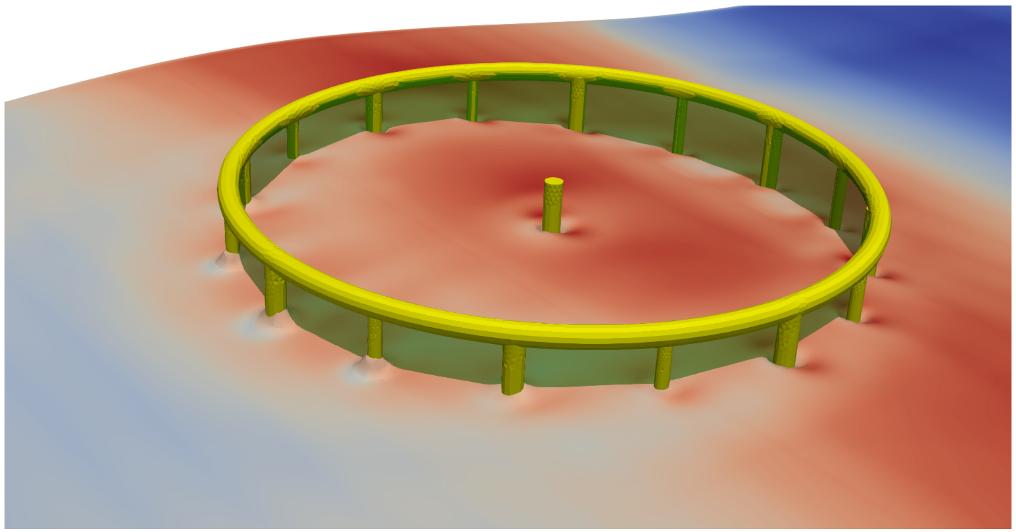
A CFD-Based Numerical Framework for Modelling Open Ocean Aquaculture Structures

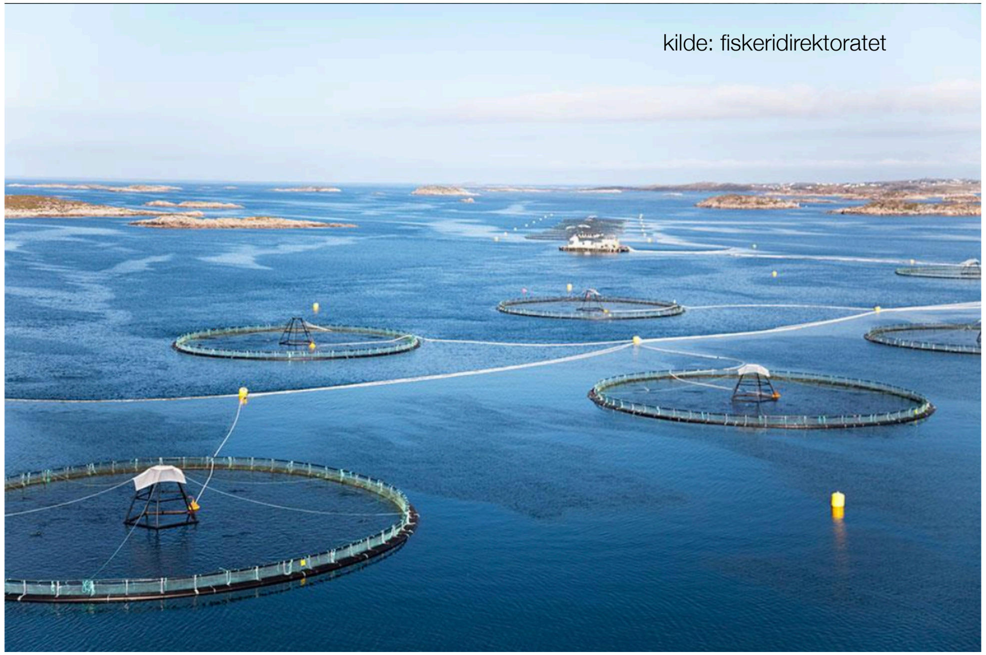
Hans Bihs
Tobias Martin
Arun Kamath

Marine Civil Engineering
NTNU Trondheim



Today's Aquaculture Structures

- mostly inside fjords
- hydrodynamic loading: currents
- protected against large waves
  - mostly Hs,max< 1 m
  - very few places with Hs> 1.5 m
- traffic light system for salmon lice
- higher environmental impact on closed water systems



Ambitious Goals

- increased production
- larger devices
- exposed area: Hs= 5 m, Hs= 16 m
- exposed for large waves and extreme weather
- outside the traffic light system for salmon lice
- reduced environmental impact in open ocean
- challenging: fish escape & fish mortality

kilde: salmar.no

Project Objectives

Traditional aquaculture in fjords

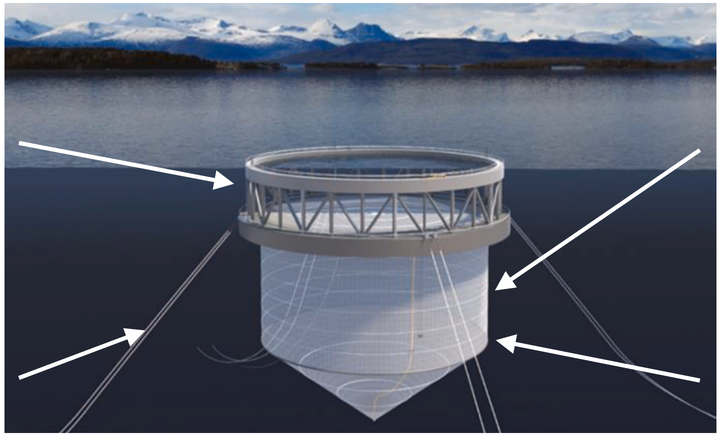
Open ocean structures

Challenges

- <u>Enable the investigation of offshore aquaculture structures in the ocean</u>
    - Complex FSI
    - Including flexible structures

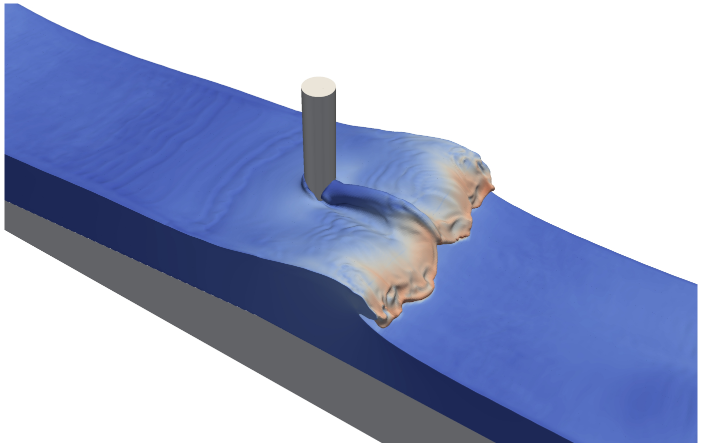
- <u>Computational Fluid Dynamics</u>
    - Inside into flow pattern around and in the cages
    - Accurate force calculations in severe weather conditions

- <u>Tasks:</u>
    - Developing suitable mooring model
    - Developing suitable net model
    - Modelling the fluid-structure interaction in CFD solver



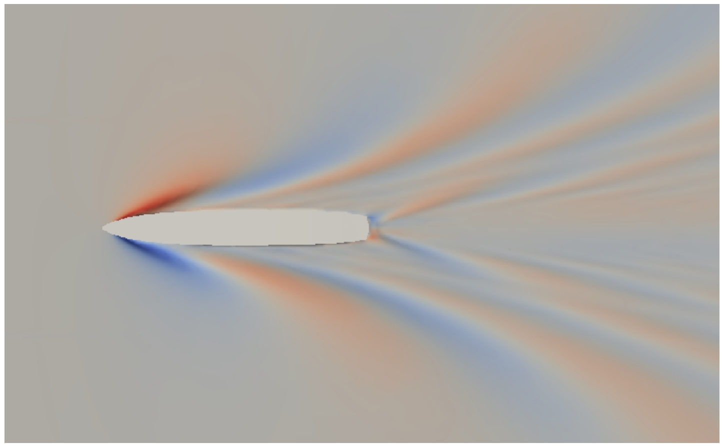
REEF3D::CFD

- **Solves:**
  - Full 3D Navier-Stokes Equations
  - Free Surface: Two-Phase Flow - Water & Air



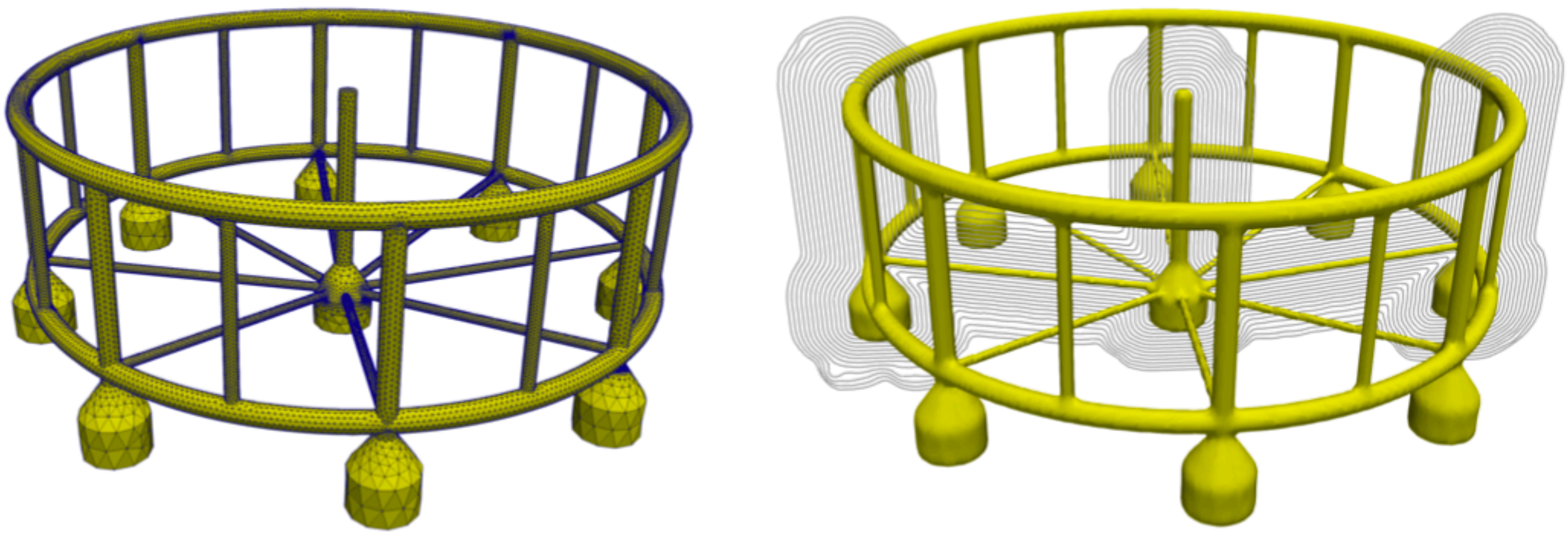
- **Focus on:**
  - Free Surface Flows
  - Wave Hydrodynamics
  - Floating Structures
  - Open Channel Flow
  - Sediment Transport

- **The Code**
  - part of the REEF3D hydrodynamic framework
  - C++ (modular & extensible)
  - Parallel Computing / HPC
  - Open-Source: https://github.com/REEF3D
  - Developed at the Department of Civil and Environmental Engineering, NTNU Trondheim
  - More info at: www.reef3d.com
  - CFD Online Forum: https://www.cfd-online.com/Forums/reef3d/



Modelling the Fluid-Structure Interaction

- Direct forcing immersed boundary method
    - Rigid body dynamics described by Euler parameters
    - Weak coupling
    - Implicit boundary conditions enforced with forcing term



(a) Original STL representation.

(b) Level set representation indicated by grey contour lines in x-z plane. Yellow surface shows $\Phi_s = 0$.

Mooring Models

- Dynamics of a mooring line neglecting bending stiffness [31]:

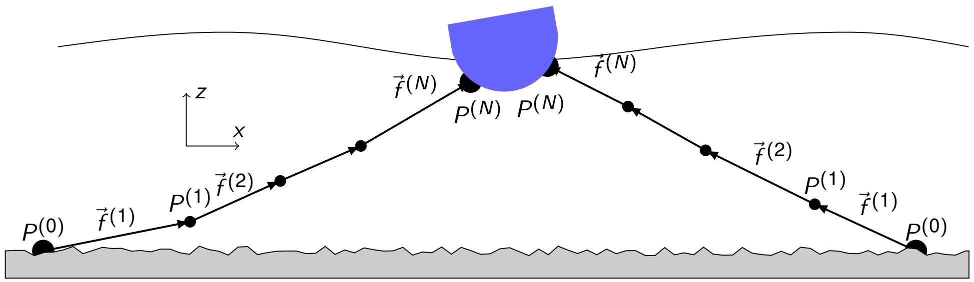
$$\gamma \frac{\partial^2 \mathbf{r}}{\partial t^2} = \frac{\partial F_T \mathbf{f}}{\partial s} + \mathbf{F}_e. \tag{10}$$

$\mathbf{r}$ - line coordinates
γ - specific weight of the material
F_T - magnitude of the tension force
$\mathbf{f}$ - unit vector pointing in the direction of tension force
$\mathbf{F}_e$ - external forces including gravitation and hydrodynamic effects.

- Assuming small line motion in time, (10) simplifies to static equilibrium

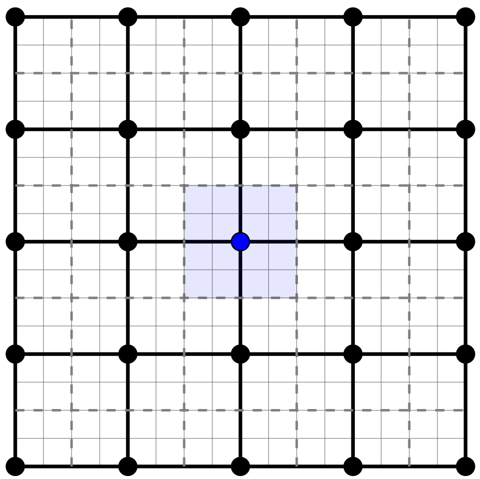
$$\frac{\partial F_T \mathbf{f}}{\partial s} = -\mathbf{F}_e. \tag{11}$$

- Lumped mass method solved for bar vector directions.
- Equally distributed mass, linear elasticity and hydrodynamic transparency.



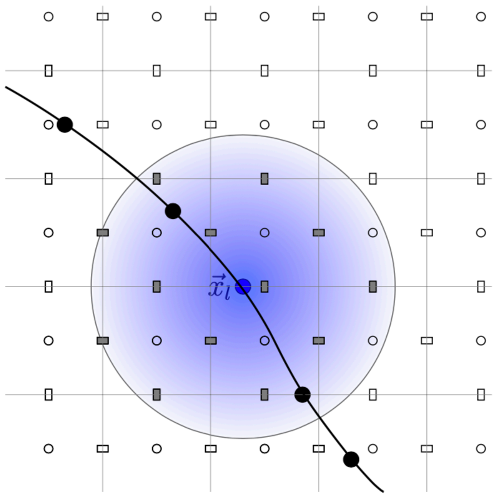
Net Model

- Coupling net and fluid dynamics
  - Structure cannot be resolved in fluid domain
  - Hydrodynamic forces on net using screen force model (alternative to Morison equation)
  - Effect of net on fluid trough additional source term in Navier-Stokes equations



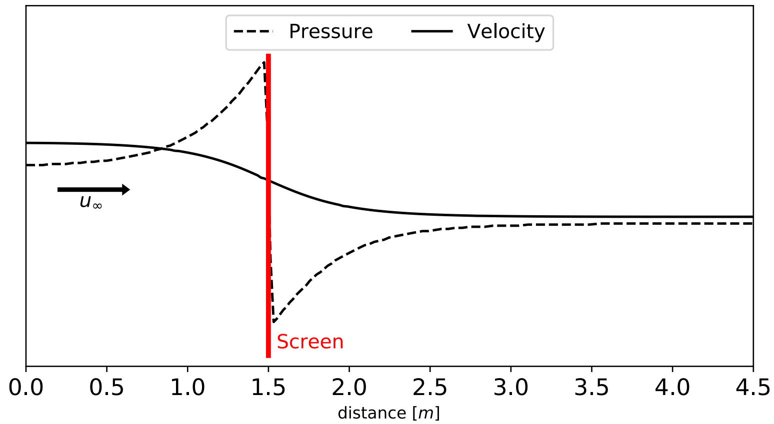
screen force model

$$\vec{F}_D = \frac{\rho}{2} C_D A u_{rel}^2 \vec{n}_d,$$
$$\vec{F}_L = \frac{\rho}{2} C_L A u_{rel}^2 \vec{n}_l, .$$



Lagrangian markers within a kernel D

$$\frac{\partial}{\partial x_i}\left(\frac{1}{\rho}\frac{\partial p^{(n+1)}}{\partial x_i}\right) = \frac{1}{\Delta t}\frac{\partial}{\partial x_i}\left(u_i^{(*)} - F_i\right),$$



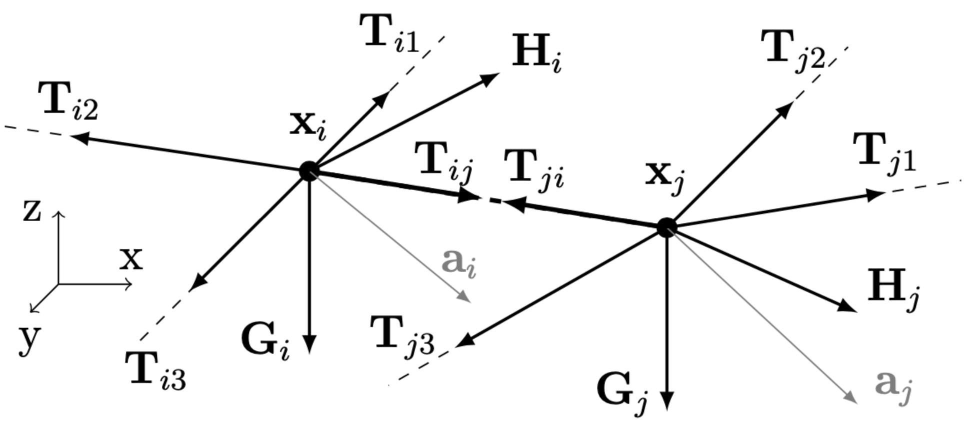
resulting pressure jump at the net

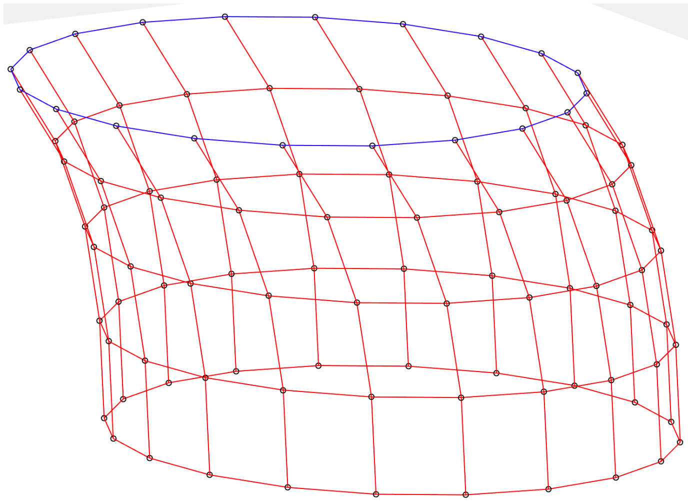
Net Dynamics Model

- **Challenges:**
  - Non-linear material laws
  - Large deformations
  - Two distinct stress directions

$$m_i \, \mathbf{a}_i = \sum_{k=1}^{N_i} \mathbf{T}_{ik} + \mathbf{F}_i.$$

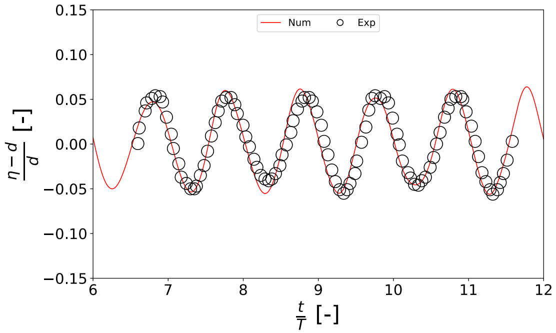
- **Solution:**
  - finite number of mass points
  - connected by non-linear elastic bars pointing in the principal directions of the meshes
  - Solving dynamic force equilibrium (Newton's second law)
  - Implicit method to keep physical connections automatically fulfilled



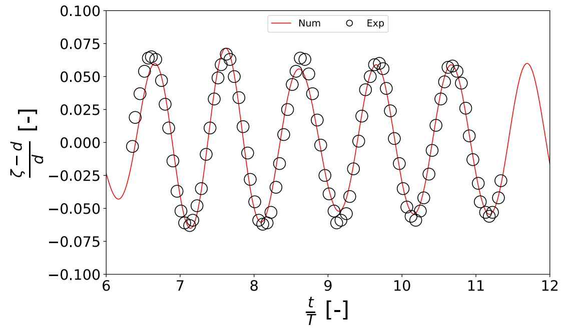


Floating Algorithm Validation

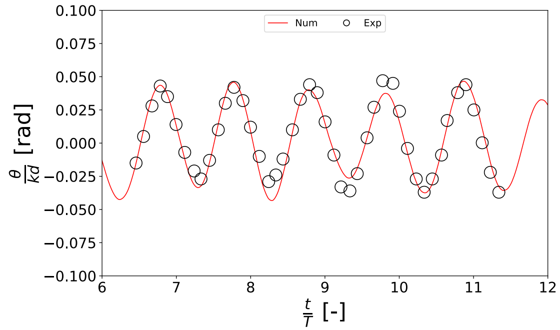
- d = 0.4m
- barge density = 500 kg/m^3
- H = 0.04m
- T = 1.2s



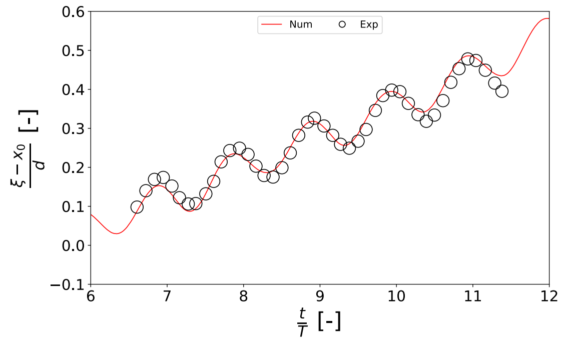
(a) Wave elevation over time at $x = 5.5$ m.



(b) Heave motion over time.



(c) Pitch motion over time.

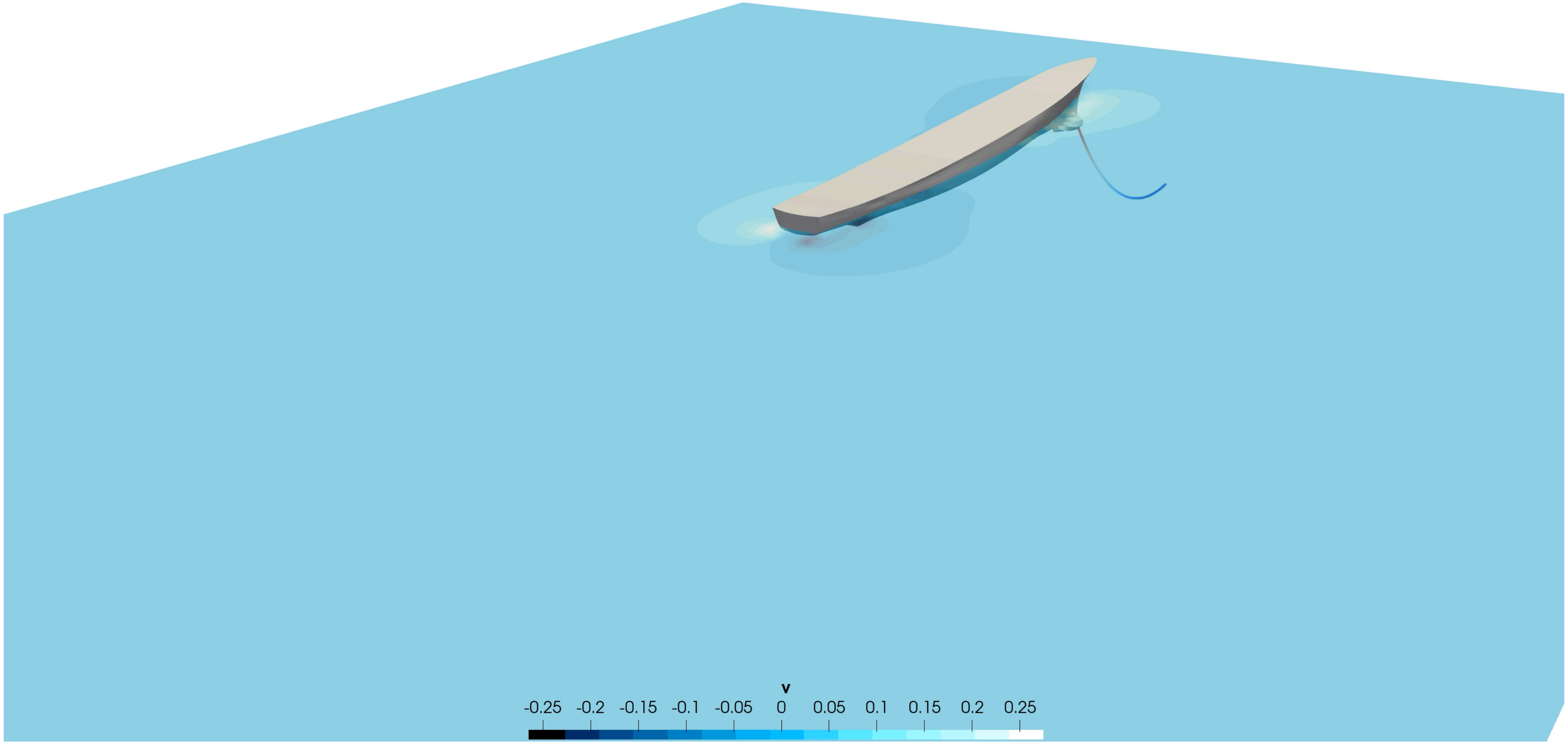


(d) Surge motion over time.

Figure 10: 3DOF motion of the two-dimensional barge over time. Comparison of numerical and experimental results for $\Delta x = 0.01$ m and CFL$= 0.1$.

Mooring Models

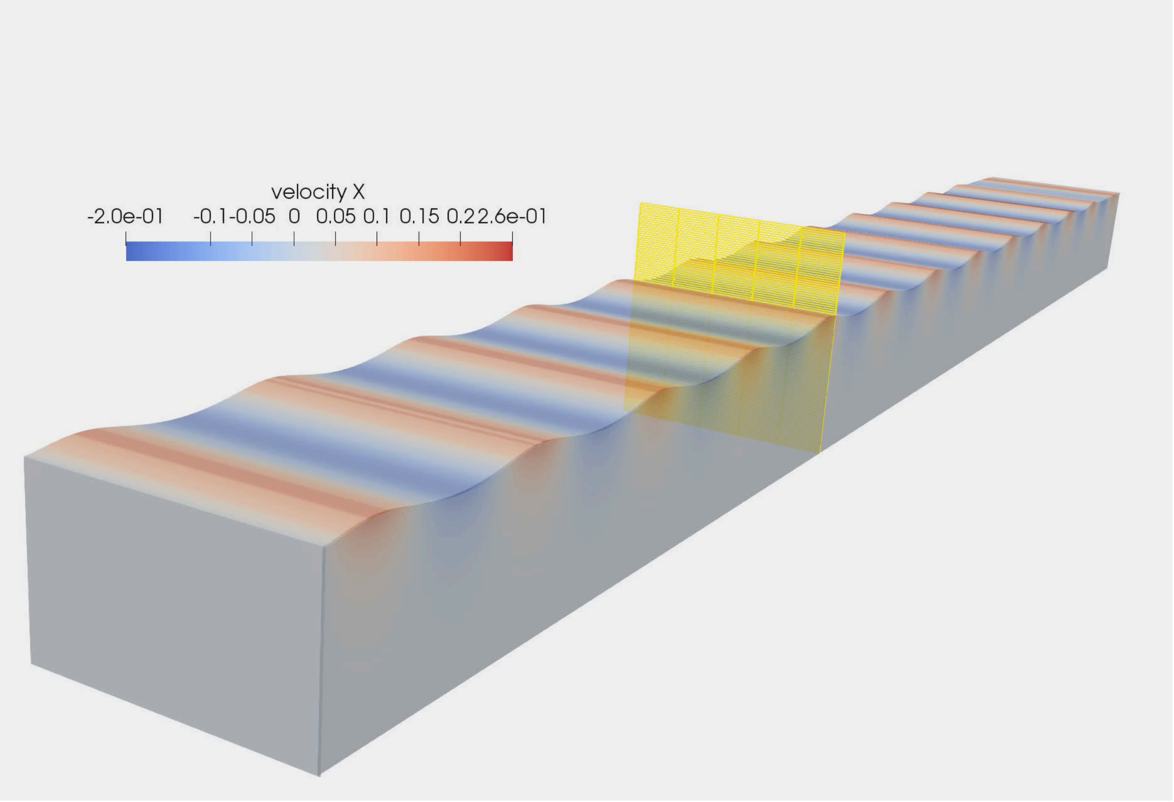
- Quasi-static approach = Robustness

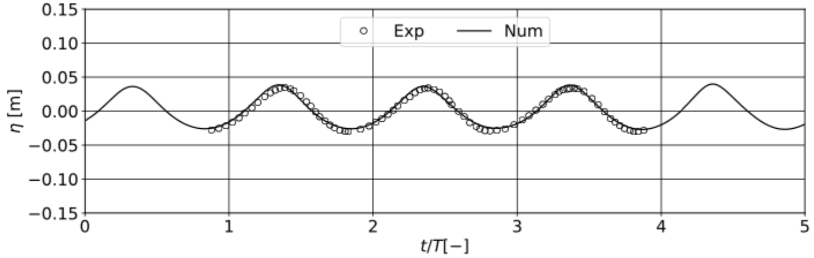


Net Model Validation: Waves

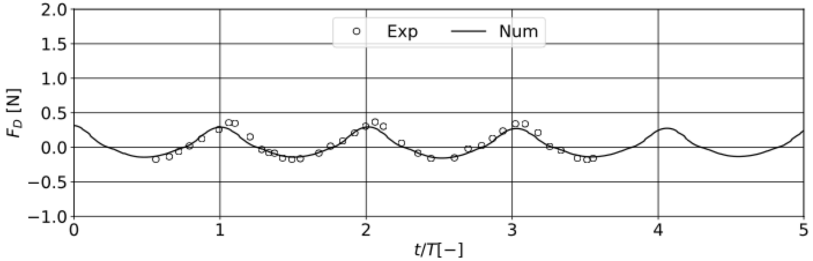
- Fixed net panels with $Sn = 0.095 - 0.288$ in regular waves
- Wave heights $H = 0.045$ m $- 0.167$ m.
- Wave frequencies $f = 1.0$ Hz $- 1.42$ Hz.
- 5th-order Stokes waves.

P.F. Lader et al. "Experimental Investigation of Wave Forces on Net Structures". In: *Applied Ocean Research* 29 (3) (2007), 112–127.





(a) Surface elevation at the wave gage.

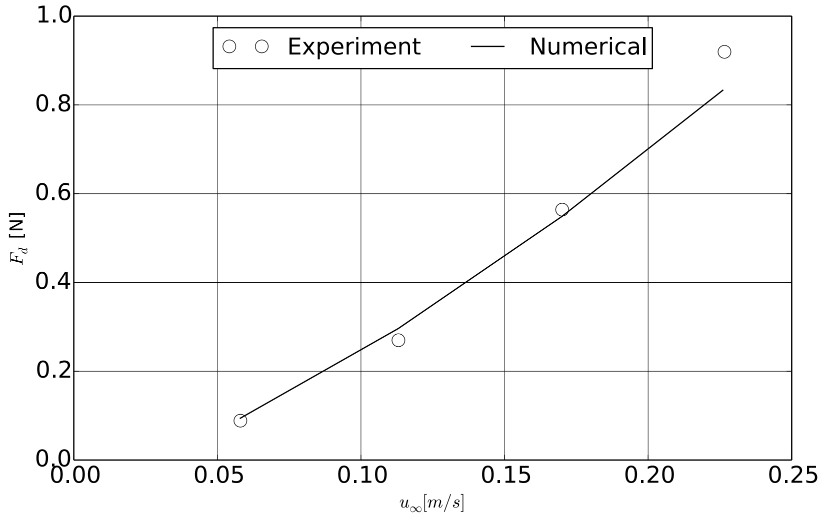


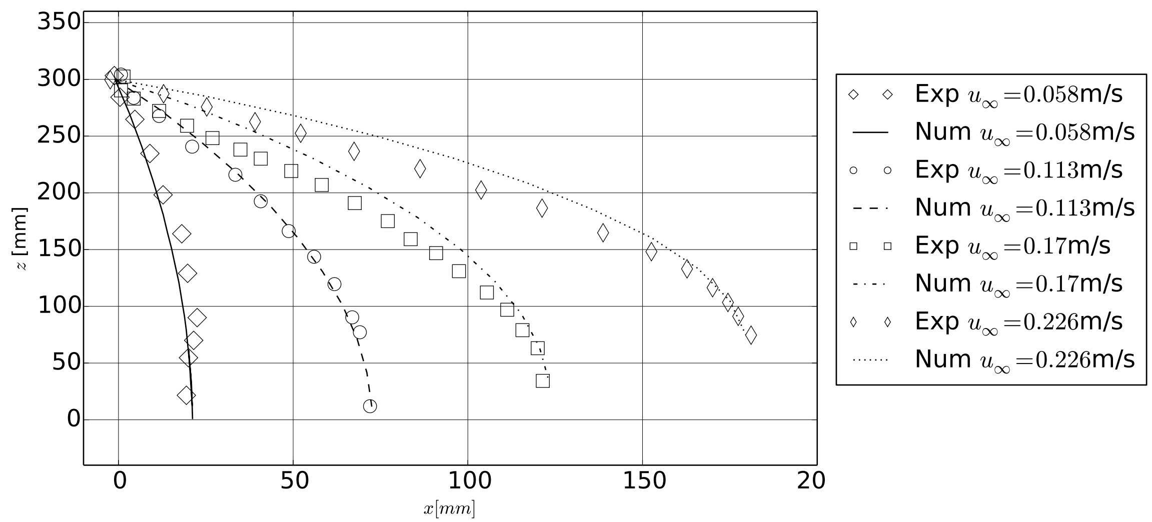
(b) Drag force for net case 1.

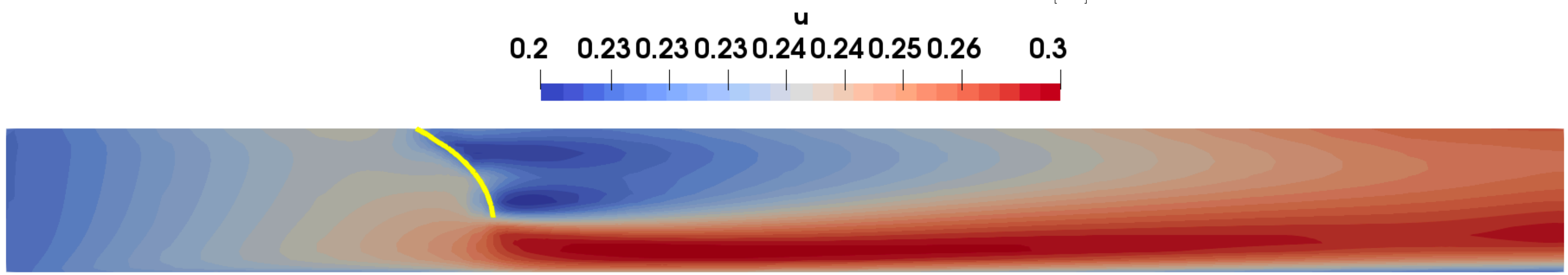
Net Dynamics Model Validation

- Validation for moving net wall in current

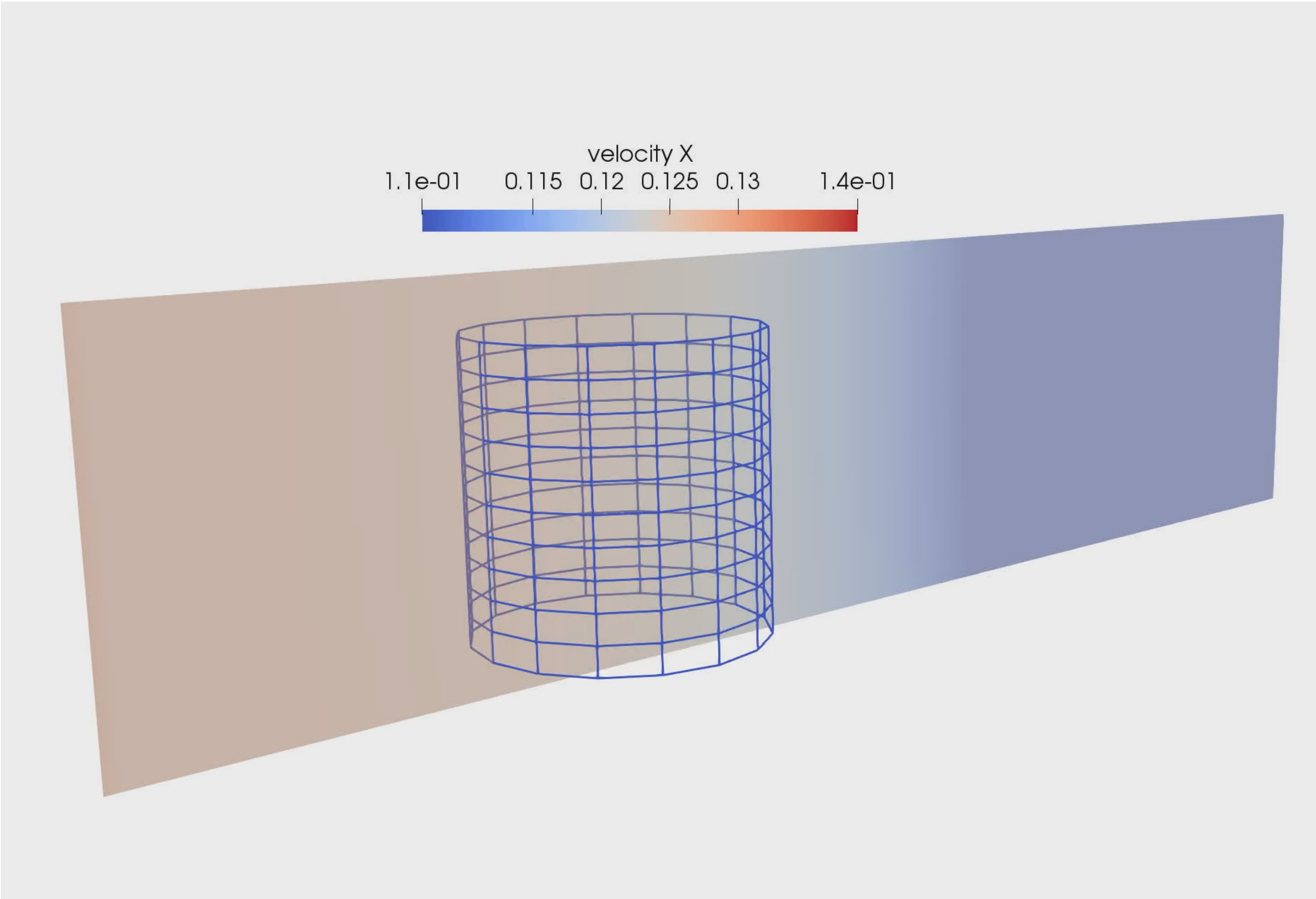
C.-W. Bi et al. "Numerical simulation of the interaction between flow and flexible nets". In: *J. Fluids Struct.* 45 (2014), 180–201.







Net Model

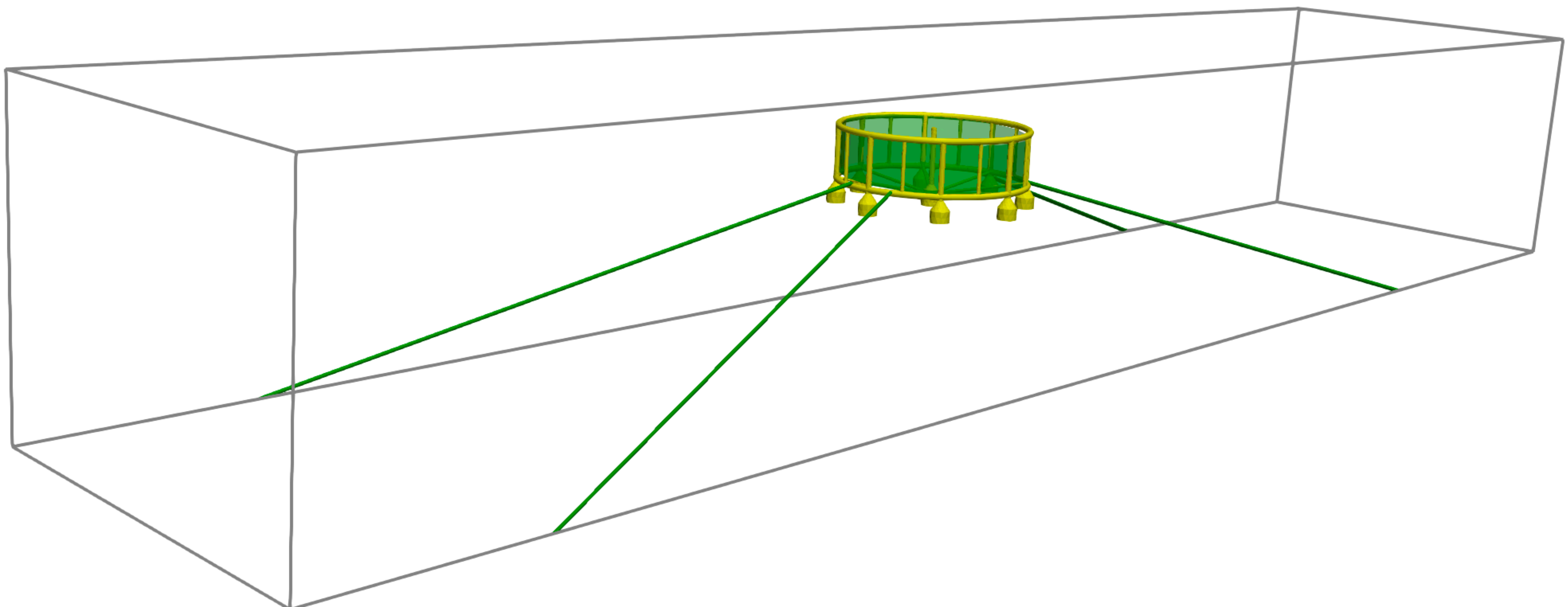


Application to Open Ocean Aquaculture structures

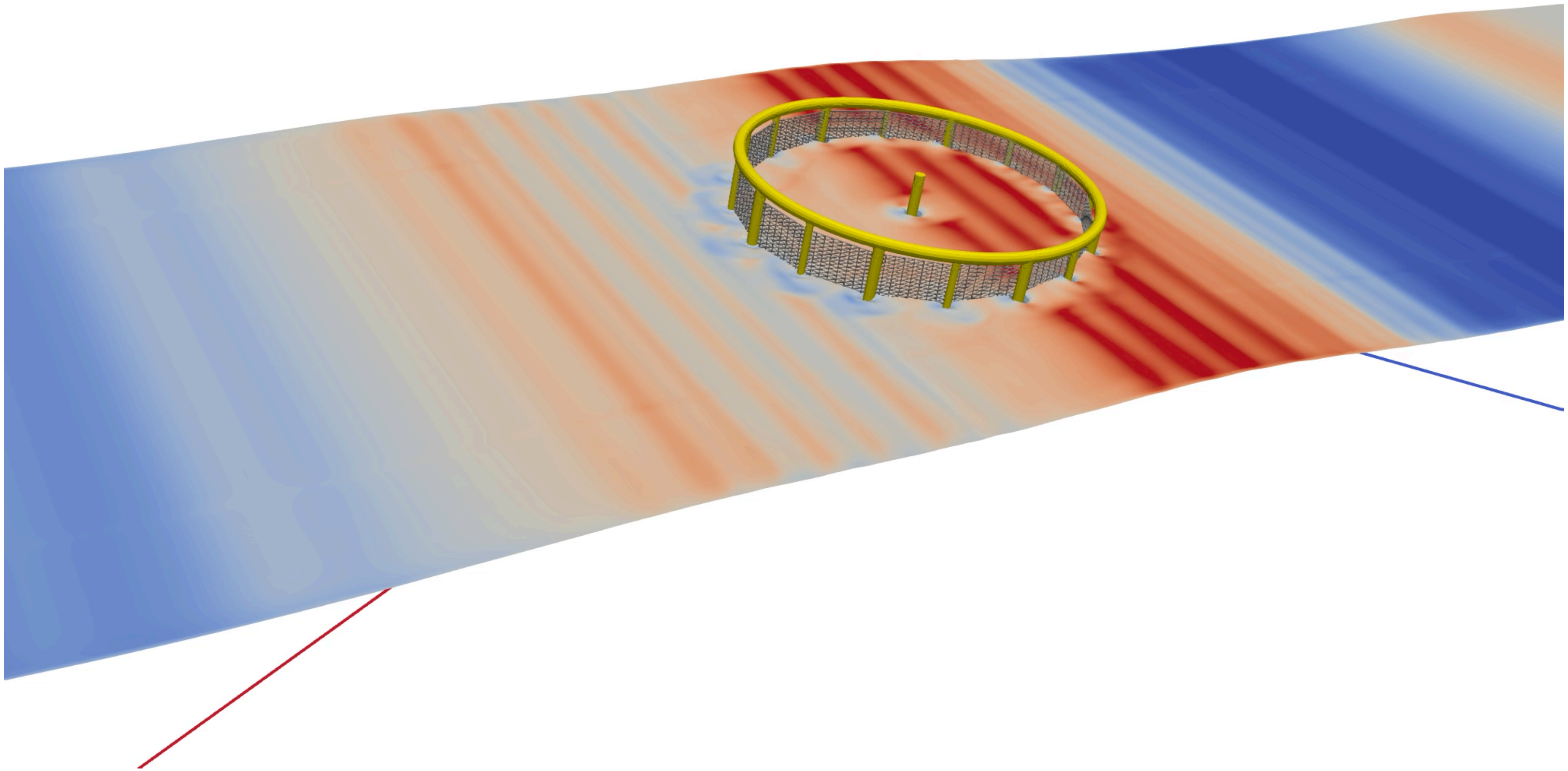
- Circular structure with $D = 1$ m adapted from Zhao et al.
- 9 pontoons with columns on top connected with pipes.
- Uniform mass distribution assumed.
- Rigid net system with solidity 0.145.
- Mooring system: 4 linear springs with pretension.

- Convergence test for heave and pitch decay $\rightarrow \Delta x = 8$ mm around structure.
- Regular waves with $H = 0.06$ m and 0.1 m and $T = 1.0\ s, 1.2\ s, 1.4\ s$.
- Jonswap spectra with $H_s = 0.1$ m and $T_p = 0.5$ s $-$ 3.5 s.
- Response amplitude operators from power spectra using discrete FFT.

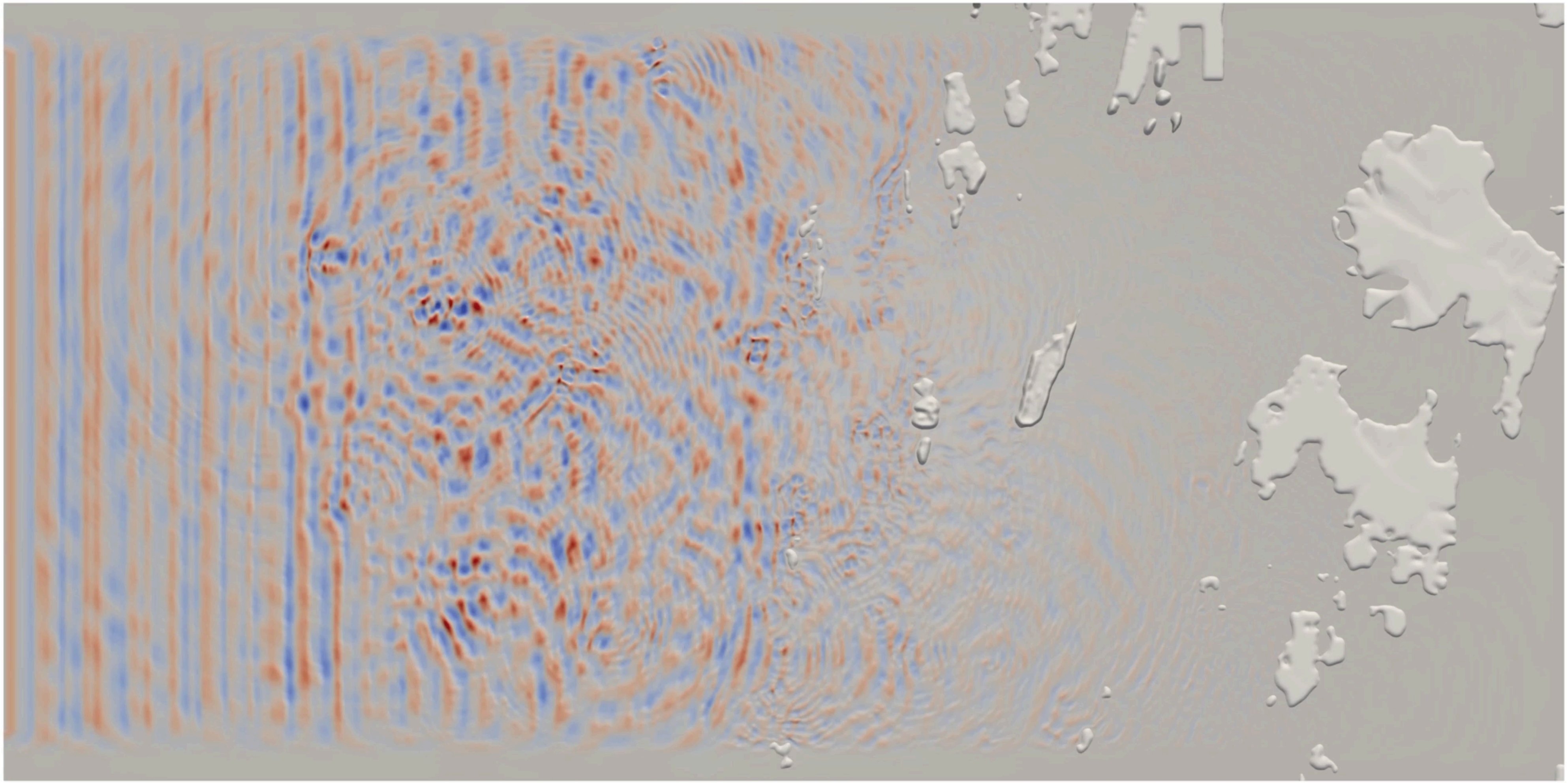
Y. Zhao et al. "Experimental Investigations on Hydrodynamic Responses of a Semi-Submersible Offshore Fish Farm in Waves". In: *Journal of Marine Science and Engineering* 7 (2019). DOI: 10.3390/jmse7070238.



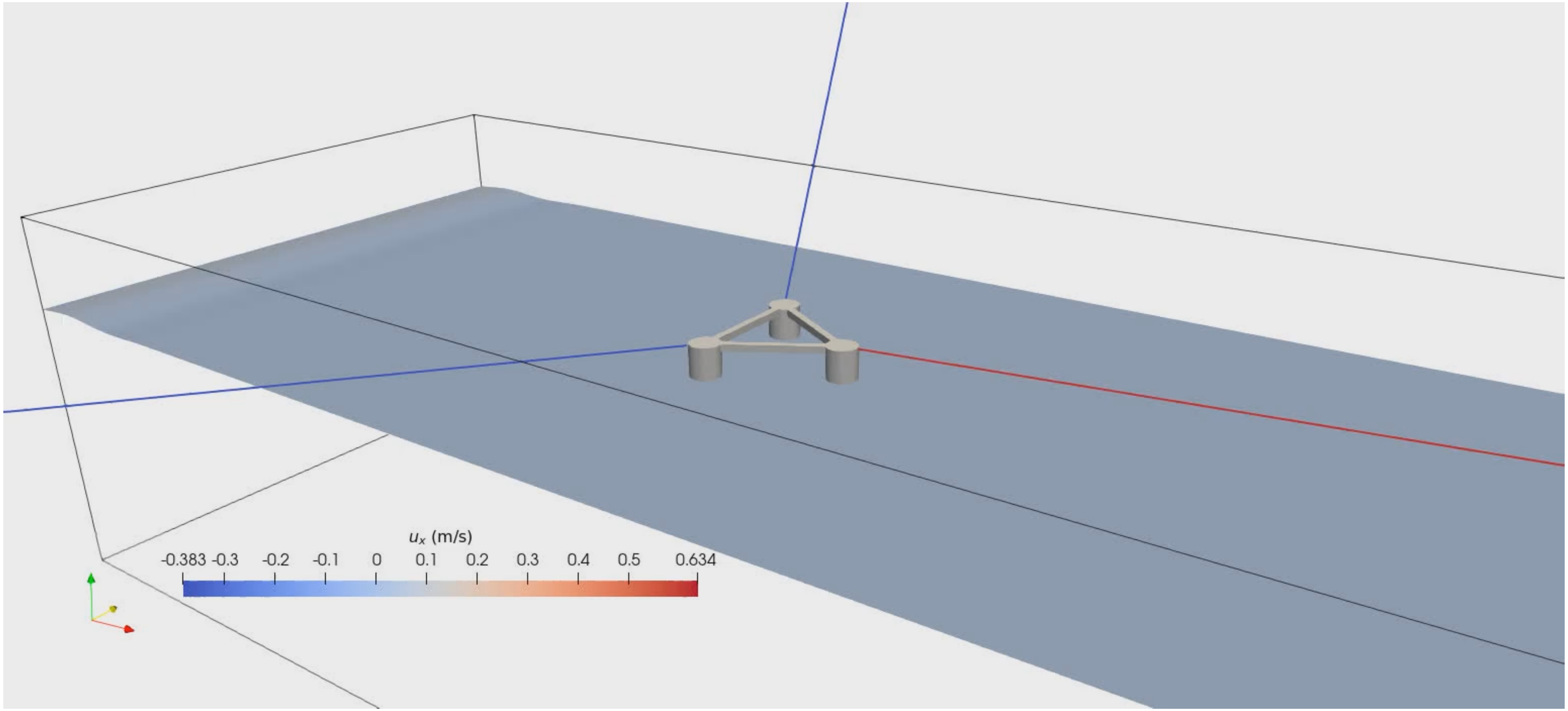
Application to Open Ocean Aquaculture structures



Flatøya Aquaculture Site



WINDMOOR floating offshore wind



Vegetation in a flow field