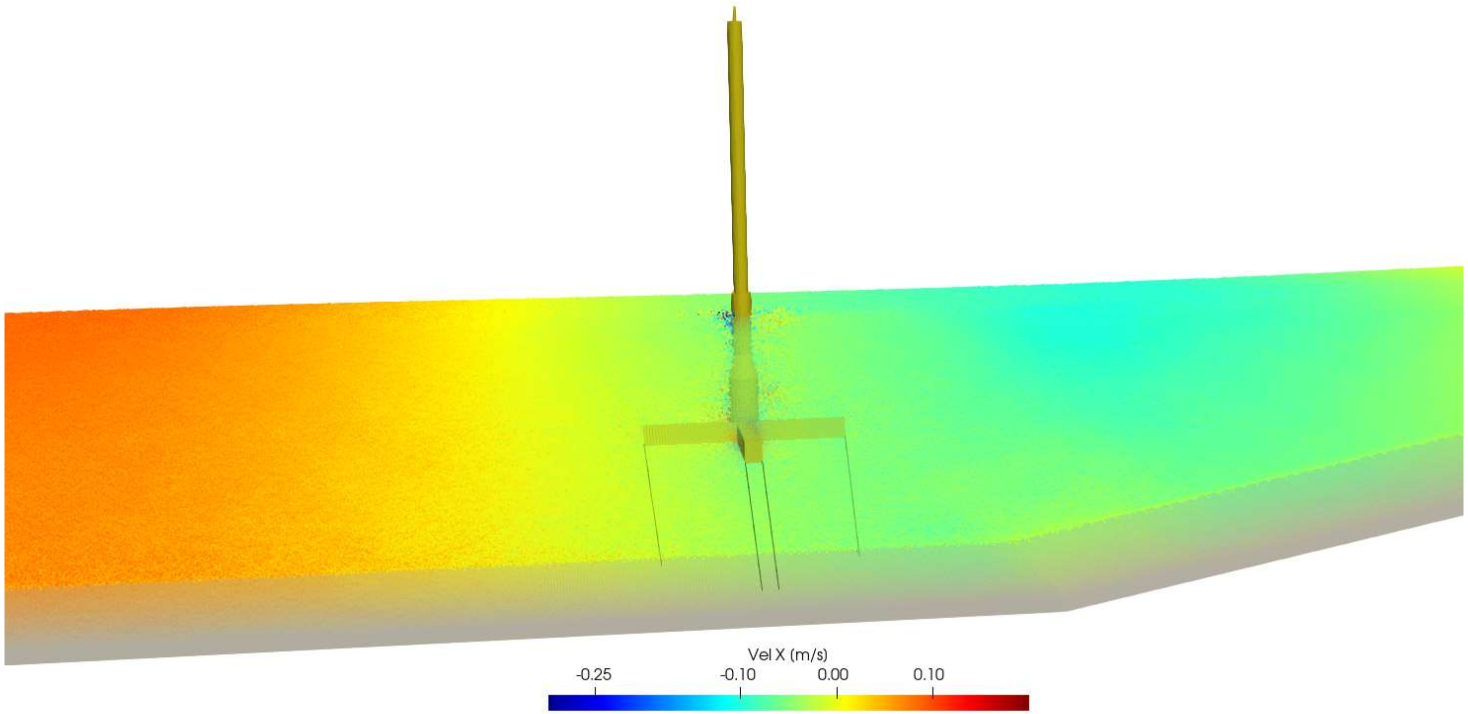
A CFD tool for the simulation of renewable energy devices using GPU accelerated hardware



by

Bonaventura
TAGLIAFIERRO

AIM & MOTIVATION

1. PhD student in Civil Engineering
    - Design of Steel Structures
    - Earthquake Engineering
    - Structural Safety

2. CFD code development
    - Applicability of numerical models
    - Coupling with new libraries

PROJECT:
Towards a New Numerical Tool for Multiphysics Simulations of Floating Offshore Wind Turbines

Prof. Madjid KARIMIRAD

A tension-leg platform wind turbine

Objectives:

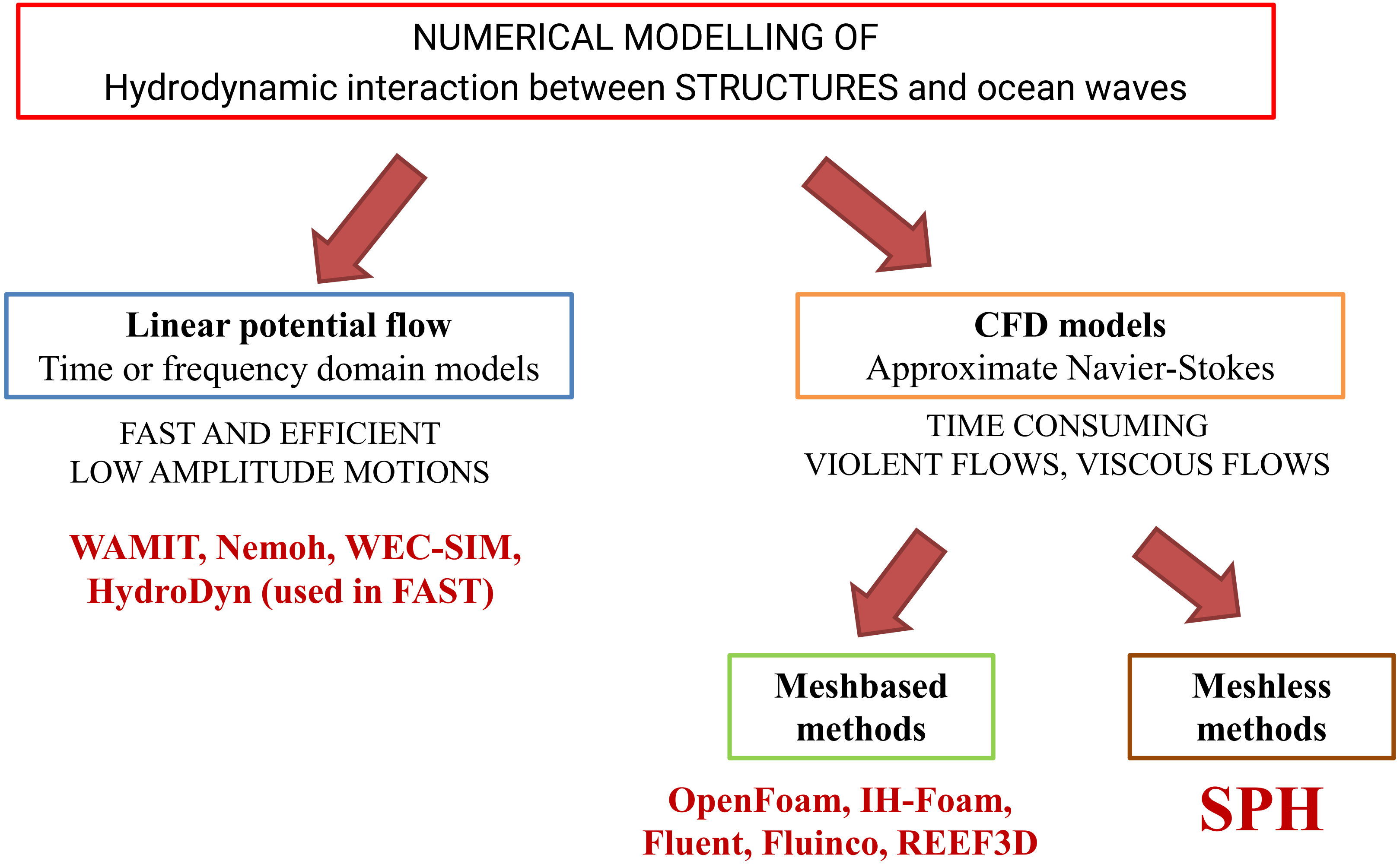
- SPH Code validation
- CFD simulations with real sea states
- Use of GPU supercomputers

4 months
Jan-Apr 2022

OUTLINE

1. Introduction
2. The SPH numerical method
3. DualSPHysics code
4. Floating offshore wind turbines
5. Wave energy converters
6. Conclusions

FLUID MODELING



NUMERICAL MODELLING OF
Hydrodynamic interaction between STRUCTURES and ocean waves

Linear potential flow
Time or frequency domain models

FAST AND EFFICIENT
LOW AMPLITUDE MOTIONS

WAMIT, Nemoh, WEC-SIM, HydroDyn (used in FAST)

CFD models
Approximate Navier-Stokes

TIME CONSUMING
VIOLENT FLOWS, VISCOUS FLOWS

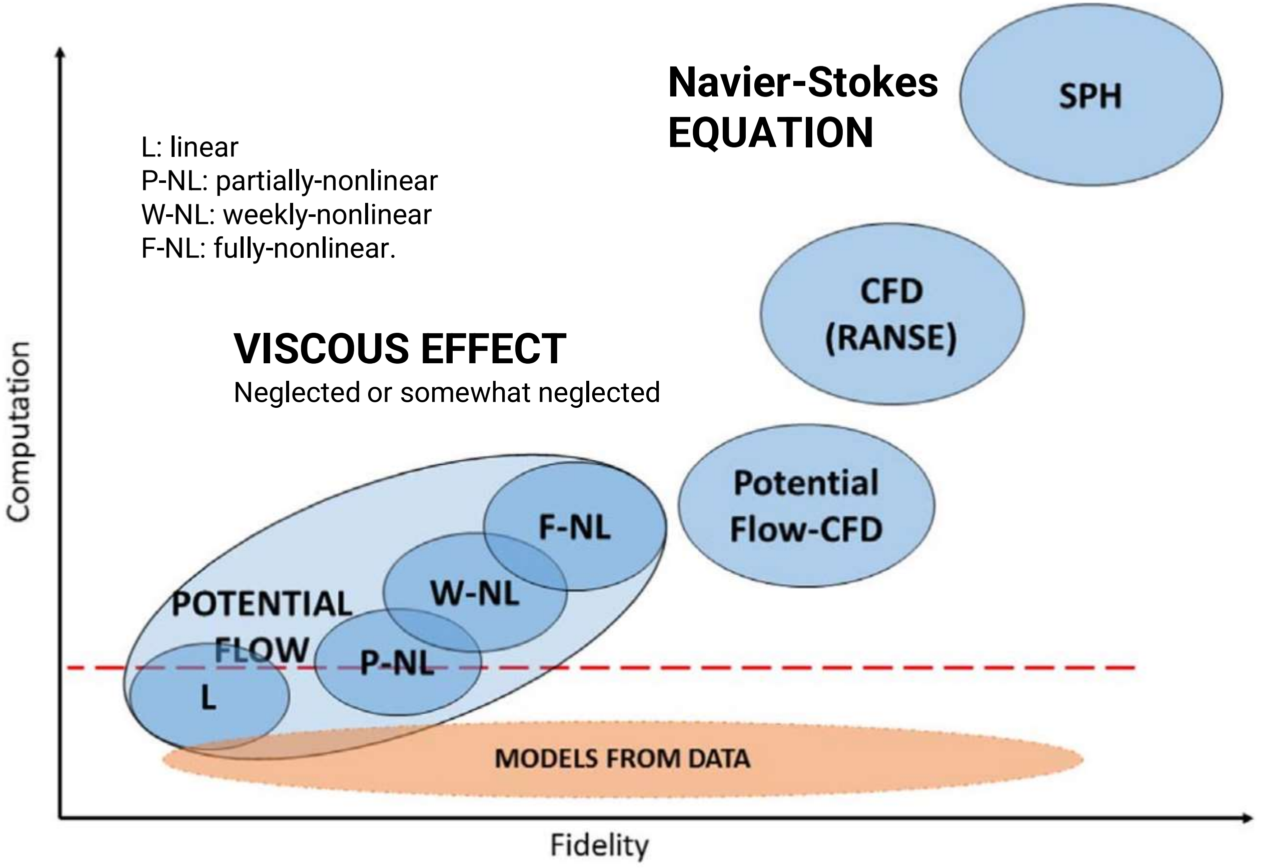
Meshbased methods

OpenFoam, IH-Foam, Fluent, Fluinco, REEF3D

Meshless methods

SPH

FLUID MODELING

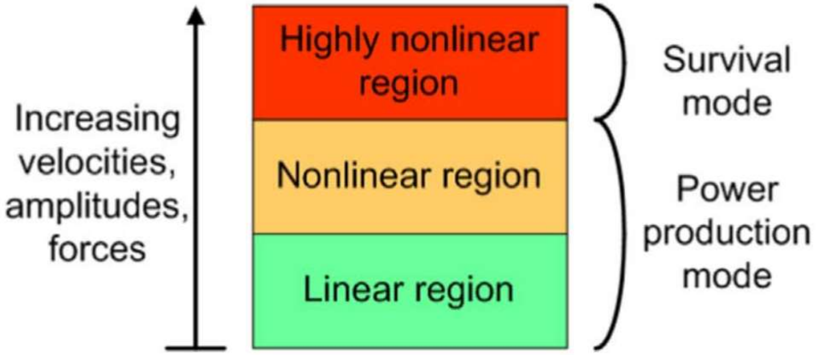


Navier-Stokes EQUATION

L: linear
P-NL: partially-nonlinear
W-NL: weekly-nonlinear
F-NL: fully-nonlinear.

VISCOUS EFFECT

Neglected or somewhat neglected



Different operating regions for wave energy devices

Penalba et al. (2017). Mathematical modelling of wave energy converters: A review of nonlinear approaches. **Renewable and Sustainable Energy Reviews**, 78, 1188-1207. Link

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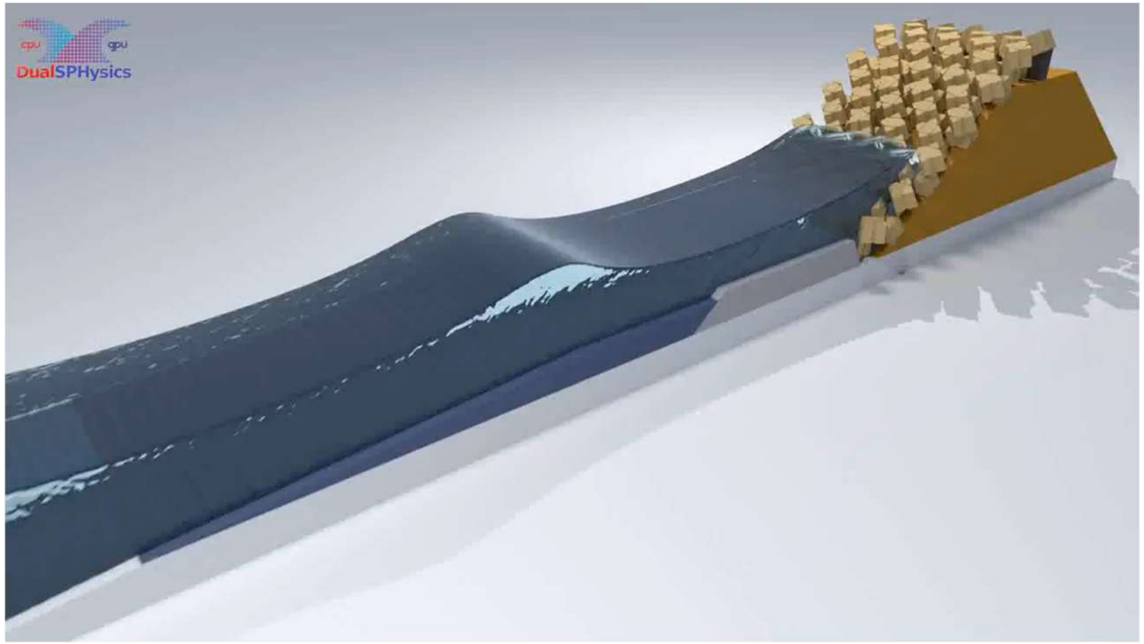
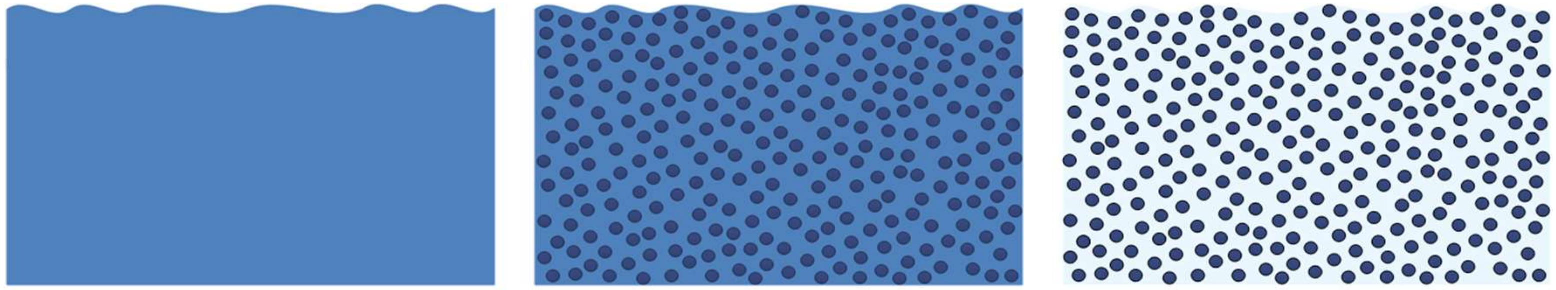


SMOOTHED PARTICLE HYDRODYNAMICS



Continuos fluid

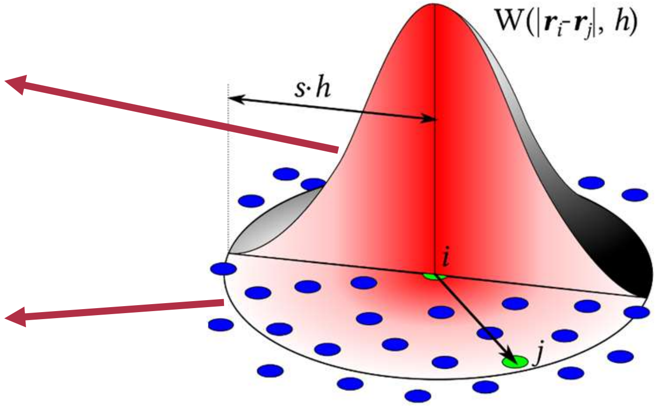
Set of particles

Each particle is a **nodal point** where **physical quantities** are computed as an **interpolation** of the values of the **neighboring particles** solving the N-S equations and using **summations.**

Generic properties

$$A_i = \sum_{j=1}^{N} A_j W(r_i - r_j, h) \frac{m_j}{\rho_j}$$

KERNEL FUNCTION



KERNEL

COMPACT SUPPORT

Schematic view of a SPH convolution (Wikipedia CC BY-SA 4.0)

IMPLEMENTATION

(Density Diffusion Term, Fourtakas et al., 2020)

Mass conservation

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{v}$$

$$\frac{d\rho_a}{dt} = \sum_b m_b \boldsymbol{v}_{ab}\nabla_a W_{ab} + 2\delta h c\sum_b(\rho_b-\rho_a)\frac{\boldsymbol{v}_{ab}\nabla_a W_{ab}}{\boldsymbol{r}_{ab}^2}\frac{m_b}{\rho_b}$$

Momentum conservation

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \boldsymbol{F}$$

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b\left(\frac{p_b+p_a}{\rho_b\cdot\rho_a}+\Pi_{ab}\right)\nabla_a W_{ab} + \boldsymbol{g}$$

$$\frac{d\boldsymbol{r}_a}{dt} = \boldsymbol{v}_a$$

Artificial viscosity

(Monaghan, 1992)

State's equation

(Monaghan, 1994)

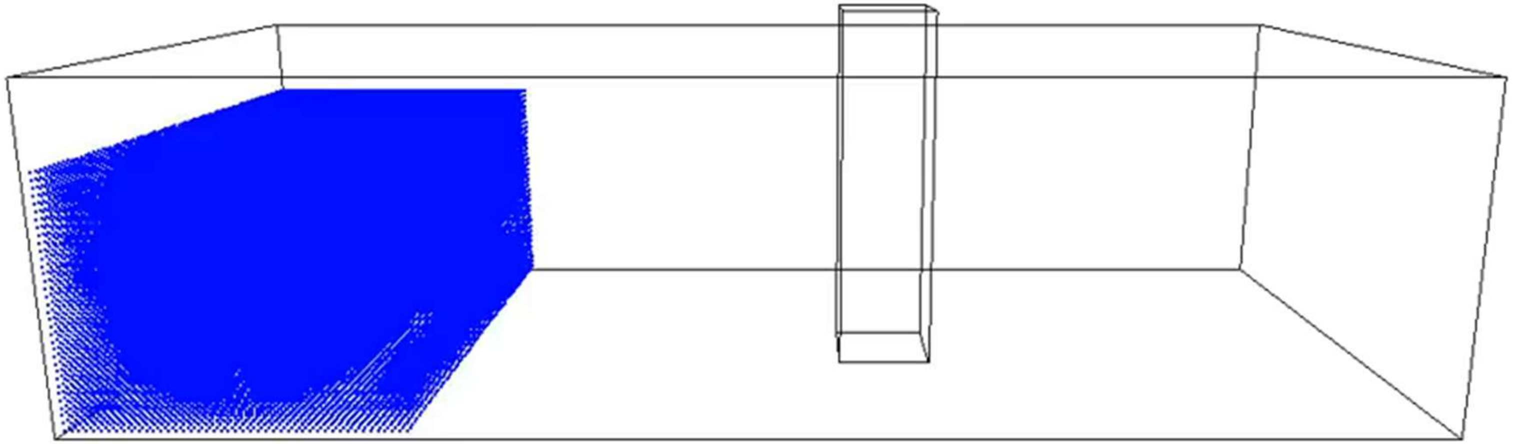
$$p = \frac{c_0^2\rho_0}{\gamma}\left(\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right)$$

Weakly compressible approach
(WCSPH)

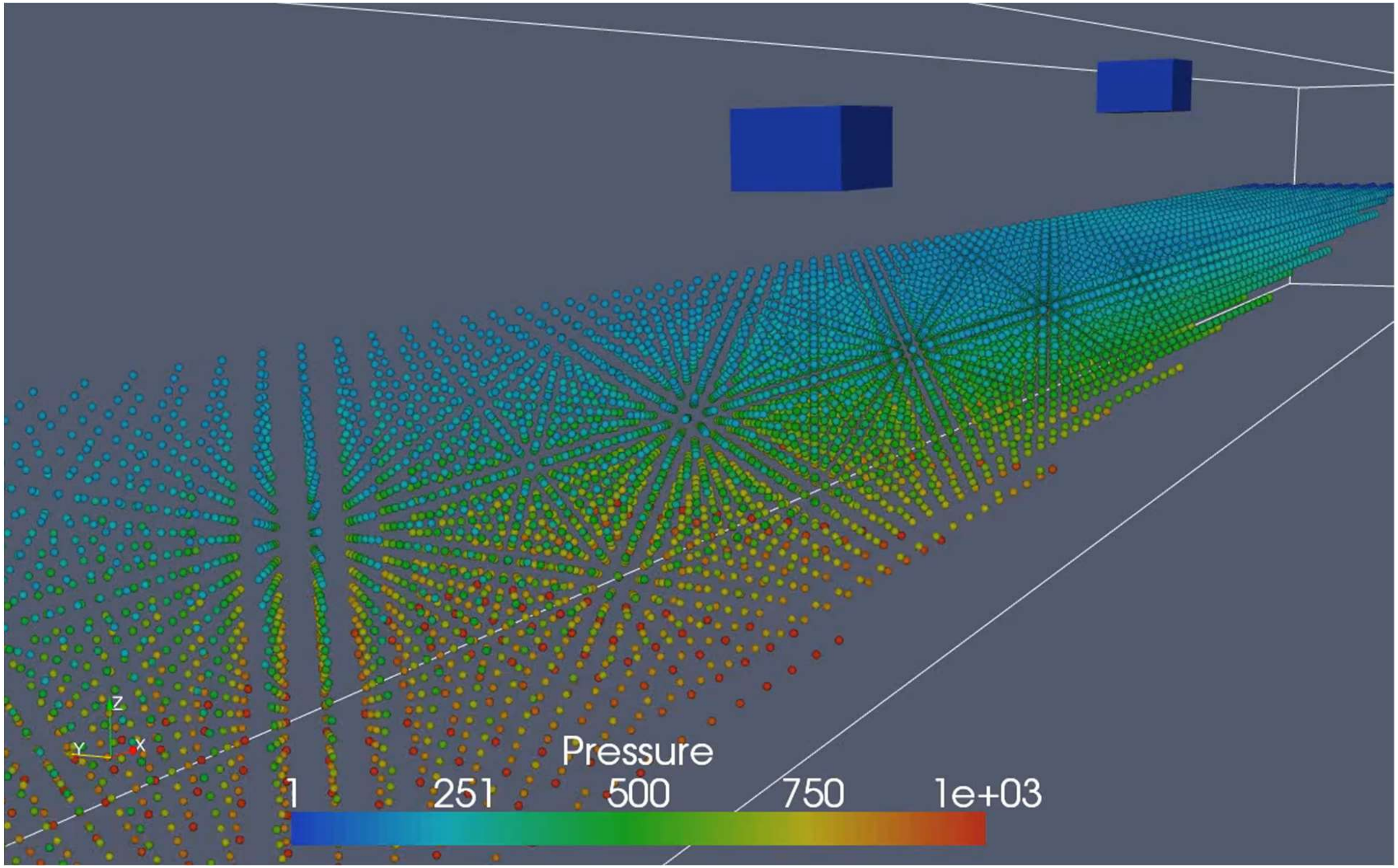
cpu gpu
DualSPHysics

SMOOTHED PARTICLE HYDRODYNAMICS

Particles = Computational nodes



SMOOTHED PARTICLE HYDRODYNAMICS



SPHERIC YouTube: https://youtu.be/huXY-rhwMJA

SMOOTHED PARTICLE HYDRODYNAMICS

PROS (comparing with mesh-based CFD codes)**:**

- Handling **complex geometries** and **high deformation;**
- Distinguishing **between phases** due to holding material properties at each particle;
- Easier to couple with other methods.

CONS (comparing with mesh-based CFD codes)**:**

- **Boundary conditions** are still an open issue**;**
- **Turbulence treatment** not fully developed yet**;**
- **Time computation is expensive**.

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DualSPHysics

Free, open-source code

Collaborative project

LGPL license

Highly parallelised

Pre- & post-processing

Applied to real problems

cpu gpu DualSPHysics

LGPL Free Software

https://dual.sphysics.org/

COLLABORATOR:

UNIVERSITÀ DEGLI STUDI DI SALERNO

DualSPHysics

Free, open-source code

Collaborative project

LGPL license

Highly parallelised

Pre- & post-processing

Applied to real problems

GPU

CPU

GPU CPU

x100

DualSPHysics

Free, open-source code

Collaborative project

LGPL license

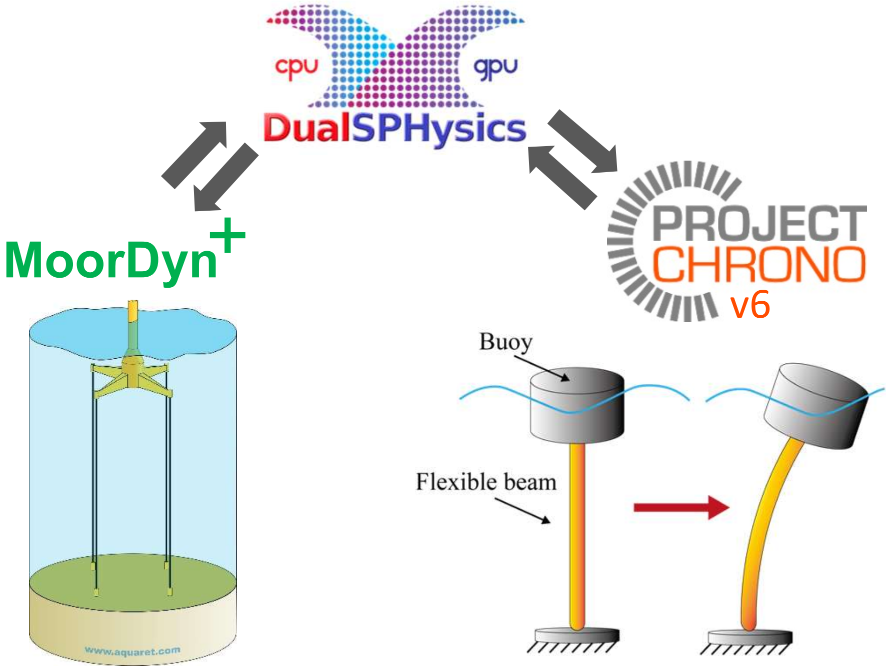
Highly parallelised

Pre- & post-processing

Applied to real problems

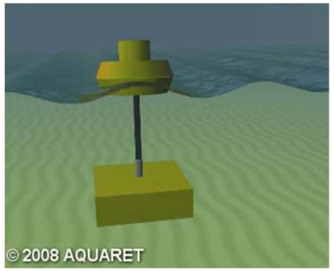
Domínguez et al. (2021). DualSPHysics: From fluid dynamics to multiphysics problems. **Computational Particle Mechanics**. Link

Coupling with other models

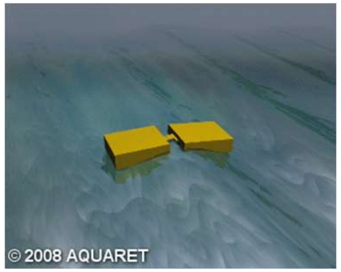


Partitioned approach for coupling

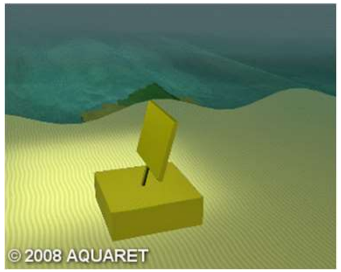
Numerical modelling to study the efficiency and survival of WECs



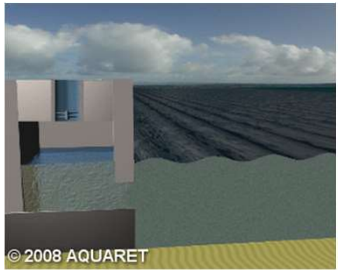
Point absorber



Attenuator



Oscillating wave
surge converter
(OWSC)



Oscillating water
column (OWC)

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DE VIGO

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DI SALERNO

UNIVERSITEIT
GENT

Coupling with other models

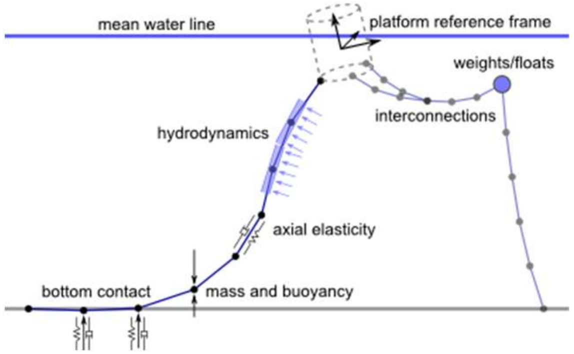
Reimplement

MoorDyn+

https://github.com/imestevez/MoorDynPlus

MoorDyn

http://www.matt-hall.ca/moordyn/



New Features

- C++ implementation
- Bugs in MoorDyn are solved
- Robust control of exceptions
- Different water depths
- More than one moored floating object
- Mooring connected to more than one floating object
- Define a maximum value of tension for the mooring lines

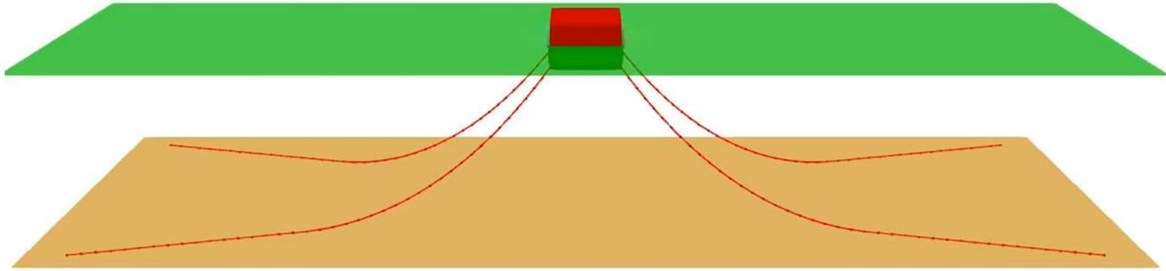
Ph.D. program: Mr. Iván Martínez-Estévez

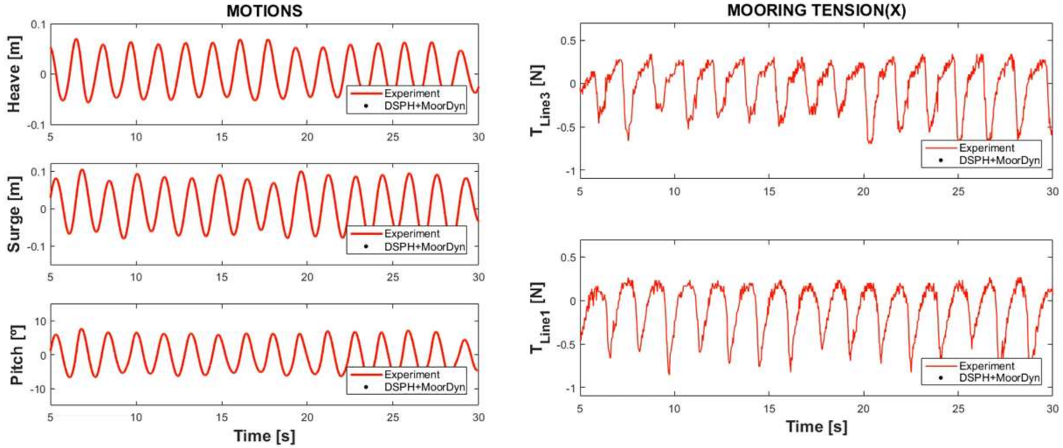
Coupling with other models

MoorDyn+

https://github.com/imestevez/MoorDynPlus

cpu gpu
DualSPHysics





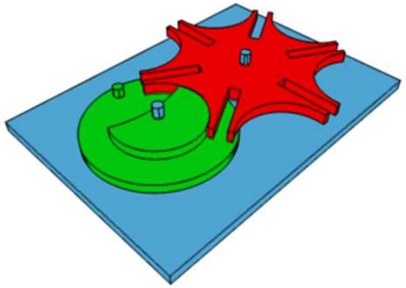
Coupling with other models

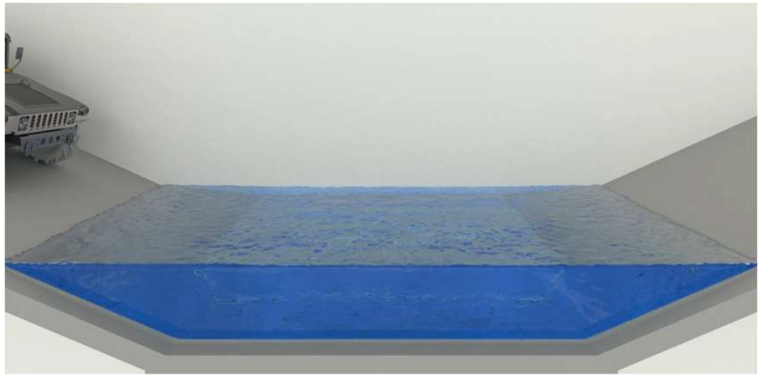
PROJECT CHRONO

Main developers: UW-Madison (US) and University of Parma (Italy)

Open-source **multi-physics** simulation engine

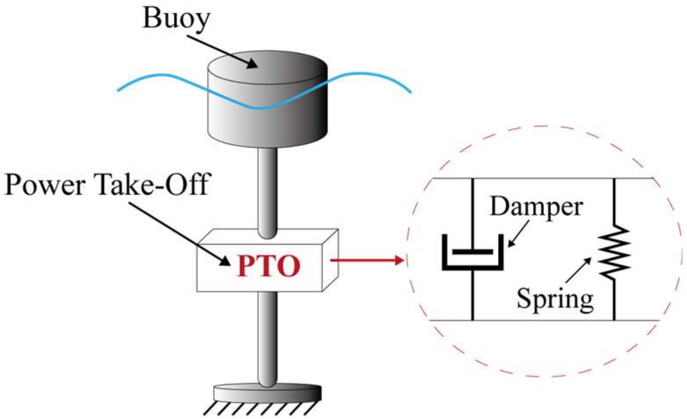
Tasora et al., 2016





https://projectchrono.org/

- **Collision detection**
- **Multibody dynamics**
- **Flexible elements**



UNIVERSIDADE DE VIGO

EPhysLab

Ph.D. program: Mr. Iván Martínez-Estévez

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Towards a New Numerical Tool for Multiphysics Simulations of Floating Offshore Wind Turbines

325,000 CPU core· hour

1 GPU · hour = 25 CPU core· hour

13,000 GPU · hour

Reference paper

Oguz et al. (2018). *Experimental and numerical analysis of a TLP floating offshore wind turbine*. **Ocean Engineering**

36 GPU nodes each housing 4 **NVIDIA V100s** (16 GB RAM)

TDP=150 W

325,000 CPU core· hour

1 GPU · hour = 25 CPU core· hour

13,000 GPU · hour

TDP=300 W

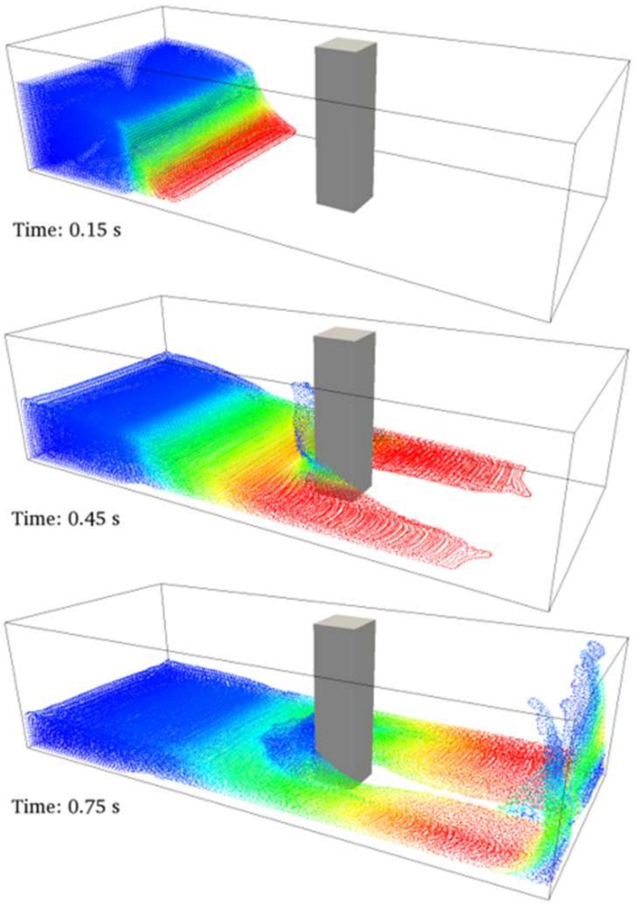
Computing node

2X 20-core (40 threads) 2.50 GHz Intel Xeon Gold 6248
4X NVIDIA Tesla V100-SXM2-16GN (Volta) GPU
RAM 384 GB

TDP=Thermal Design Power

Performance issue in SPH

The SPH method is very expensive in terms of computing time.



For example, a simulation of this dam break

300,000 particles

+

1.5 s (*physical time*)

➡

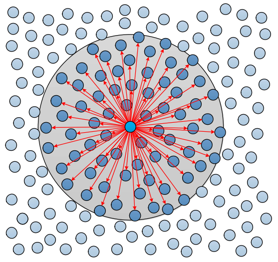
Takes more than

15 hours

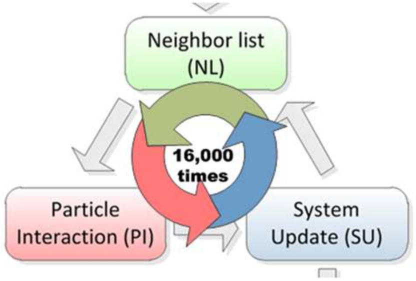
(*execution time*)

because:

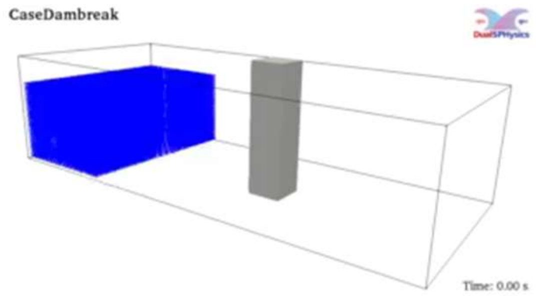
- Each particle interacts with **more than 250 neighbours**.



- **$\Delta t=10^{-5}$-10^{-4} so more than 16,000 steps** are needed to simulate 1.5 s of physical time.



Performance issue in SPH



- SPH presents a **high computational cost** that increases when increasing the number of particles.

✚

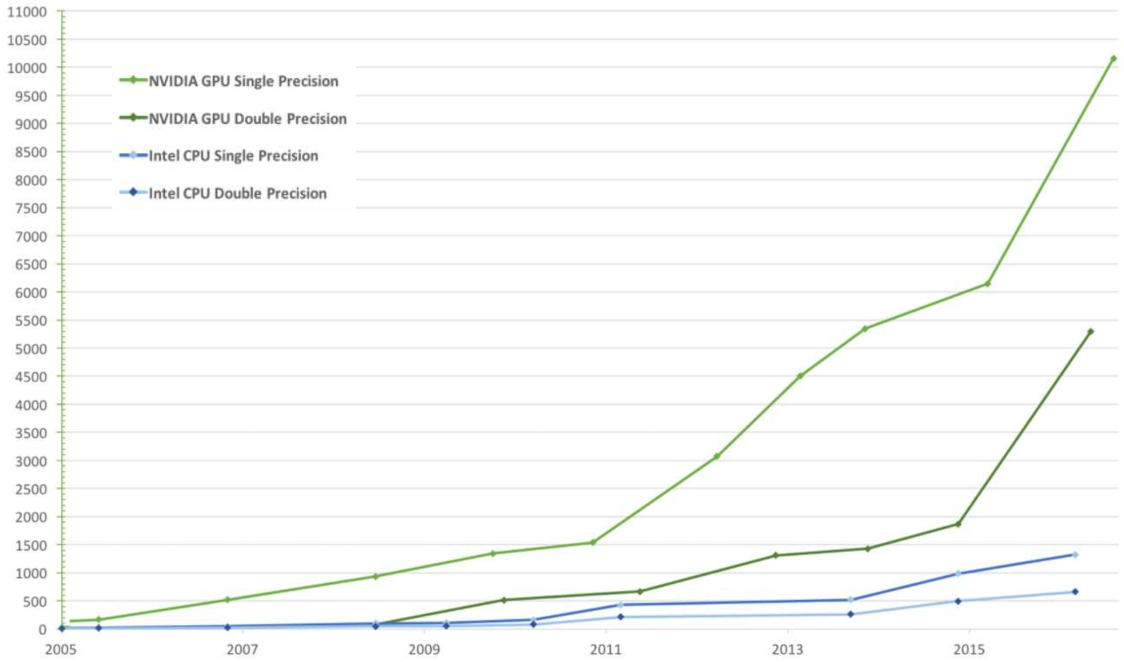
- The simulation of **real problems** requires a high resolution which implies simulating **millions of particles**.

⬇

The **time required** to simulate a few seconds is **too large**. One second of physical time can take several days of calculation.

It is necessary to use HPC techniques to reduce these computation times.

GPU acceleration



Theoretical GFLOP/s at base clock

CUDA Programming Guide v9.1

Graphics Processing Units (GPUs)

- video game market boosted its improvement
- their computing power has increased much faster than CPUs.
- powerful parallel processors

Advantages: GPUs provide a high calculation power with very low cost and without expensive infrastructures.

Drawbacks: An efficient and full use of the capabilities of the GPUs is not straightforward.

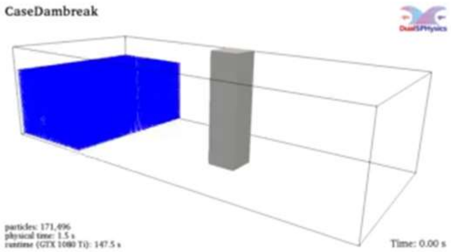
DualSPHysics performance

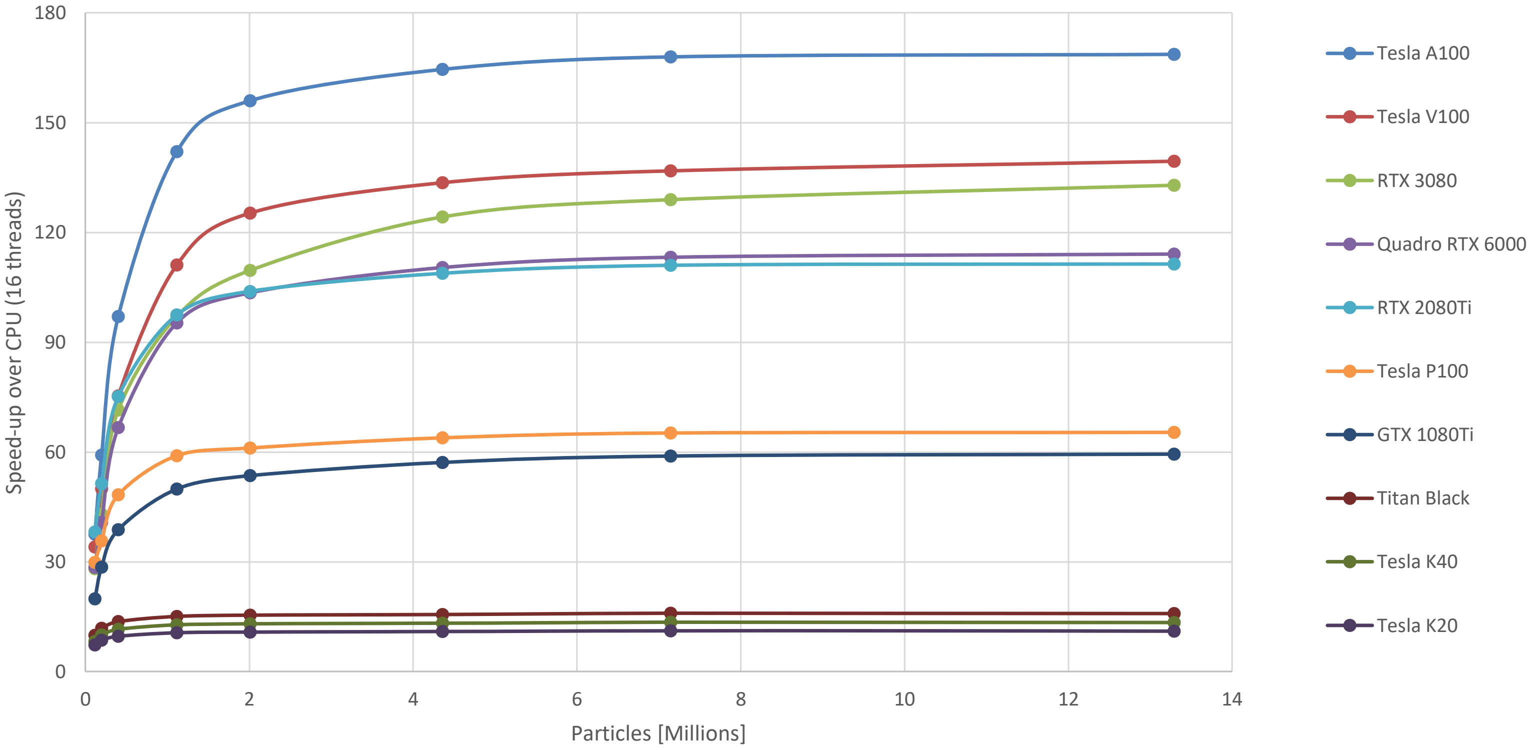
Domínguez et al., 2021. **DualSPHysics: from fluid dynamics to multiphysics problems.** Computational Particle Mechanics. **doi:10.1007/s40571-021-00404-2**

Speed-up: 165x on **Tesla A100**
110x on **RTX 2080 Ti**
over
Intel i9-10900K CPU (4.90 GHz - 16 threads)

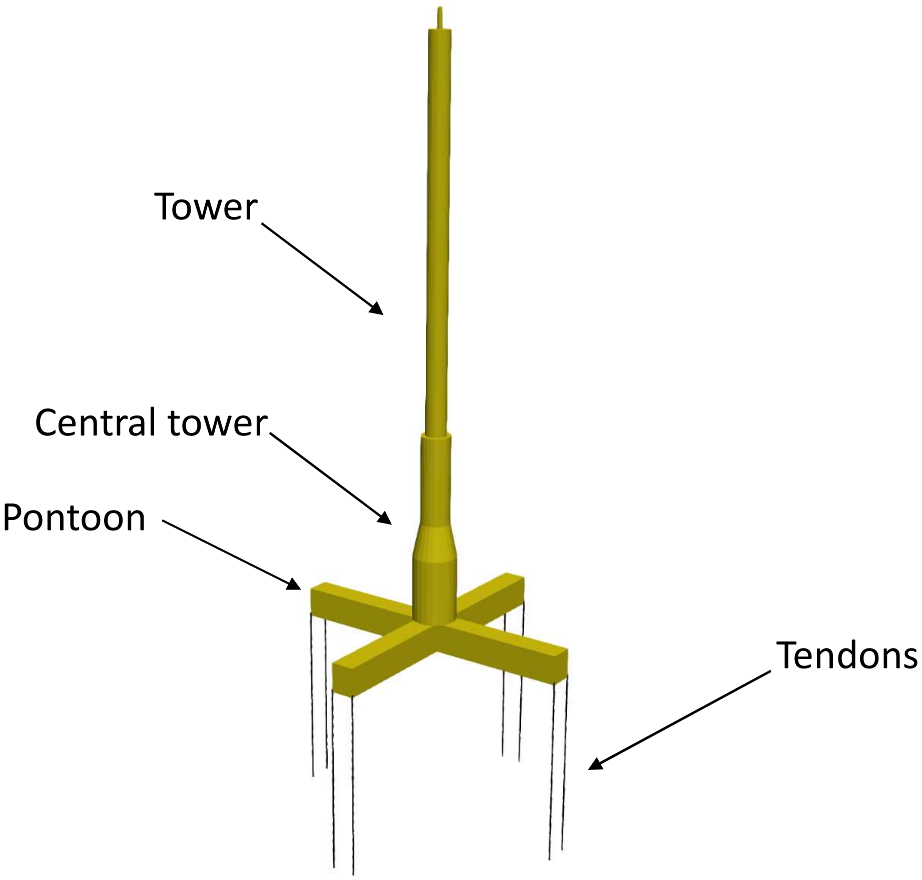
Like using

≈1700 threads!

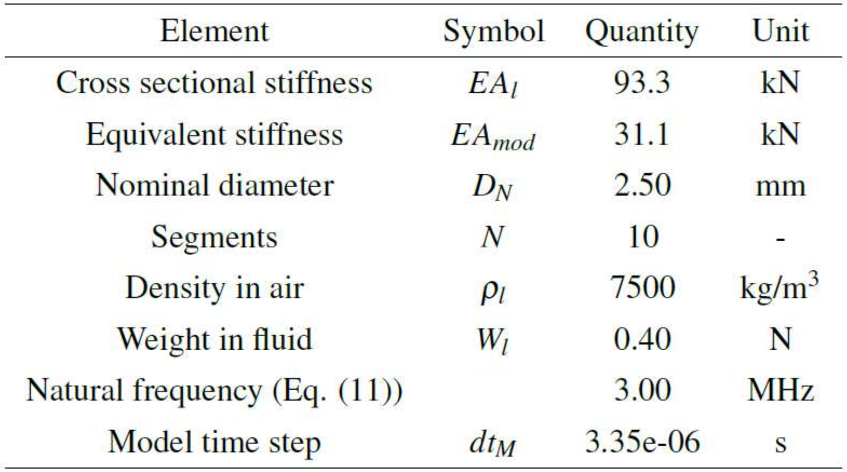




INITIAL SETUP

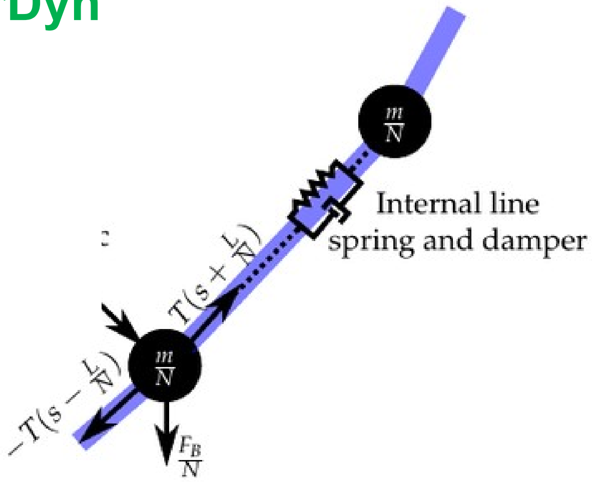


Oguz et al. (2018). *Experimental and numerical analysis of a TLP floating offshore wind turbine*. **Ocean Engineering**

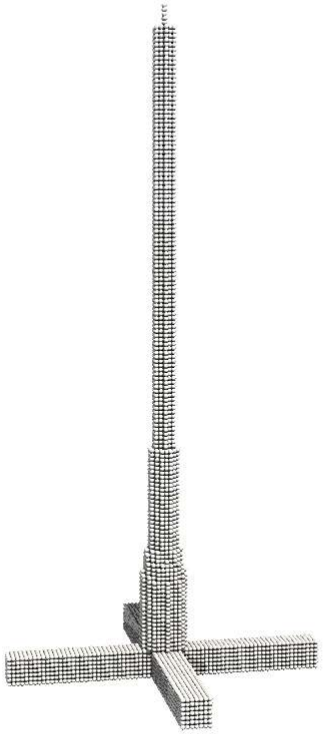


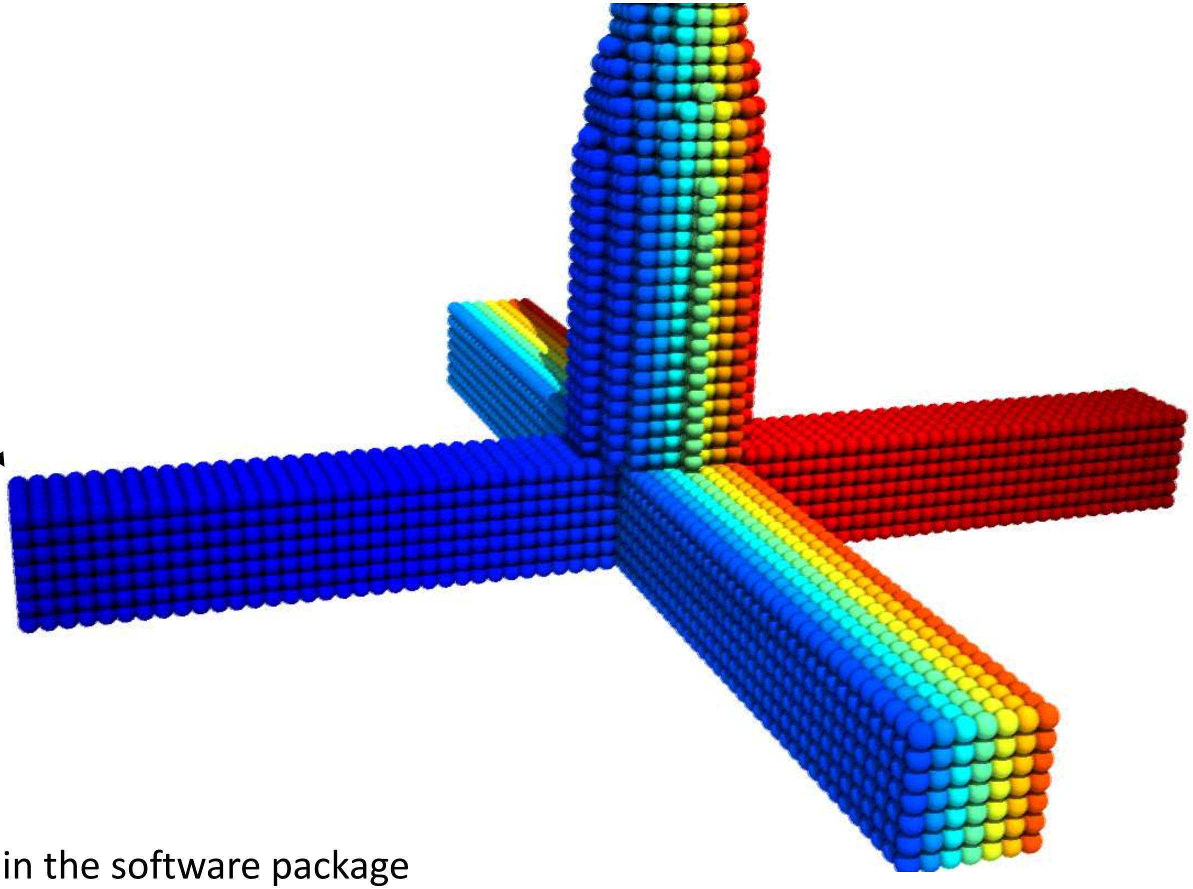
Element	Symbol	Quantity	Unit
Cross sectional stiffness	EA_l	93.3	kN
Equivalent stiffness	EA_{mod}	31.1	kN
Nominal diameter	D_N	2.50	mm
Segments	N	10	-
Density in air	ρ_l	7500	kg/m^3
Weight in fluid	W_l	0.40	N
Natural frequency (Eq. (11))		3.00	MHz
Model time step	dt_M	3.35e-06	s

MoorDyn+



PARTICLE DISCRETIZATION





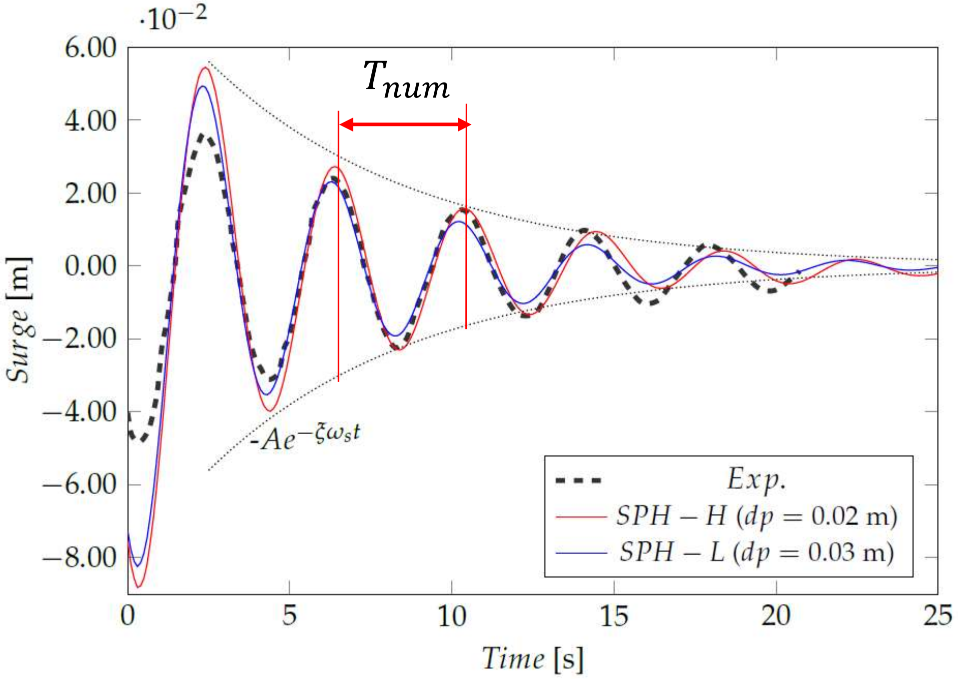
Nodal point
(or *particle*)

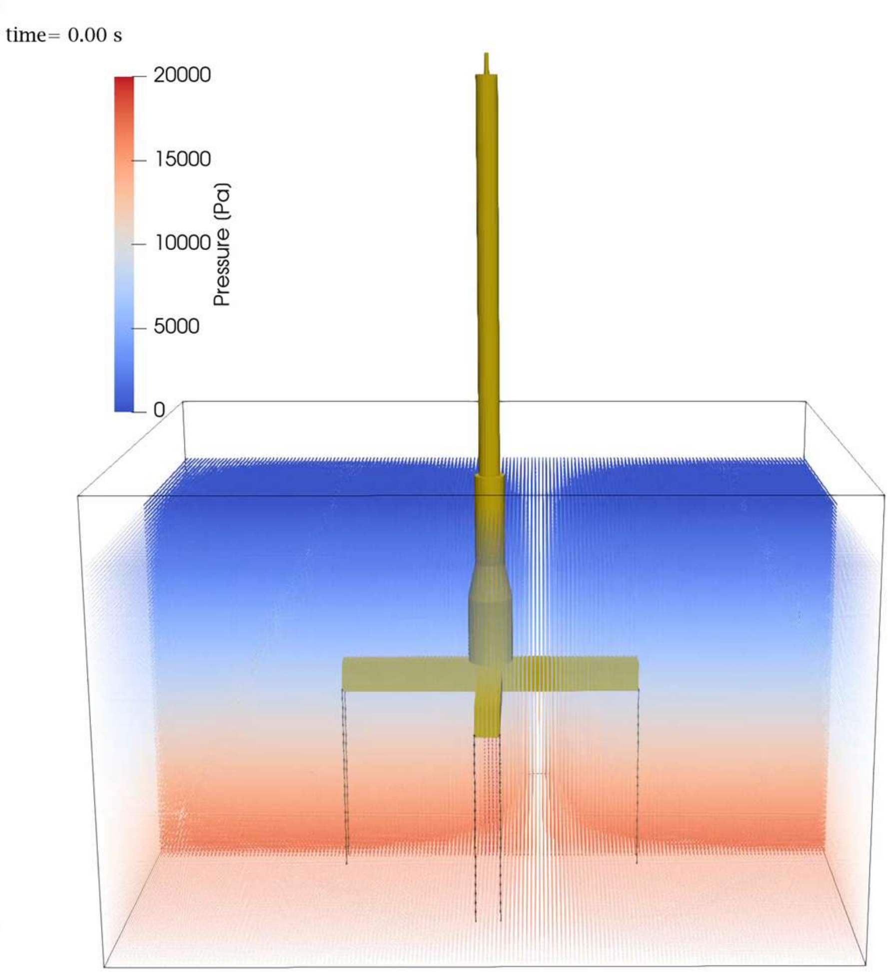
Pre-processing tool comes bundled in the software package

SURGE DECAY TEST

$$T_{exp} = 4.05\ s$$

$$T_{num} \approx 4.02\ s$$



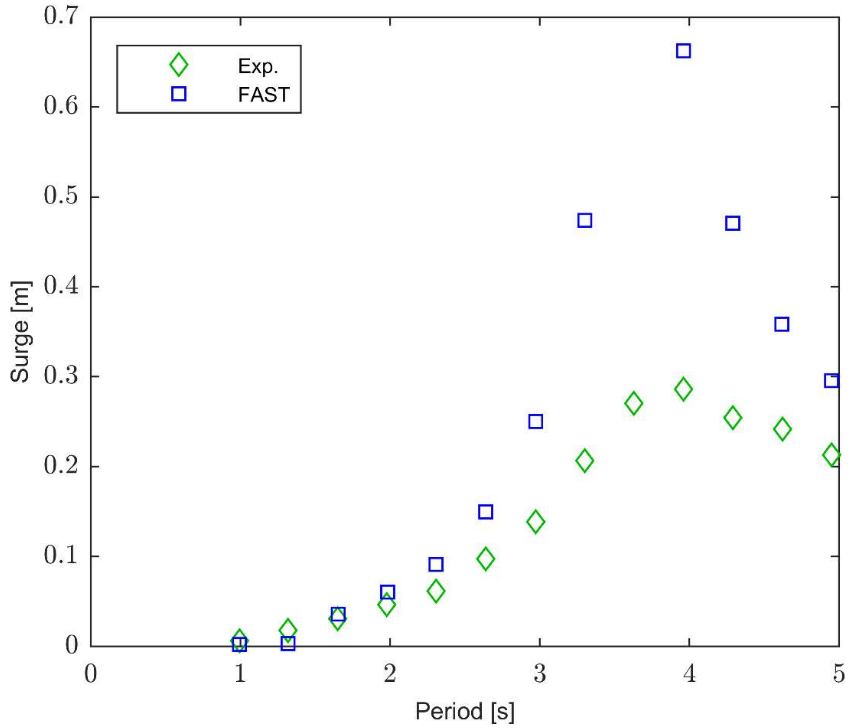


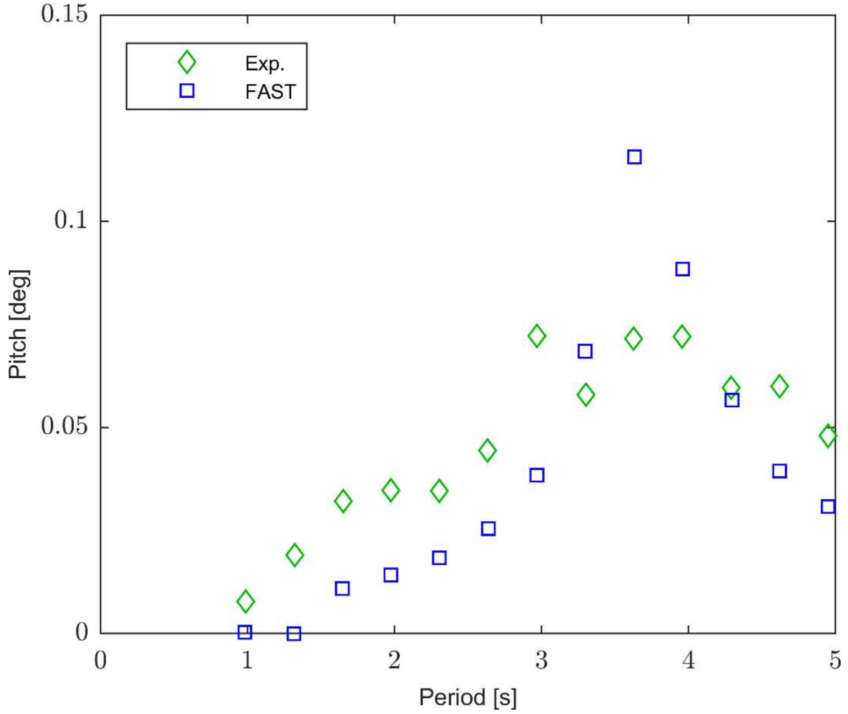
Oguz et al. (2018). *Experimental and numerical analysis of a TLP floating offshore wind turbine*. **Ocean Engineering**

1 GPU **NVIDIA V100s**

35 s	Physical time
2.65 M	particles
23 h	Runtime

Response Amplitude Operator (RAO)





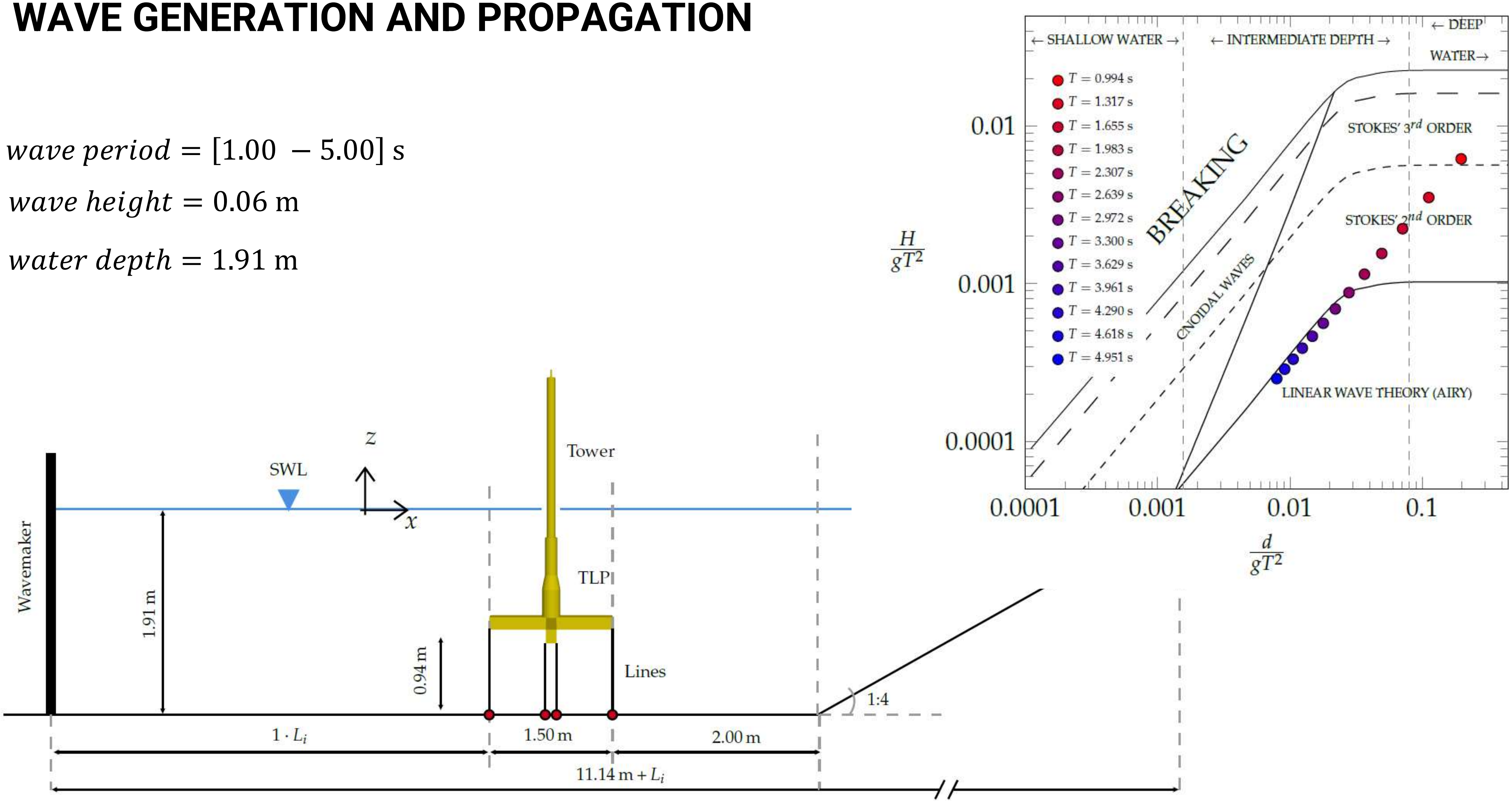
Oguz et al. (2018). *Experimental and numerical analysis of a TLP floating offshore wind turbine*. **Ocean Engineering**

WAVE GENERATION AND PROPAGATION

$wave\ period = [1.00\ - 5.00]\ \mathrm{s}$

$wave\ height = 0.06\ \mathrm{m}$

$water\ depth = 1.91\ \mathrm{m}$



WAVE GENERATION AND PROPAGATION

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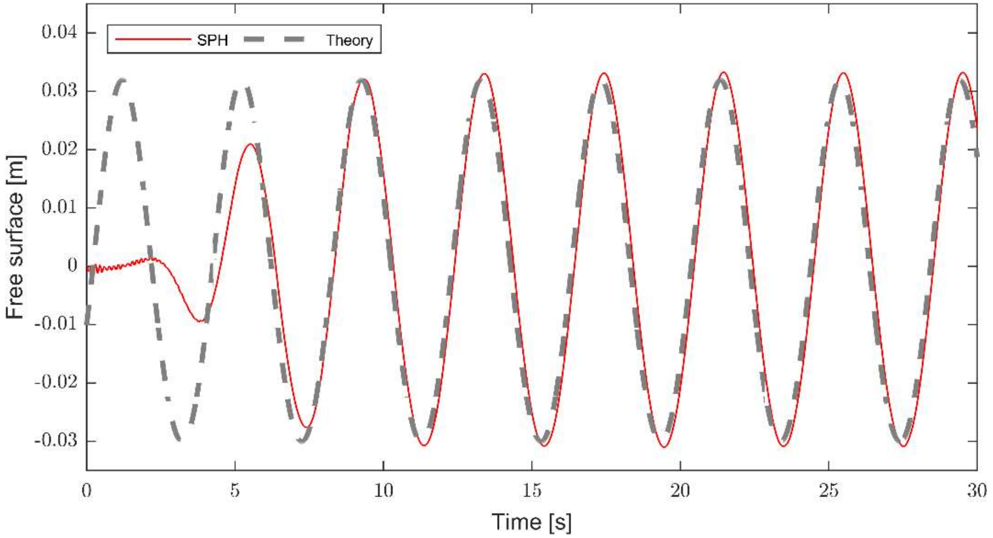
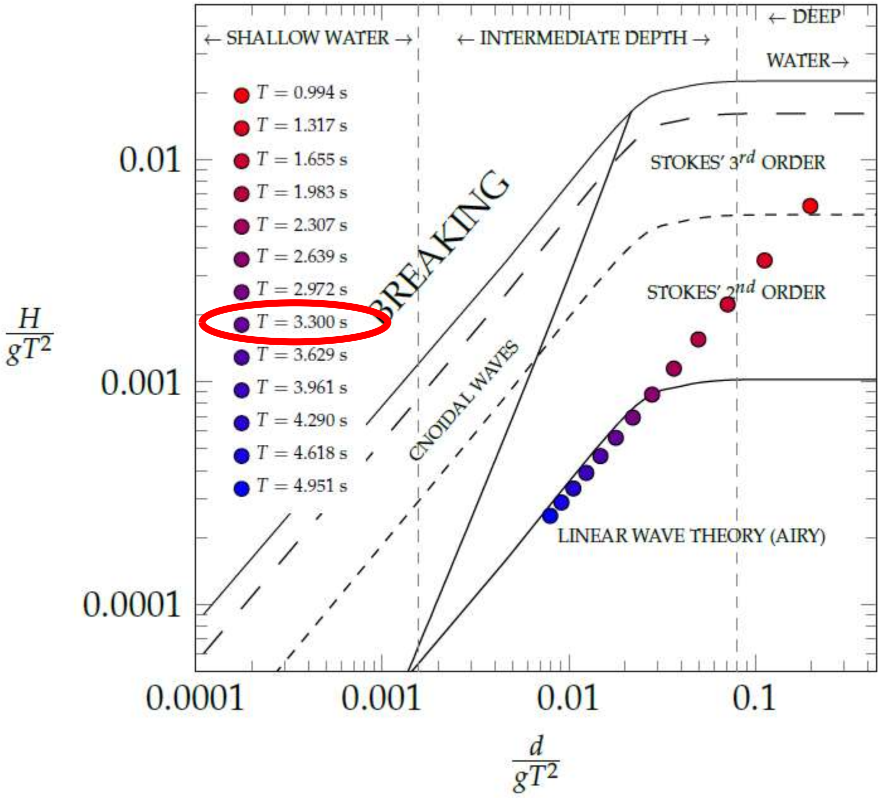
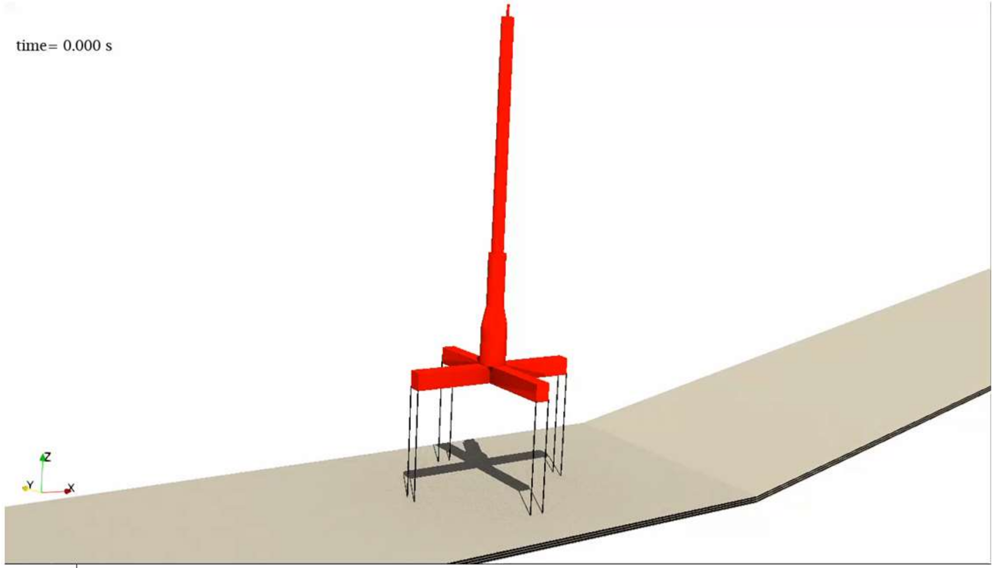
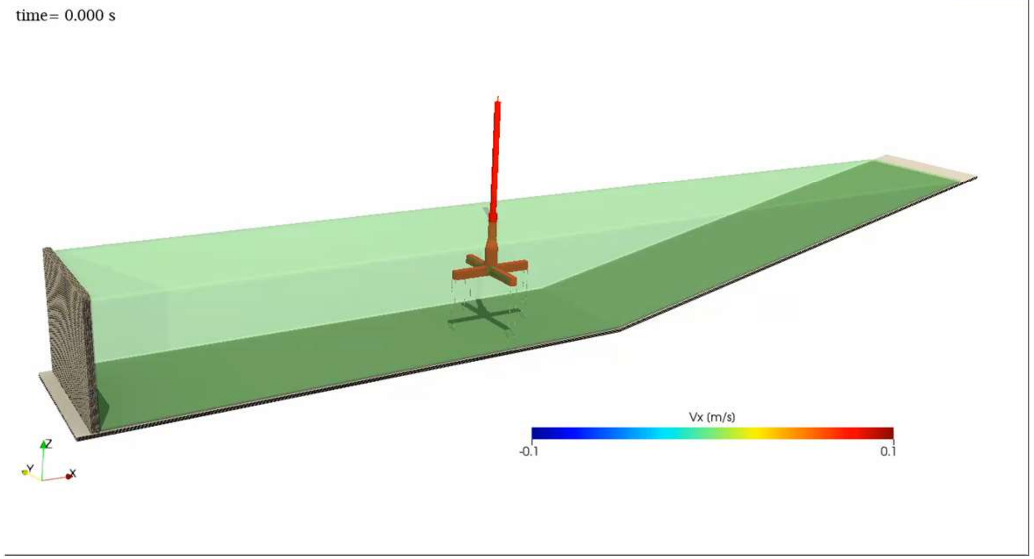




RAO VALIDATION

Tests under regular waves



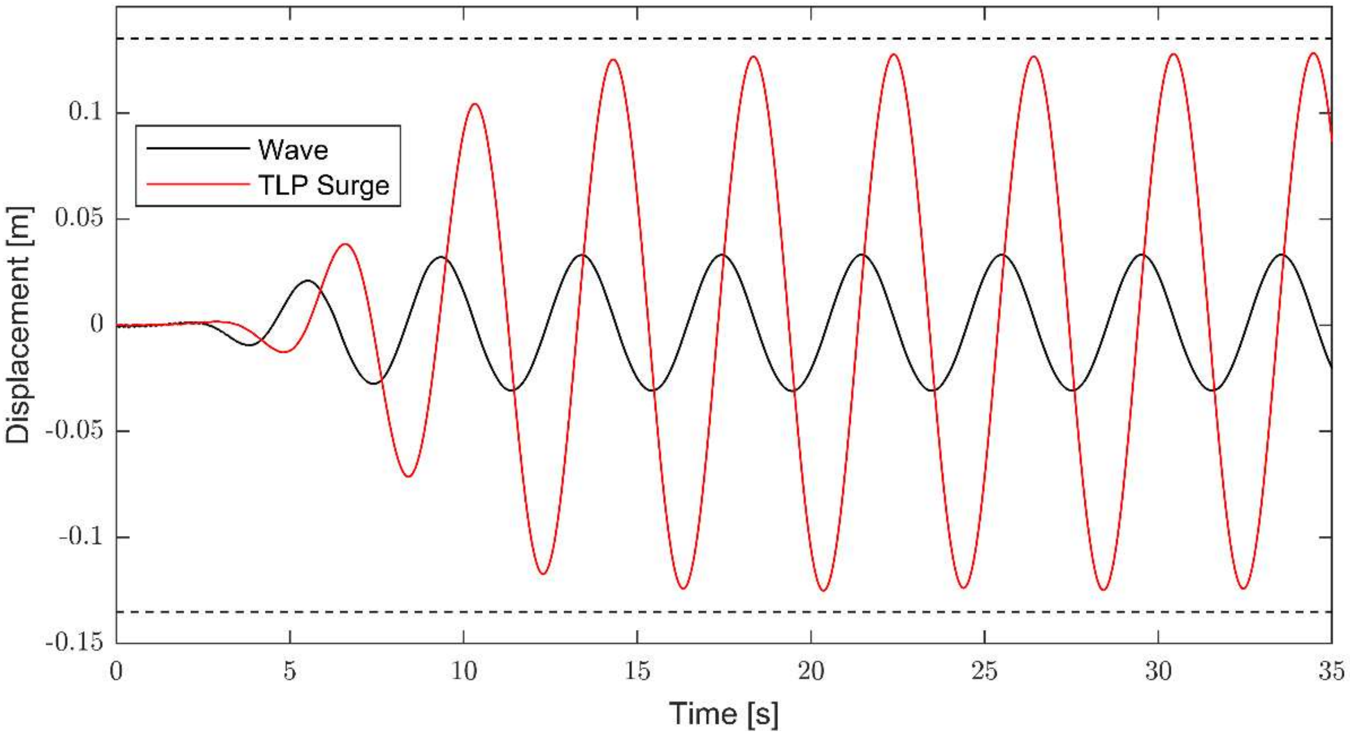


1 GPU **NVIDIA V100s**

48 s	Physical time
5.82 M	Particles
79 h	Runtime

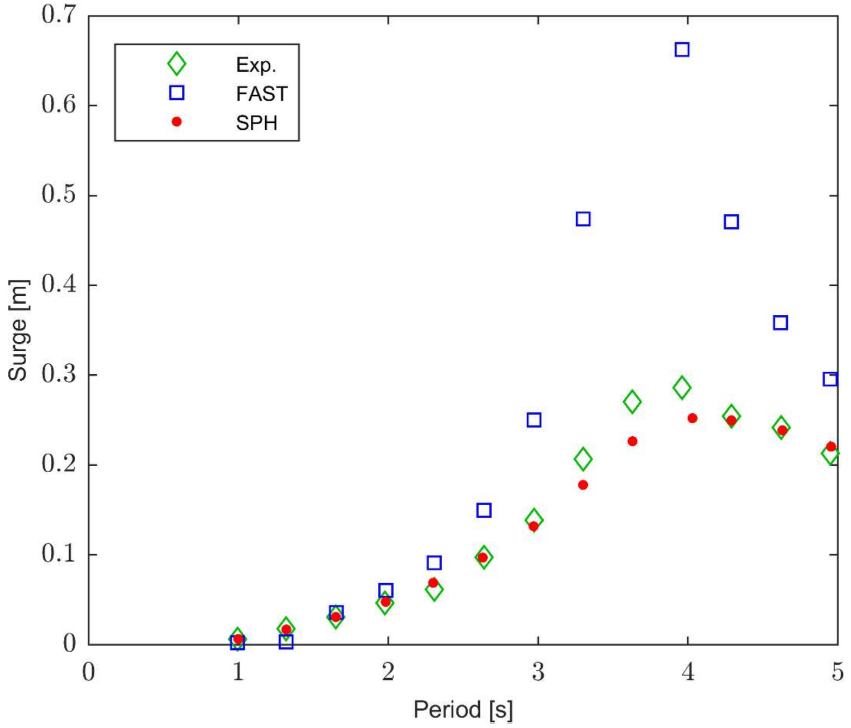
RAO VALIDATION

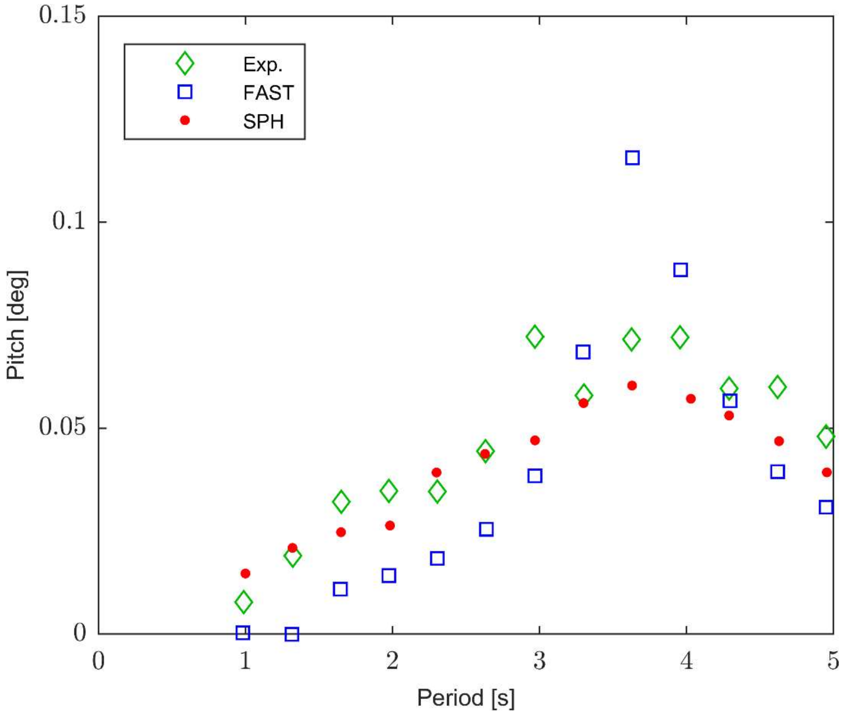
Tests under regular waves



RAO VALIDATION

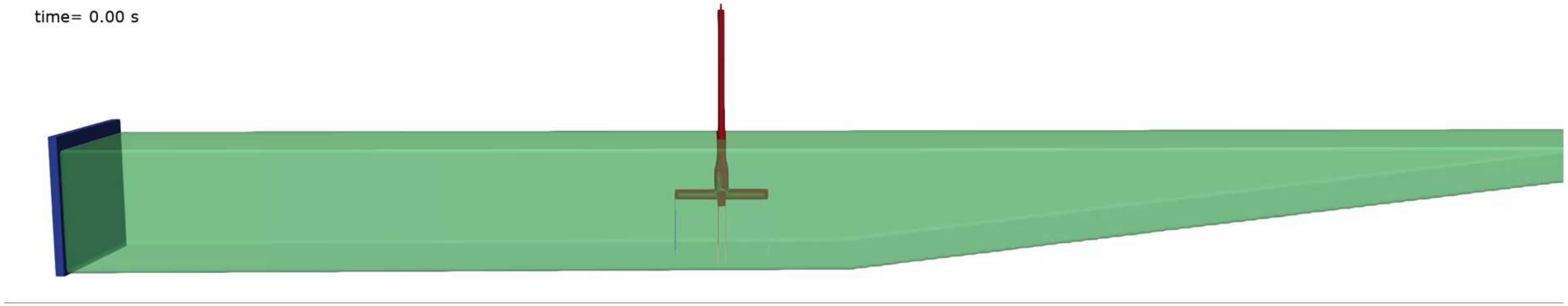
"[…] it is presumed that this lack of **viscous effects** leads to the overestimation of the surge response at the peak of the RAO."

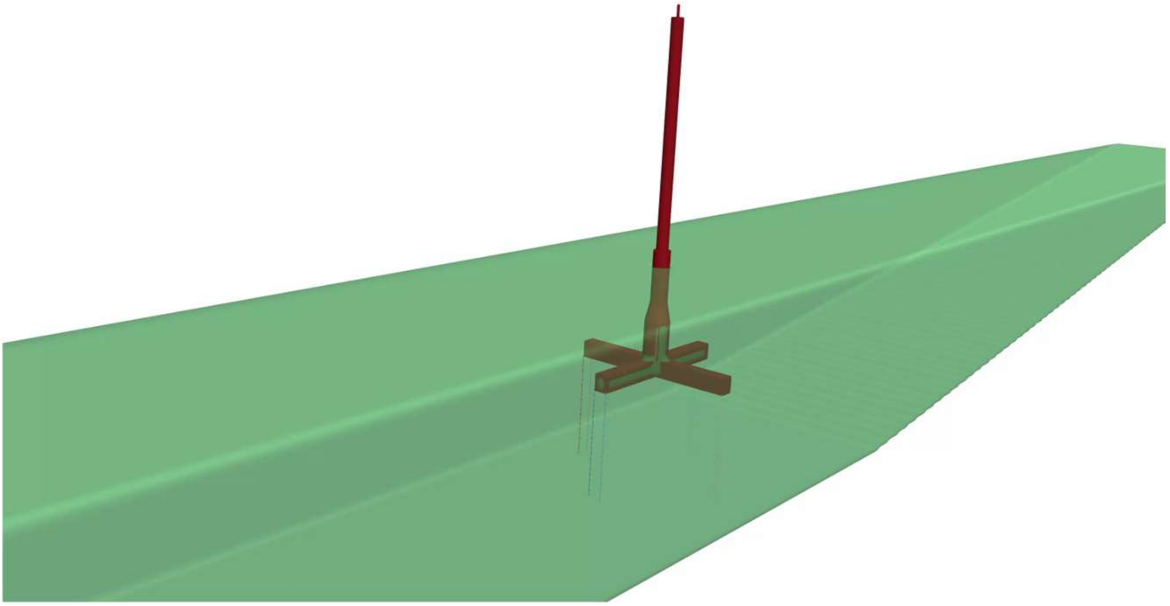




Oguz et al. (2018). *Experimental and numerical analysis of a TLP floating offshore wind turbine*. **Ocean Engineering**

INVESTIGATION





Tagliafierro B., Karimirad M., et al. (2022). *Numerical assessment of a Tension-leg platform wind turbine in intermediate water using the Smoothed Particle Hydrodynamics method*. **Energies (under review)**

energies

1 GPU **NVIDIA V100s**

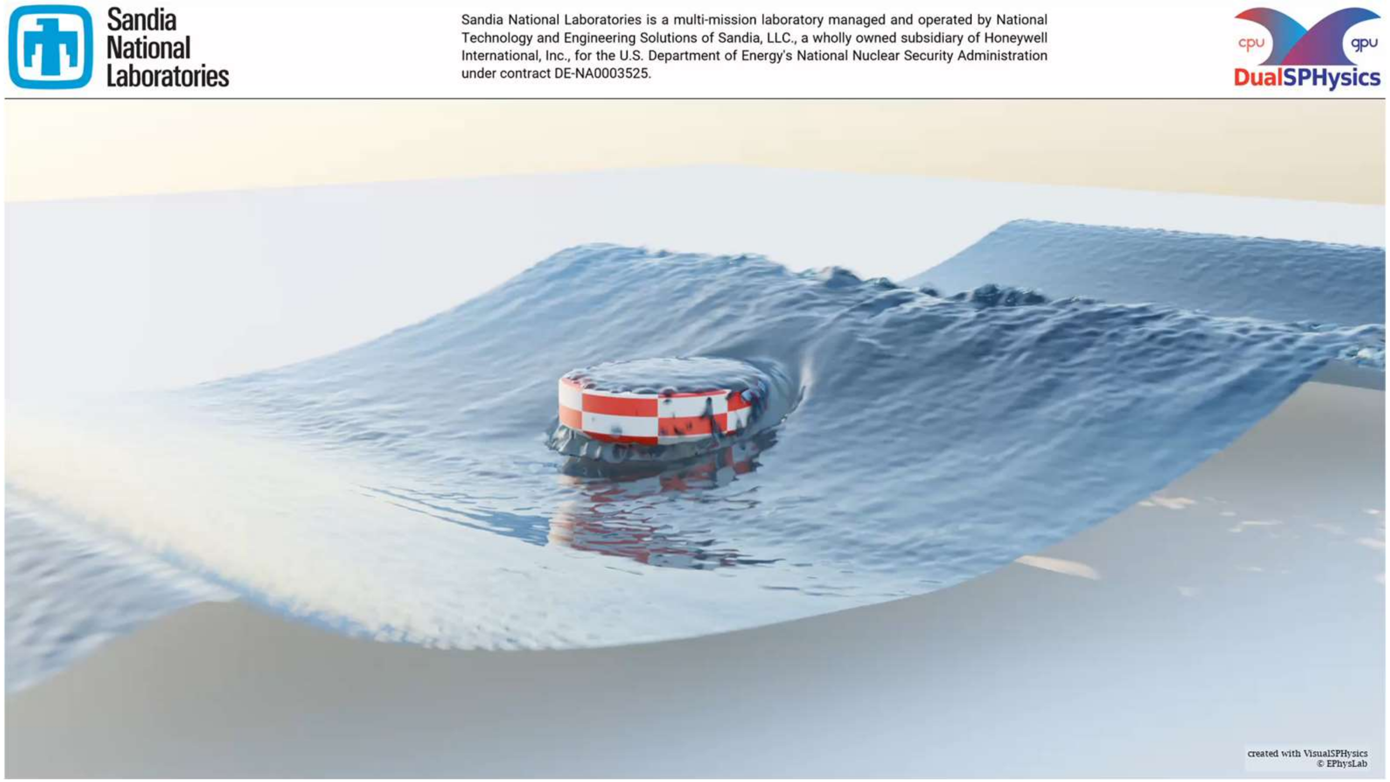
1227 s Physical time

2.58 M Particles

28.5 d Runtime

OUTLINE

1. Introduction
2. The SPH numerical method
3. DualSPHysics code
4. Floating offshore wind turbine
5. **Wave energy converters**
6. Conclusions



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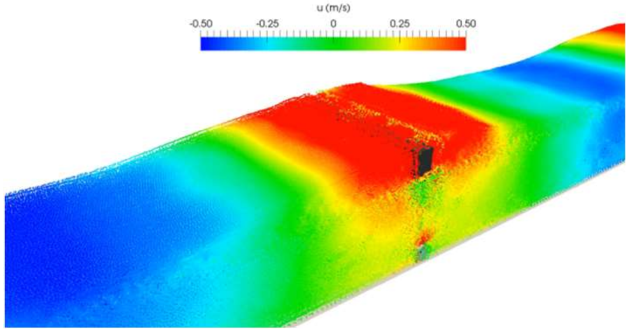
Simulating WECs with DualSPHysics

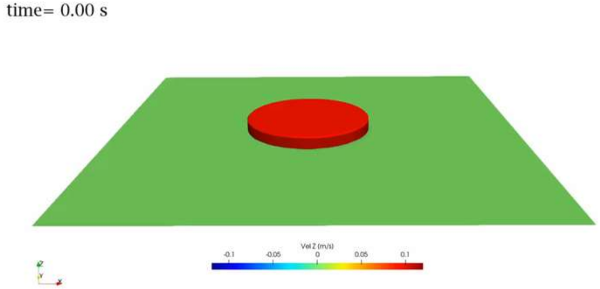
Project PI: Prof. Alex CRESPO

Wave energy converters (WECs)

Crespo et al., 2017	Coastal Engineering Oscillating water column
Verbrugghe et al., 2018	Coastal Engineering Oscillating water column and point absorber
Verbrugghe et al., 2019	Energies Point absorber
Brito et al., 2020	Renewable Energy Oscillating wave surge converter with PTO
Ropero-Giralda et al., 2020	Renewable Energy Point absorber under regular and focused waves
Quartier et al., 2021	Water Hydrodynamics drag on point absorbers
Ropero-Giralda et al., 2021	Energies System Identification of Point absorbers
Quartier et al., 2021	Applied Ocean Research Oscillating water column including air effects
Tagliafierro et al., 2022	Applied Energy Taut moored point absorber under focused waves



Oscillating wave surge converter under regular waves (Brito et al. 2020)



Radiation test for a point absorber (Ropero-Giralda et al. 2021)

Wave-WEC interaction

Mooring systems

Power Take Off systems

WEC array or farm

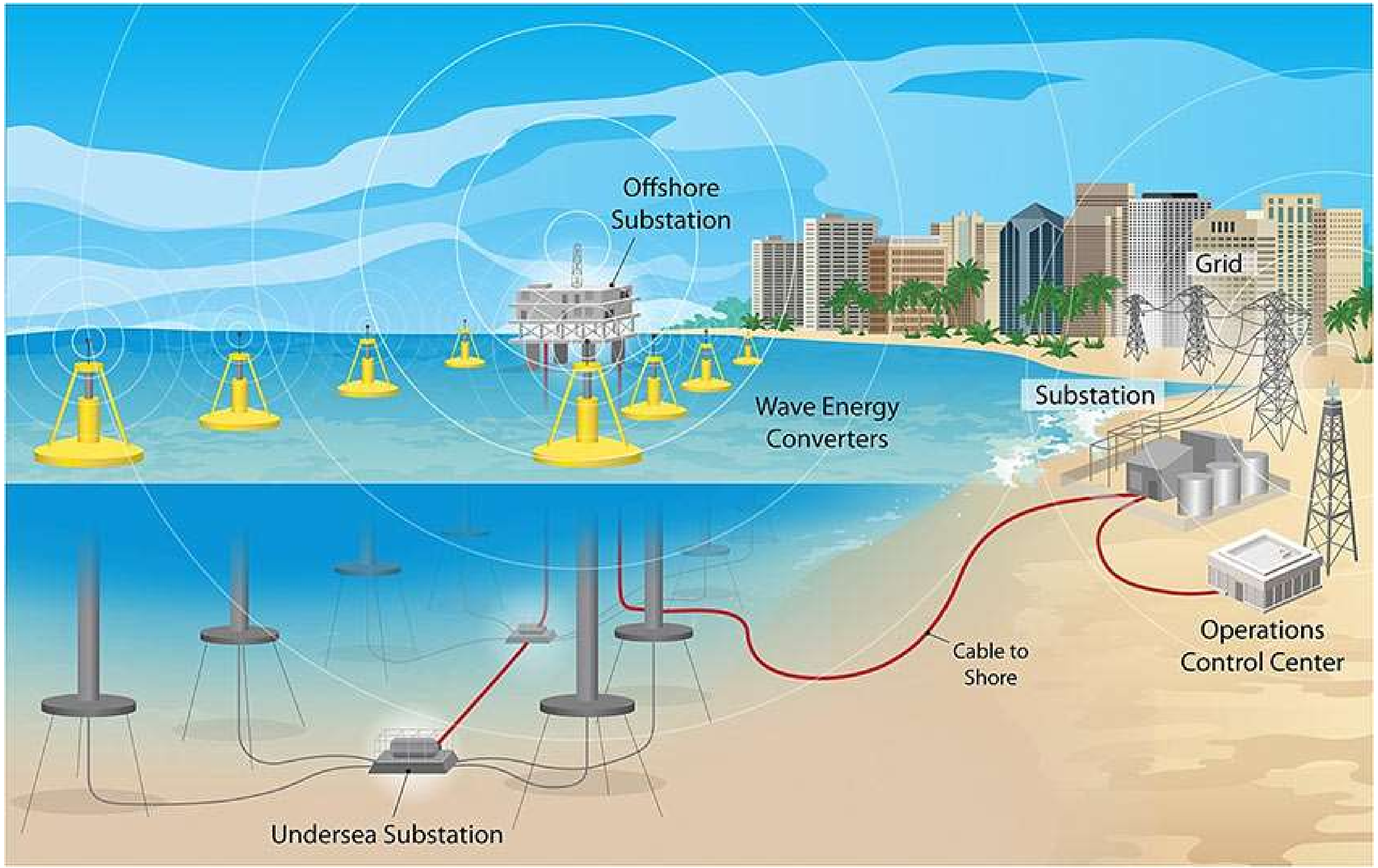
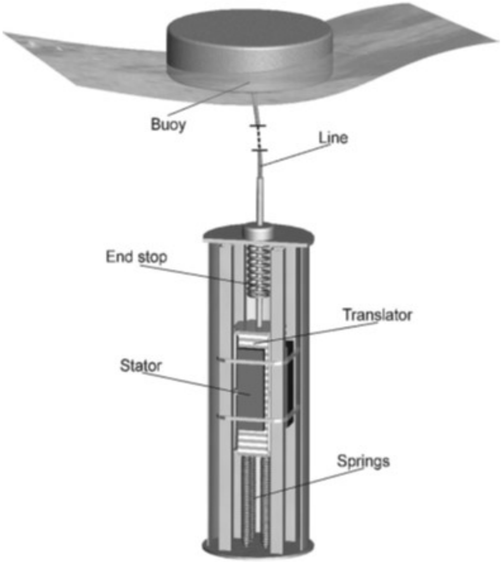


Illustration by Alfred Hicks, NREL. https://www.nrel.gov/water/wave-array.html

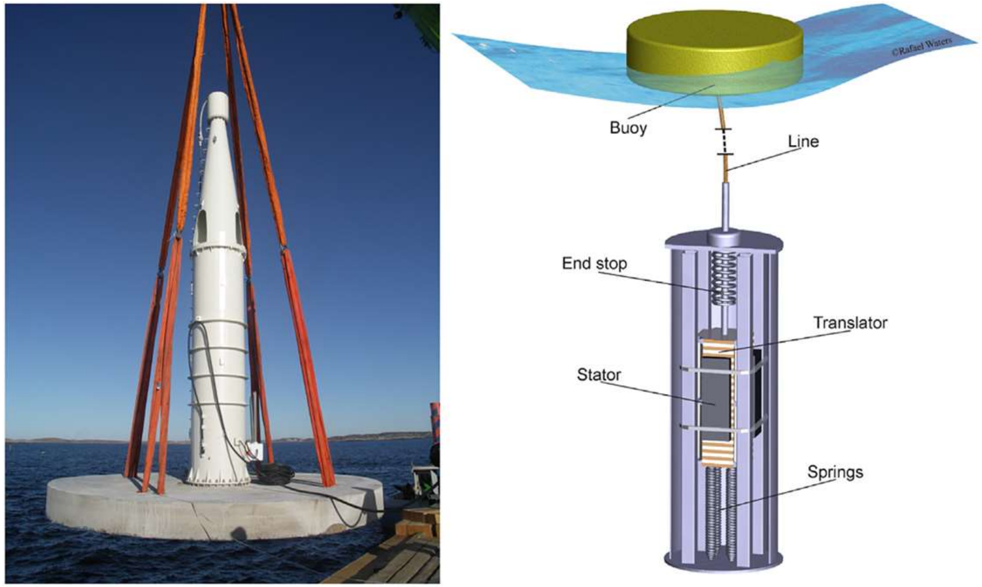
UPPSALA
UNIVERSITET

Uppsala WEC



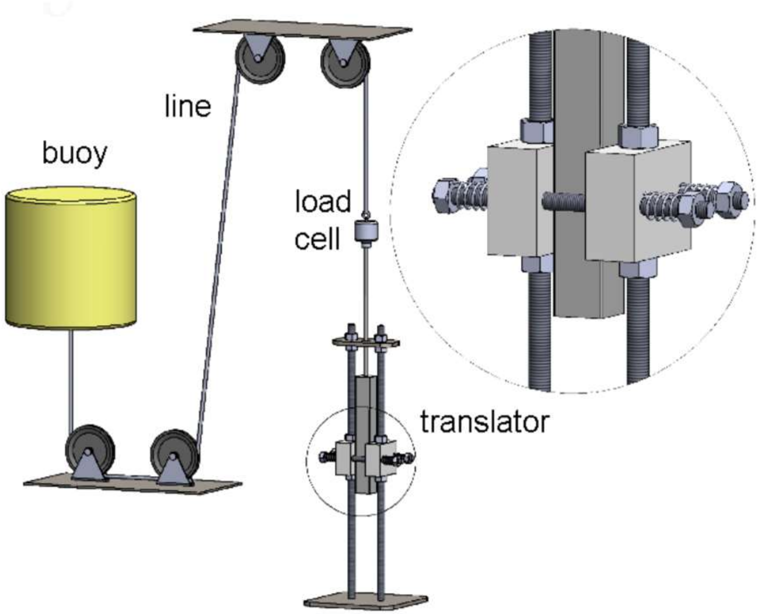
Göteman et al., 2015

WAVE ENERGY CONVERTERS



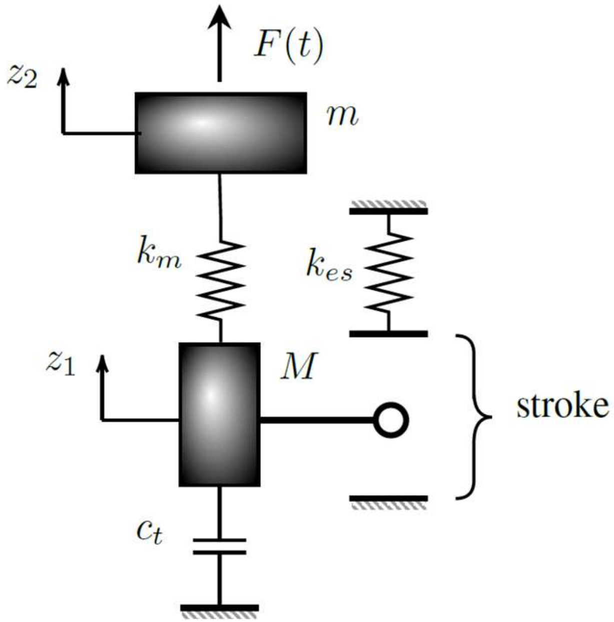
Schematic of the WEC (Waters et al. 2007) with a cylinder buoy. Copyright 2007 AIP Publishing LLC.

Experimental setup for testing under wave actions.



Engström et al., 2017

WAVE ENERGY CONVERTERS

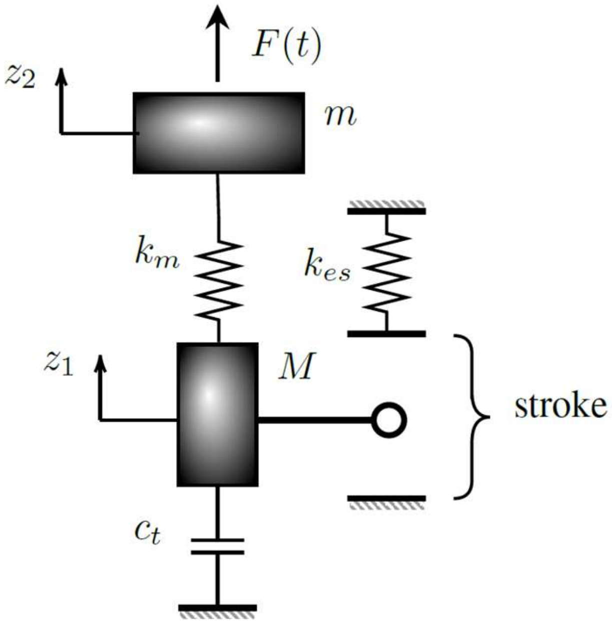


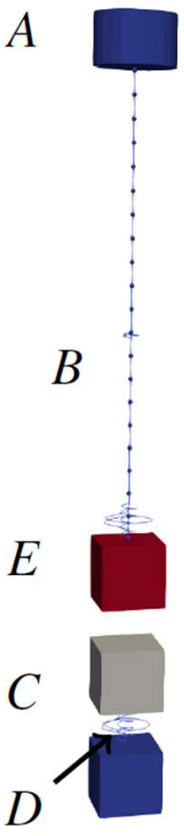
$$\begin{cases} M\ddot{z}_1 + c_{PTO}\dot{z}_1 + K(z_1)(z_2 - z_1) = -Mg, \\ m\ddot{z}_2 + k_m(z_1 - z_2) = mg + F(t), \end{cases}$$

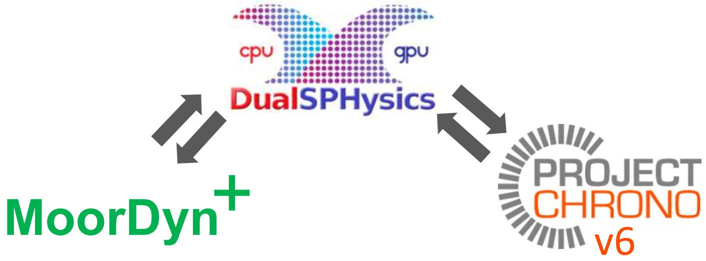
$$K = \begin{cases} k_m & \text{if } |z_1| < L_s/2; \\ k_m + k_{es} & \text{if } |z_1| \geq L_s/2; \end{cases}$$

Tagliafierro et al., 2022

WAVE ENERGY CONVERTERS





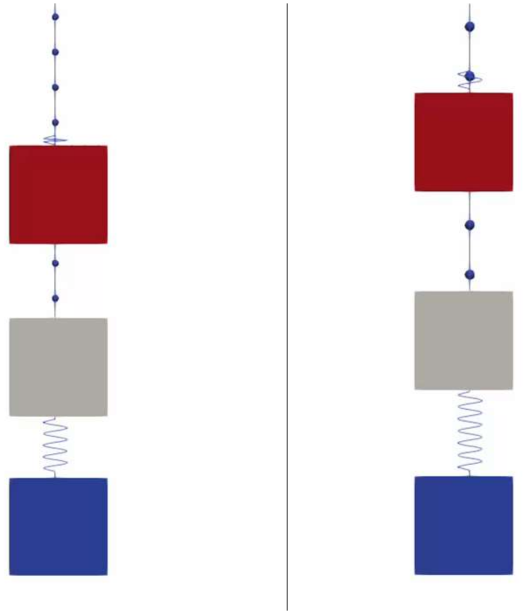


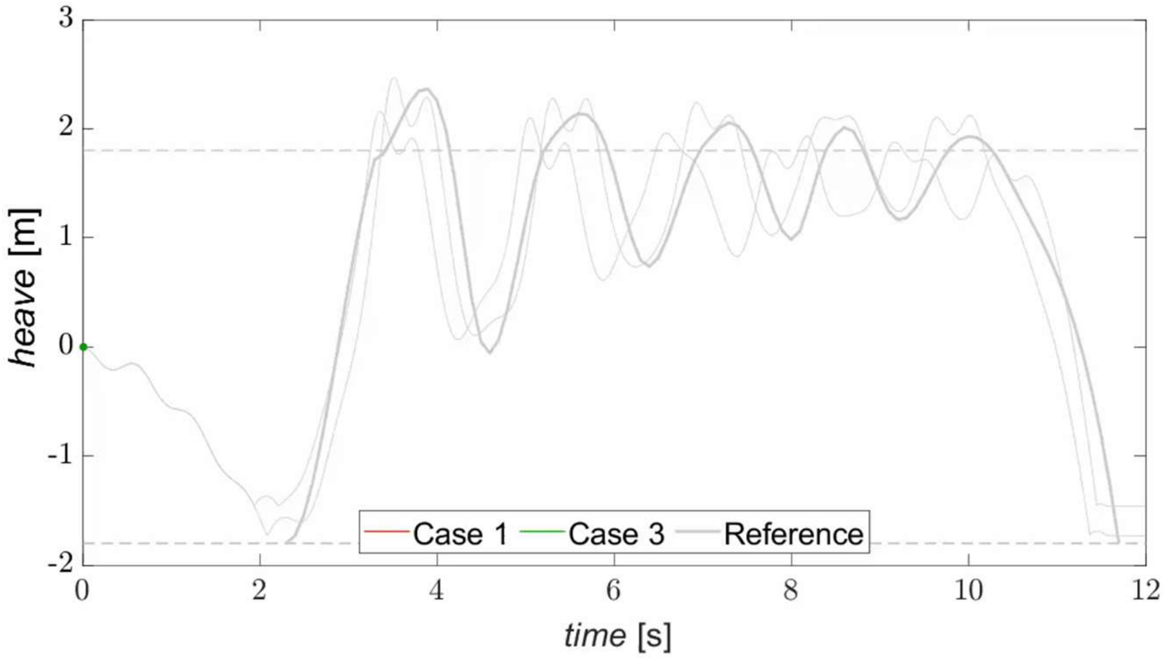
Label	Function	Instance	Manager
A	Buoy	Moving	CHRONO
B	Taut Line	Mooring line	MoorDyn
C	End-stopper	Moving Spring Contact	CHRONO CHRONO CHRONO SMC
D	Translator	Moving Contact	CHRONO CHRONO SMC
E	Energy	Damper	CHRONO
F	End-stopper	Contact	CHRONO SMC

Tagliafierro et al., 2022

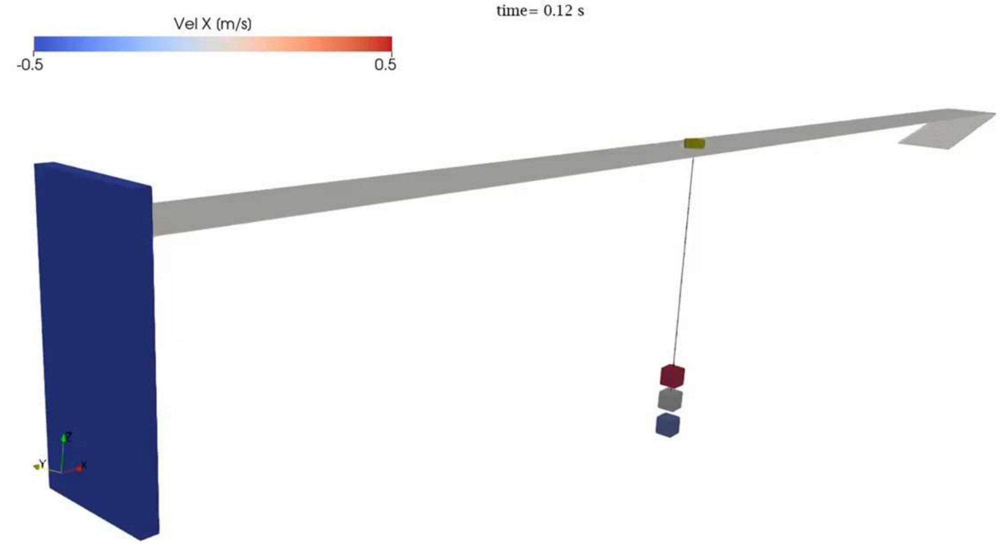
WAVE ENERGY CONVERTERS

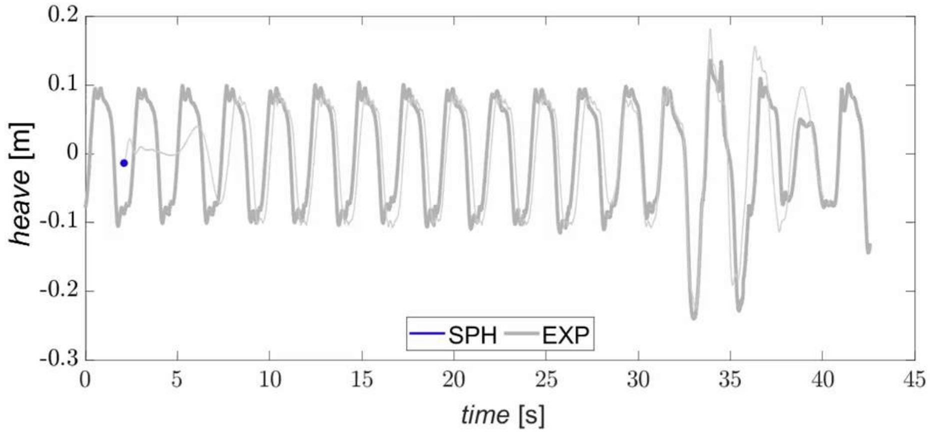
Label	*dp* **[m]**	*contact_distance* **[m]**
Case ①	R/5	0.5dp
Case ②	R/5	0.1dp
Case ③	R/7	0.1dp

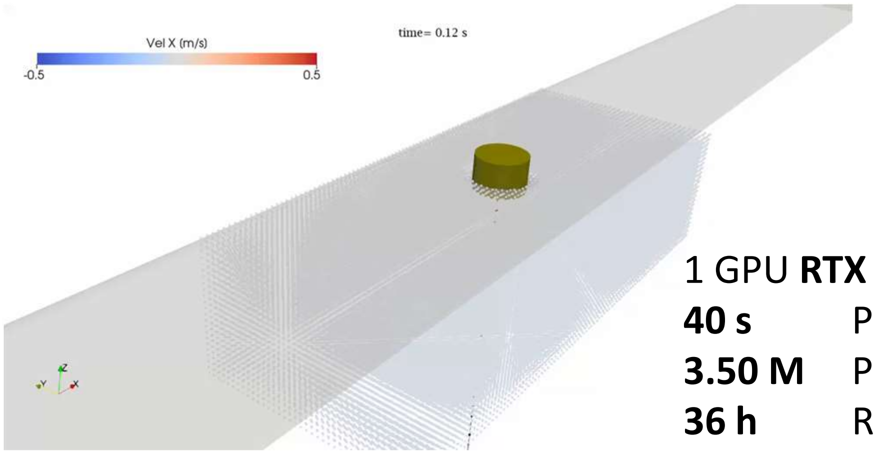




WAVE ENERGY CONVERTERS

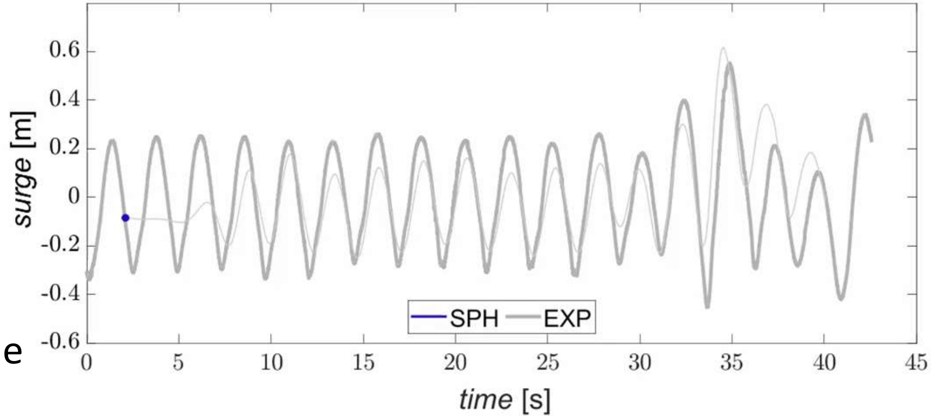




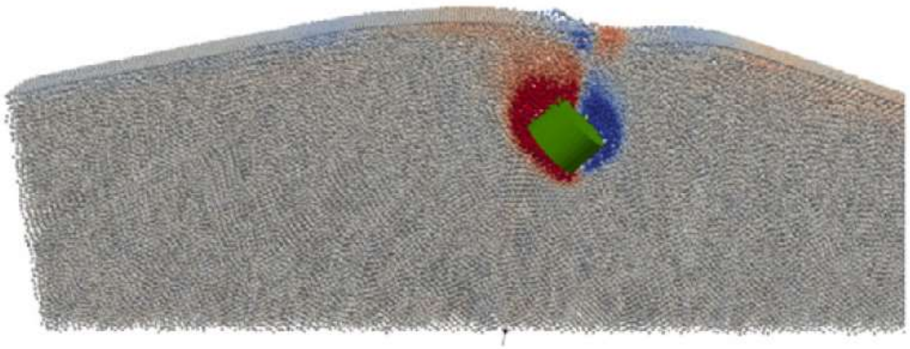


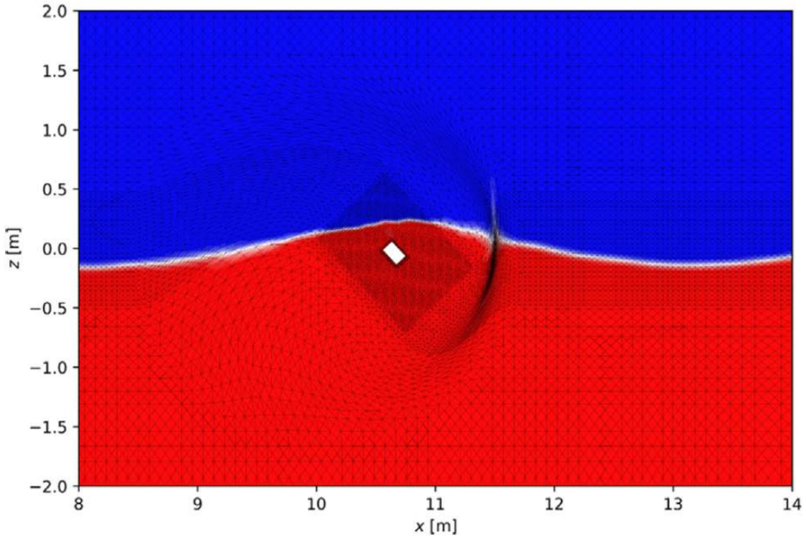
1 GPU **RTX 2080 Ti**

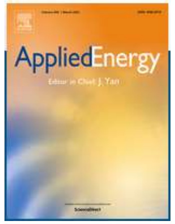
40 s	Physical time
3.50 M	Particles
36 h	Runtime



UPPSALA WEC







Tagliafierro, B., Martínez-Estévez, I., Domínguez J.M., Crespo, A.J.C., Göteman, M., Engström, J., Gómez-Gesteira, M. **(2022)**. *A numerical study of a taut-moored point-absorber wave energy converter with a linear power take-off system under extreme wave conditions*. Applied Energy, 311 https://doi.org/10.1016/j.apenergy.2022.118629

Katsidoniotaki, E., & Göteman, M. **(2022)**. *Numerical modeling of extreme wave interaction with point-absorber using OpenFOAM*. Ocean Engineering, 245 doi:10.1016/j.oceaneng.2021.110268

FOSWEC 2

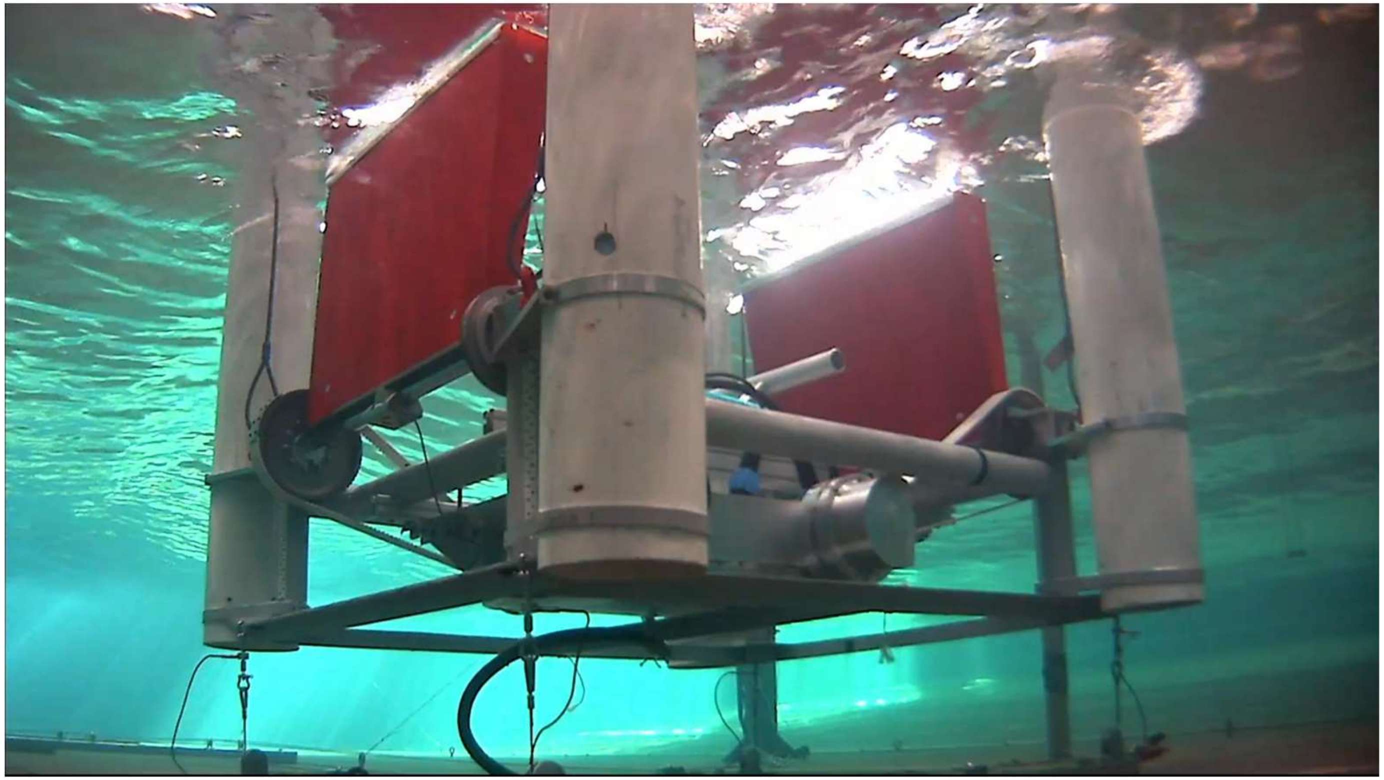
FLOATING OSCILLATING SURGE WAVE ENERGY CONVERTER

Sandia National Laboratories

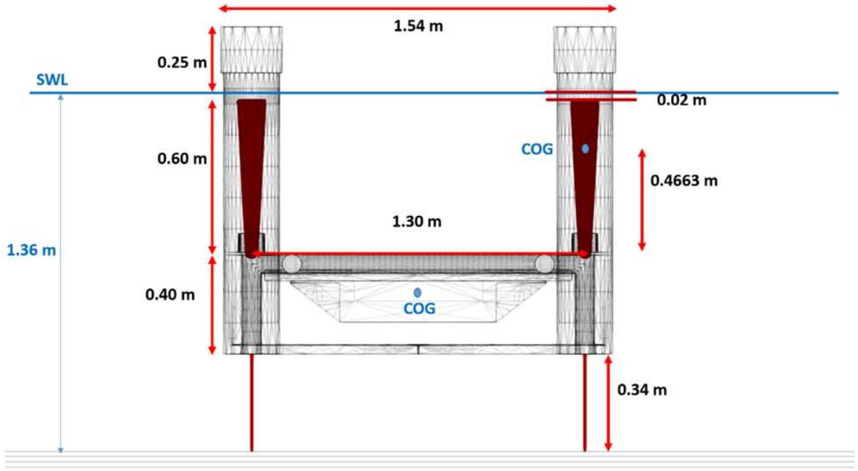
2 flaps attached to a submerged moored platform

Platform includes a Power Take-Off (PTO) box

https://youtu.be/OUxbaEC2K6Y



WAVE ENERGY CONVERTERS



WAVE ENERGY CONVERTERS

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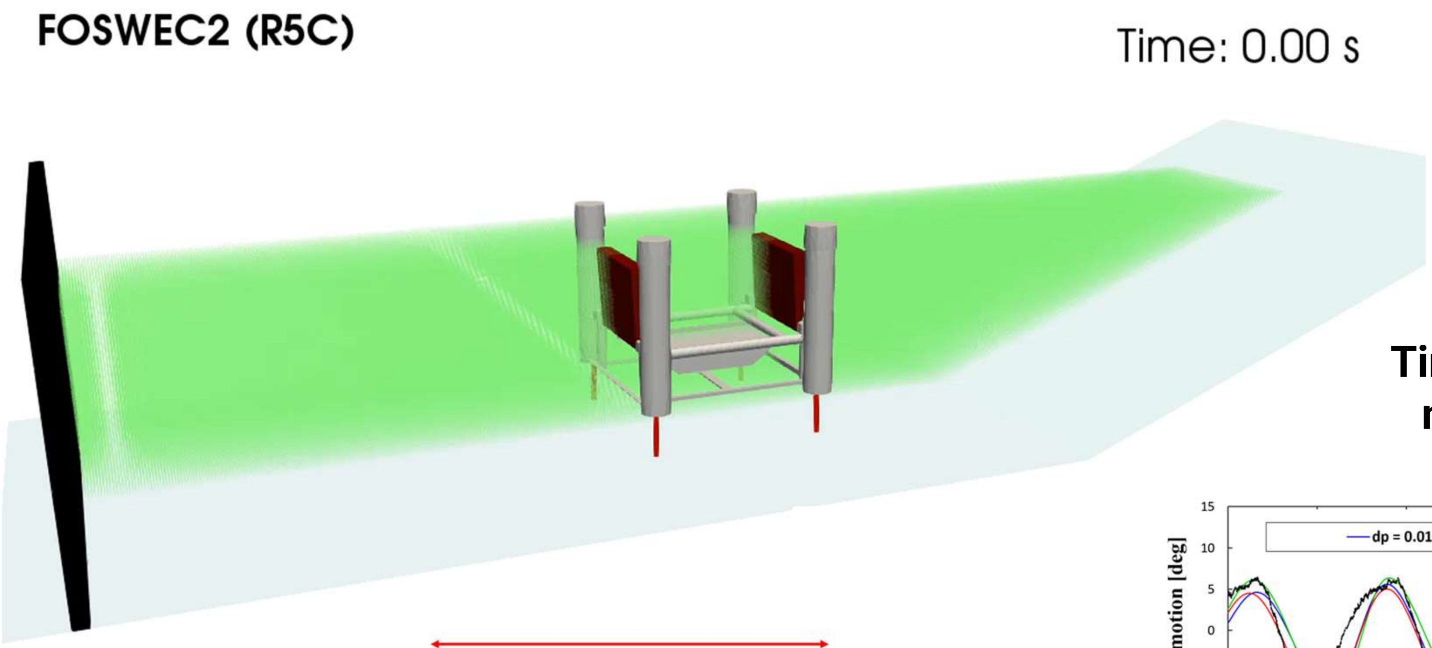
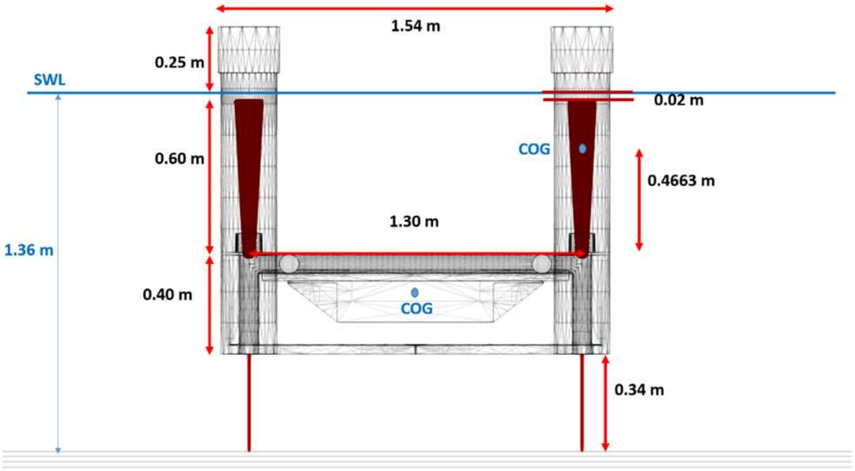
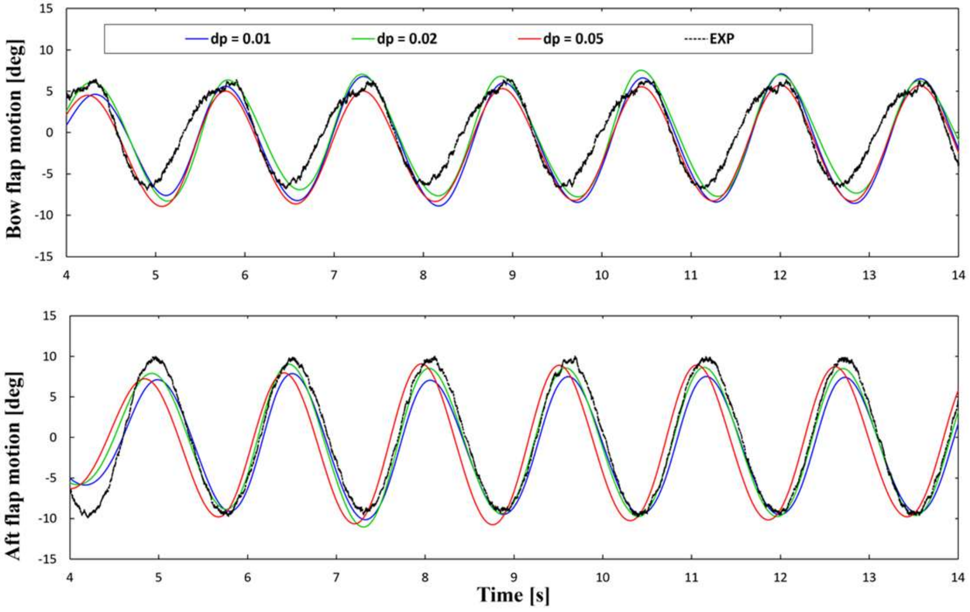


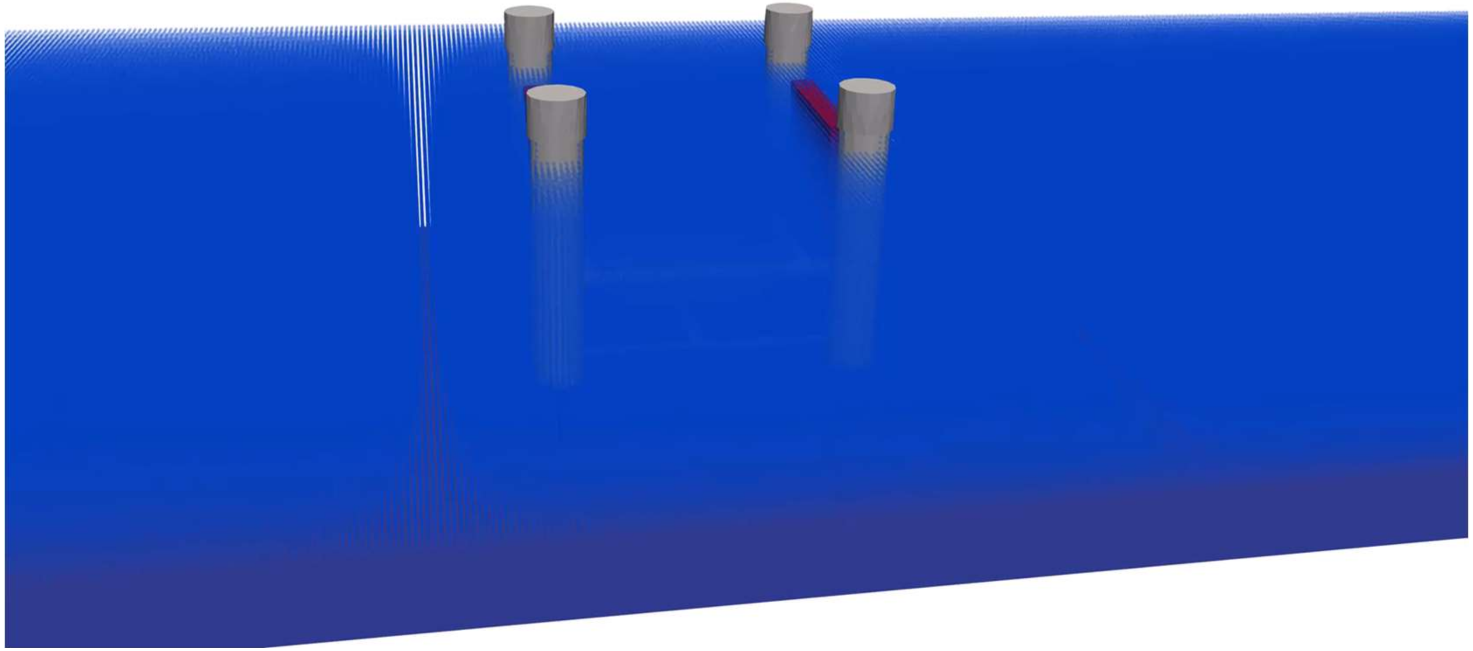


Time series of experimental and numerical angles of the flaps



FOSWEC – EXTREME WAVES

time= 0.00 s



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ACKNOWLEDGEMENTS

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COST Action CA17105, COST Association.
WECANet: A pan-European Network for Marine Renewable Energy

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OUTLINE

1. Introduction
2. The SPH numerical method
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6. **Conclusions**

CONCLUSIONS

- An SPH framework can be both as accurate as other CFD solvers;
- A wide variety of structures can be simulated;
- Find the right balance between runtime and accuracy;
- GPU-accelerated hardware.

FUTURE WORK

- Investigation of more complex systems;
- Investigate Control effects on the structure performance for extreme events.

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