Università degli Studi di Padova
Centro di Ateneo di Studi e Attività Spaziali “Giuseppe Colombo”

PhD XXXIII cycle
Event: Request of admission to the second year of the PhD course

A novel numerical method for fluid-structure interaction problems

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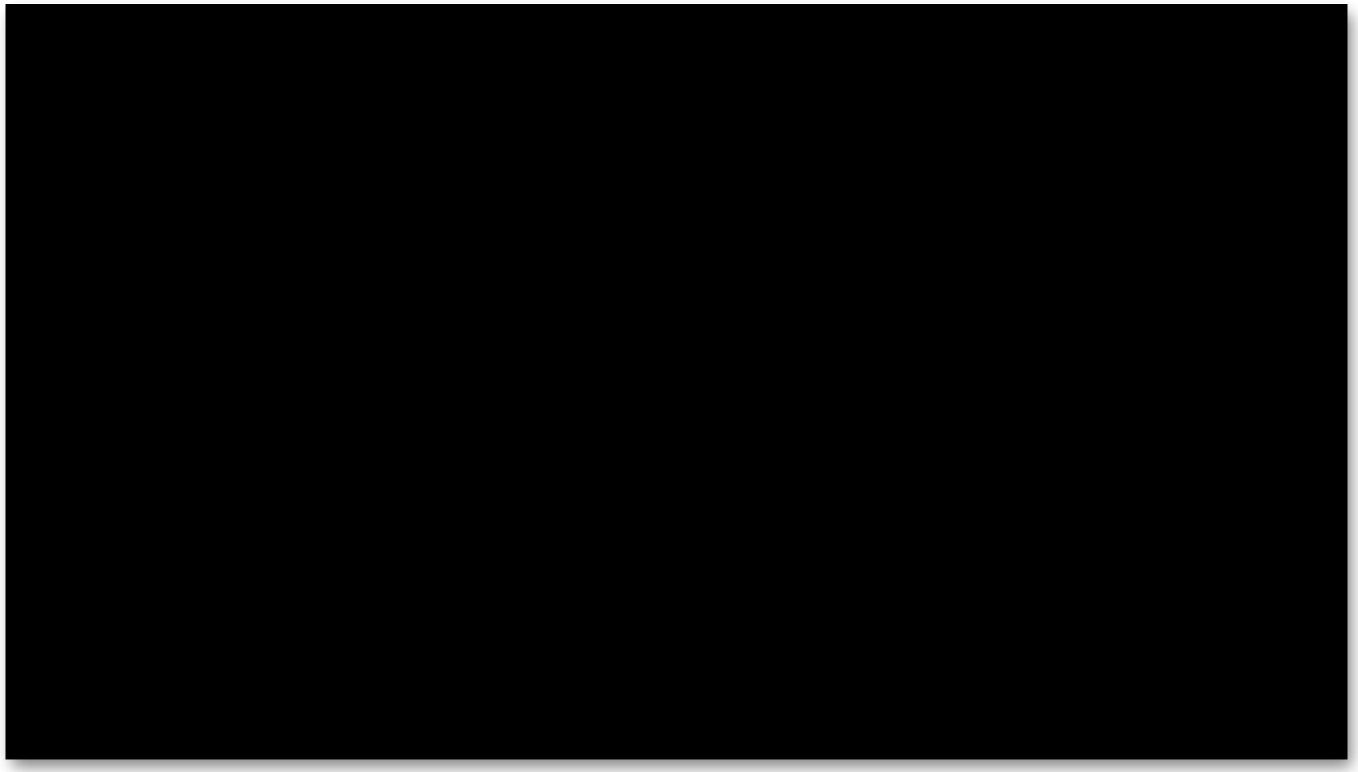
Supervisor: Prof. Francesco Picano
Co-supervisor: Prof: Mirco Zaccariotto

MOTIVATIONS

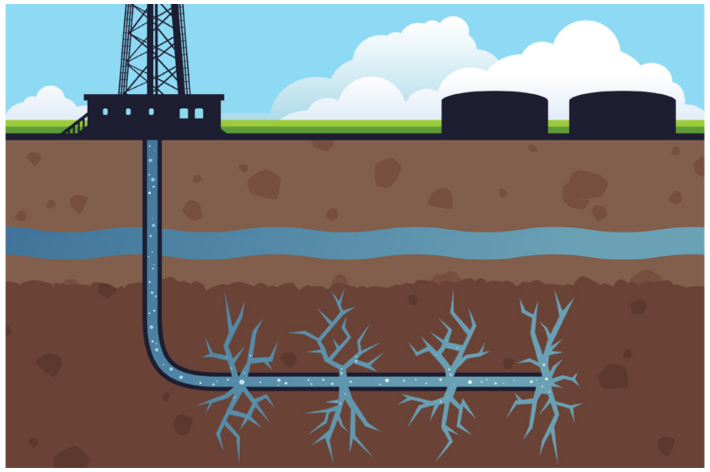
- **FLUID STRUCTURE INTERACTION (FSI) PROBLEMS**
  - **Interaction among fluid flows and a rigid or deformable immersed solid structures:**
    - **Force exchange across sharp, complex interfaces**
    - **Time-evolving interfaces**
    - **Solid and fluid media dynamics governed by different constitutive laws**
  - **Complex dynamics, multi-physics, strong nonlinearity**

- **FSI is a key problem in aerospace engineering:**
  - **Liquid sloshing in fuel tanks**
  - **Acoustic induced vibration**
  - **Aeroelastic flutter of wings**



More complexity is add when solid fracture occurs within a fluid flow:

- **Hydraulic fracture**

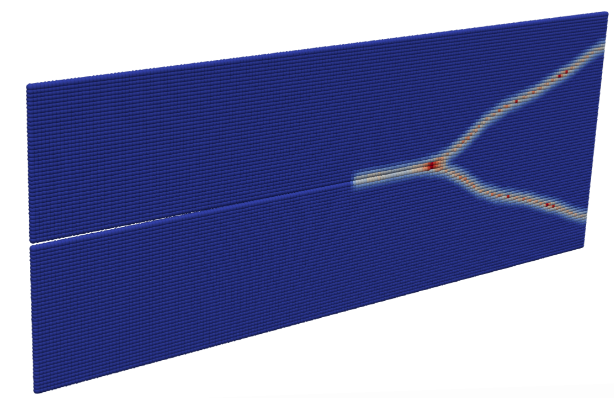


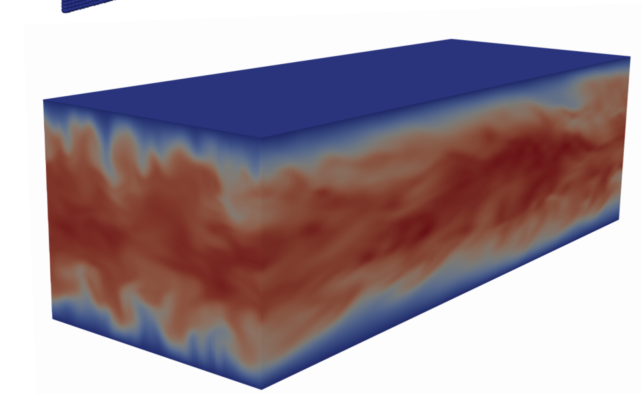
To date, a satisfactory comprehension of FSI remains a challenge and the capabilities of existing numerical models for applications are still limited.

OBJECTIVES AND METHODOLOGY

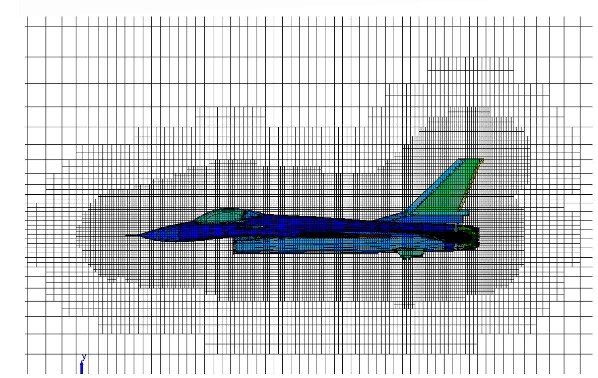
- **OBJECTIVES:**
  - **DEVELOPMENT OF A NUMERICAL TOOL CAPABLE TO REPRODUCE THE PHYSICS OF GENERIC FSI PROBLEMS ACCOUNTING FOR SOLID FRACTURE**
  - **INVESTIGATION OF FSI WITH SOLID FRACTURE**

- **METHODOLOGY:**
  - **PERIDYNAMICS:** →
    - **Crack detection/branching and solid fracture prediction capabilities**





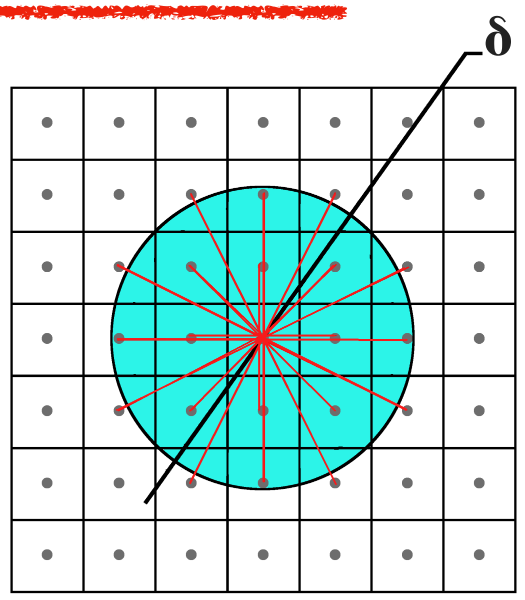
  - **NAVIER STOKES EQUATIONS (NS)** →
    - **Prediction of fluid flow dynamics**

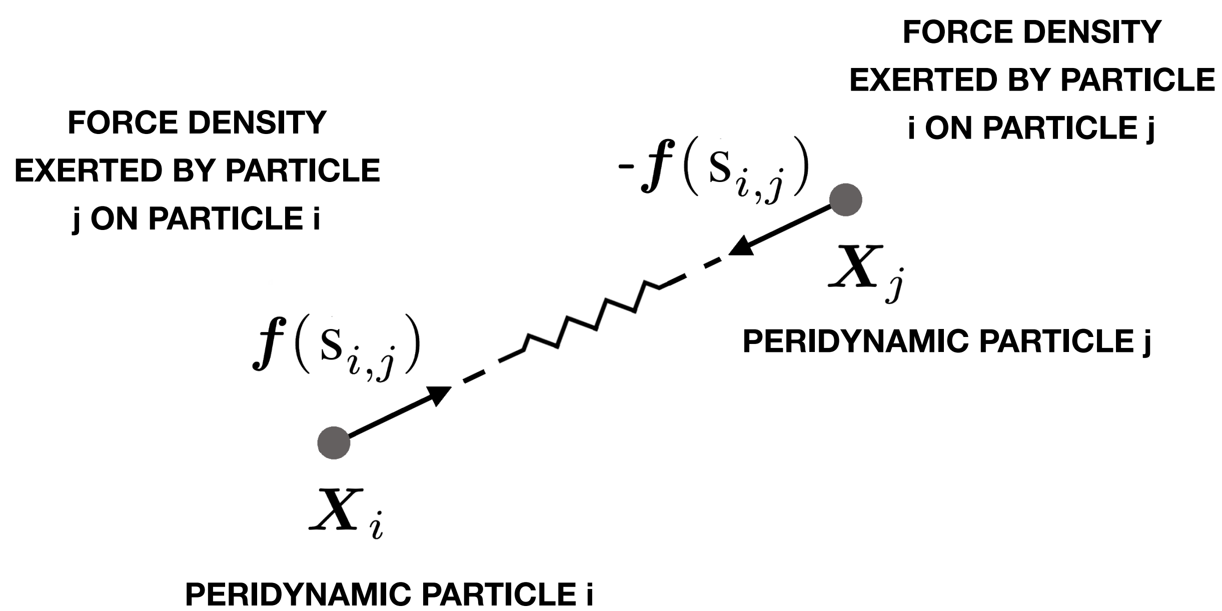


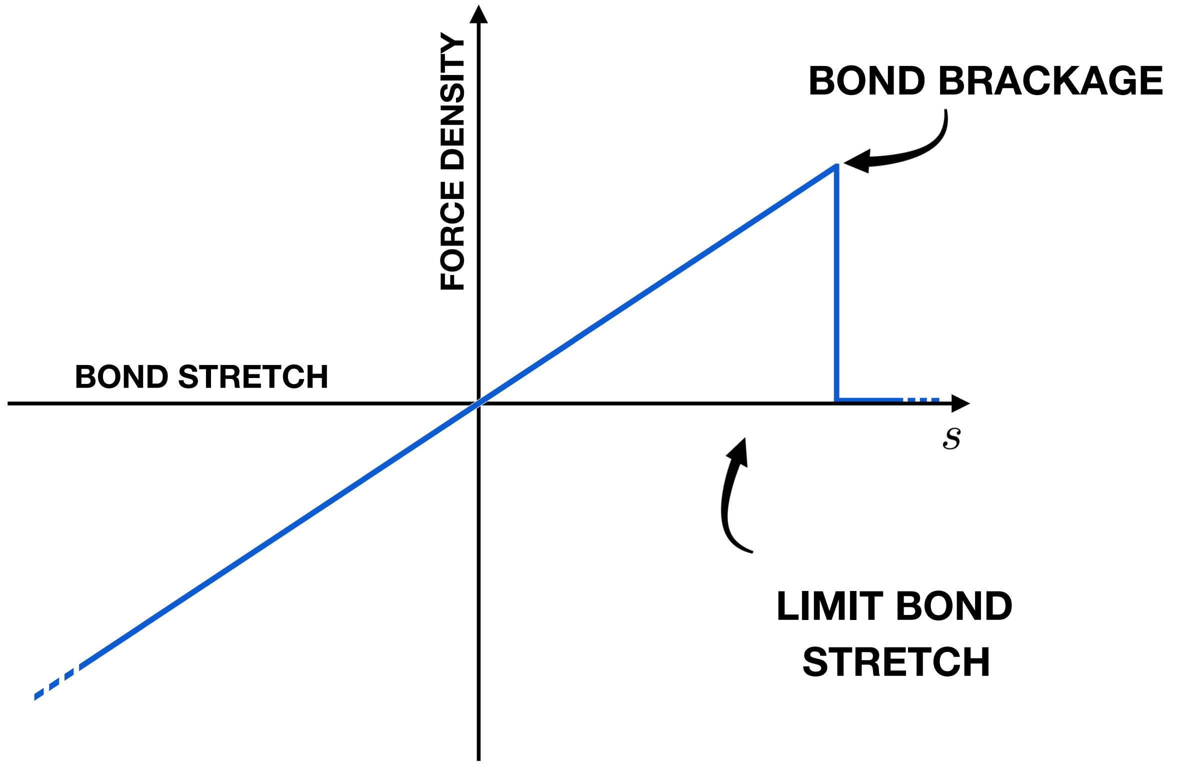
  - **IMMERSED BOUNDARY METHOD (IBM)** →
    - **Coupling and force exchange across complex interfaces**

DISCRETE BOND-BASED PERIDYNAMIC FORMULATION

- **Peridynamics is a formulation of continuum mechanics based on non-local integral equations:**
  - **A discretized peridynamic solid is represented by a set of finite size material particles**
  - **Material particles mutually interact via micro-elastic potentials that generate bond forces**
  - **Interactions (*bonds*) vanish beyond *peridynamic horizon*, δ**







- **Automatic crack detection and crack branching:**
  - **A bond breaks when its stretch overcomes a threshold value, the limit bond stretch s_0**
  - **Bond breakage is permanent: once a bond breaks it can not be restored**

Silling S.A., Epton M., Weckner O., Xu J. & Askari E. *Peridynamic states and constitutive modeling*. Journal of Elasticity (2007).

Silling S.A. *Reformulation of elasticity theory for discontinuities and long-range forces*. Journal of Mechanics and Physics of Solids (2000).

NAVIER STOKES EQUATIONS AND IBM

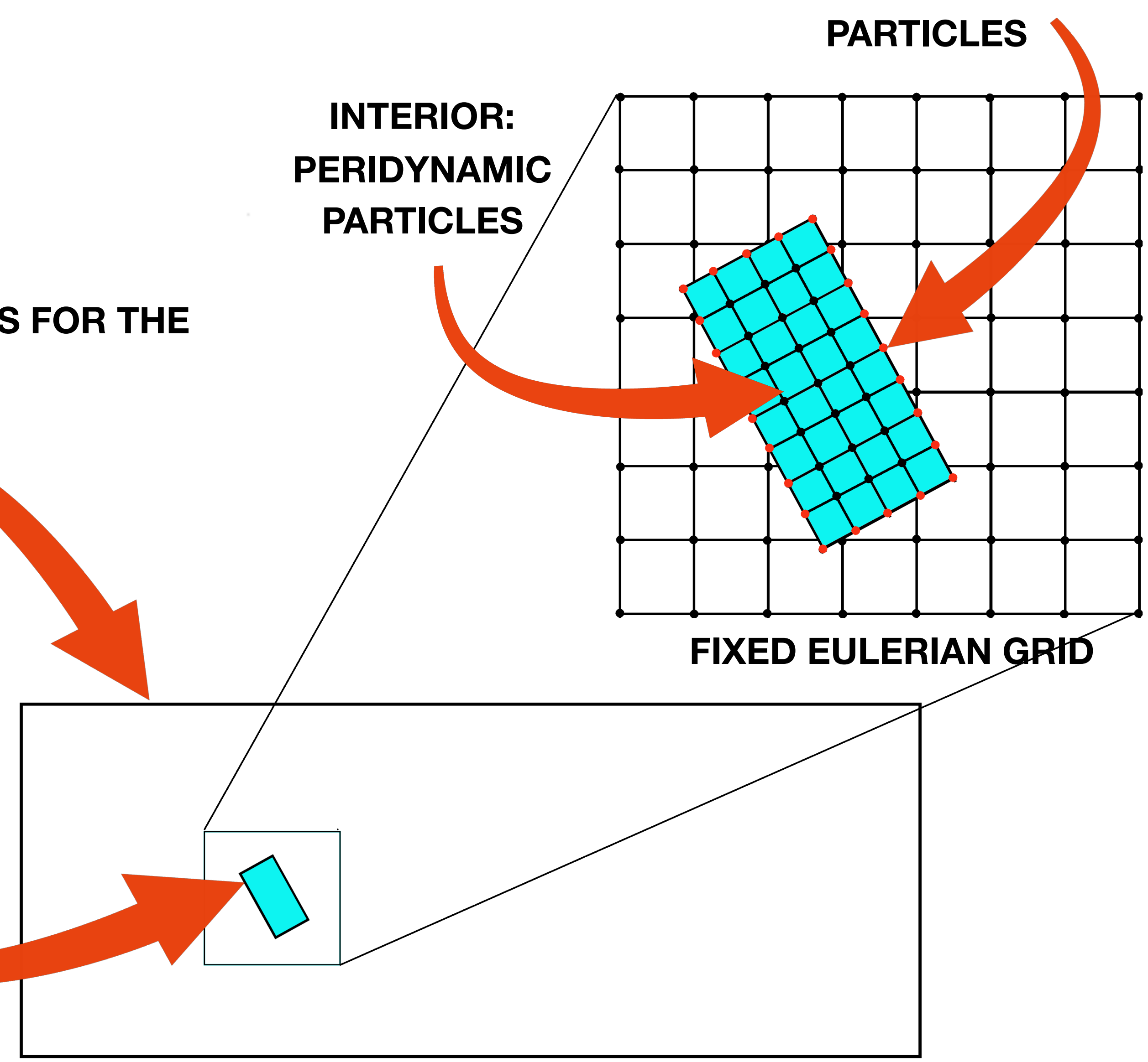
- **Liquid phase governed by incompressible formulation of NS equations**
- **Fixed Eulerian grid and moving Lagrangian grid on liquid-solid interface**
- **Force exchange accounted for via Immersed Boundary Method (IBM)**

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\rho_f \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} \right) = -\nabla p + \mu_f \nabla^2 \boldsymbol{u} + \rho_f \boldsymbol{f}$$

IBM FORCING ON THE LIQUID PHASE THAT ACCOUNTS FOR THE PRESENCE OF THE SOLID STRUCTURE

- **BCs are imposed directly at the limit boundaries of the computational domain**
- **A distributed force imposes no-slip and no-penetration BCs at the liquid-solid interface**



- **Action-reaction principle:**
  - **IBM forcing on the Lagrangian grid: fluid -> solid**
  - **IBM forcing on the Eulerian grid: solid -> fluid**

Mittal R. & Iaccarino G. *Immersed boundary Methods*. Annual Review of Fluid Mechanics (2005)

REPORT OF TASKS COMPLETED IN THE FIRST YEAR OF PhD COURSE

- **TASK 1: DEVELOPMENT OF FLUID SOLVER:**
  - **Open-source CaNS code by Pedro Costa (KTH Stockholm) as a fluid solver**
  - **Minor modifications to achieve the coupling with solid solver**
- **TASK 2: DEVELOPMENT OF MASSIVE PARALLEL PERIDYNAMIC SOLVER**
  - **Serial code development and testing**
  - **Parallelization of the algorithms (MPI and OpenMP standards)**
  - **Validation**

- **TASK 3: DEVELOPMENT OF PARALLEL IBM ALGORITHM**

- **TASK 4: MERGING AND INTEGRATION**
  - **Fluid solver, solid solver and IBM algorithm have been merged to obtain a complete numerical tool for FSI problems**
  - **Optimization of the algorithms to grant high efficiency running on supercomputer (1-100000 cores)**
  - **IscraC application: a budget of 100000 core hours on Marconi cluster has been granted by CINECA for testing**
- **TASK 5: CONFERENCES**

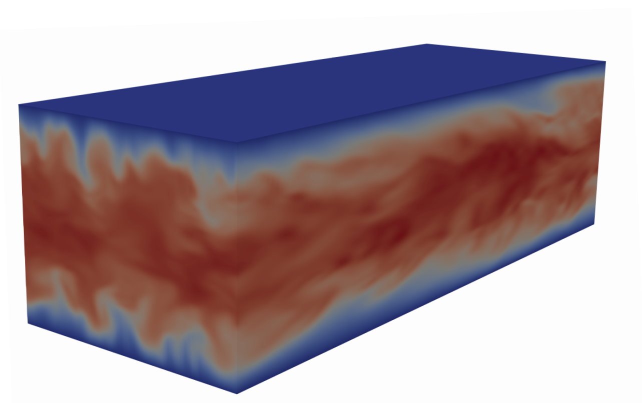
Costa P. *A FFT-based finite-difference solver for massively-parallel direct numerical simulations of turbulent flows*. arXiv preprint (2018).

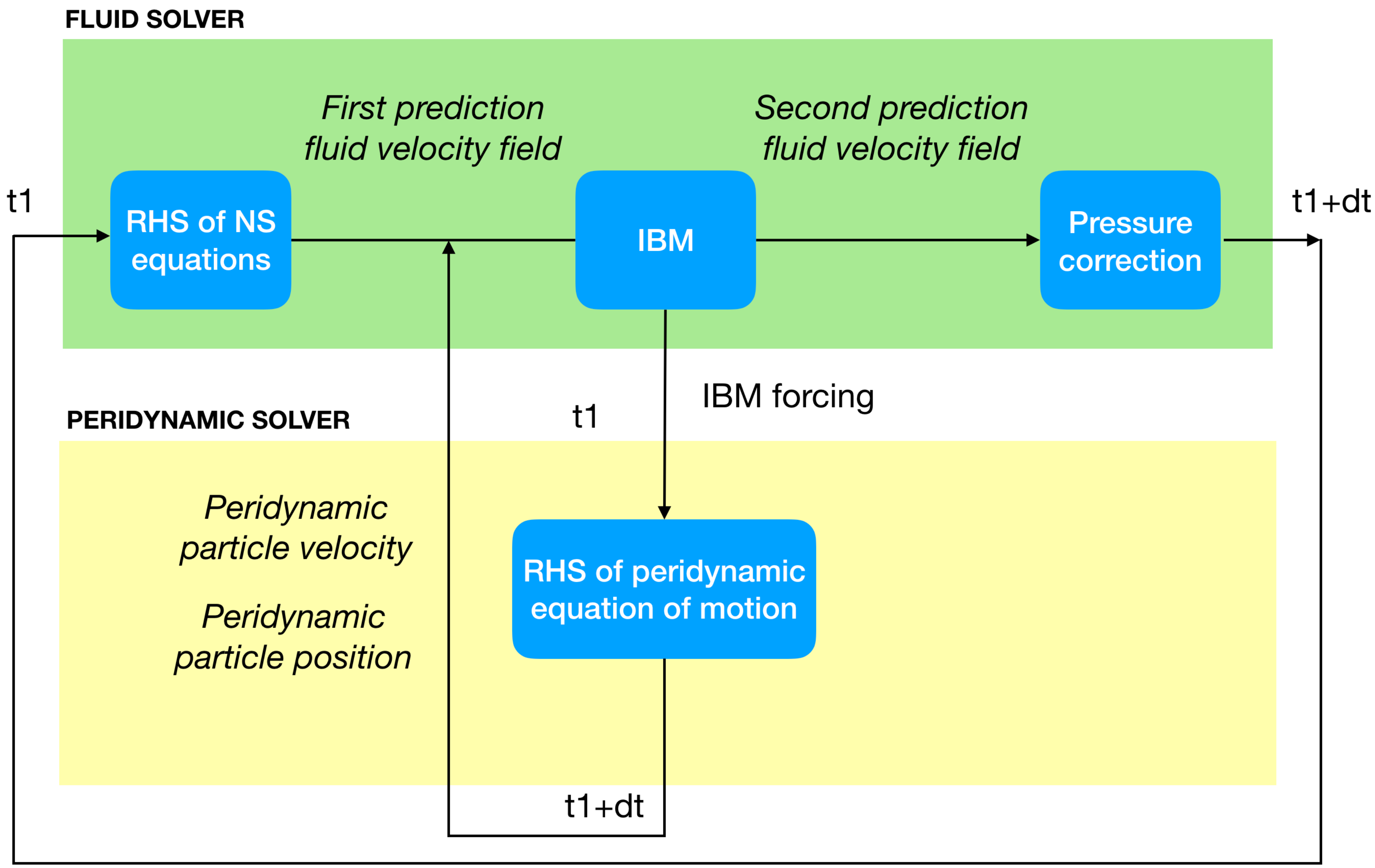
NUMERICAL METHOD: AN OVERVIEW

- **FLUID SOLVER (CaNS by Pedro Costa):**
  - **Pressure correction algorithm**
  - **Second order finite difference scheme for space discretization**
  - **Third order, low storage Runge-Kutta time marching algorithm**

- **PERIDYNAMIC SOLVER:**
  - **Fully explicit algorithm**
  - **Fictious damping of relative motions to filter high frequency vibrations**
  - **Third order, low storage Runge-Kutta time marching algorithm**

- **IBM:**
  - **Multidirect forcing scheme (3 steps)**



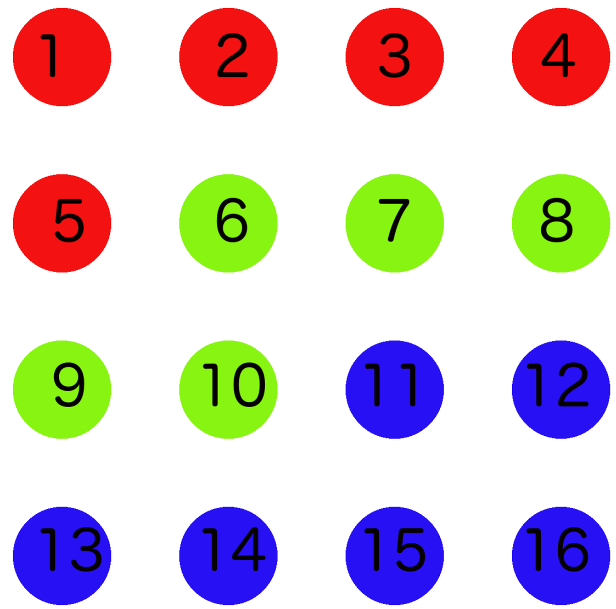


Costa P. *A FFT-based finite-difference solver for massively-parallel direct numerical simulations of turbulent flows*. arXiv preprint (2018).

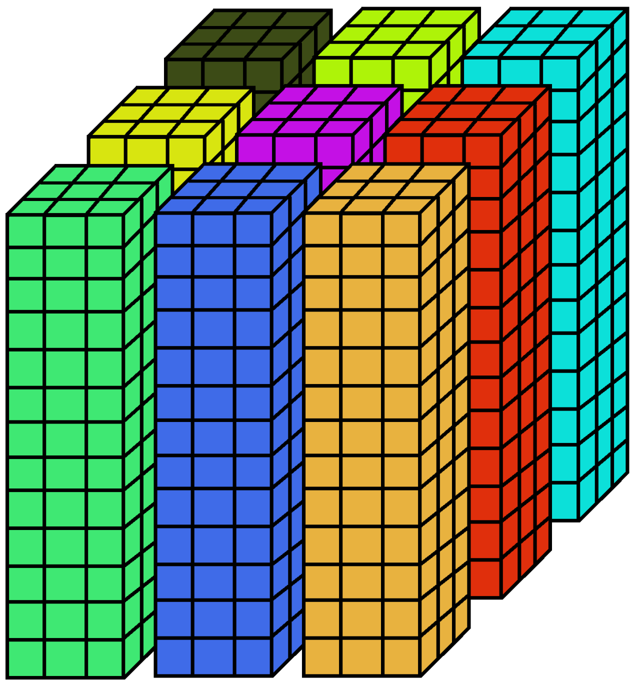
IMPLEMENTATION

- **IMPLEMENTATION IN *FORTRAN90***
- **PARALLELIZATION STRATEGY:**
  - **Hybrid OpenMP/MPI massive parallel code**
  - **2D space-based decomposition for fluid solver**
  - **Index-based decomposition for peridynamic solver**
- **PROS:**
  - **Eulerian grid nodes are equally distributed over MPI processes**
  - **Lagrangian points are equally distributed over MPI processes**
  - **Avoid bottle-neck degradation of performances if all peridynamic particles are located in few subdomains**
- **CONS:**
  - **MPI communication buffer size depends on particle enumeration**
  - **Surface peridynamic particles must be distributed over MPI processes according to the space based domain decomposition at each iteration. Surface particles are few! Good scaling performances.**

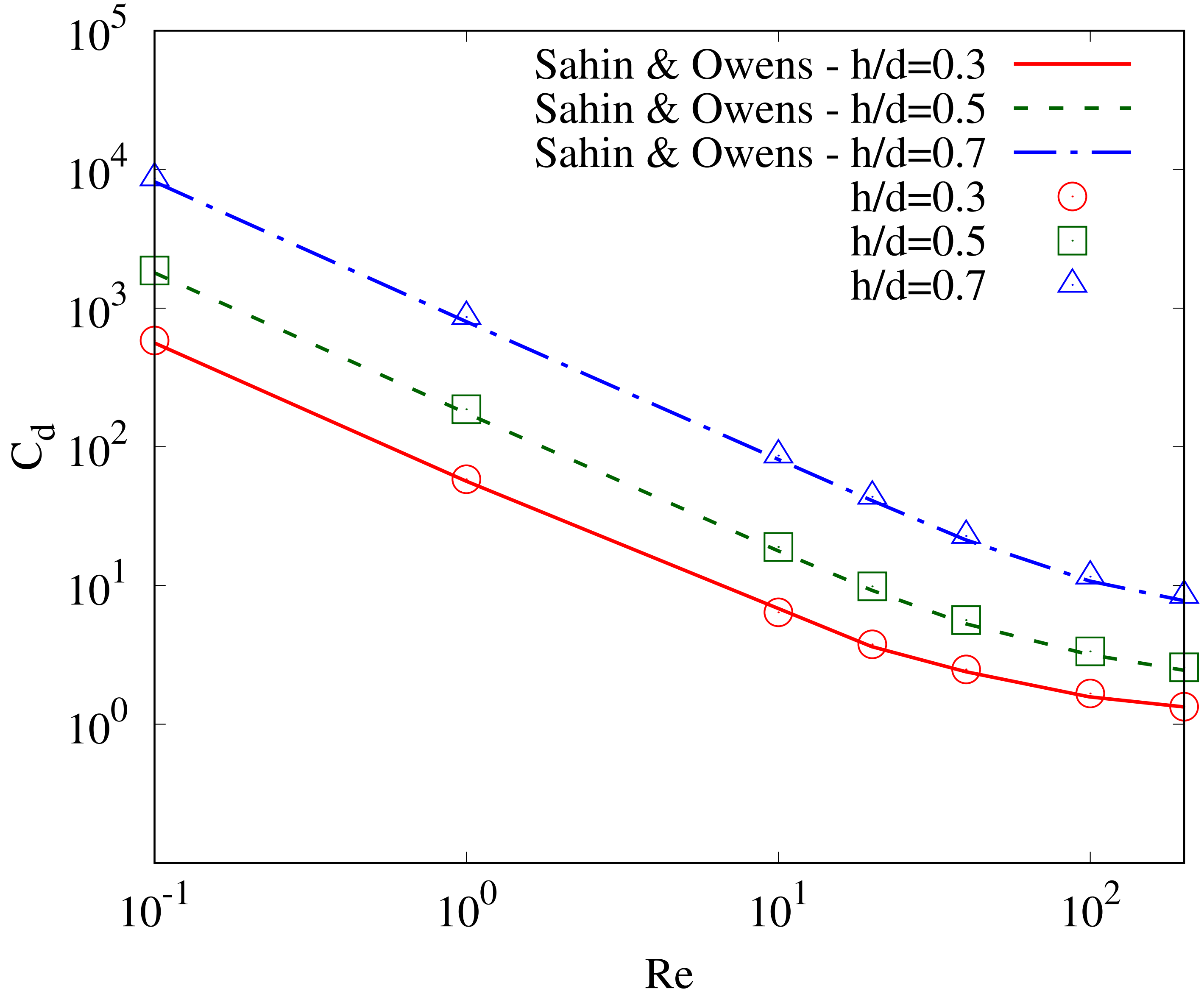
INDEX BASED PERIDYNAMIC PARTICLE DECOMPOSITION



2D SPACE BASED DOMAIN DECOMPOSITION

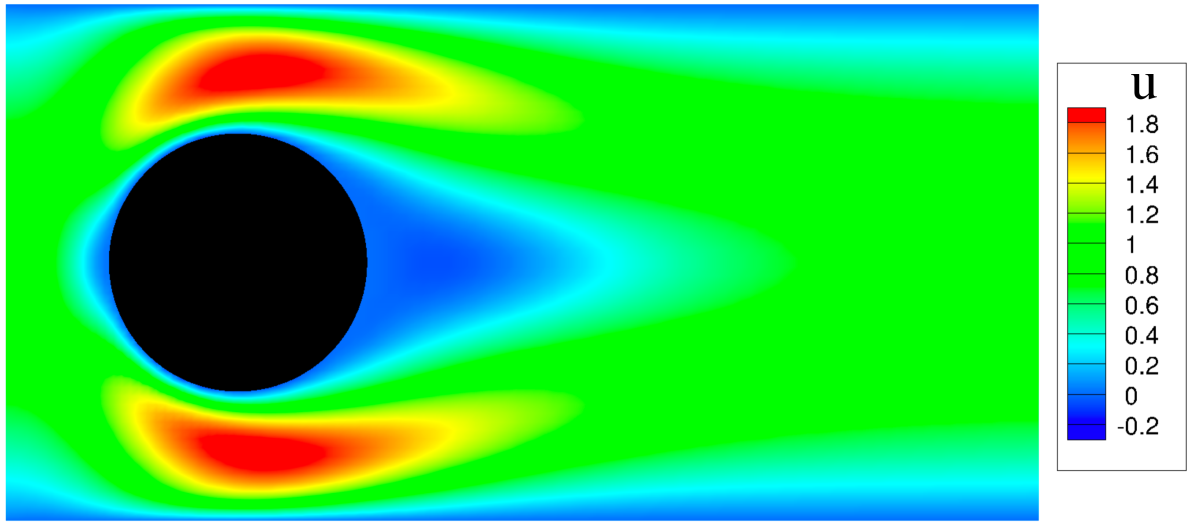


VALIDATION - IBM



- **Cylinder in laminar channel flow:**
  - **Periodic channel in span-wise direction**
  - **Inflow-outflow-wall BCs**
  - **Poiseuille flow prescribed at inflow**
  - **$Re_d = \rho_f U_{max} d / \mu_f = 0.1 - 200$**
  - **Three different blocking ratios d/h with h the channel height and d the cylinder diameter**
  - **Multidirect forcing IBM (3 steps)**
  - **1K Lagrangian points**

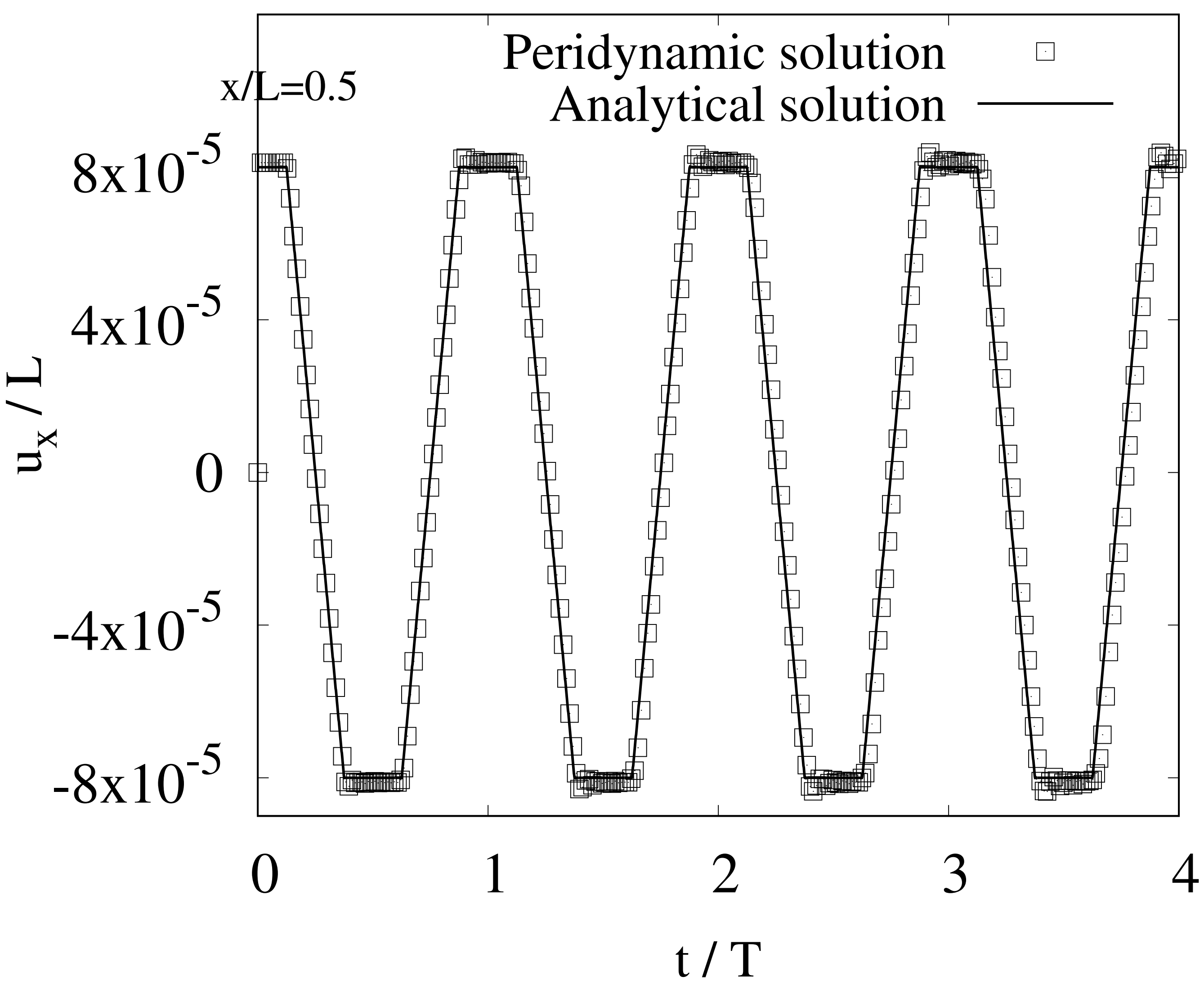
- **600 x 100 x 20 grid nodes in flow, wall normal and span-wise directions**
- **6h x h x 0.2h computational domain in flow, wall normal and span-wise directions**
- **Comparison with data of Sahin & Owens**



Sahin M. & Owens R.G. *A numerical investigation of wall effects up to high blockage ratios on two-dimensional flow past a confined circular cylinder*. Physics of Fluids (2004).

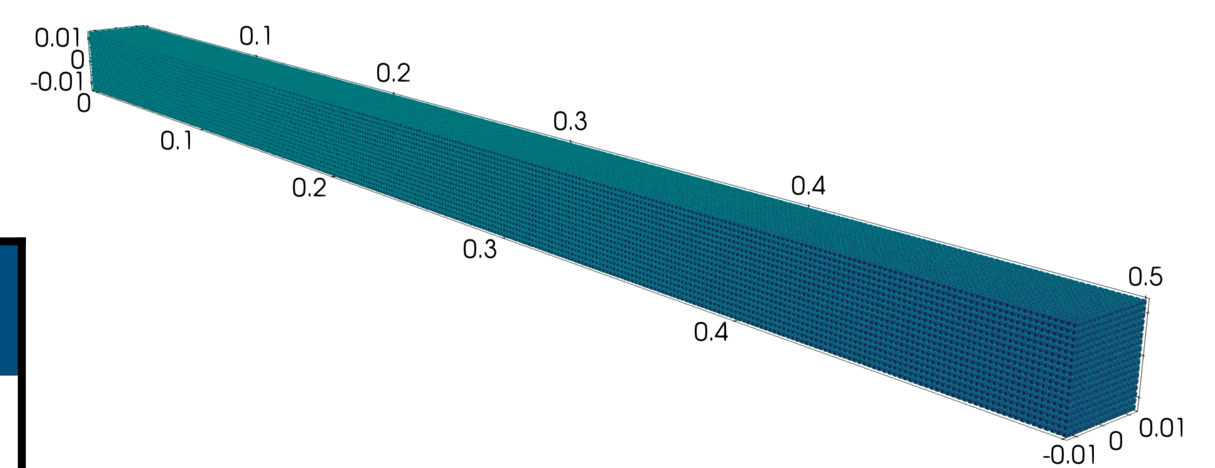
VALIDATION - PERIDYNAMICS: DYNAMIC RESPONCE

BAR DISPLACEMENT AT x/L=0.5 vs time



- **Free axial vibration of an elastic bar clamped at one side:**
  - **20K peridynamic particles**
  - **Initial displacement: first axial mode shape**
  - **Constraints: no axial displacements + free transversal displacements at one bar side; no constraints at the free end**
  - **4 periods**
  - **Comparison with analytical solution:**

$$u_x(x,t) = \frac{8\varepsilon L}{\pi^2}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)^2}\sin\left(\frac{(2n+1)\pi x}{2}\right)\cos\left(\sqrt{\frac{E}{\rho}}\frac{(2n+1)\pi}{2}t\right)$$



- **Bar properties:**

L [m]	0.5	b [m]	0.025	h [m]	0.025
E [N/m²]	100 10⁹	ρ [Kg/m³]	8000	ν	0.33

L length, b span, h height

Madenci E. & Oterkus E. *Peridynamic Theory and Its Applications*. Springer (2014).

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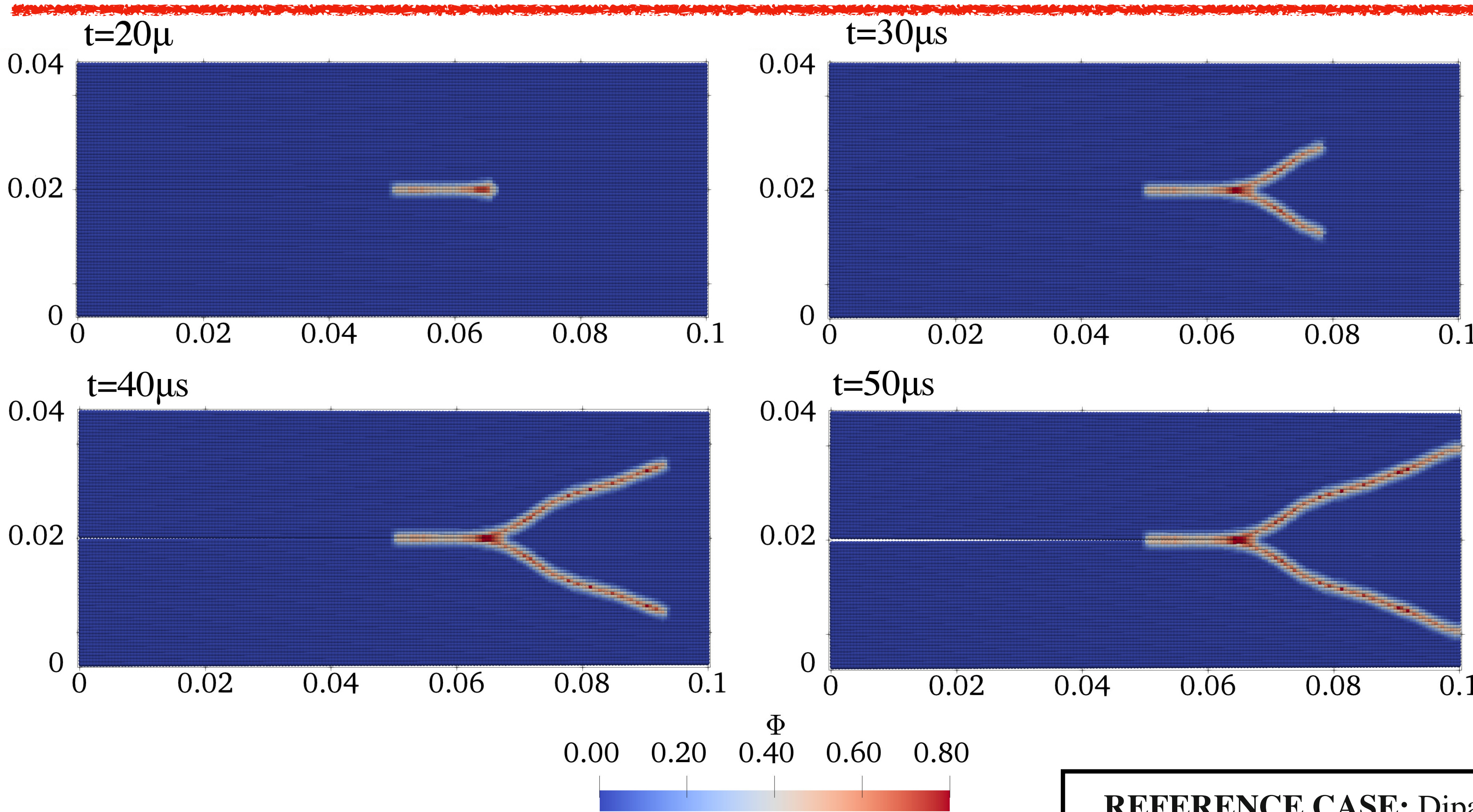
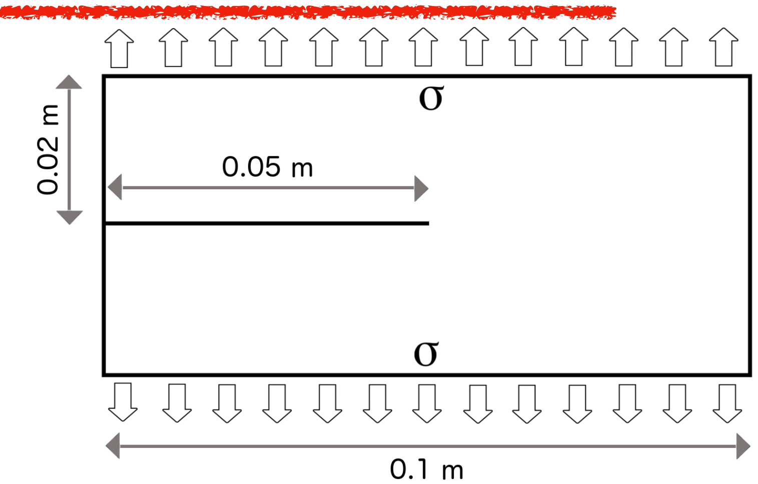
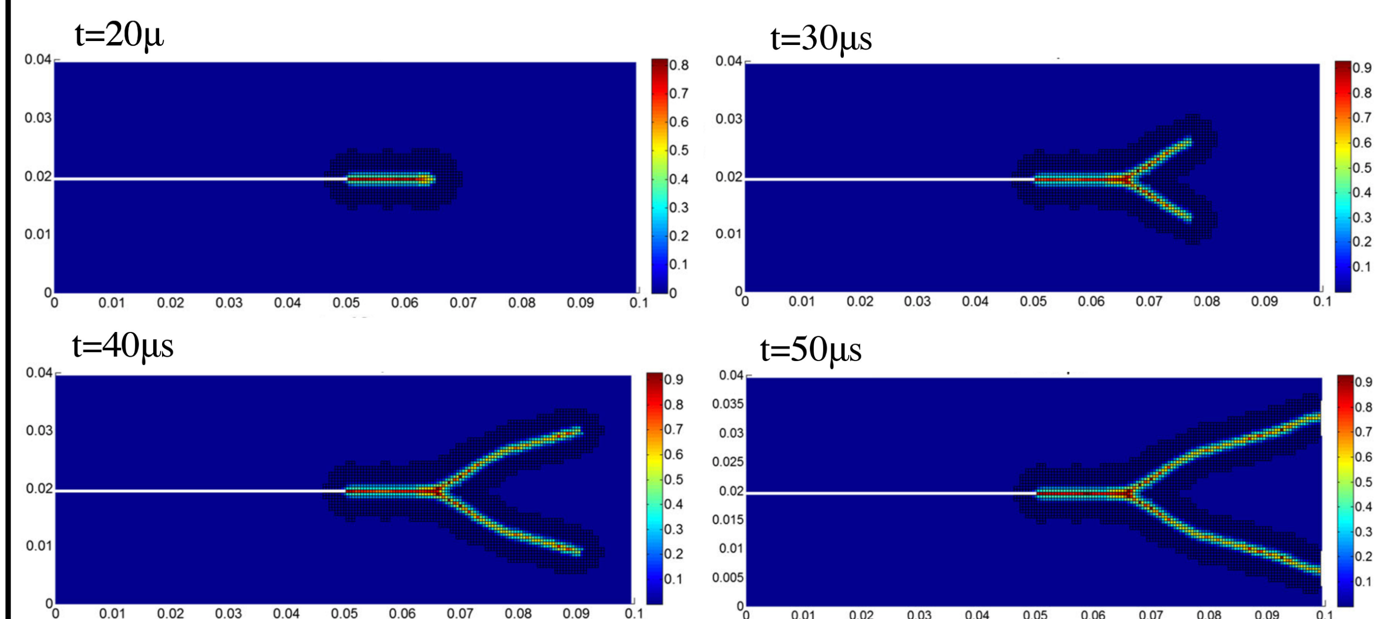
VALIDATION - PERIDYNAMICS: CRACK BRANCHING





- **Plate properties (soda-lime glass):**
  - **E = 72 GPa**
  - **ρ = 2440 kg/m³**
  - **G = 135 J/m2**
  - **δ = 1.5 mm**

REFERENCE CASE: Dipasquale D., Zaccariotto M. & Galvanetto U. *Crack propagation with adaptive grid refinement in 2D peridynamics*. Int. J. Frac. (2014).



- **Crack branching in 2D plate with pre-notch:**
  - **16K peridynamic particles**
  - **Pre-cracked plate uniformly loaded at upper and lower edges**
  - **Material damage level:**

$$\Phi_i = 1 - \frac{\sum_{j=1}^{N_i} \lambda(s_{i,j}) \Delta V_j}{\sum_{j=1}^{N_i} \Delta V_j}$$

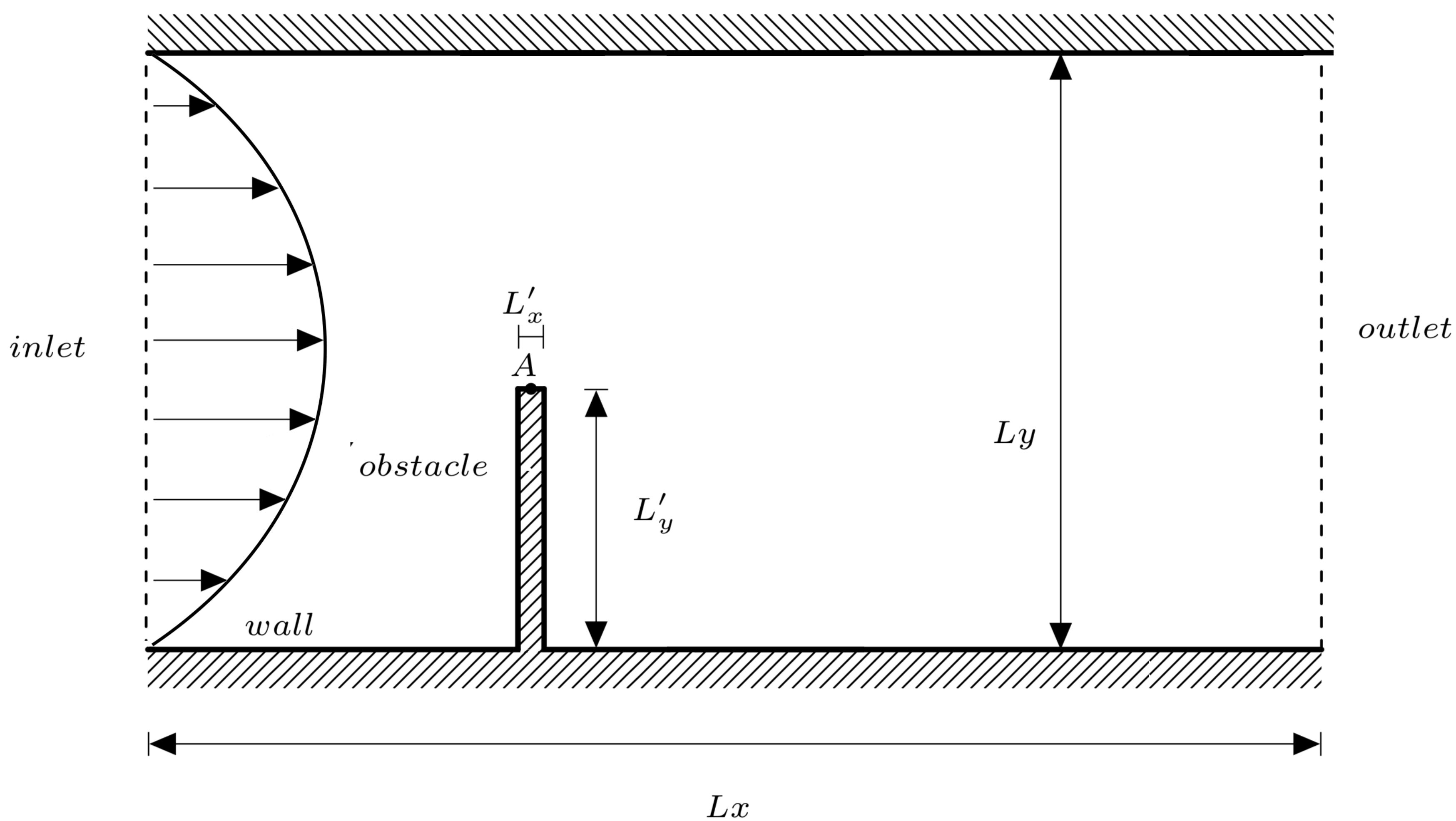
Youn D.H. & Bobaru F. *Studies of dynamic crack propagation and crack branching with peridynamics*. International Journal of Fracture (2017).

PRELIMINARY RESULTS

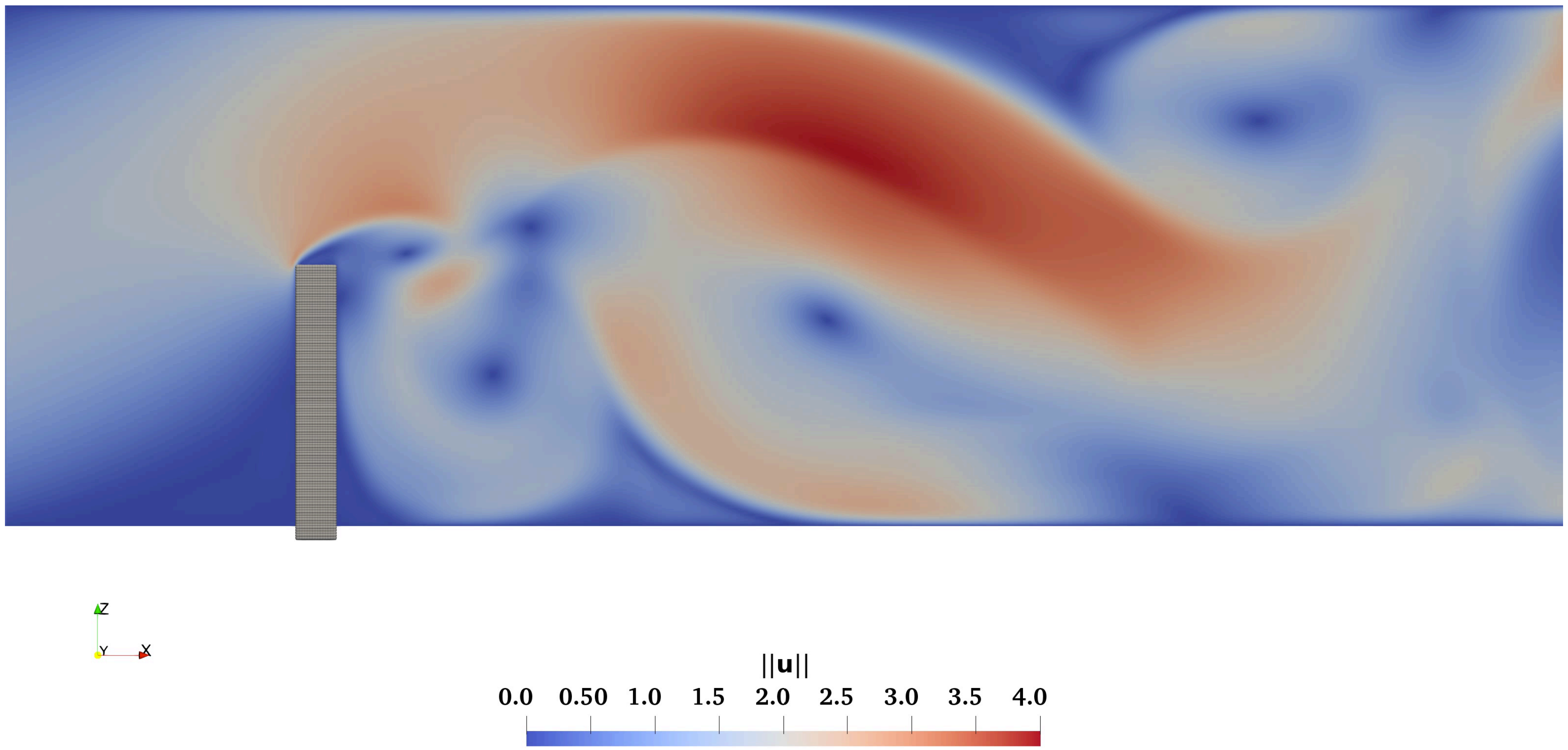
- **2D BENDING PLATE IN LAMINAR FLOW:**
  - **Computational domain extends for 3.0 10^{-2} m x 1.0 10^{-2} m in flow and wall normal directions**
  - **Poiseuille flow prescribed at inlet, wall BCs at lower and upper boundaries**
  - **540 x 180 grid nodes**
  - **2K peridynamic particles**

- **FLUID PROPERTIES:**
  - ρ_f = 1000 kg/m^3
  - ν_f = 1.6 10^{-6} m^2/s
  - Re_b = 1000

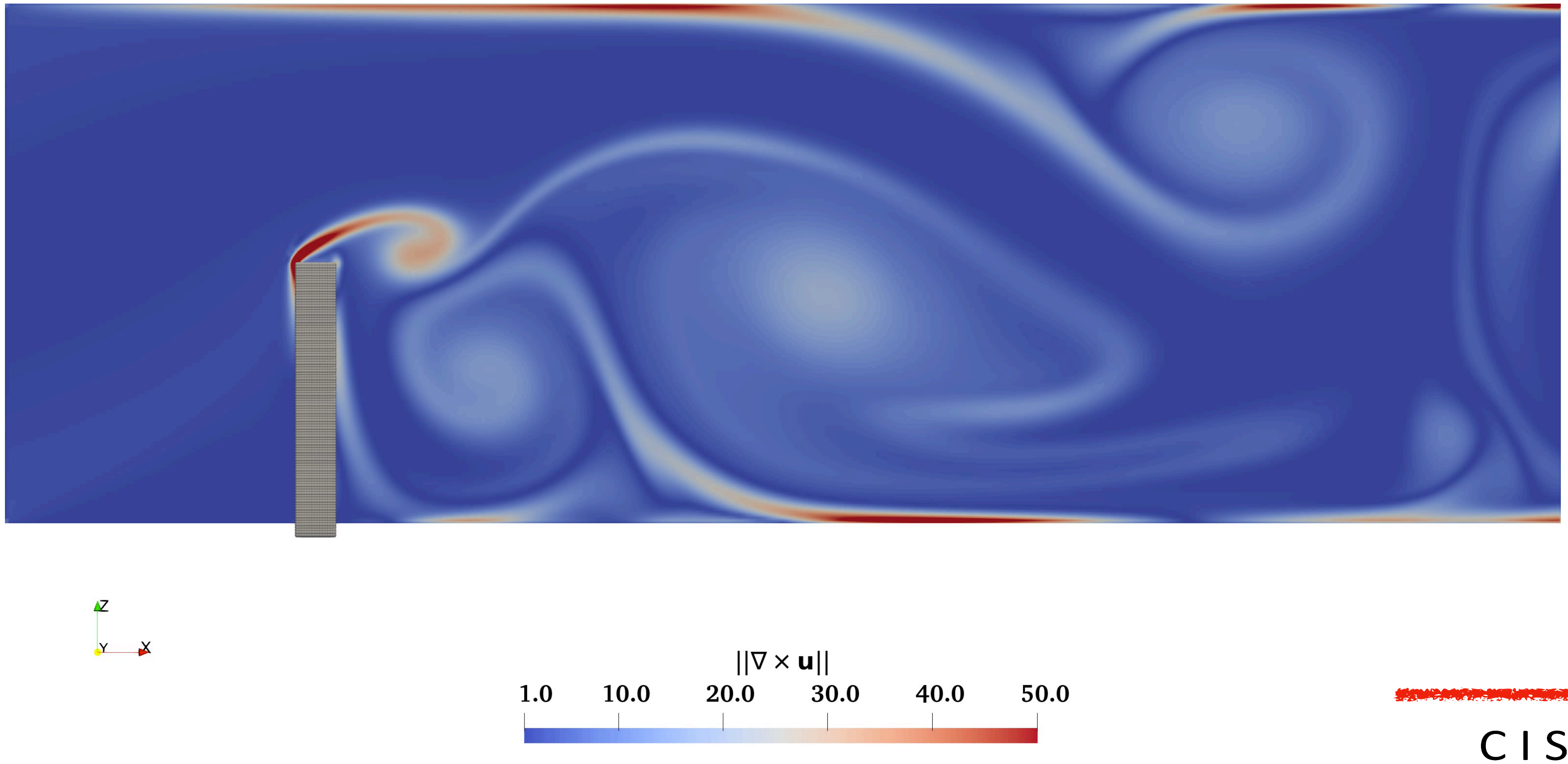
- **PLATE PROPERTIES:**
  - L'_x = 7.5 10^{-5} m
  - L'_y = 1.5 10^{-2} m
  - E = 1.0 10^6 Pa
  - ρ_s = 1130 kg/m^3



PRELIMINARY RESULTS: BENDING



VELOCITY CONTOUR PLOT



ENSTROPHY CONTOUR PLOT

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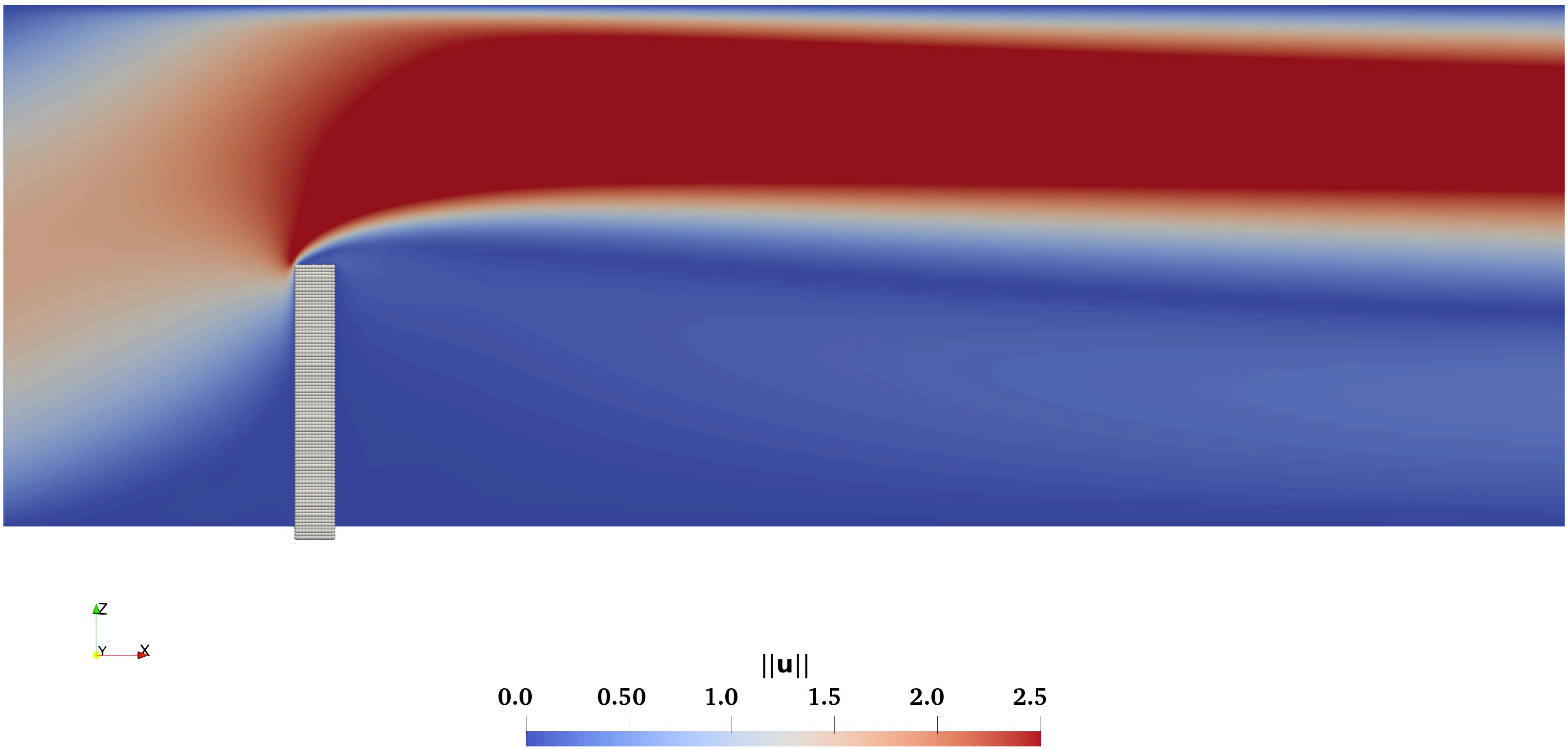
PRELIMINARY RESULTS: FRACTURE



AUTOMATIC CRAK DETECTION:
bond stretch overgrows limit bond stretch

AUTOMATIC INTERFACE DETECTION:
new interface regions are automatically detected

REPORT OF TASKS FORESEEN IN THE NEXT YEARS OF PhD COURSE

- **TASK 1: VALIDATION OF METHOD AND SOFTWARE**
  - **The tool developed during the first year of the PhD course will be fully validated reproducing FSI benchmarks available in literature**
- **TASK 2: METHODOLOGICAL INVESTIGATION**
  - **Investigation of different synchronization strategy**
  - **Investigation of Immersed Boundary Method vs. Immersed Domain Methods**
- **TASK 3: SIMULATIONS**
  - **At least two cases of practical interest will be simulated using the new numerical tool:**
    - **Simulation of the fracture of a solid structure due to interaction with surrounding flow:**
      - **Prediction of failure modes**
      - **Tracking of debris produced by fracture**
    - **Simulation of the aeroelastic flutter of a scaled wing model**
- **TASK 4: SCIENTIFIC PAPERS**
  - **Drafting of a methodological paper**
  - **Drafting of an applicative paper focusing on some applications of the proposed method**

FINAL REMARKS

- FSI problems with crack formation and solid media fracture can be treated numerically in a NS-peridynamics-IBM framework
- A massive parallel numerical tool capable to address general FSI problems accounting for solid fracture has been developed
- Validation and testing have been performed obtaining promising results:
  - Capability of the peridynamic solver to reproduce solid media fracture and crack branching
  - Capability of IBM algorithm to account for force exchange between solid and liquid phases
  - Automatic detection of cracks and new interfaces
- Preliminary testing has shown that the code can qualitative reproduce the dynamics of solid-fluid interaction in simple FSI test cases accounting for fracture due to hydraulic forces

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THANK YOU FOR YOUR ATTENTION!