NUMERICAL SIMULATION OF FIV OF NUCLEAR FUEL RODS

Vibrations in nuclear applications, 2017

Energiforsk, Stockholm

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EU Duc = N

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- Paul Smeekes [TVO]
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- Colleagues [NRG]

CONTENTS

- Introduction: NRG
- FSI (Numerical) work at NRG: CFD Group

  Three Phases:

  1. Validation
  2. Application
  3. Improvement

- Questions

NRG LOCATIONS

THE NETHERLANDS

NRG ORGANISATION

UNITS

- Irradiation Solutions
- Nuclear Operations
- Consultancy & Services
- Research & Innovation

RESEARCH & INNOVATION

Research Program

- Reactor Operation & Safety
- Advanced Nuclear Technology
- Decommissioning
- Radiation Protection

International Cooperation

- EU framework programs (FP7 – H2020)
- OECD/NEA benchmarks
- IAEA CRPs and TWGs
- US-DOE INERI
- Bilateral collaborations

FSI @ NRG: CFD GROUP

Numerical Tools: Partitioned Approach

Starting point

- OpenFOAM
  - IQN-ILS
  - FVM discretization for fluid dynamics solver
  - FVM discretization for solid mechanics solver

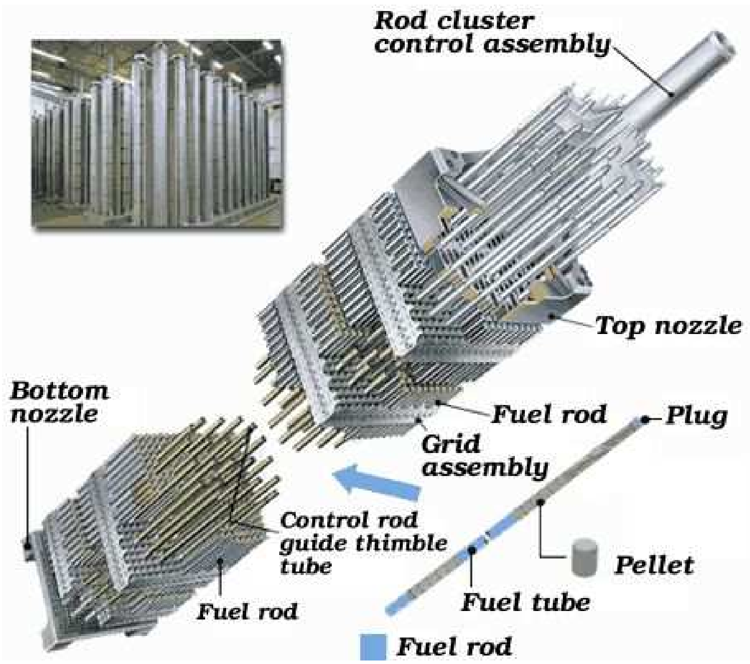
- STAR-CCM+
  - Gauss Seidel
  - FVM discretization for fluid dynamics solver
  - FEM discretization solid mechanics solver

LOOSE VS STRONG COUPLING

- **Loose coupling**: density of the solid is large compared to that of the fluid
- **Strongly coupled**: density of the fluid and the structure are comparable

In nuclear reactors, mostly we deal with strongly coupled cases
$P_{solid} / P_{fluid} < 10$

Working Fluids	ρ_s/ρ_f
Light water (H_2O)	8.24
Heavy water (D_2O)	7.23
Sodium (Na)	10.63
Lead (Pb)	0.79
Lead-Bismuth-Eutectic (LBE)	0.83



VALIDATION PHASE

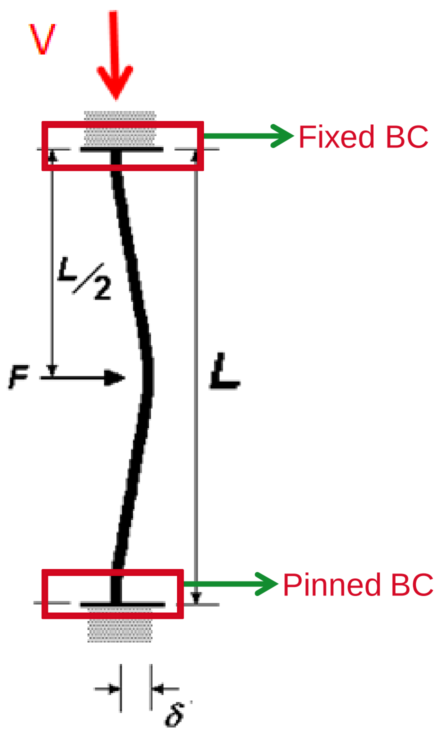
1. Vattenfall-I

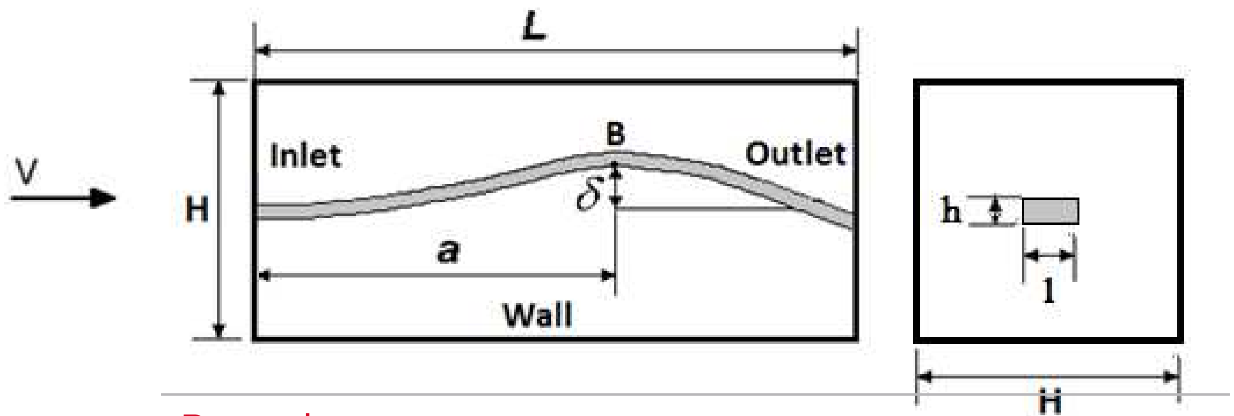
1. Vattenfall-II

2. Turek Case (s)

VATTENFALL CASE - I

- Strong coupling FSI
- Damped oscillations of a steel beam in laminar flow water flow





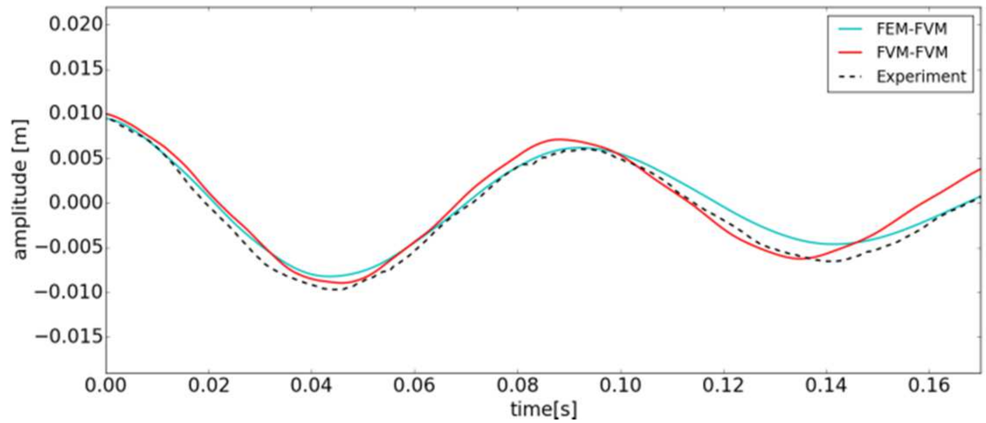
Properties

Inlet velocity	1 m/s
Flow	Laminar
Initial Displacement	10mm
Boundary conditions of solid	-Inlet side : Fixed -Outlet side : Pinned
Density ratio	**8.24 (Strong coupling)**

VATTENFALL CASE - I

FSI simulation in water flow at 1m/s

Simulation	Freq. (Hz)	Error%
Experiment	10.57	--
FEM-FVM	10.96	1.83
FVM-FVM	11.21	7.68



<u>Lesson learn</u>

- FVM-FVM: very sensitive to spatial and time discretization
- FVM-FEM: less dissipative and sensitive to discretization

- Conclusions:
  - FEM-FVM coupling *5 times cheaper* than FVM-FVM
  - Better accuracy with FEM - FVM coupling

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APPLICATION PHASE

Bare fuel rods

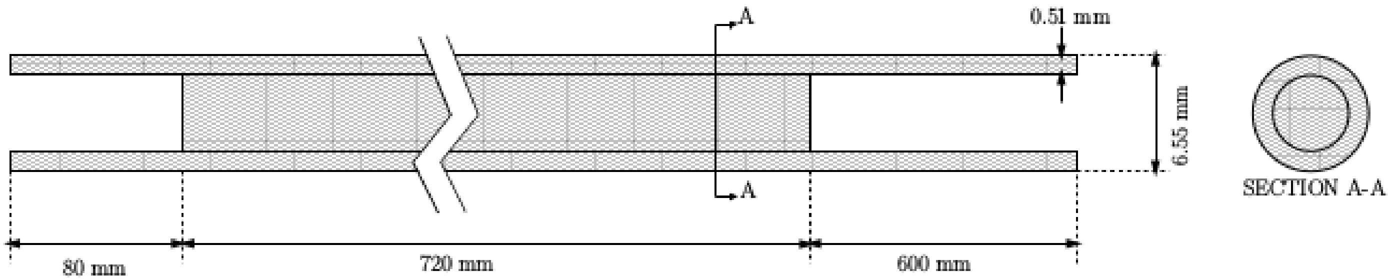
- Single rod
- Two-rods
- Seven-rods

Wire-wrapped fuel rods

- Single rod (different (i) wire-pitch (ii) working fluids)
- Two-rods

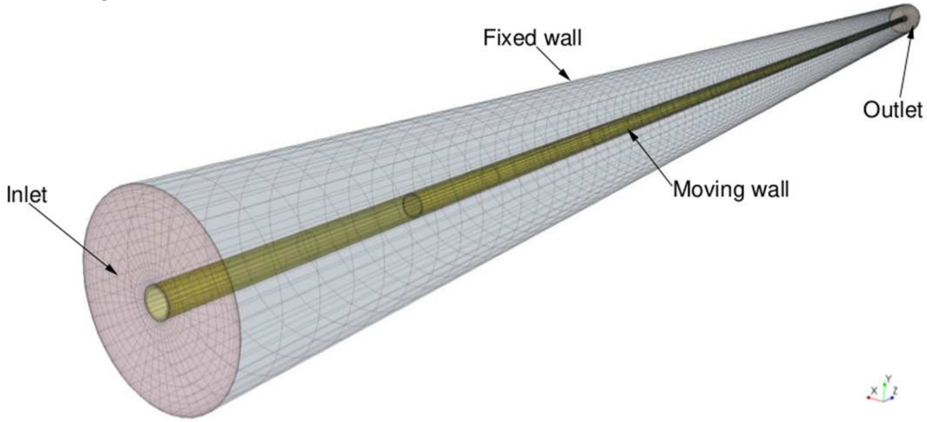
FIV OF NUCLEAR FUEL RODS

- Test cases taken from experimental configuration at ***SCK•CEN & VUB***
  - Bare rods in axial water flow

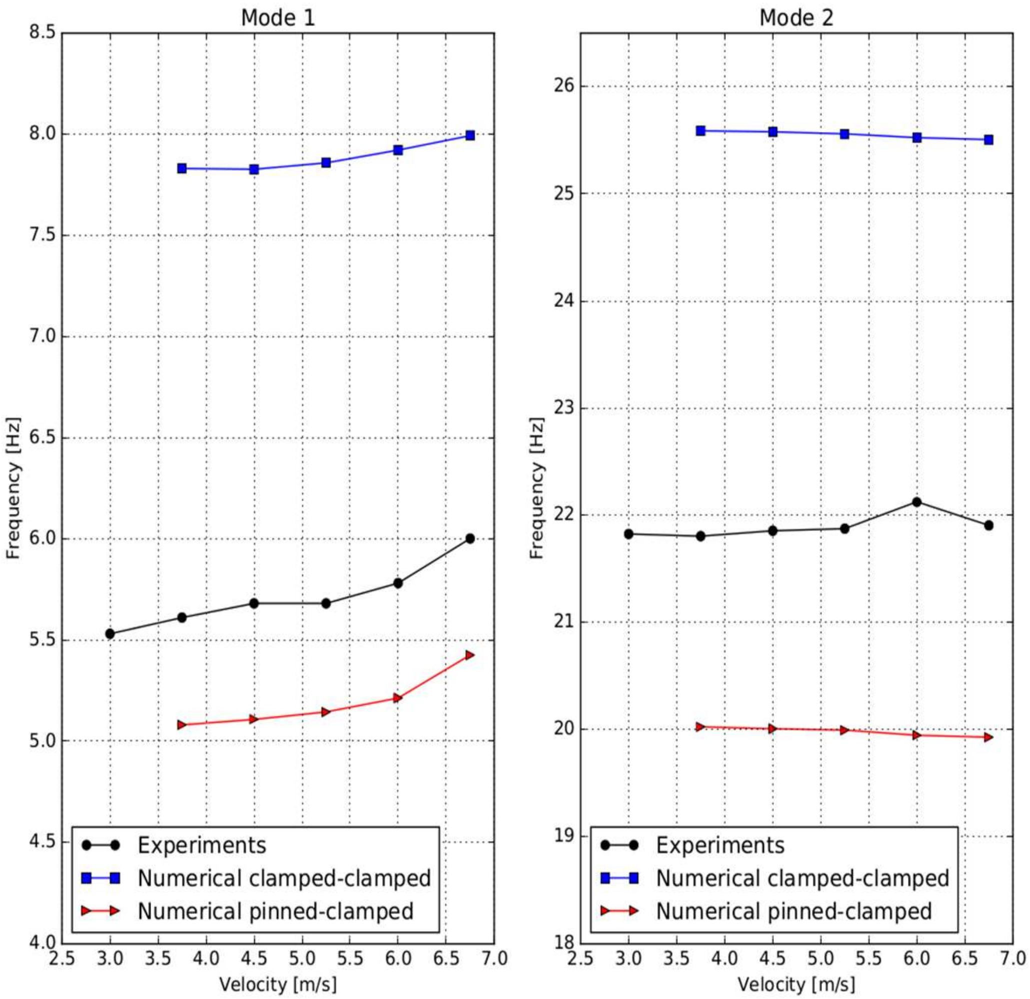


- **Numerical structural model**
  - Tuned to match the experimental natural frequencies in free air

- **Numerical fluid domain**
  - L = 1400 mm & D_h = 42.6
  - URANS model (k-ω SST)
  - Fluid: water
  - Reynolds: 2.0E+5 (v = 5.25 m/s)



NATURAL FREQUENCIES – ONE ROD



- Constraints in the FSI simulations
  - Clamped-Clamped
  - Pinned-Clamped
- Natural frequencies are
  - Overestimated with clamped-clamped
  - Underestimated with pinned-clamped
- Not enough information to model the rod constraints used in the experiments

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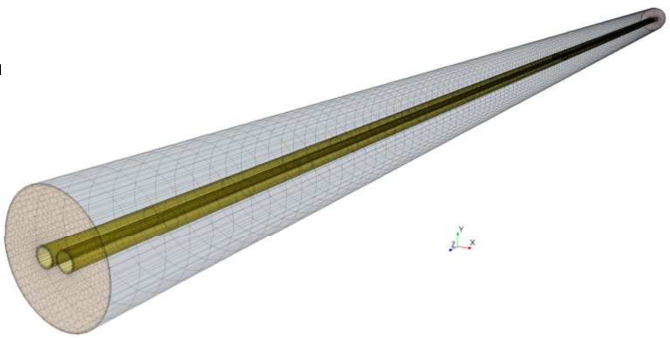
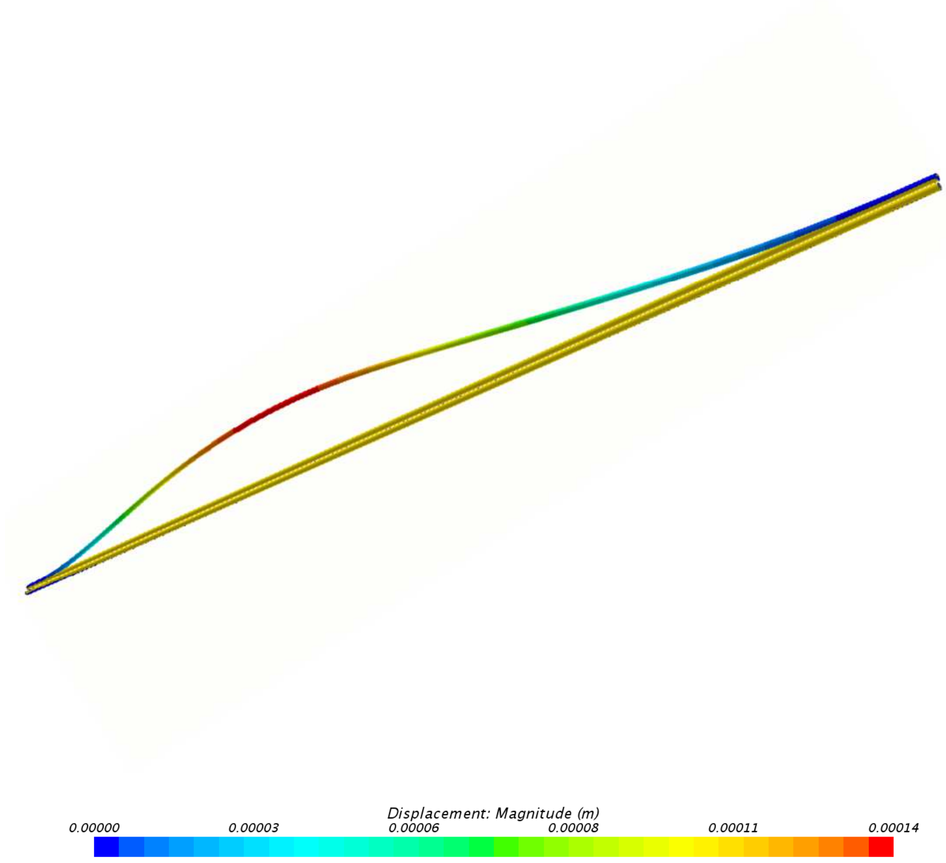
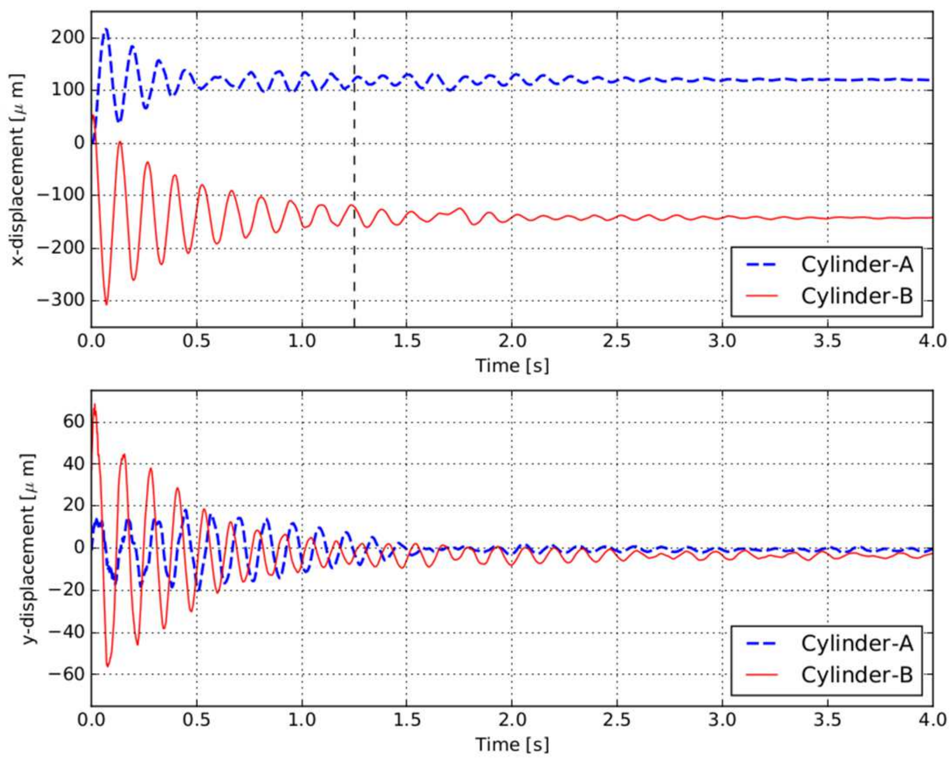
TWO-RODS CONFIGURATION

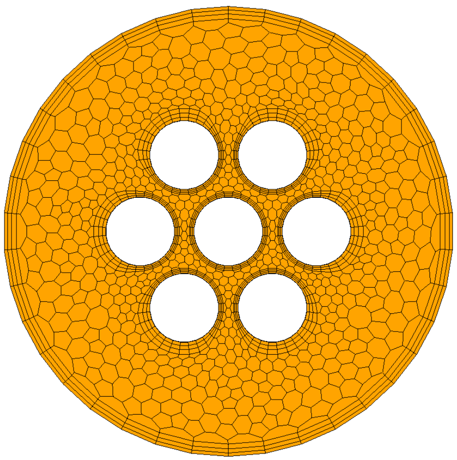
- Rod inter-coupling due to the presence of the fluid

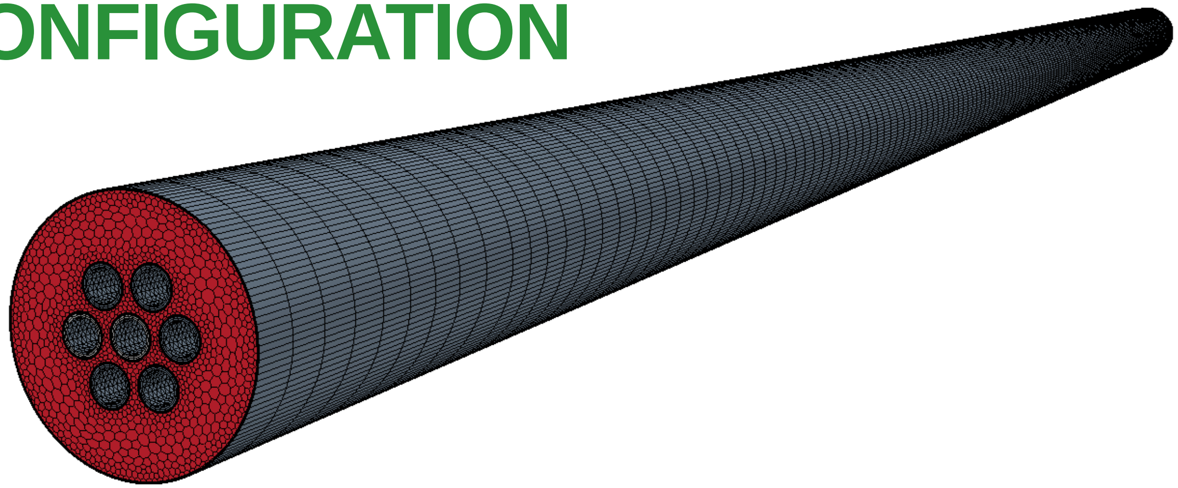


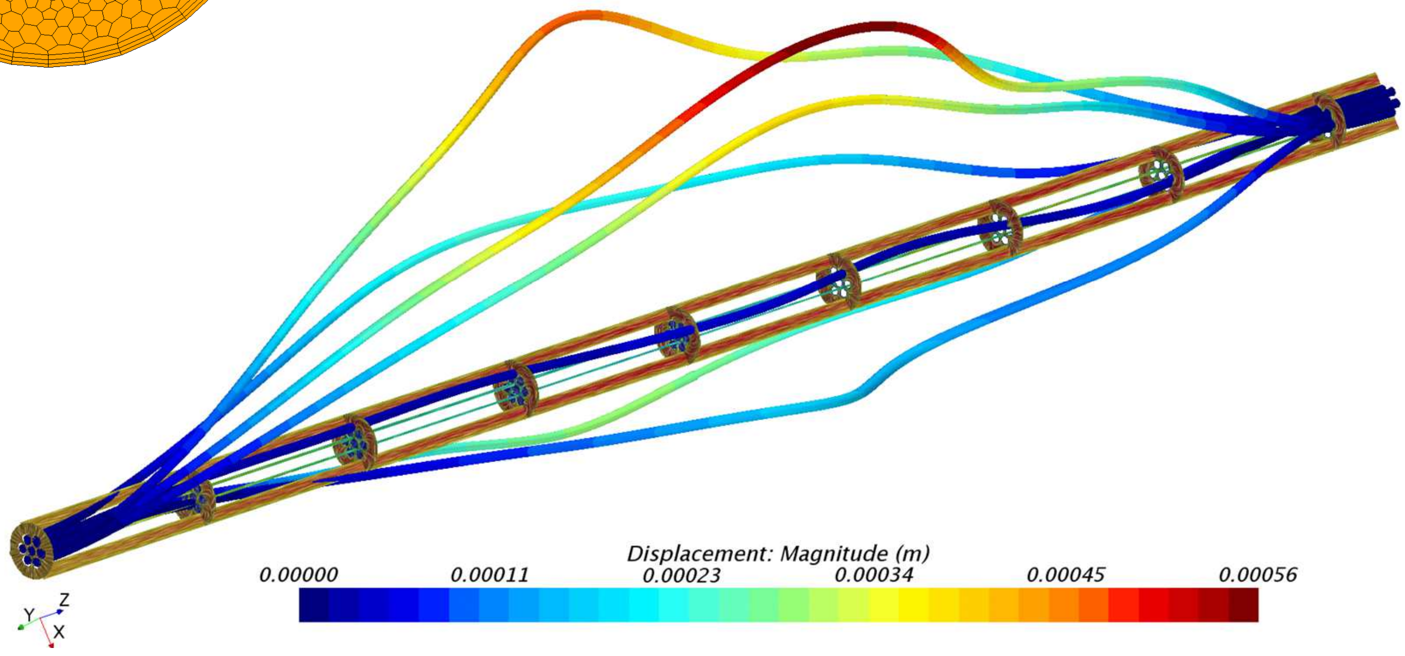




SEVEN-RODS CONFIGURATION







CONS OF USING STAR-CCM+

1. Limited licenses
2. Flexibility of coupling methods
3. Standard (U)RANS models

Hence, there is a **need** for a tool which can answer the aforementioned drawbacks

IMPROVEMENT PHASE

1. Fluid Solver

OPEN SOURCE CODES

OpenFOAM®

Fluid solver

- Finite Volume Library
- Extensively Validated Code
- Good documentation and active discussion Forums

FSI

deal.II

Structural solver

- Finite Element Library
- Developed to work on Super-Computers with optimized parallelization
- Good Documentation and Active forums

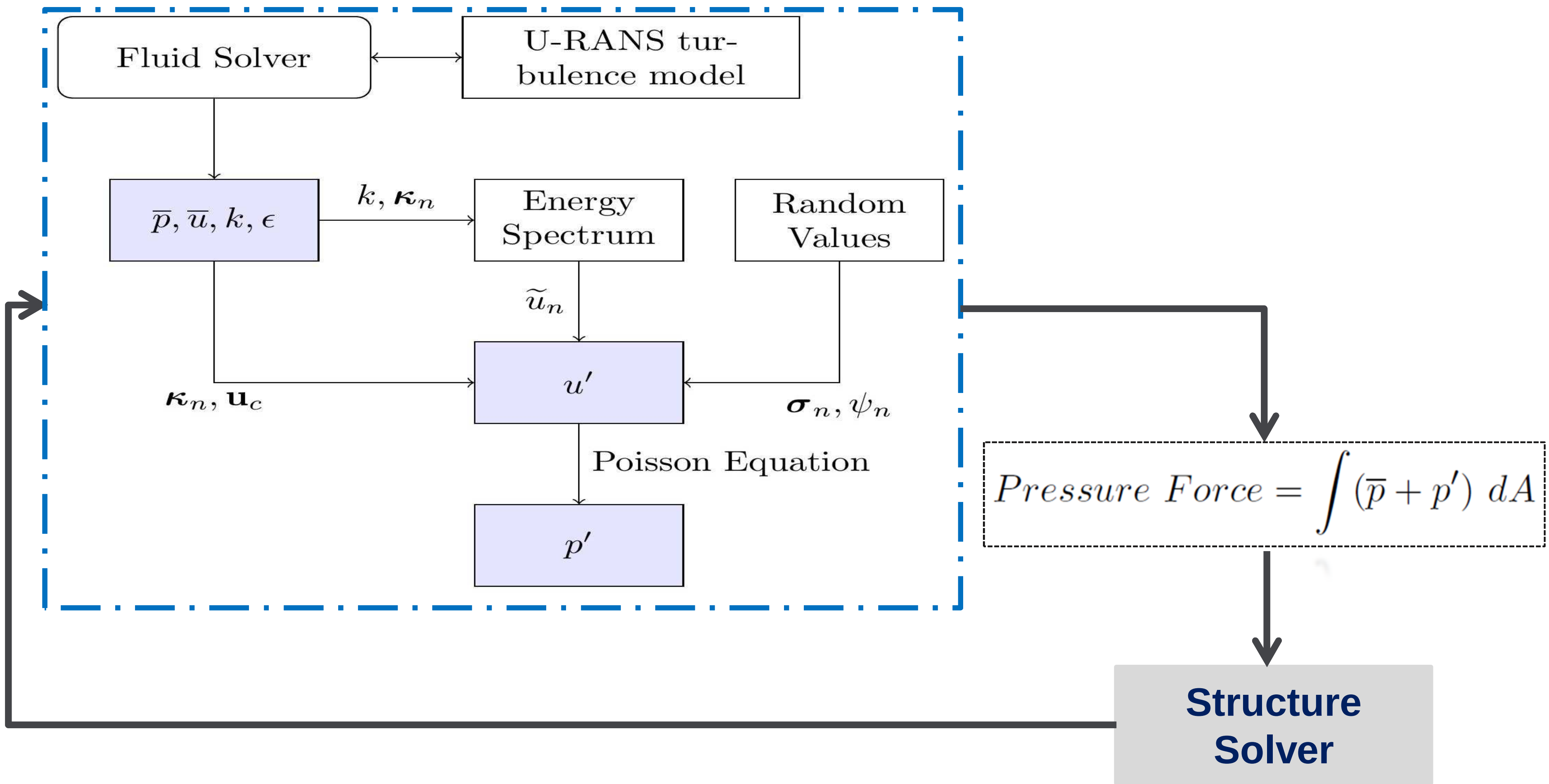
FSI-NRGFOAM

FSI-NRGFOAM

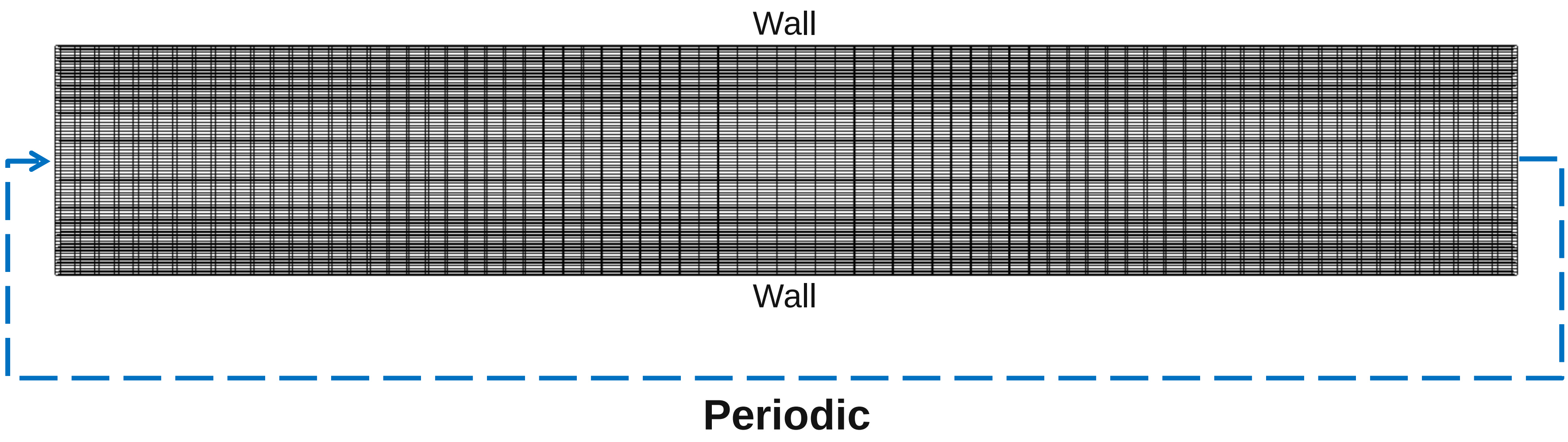
Coupling of the CFD and CSM codes

- **Advantage #1**
  - No limitation of licenses
  - Parallelized optimally to scale well on large number of clusters
- **Advantage #2**
  - State of the art coupling methods for strongly coupled problems
- **Advantage #3**
  - Independent improvement of each solver

NOVEL APPROACH: PRESSURE FLUCTUATION MODEL (PFM)

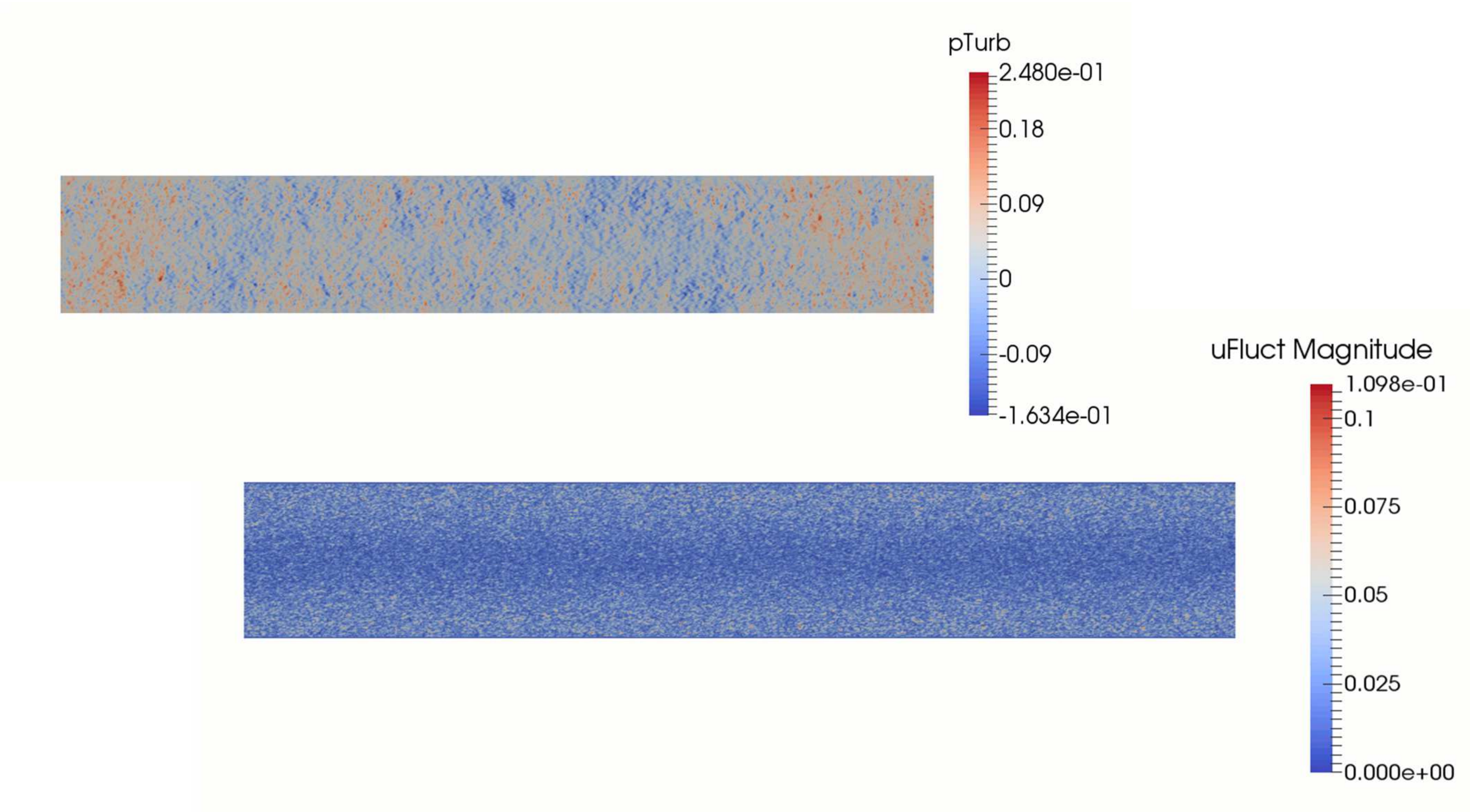


VALIDATION: TURBULENT CHANNEL FLOW (2D)

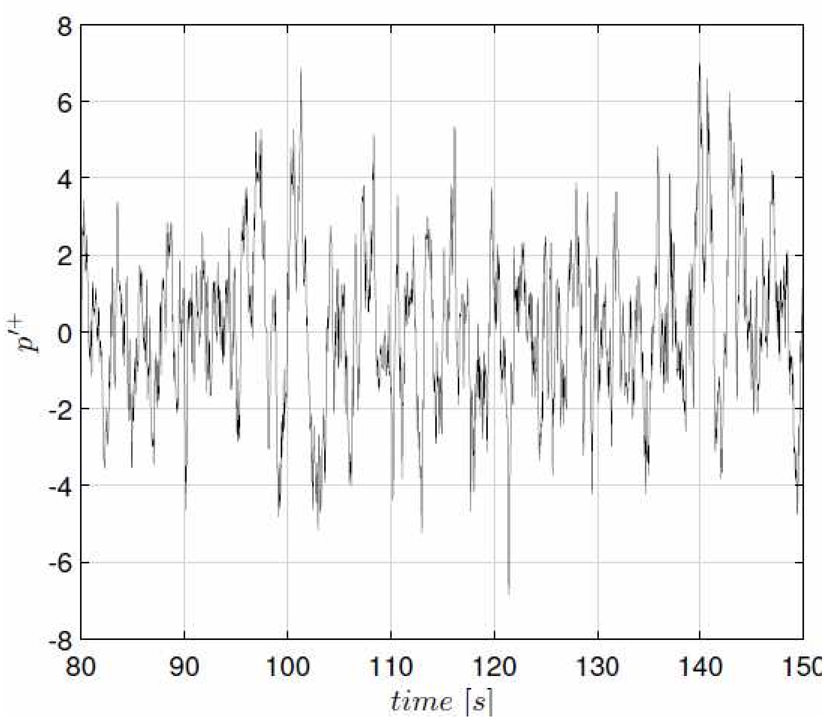


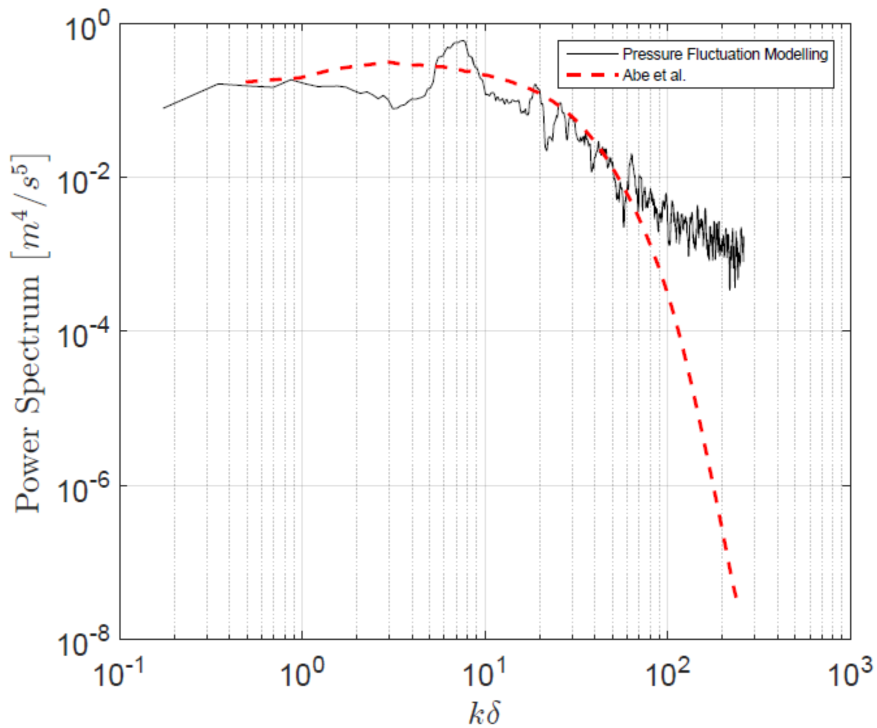
- CFD simulation
- Validation of the pressure fluctuation model
- Comparisons with high fidelity simulations: DNS (3D)

RESULTS: TEMPORAL FLUCTUATIONS



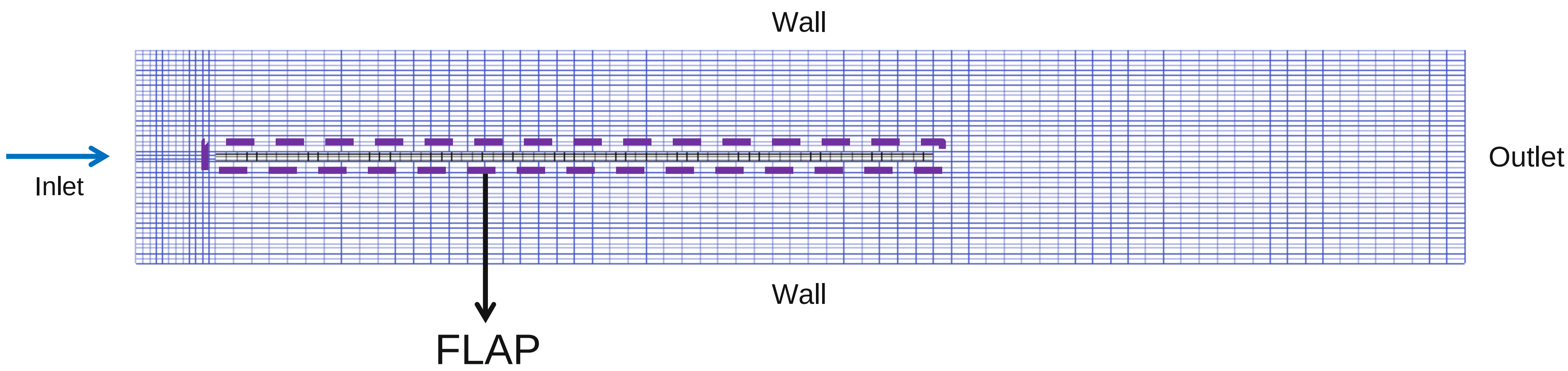
RESULTS: TEMPORAL FLUCTUATIONS





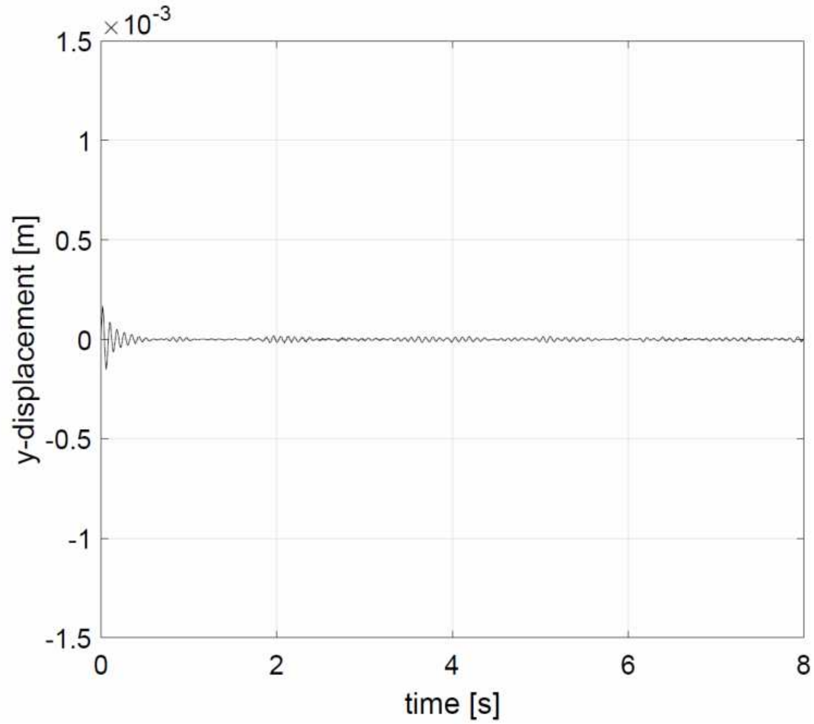
- Temporal fluctuation of the solution
- **URANS model would predict no temporal fluctuations**

FSI TEST CASE: STEEL FLAP IN WATER

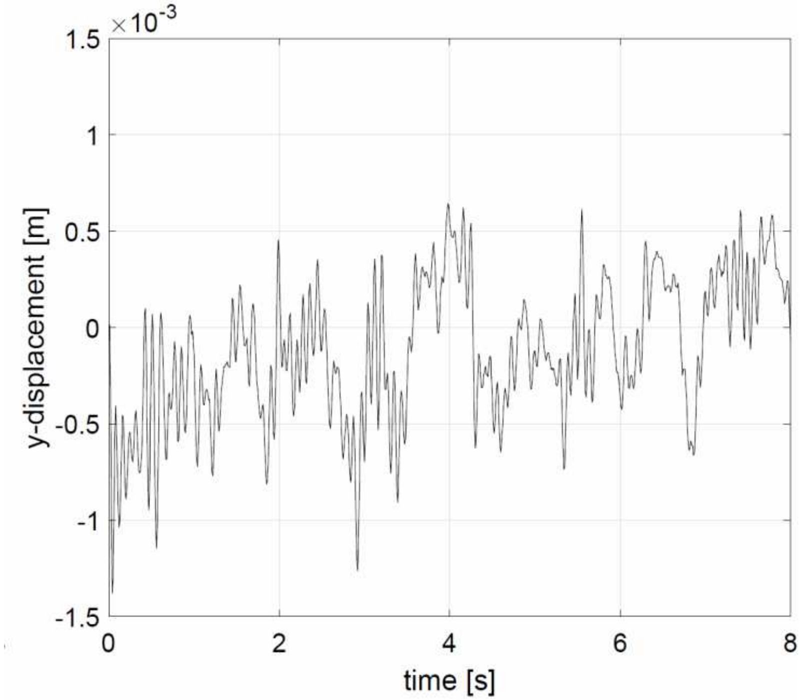


- 2D test case
- Steel Flap
- Turbulent flow of water
- Bulk Reynolds number:1.2 Million

FSI TEST CASE: RESULTS



Response from a standard (U)RANS model



Response after modeling the pressure fluctuations

CONCLUSIONS AND FUTURE WORK

Current Tool

- **STAR-CCM+**: commercial code
- Simple to complex geometries
- Tackle upcoming problems within the scope of the code (licenses, coupling, turbulence…)

Future Tool

- **FSI-NRGFOAM**: open-source approach
- In the validation phase
- Extending our capabilities further & develop a state of the art FSI tool.

THANK-YOU !

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