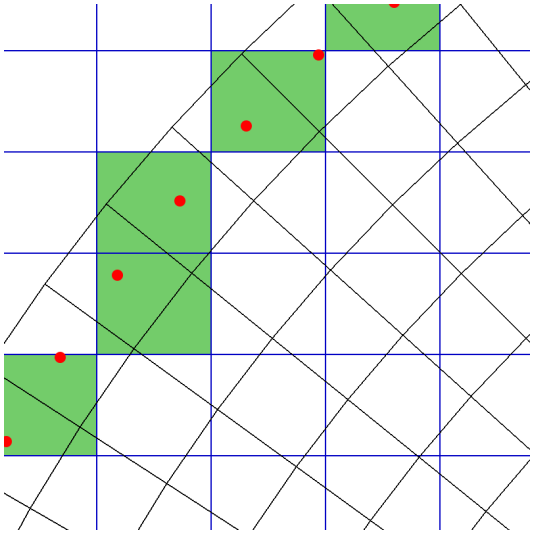

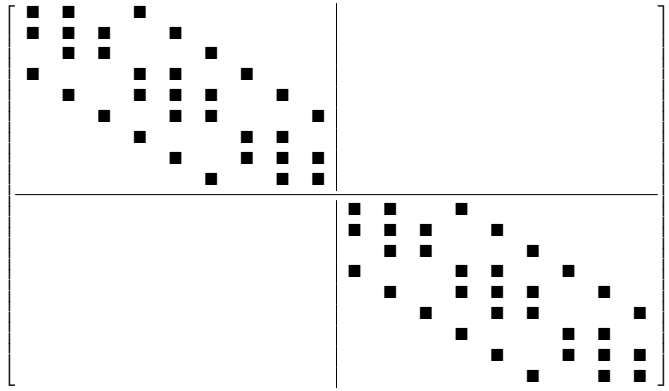

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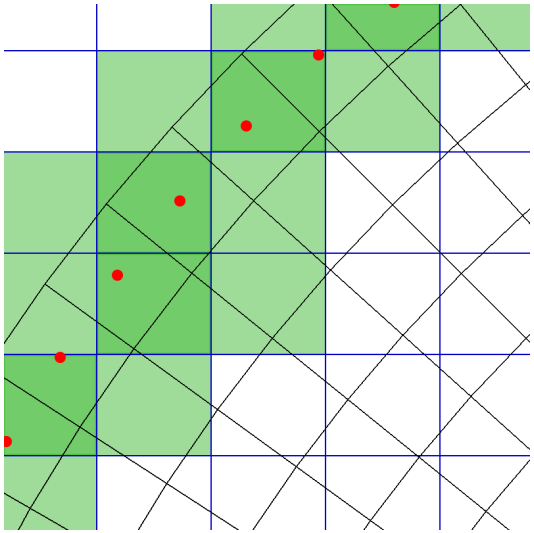

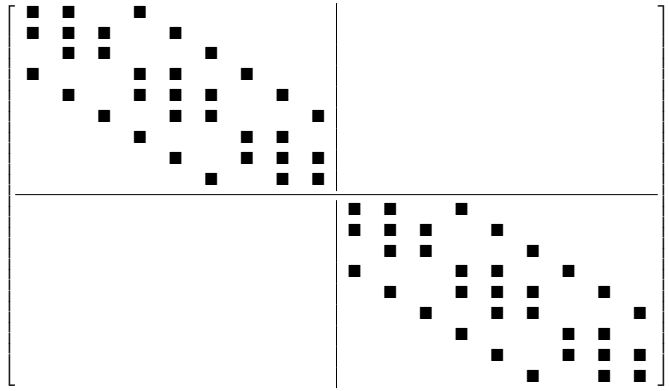

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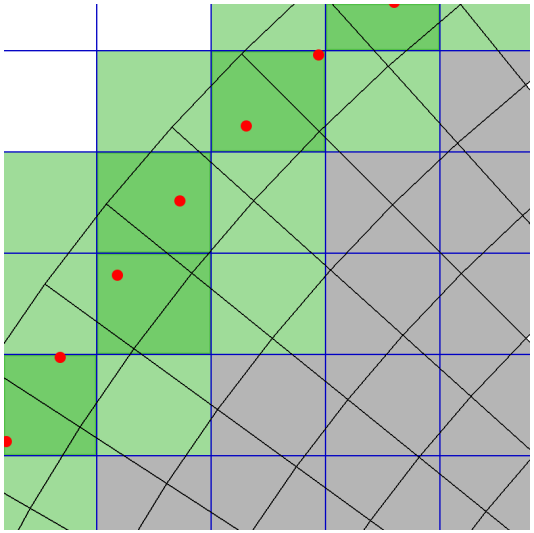

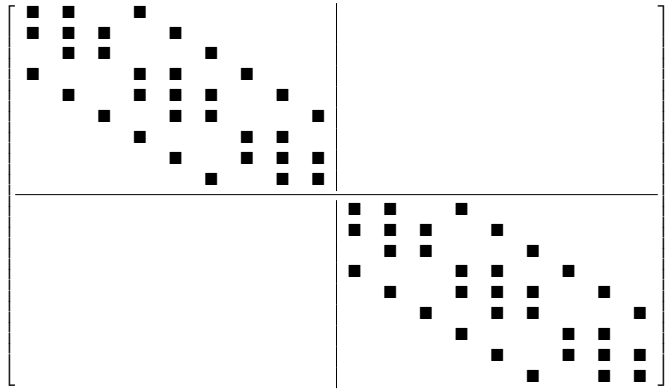

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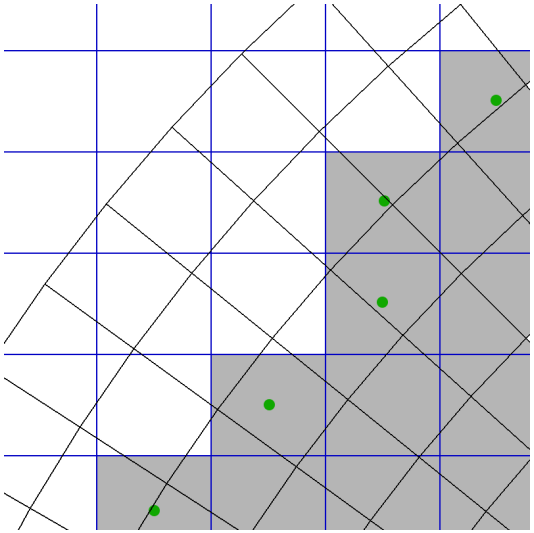

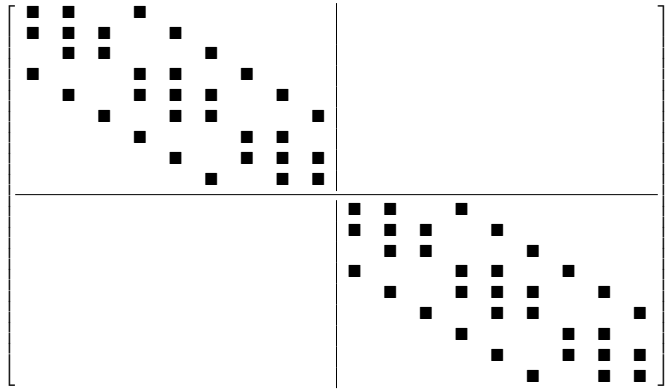

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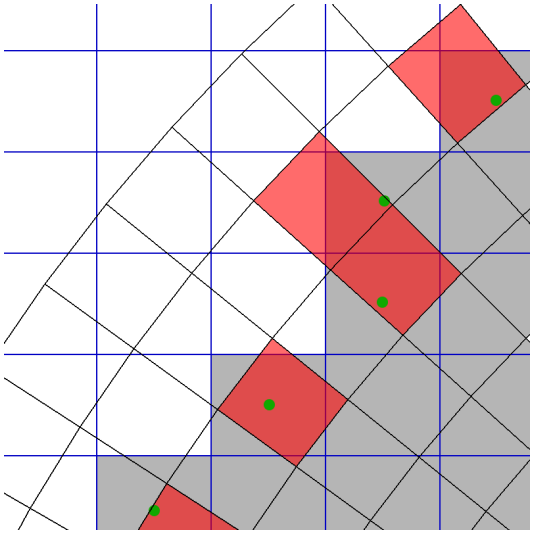

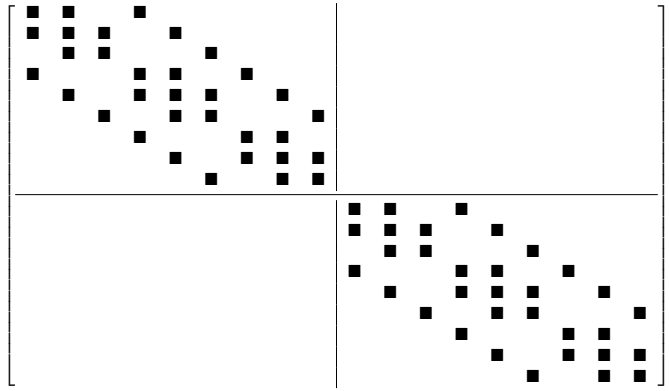

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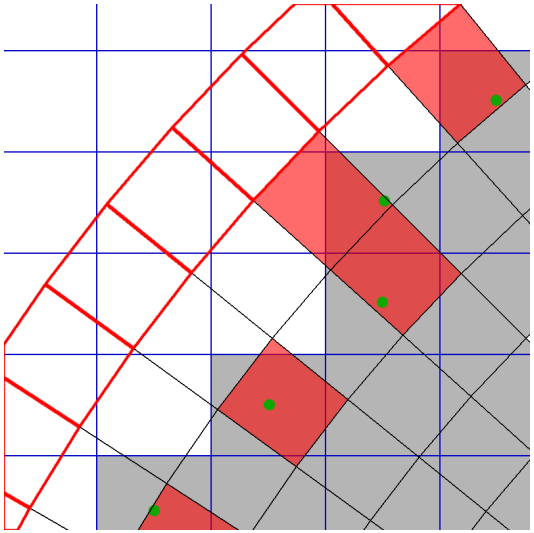

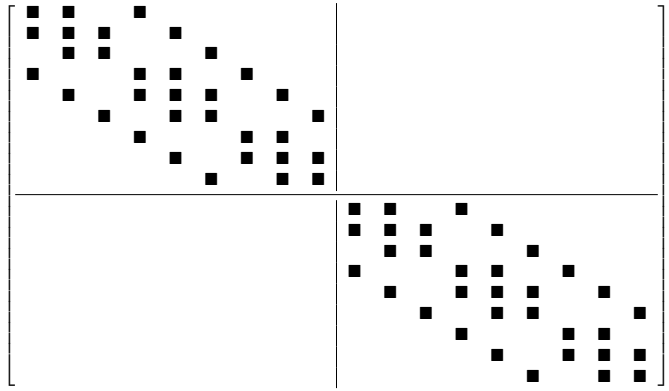

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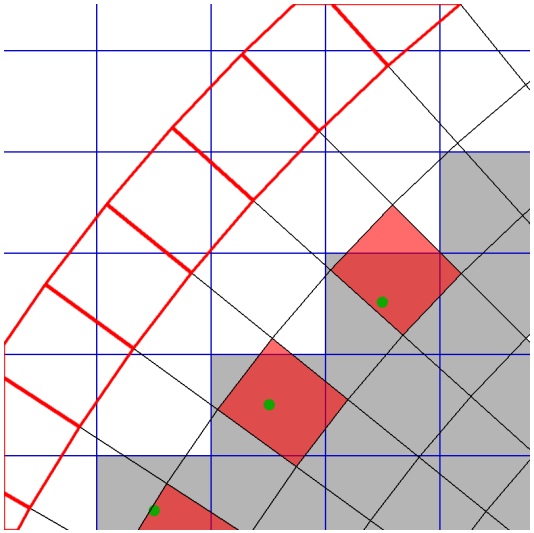

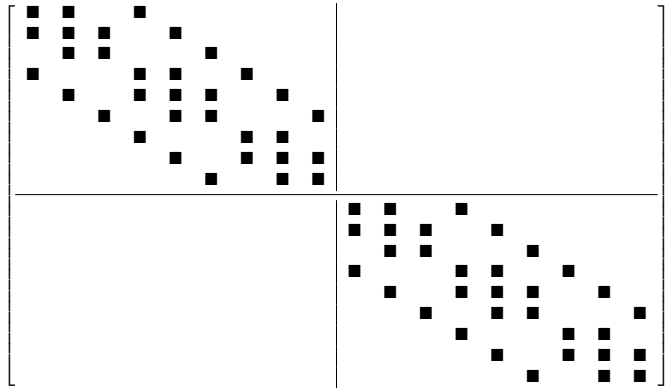

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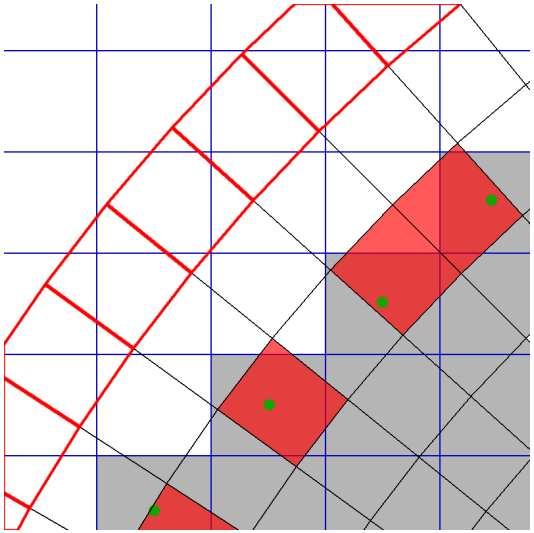

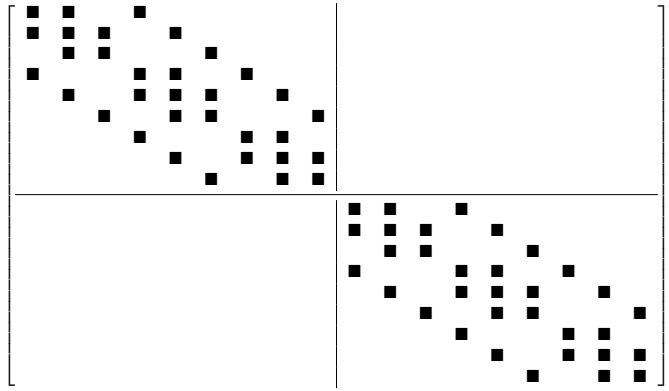

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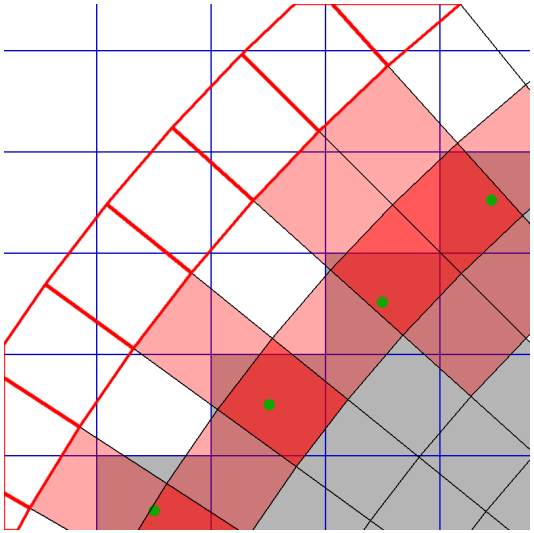

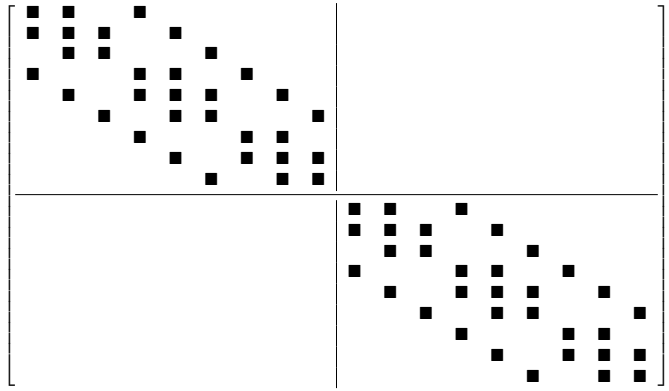

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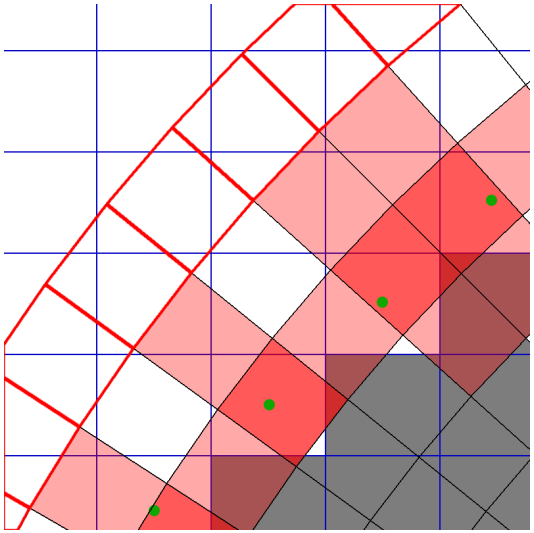

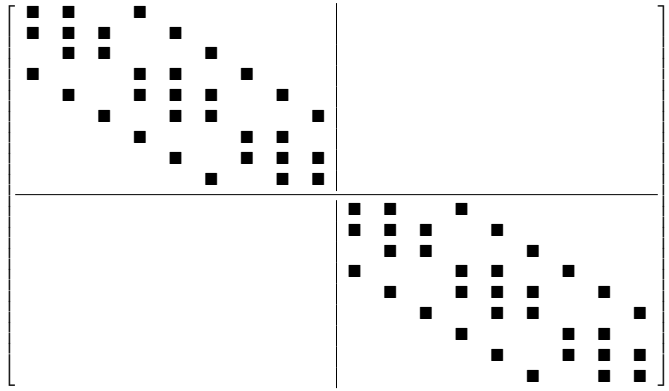

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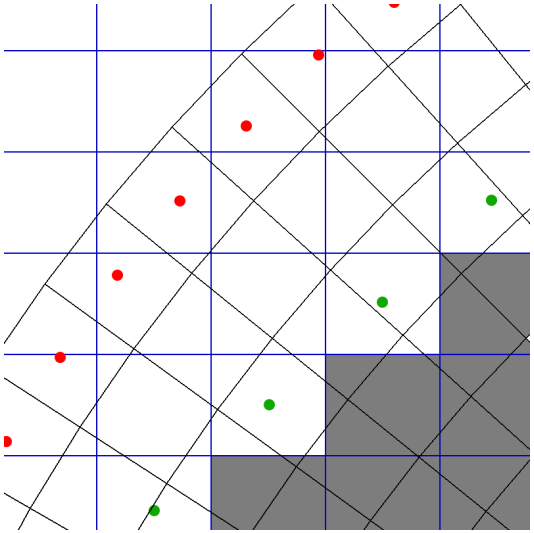

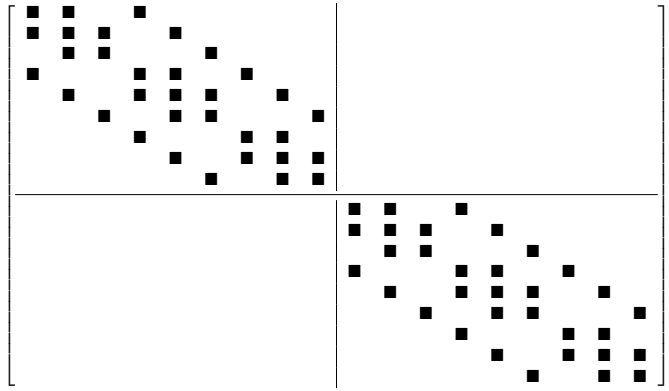

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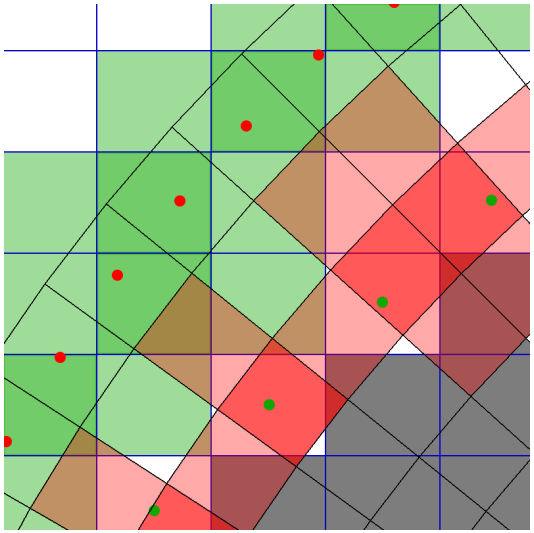

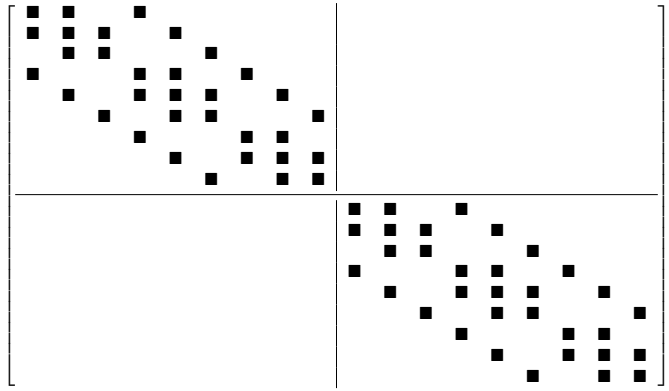

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Overset Grid Methodology

- Interpolation from Donors to Acceptors
- Trilinear interpolation not applicable
- Different methods implemented:
  - Direct (no interpolation):

$$\Phi_A = \Phi_{PD}$$

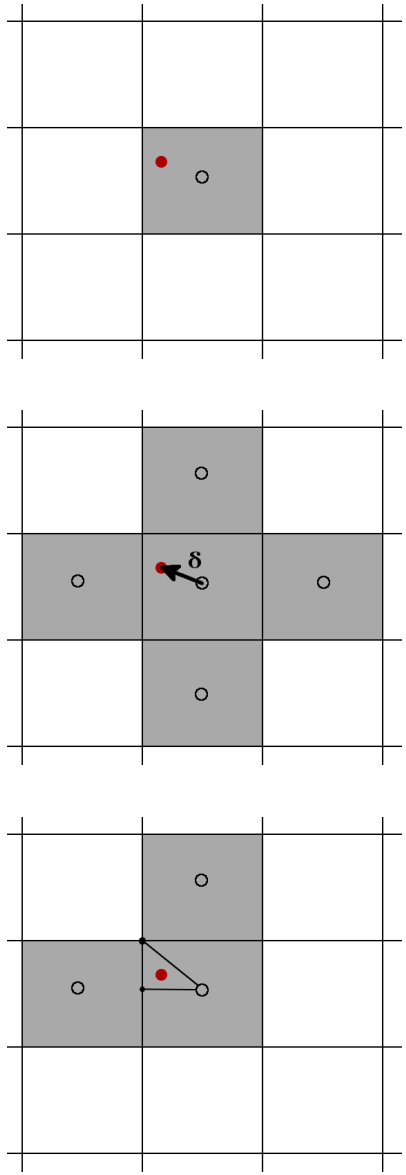
  - Implicit gradient correction:

$$\Phi_A = \Phi_{PD} + \underbrace{\nabla\Phi_{PD} \cdot \vec{\delta}}_{\text{implicit formulation}}$$

  - Inverse distance weighting:

$$\Phi_A = \frac{1}{S} \sum_{c \in C} \frac{1}{\delta_c} \Phi_c$$

$$\text{where} \quad S = \sum_{c \in C} \frac{1}{\delta_c}$$



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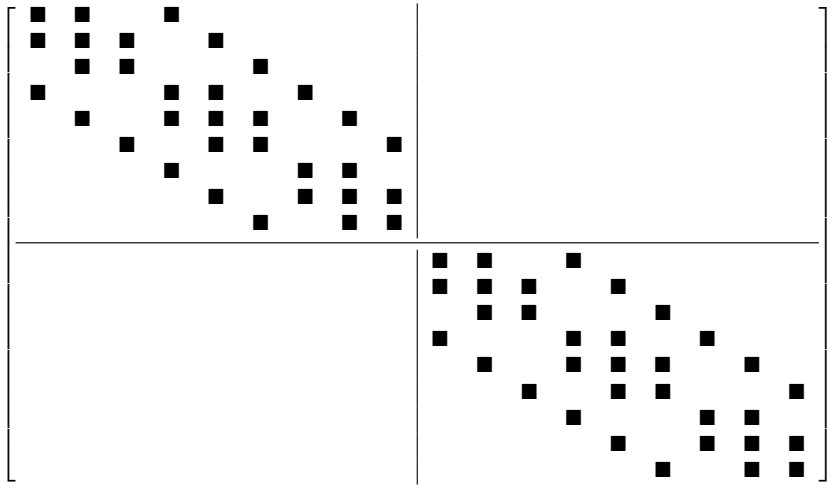
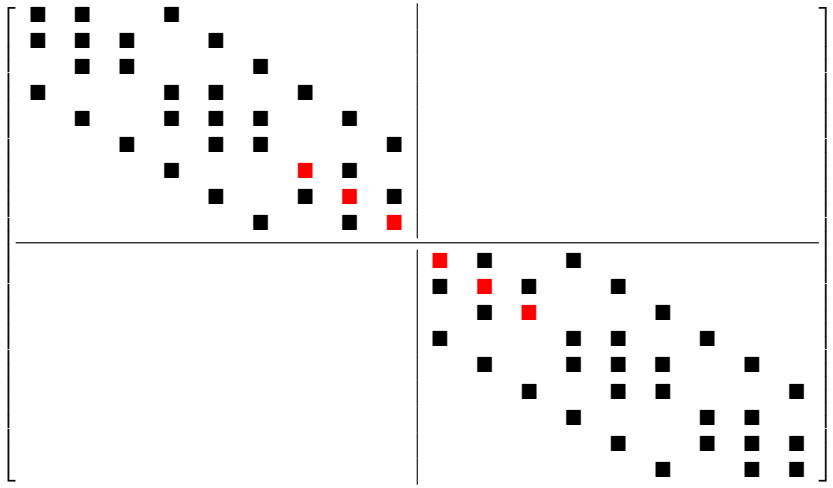


- Implicit coupling of mesh zones
- Off-diagonal coefficients for Acceptor cells zeroed
- Additional coefficients for interzonal coupling
- Matrix always asymmetric

Overset Grid Methodology



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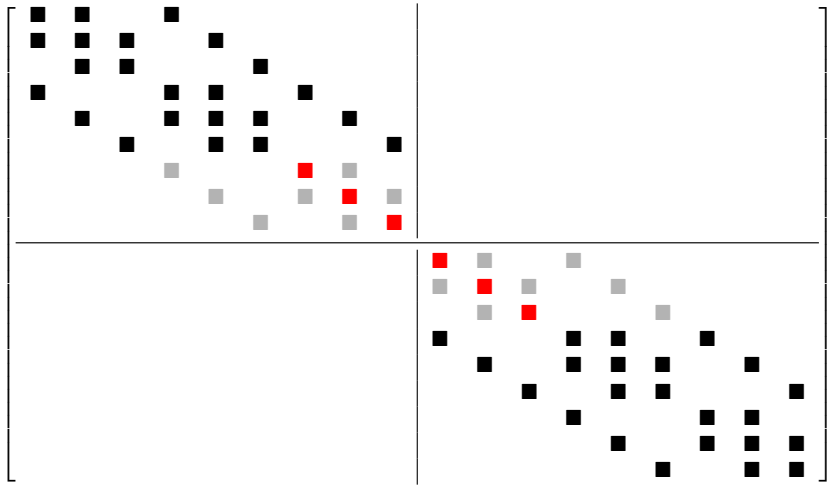

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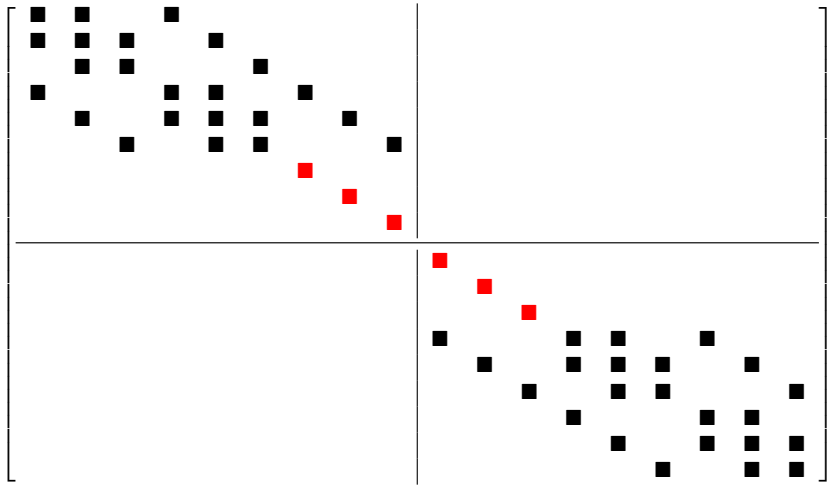

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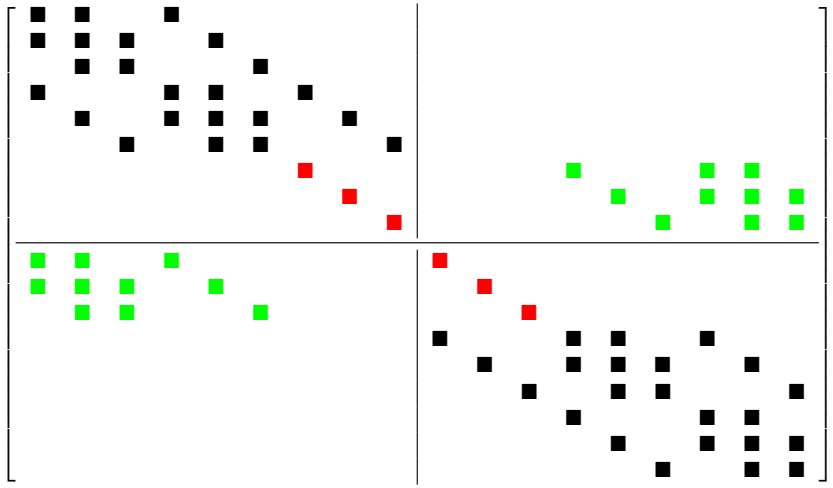

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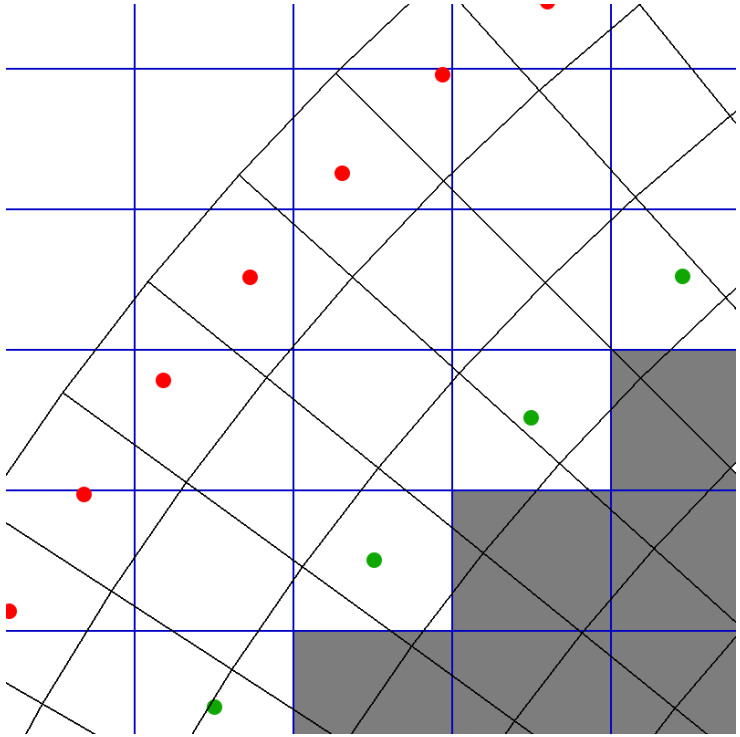


- Interpolation not strictly conservative
- Mass defect at the interface
- Impact on pressure correction
- Non-physical results if resolution insufficient (e.g. pressure oscillations)

Overset Grid Implementation

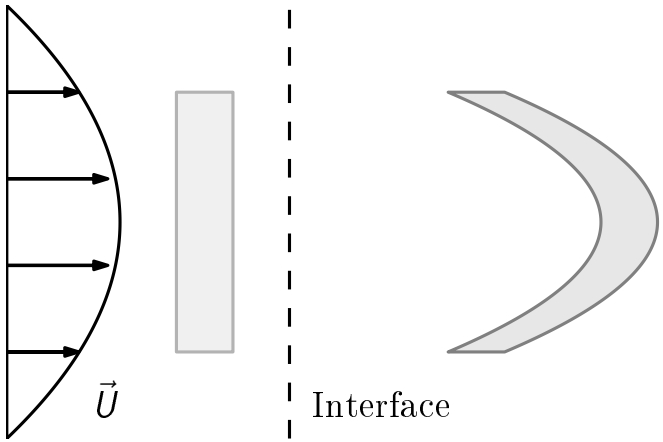
- Implemented as boundary condition for hole boundaries
- Fast and robust search algorithm for interpolation kernels
- `Foam::lduMatrix` not capable of overset grid related coefficients
- Mechanisms for coupled patches not aware of explicit matrix operation
- Extension of matrix class to support overset coupling of regions
- Selection through matrix solver (extended PBiCG-Solver)
- Independent from equations and discretisation schemes
- Dynamically linked library to “vanilla” `OpenFOAM`-dev

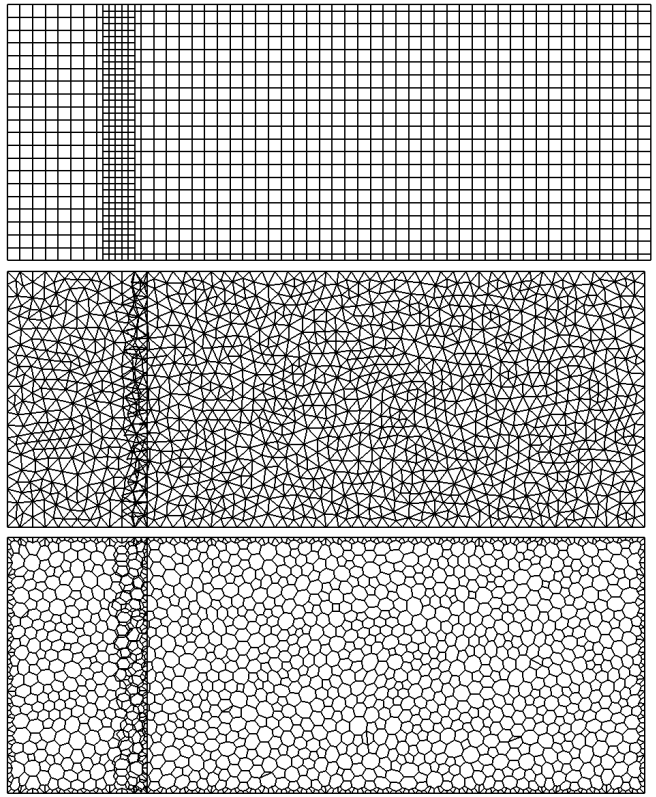
```
inner
{
    type            bellerophon;
    nFaces          15095;
    startFace       11904541;
    donorZone       stator;
}
```

```
boundaryField
(...)
    "inner|outer"
    {
        type            bellerophon;
    }
(...)
```

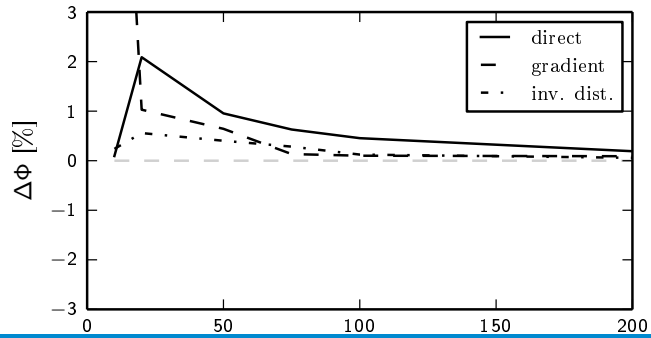
```
"U|p"
{
    solver          bellerophonPBiCG;
    preconditioner  DILU;
    tolerance       1e-07;
    relTol          1e-04;
}
```

Advection Test



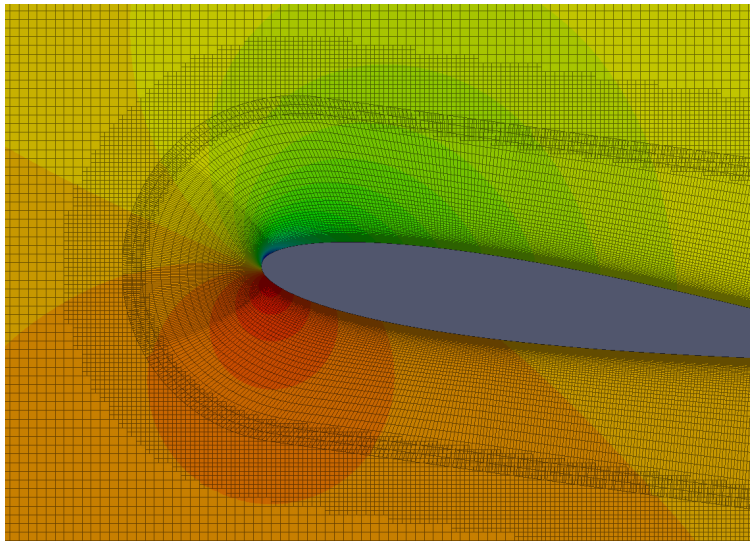


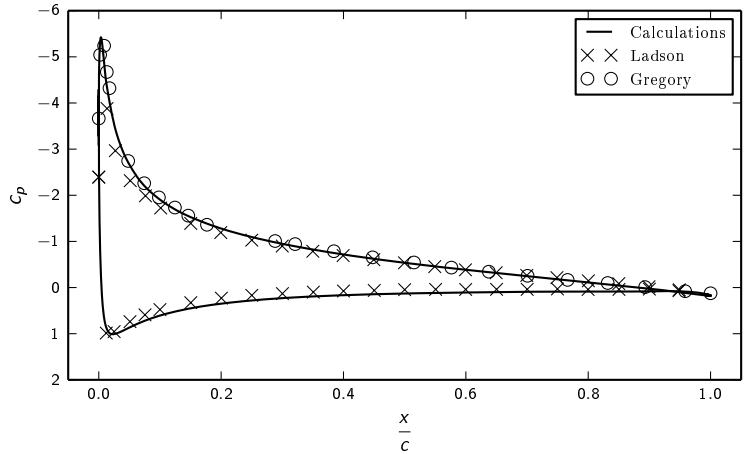
- Scalar transport in two-dimensional laminar channel flow
- Survey of interpolation methods, mesh resolution and cell types
- Interpolation error decreases with resolution
- Best results for Inverse Distance Interpolation
- Applicable for all cell types

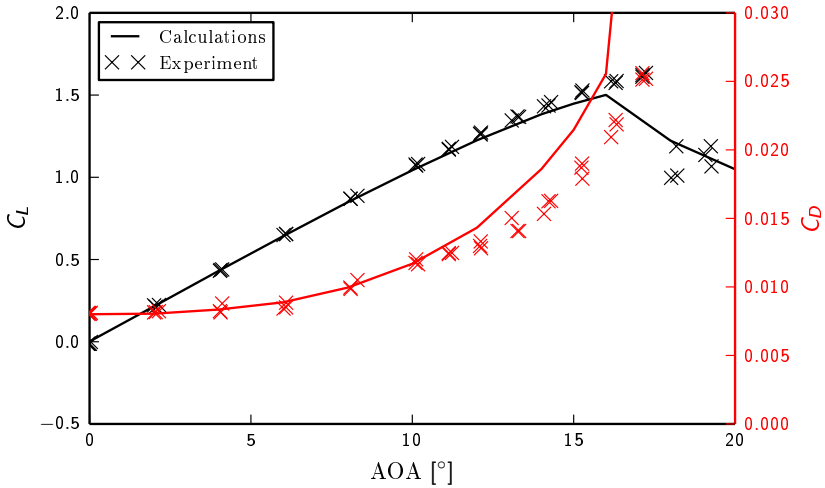


Validation

NACA 0012 2D



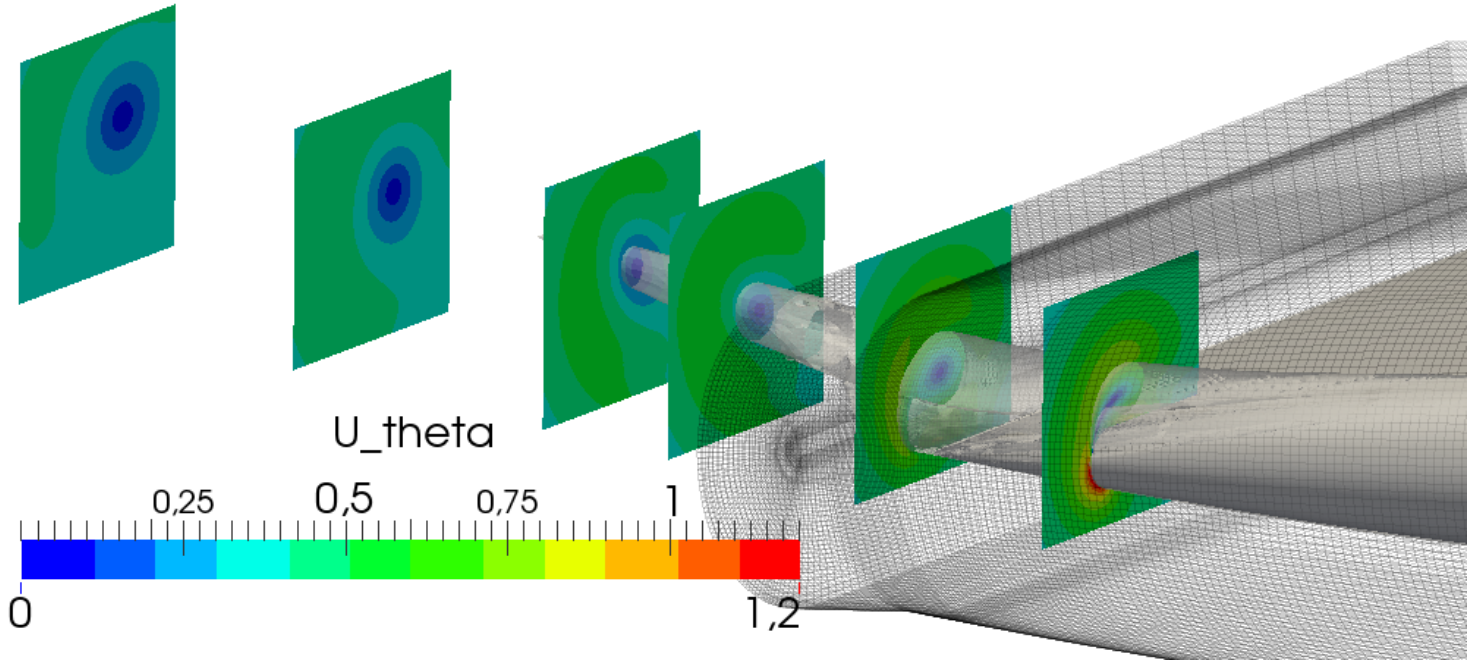




- Two-dimensional turbulent flow around airfoil
- $\mathrm{Re} = 6 \cdot 10^6,\ \mathrm{Ma} = 0.15,\ k-\omega$−SST Model
- 140k cells, $y^+ \ll 0$
- Smooth fields at interface
- Very good results pressure distribution
- Good agreement in lift and drag

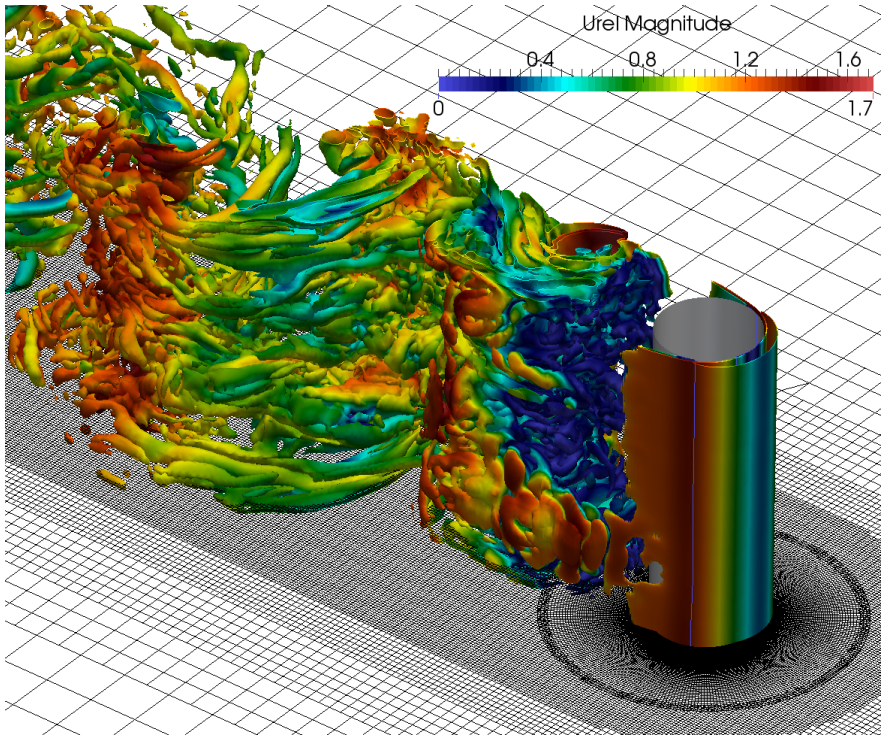
Validation

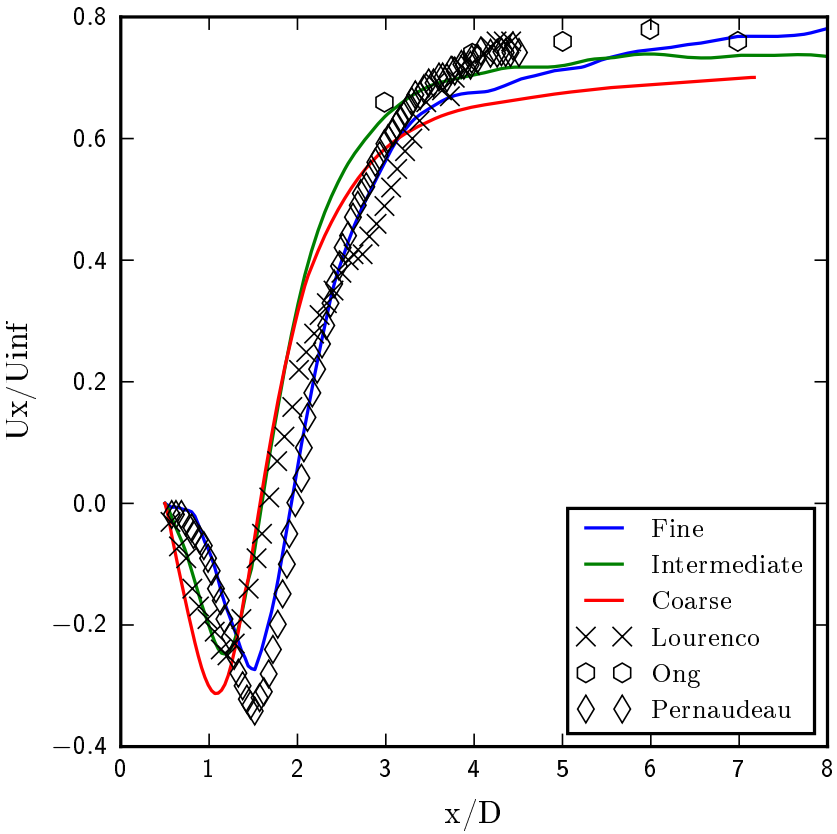
NACA 0012 3D



- Three-dimensional turbulent flow around airfoil $\Lambda = 1.5$
- $\mathrm{Re} = 4.5 \cdot 10^6$, $k - \omega$−SST Model
- Smooth fields at interface

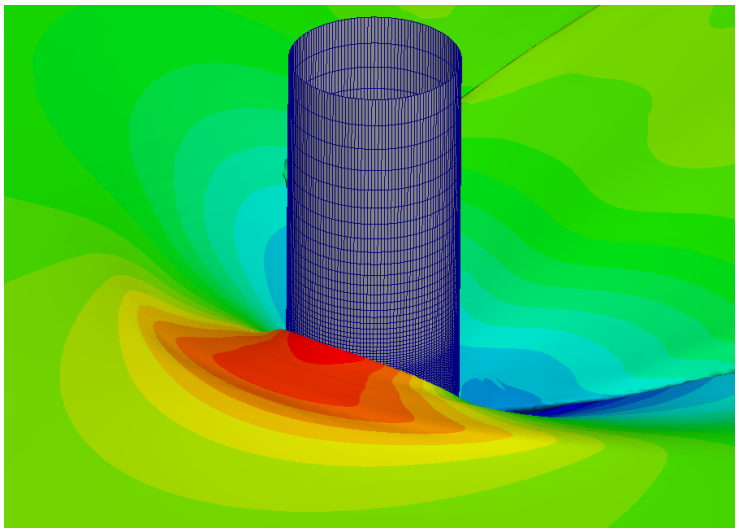
Turbulent Flow around Cylinder

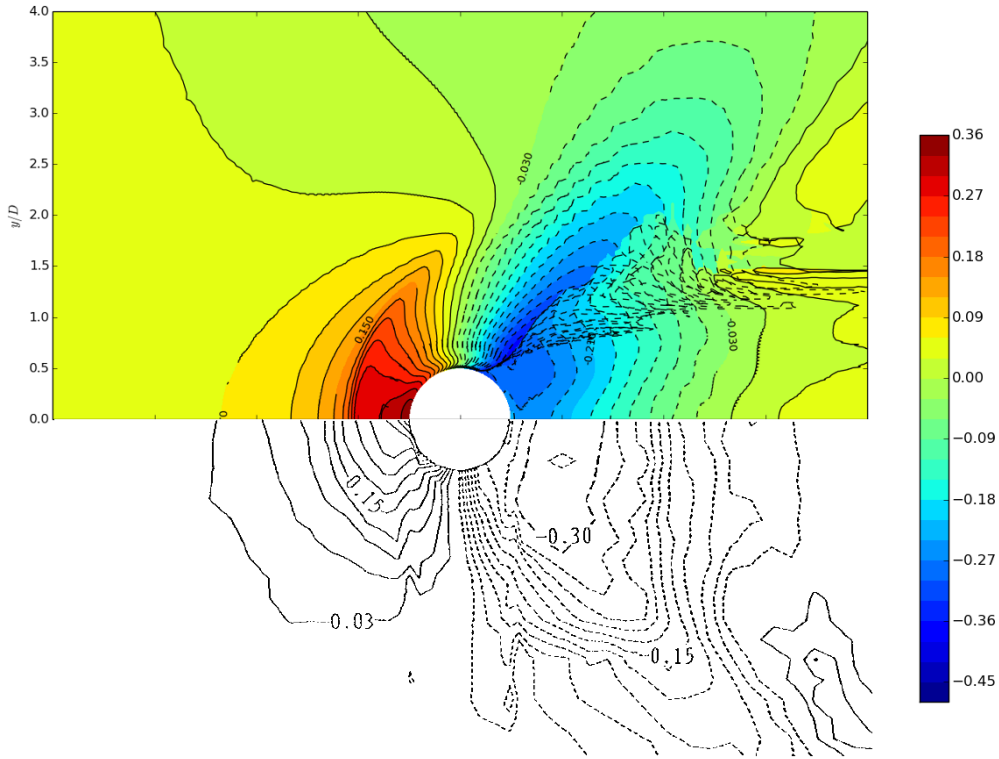




- Transient flow over infinite cylinder at $\mathrm{Re} = 3900$
- LES with One-Equation-Eddy Model
- Smooth transition of turbulent structures at interface

Surface Piercig Cylinder





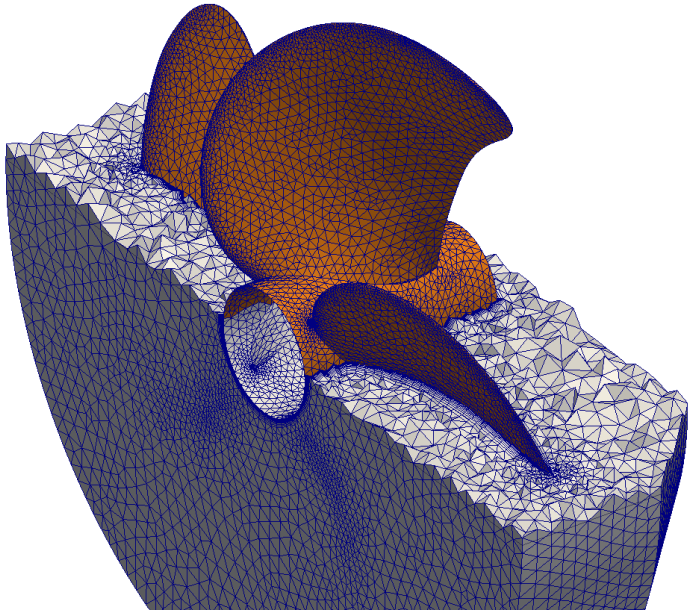
- Transient flow around semi-submerged cylinder, $\mathrm{Fn} = 0.84$
- VOF-approach, MULES-Algorithm for surface compression
- `interFoam` out of the box
- Evaluation shows good agreement with experimental results

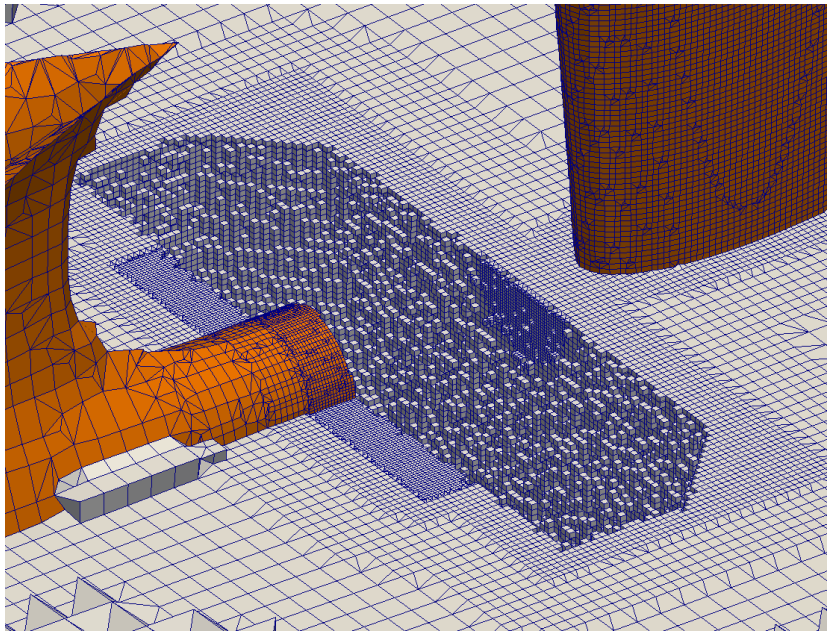
Case Setup

- Numerical self propulsion test
- Kriso Container Ship KCS and fixed pitch propeller P1380
- Model-scale $\Lambda = 31.5995 \rightsquigarrow L = 7.6\,\text{m},\ \text{Re} = 1.7 \cdot 10^7$
- Steady-state, single-phase flow with moving frame of reference for propeller region:

$$(\nabla U_R) \cdot U_l = -\nabla \frac{p}{\rho} - \vec{\Omega} \times U_l \quad \text{with} \quad U_R = U_l + \vec{\Omega} \times \vec{R}$$

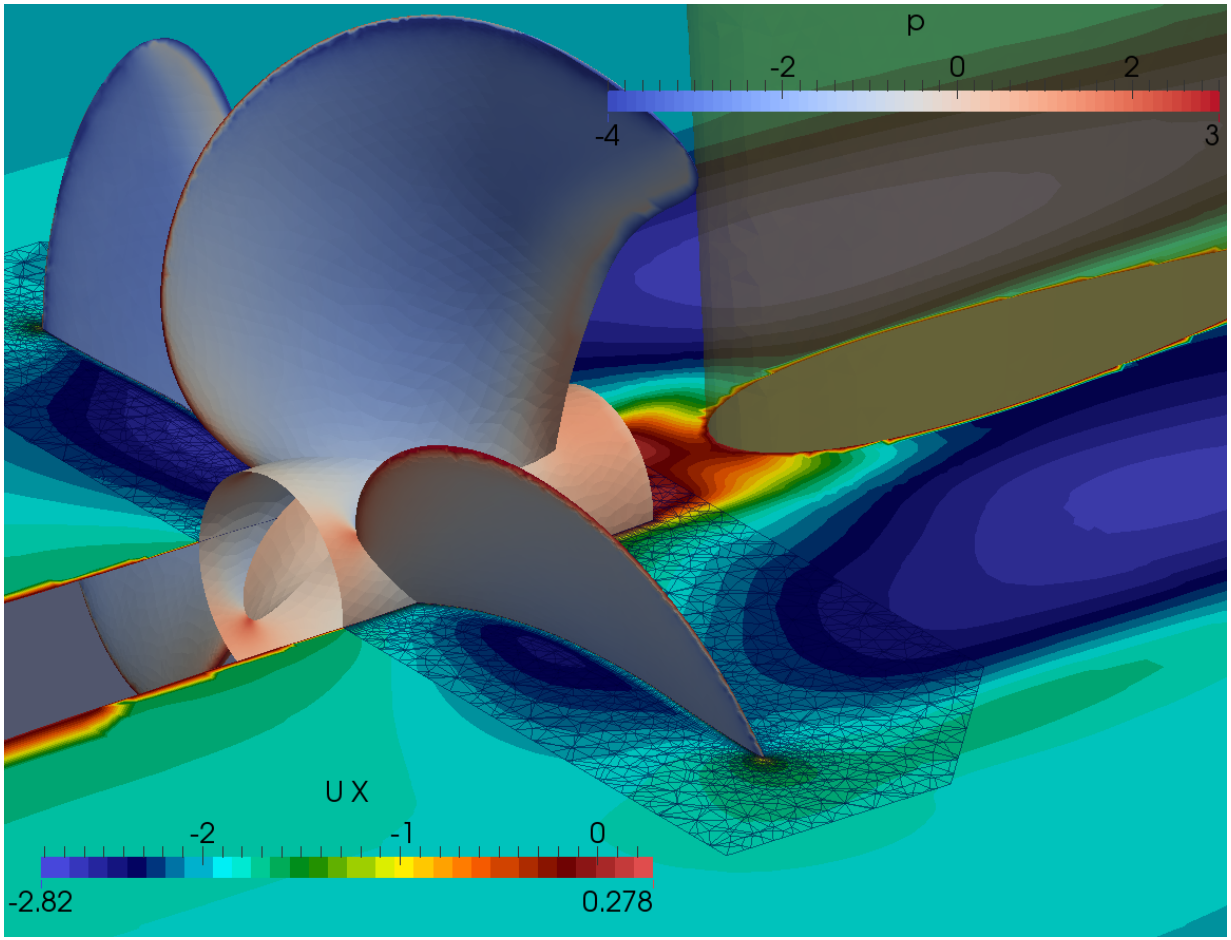
Workflow





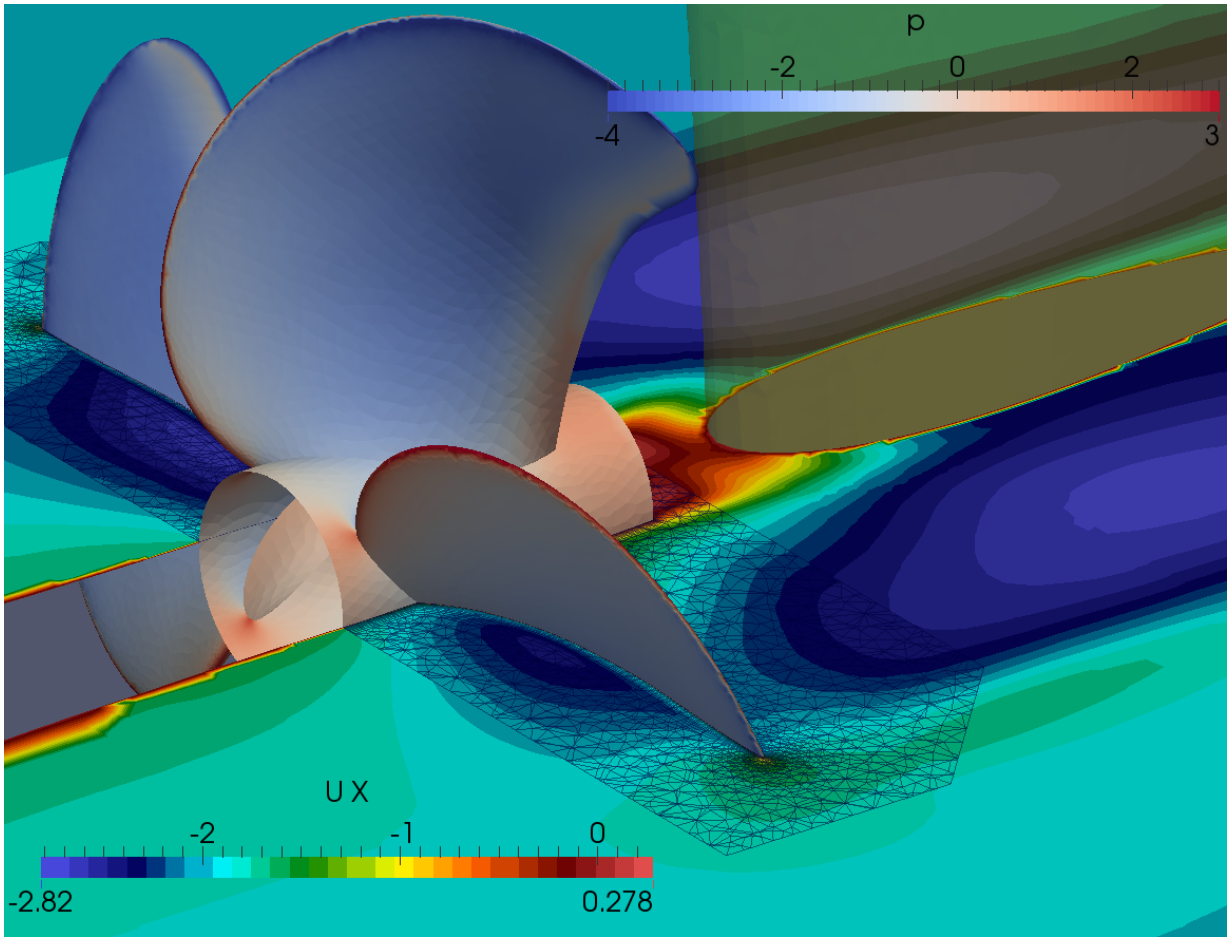
- No restrictions to interface face orientation, no Arbitrary Mesh/General Grid Interface required
- Generation of discretisation for ship and propeller independently (snappyHexMesh and ANSYS Workbench were used for this setup)
- Merging of meshes
- Hole cutting in stator region
- Simulation

Application



- 1.6M cells in stator domain, 0.9M cells for the propeller
- y^+ above 100 at the hull, 30 for the propeller
- Trust coefficient: $K_T = \frac{T}{\rho n^2 D^4} = 0.195$ -2.8% below experiment

Application



- Smooth results at the interface
- Application of MRF without meshing constrains
- easy exchange of hull/propeller/rudder/...

Conclusions

- Overset grid method implemented
- Fully parallelized and independent of problem formulation
- Tested for different turbulence modeling approaches and physical setups
- Verified and verificated on different test cases
- Works with `OpenFOAM` out-of-the-box
- Successful application to marine use case

Thank you for your attention!

Questions?