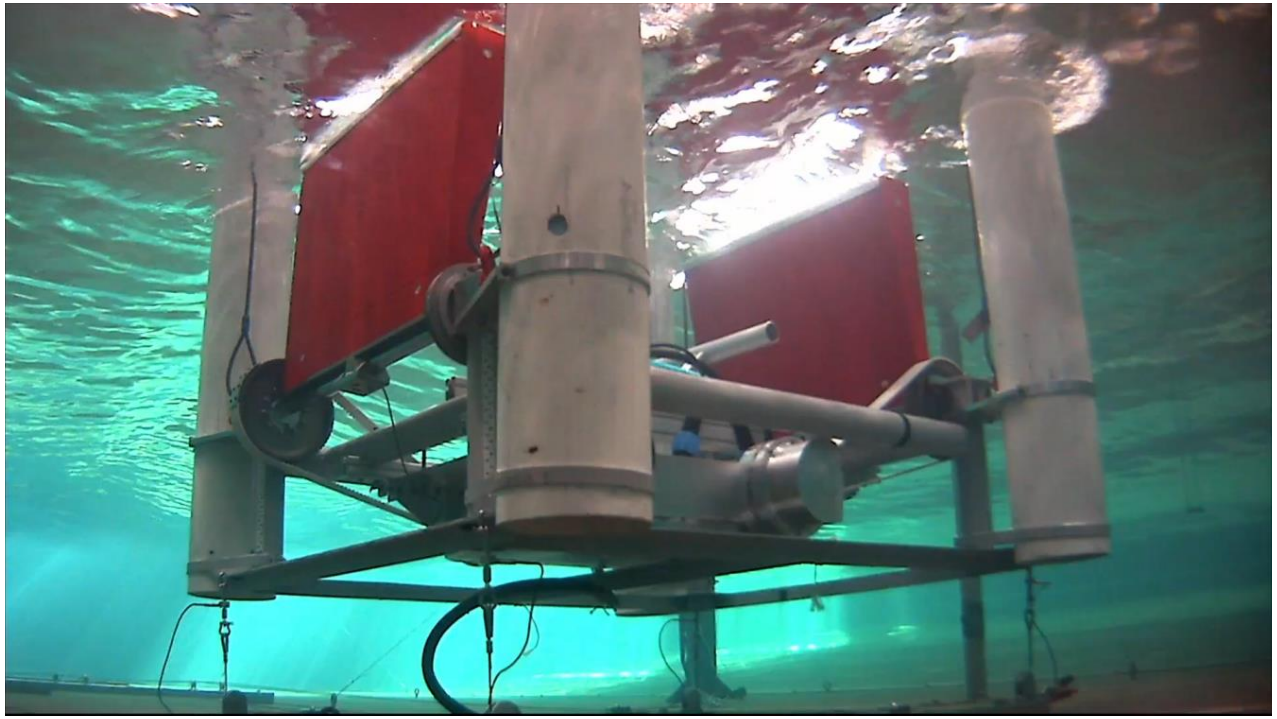
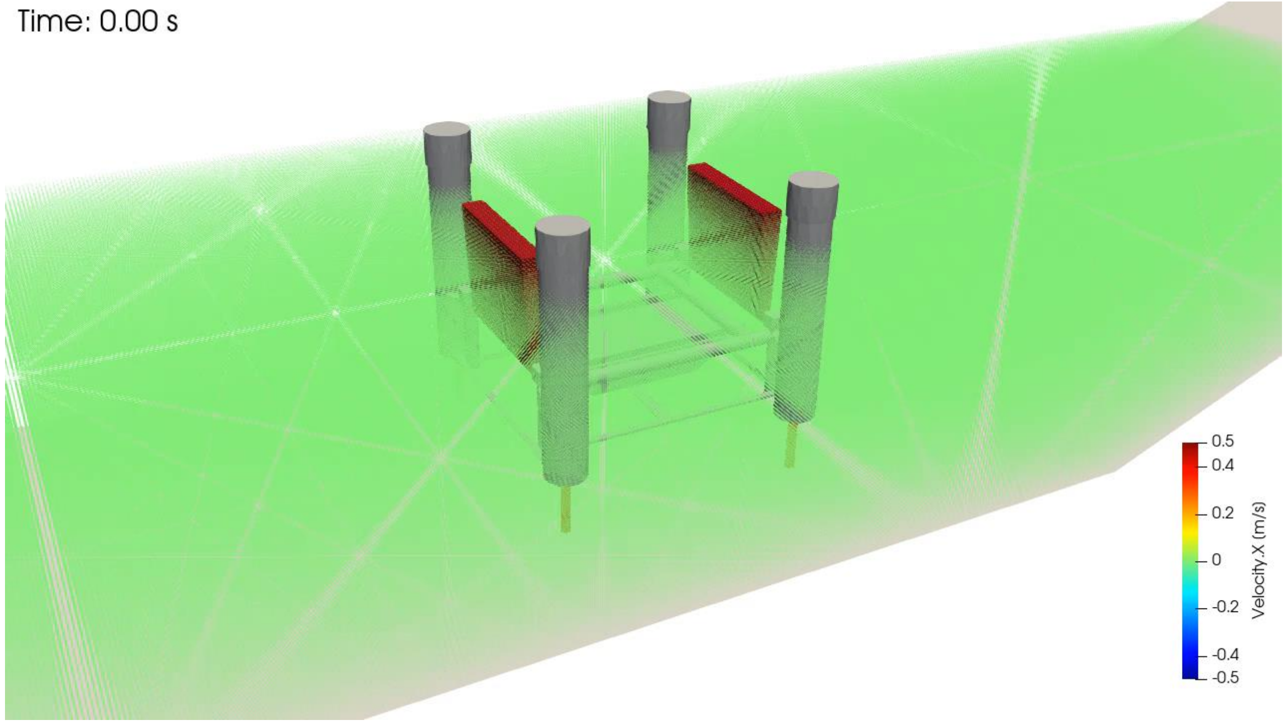
On the state-of-the-art of CFD simulations for WECs within the open-source numerical framework of DualSPHysics



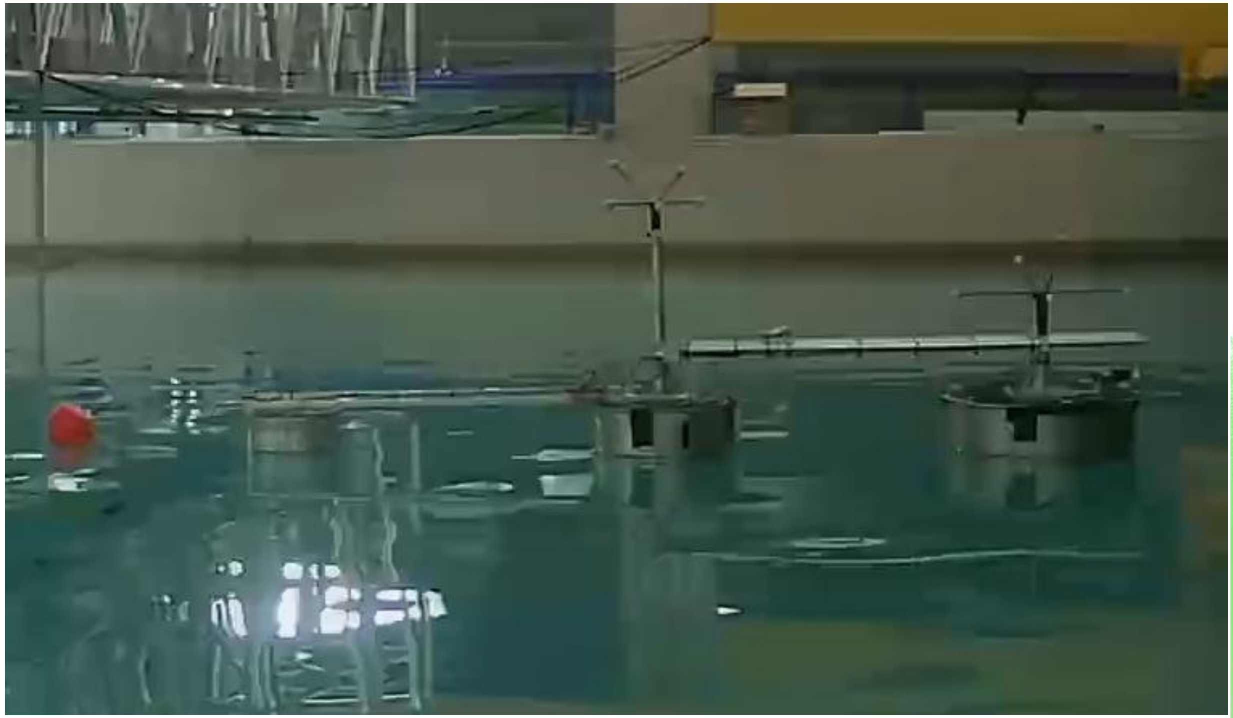


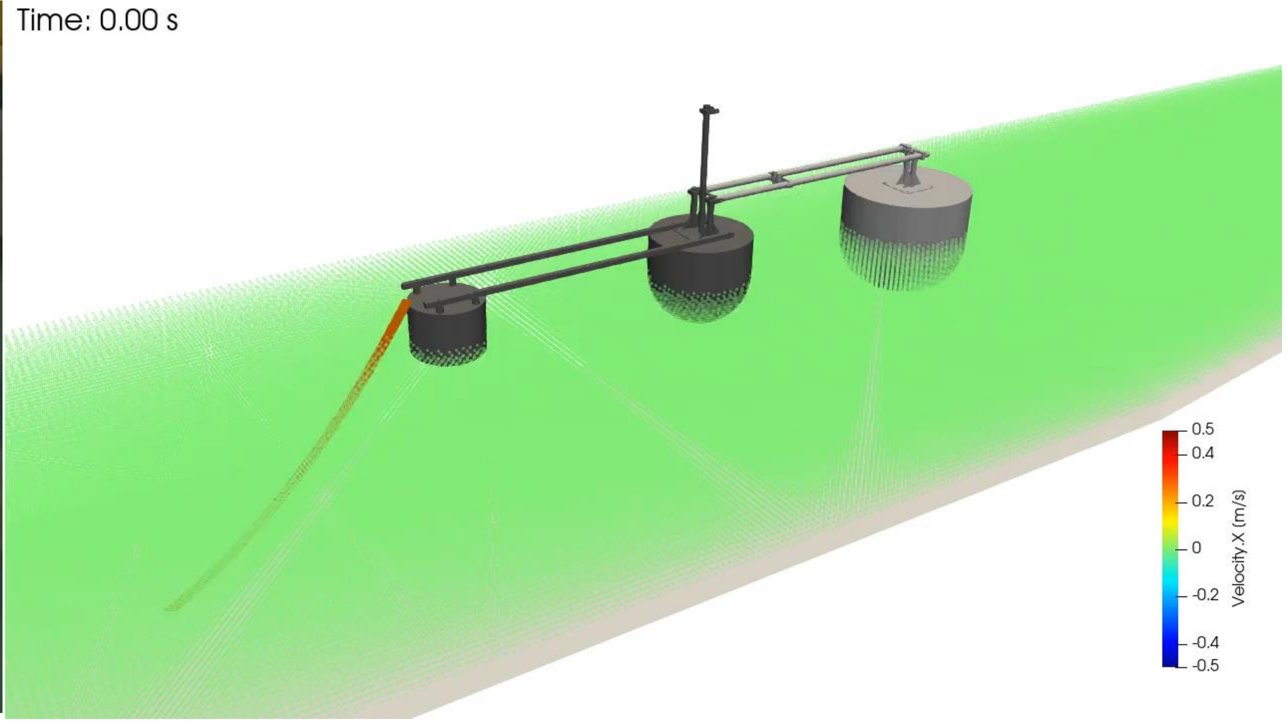
Alejandro J. Crespo (*CIM-Universidade de Vigo, Spain)*

15th EWTEC 2023 BILBAO
European Wave and Tidal Energy Conference Series
3rd -7th SEPTEMBER 2023

DualSPHysics

On the state-of-the-art of CFD simulations for WECs within the open-source numerical framework of DualSPHysics





Alejandro J. Crespo (*CIM-Universidade de Vigo, Spain)*

MOTIVATION

CHALLENGES OF WAVE ENERGY:

No unanimity on the **WEC technologies** (*Falcão et al., 2010*)

Optimal PTO in operating conditions (*Ahamed et al., 2020*)

Survivability and maintenance of WECs (*Guo et al., 2021*)

Performance **under extreme wave** loadings (*Guo et al., 2021*)

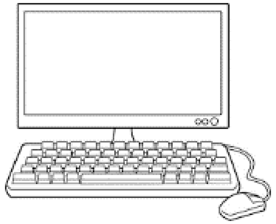
High upfront costs of wave energy (*Guo et al., 2023*)

FMARMOK-A-5 device,
developed by ***Oceantec****,*
during its installation at BiMEP

NUMERICAL MODELLING IS A KEY TO ADDRESSING THESE CHALLENGES

Data provides **valuable insights** and pushes forward the development of WEC designs

WEC problems are **highly complex and non-linear**, in particular for **survivability** studies



OUR APPROACH

Meshless **SPH** method for **violent flows** with rapidly moving or **fluid-driven devices**

DualSPHysics v5.2 is applied to **four well-established WEC concepts**

Study of not only the **efficiency but also the survivability** of WECs.

We provide a **free numerical tool** into simulating **other novel WEC** devices

OUTLINE

1. Numerical modelling of WECs
    1.1 Meshless CFD and SPH
    1.2 DualSPHysics open-source code
    1.3 Coupling with other solvers

2. Simulation of different WEC technologies
    2.1 Uppsala Point Absorber
    2.2 Oscillating Wave Surge Converter
    2.3 Floating Oscillating Surge Wave Energy Converter
    2.4 Multi-float M4

3. Work undergoing
    3.1 More WEC technologies
    3.2 Active control systems
    3.3 Flexible WECs

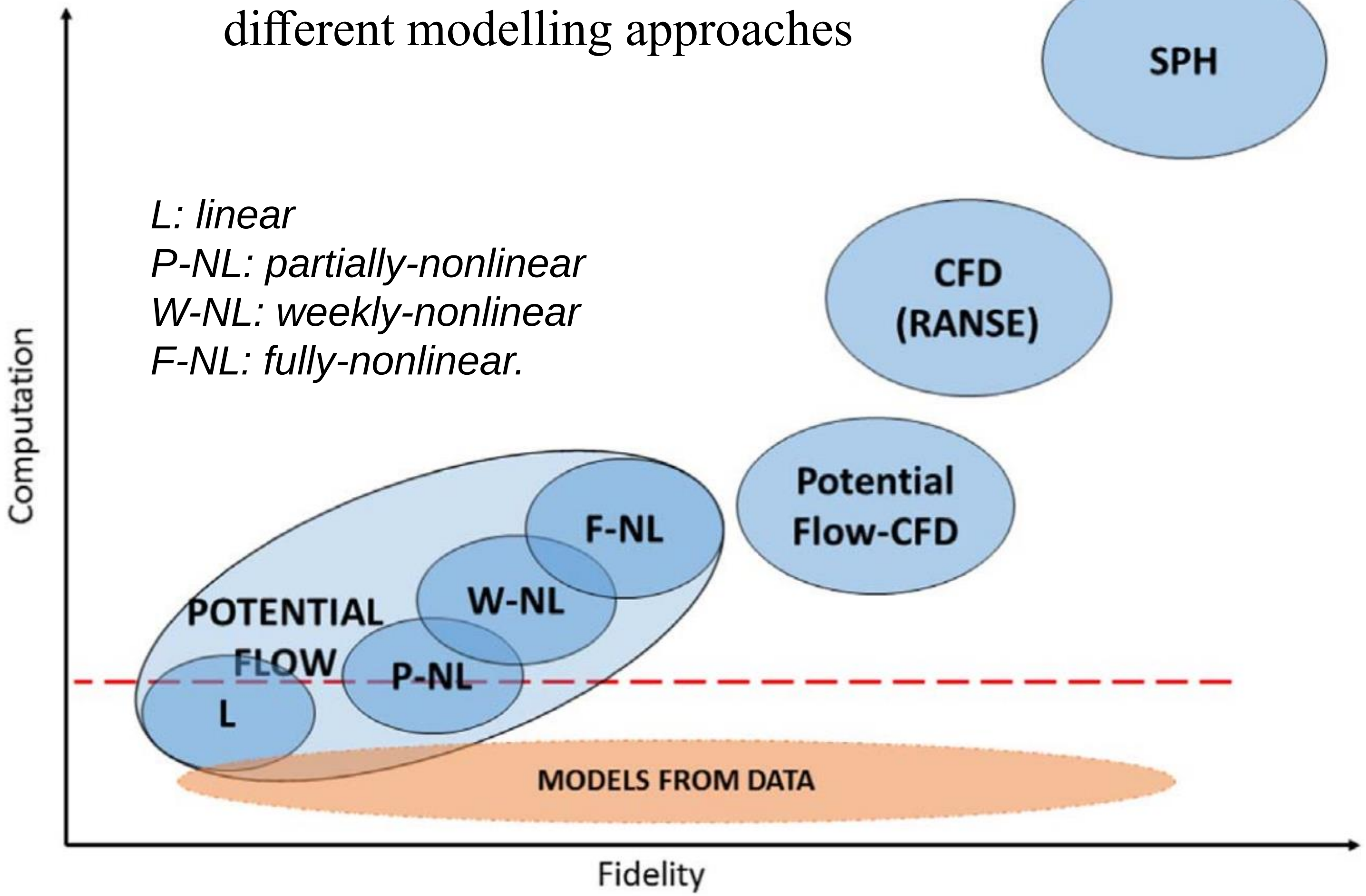
4. Conclusions

1.1 Meshless CFD and SPH

Numerical modelling of the hydrodynamic interaction wave-WECs

Computation/fidelity compromise of the different modelling approaches

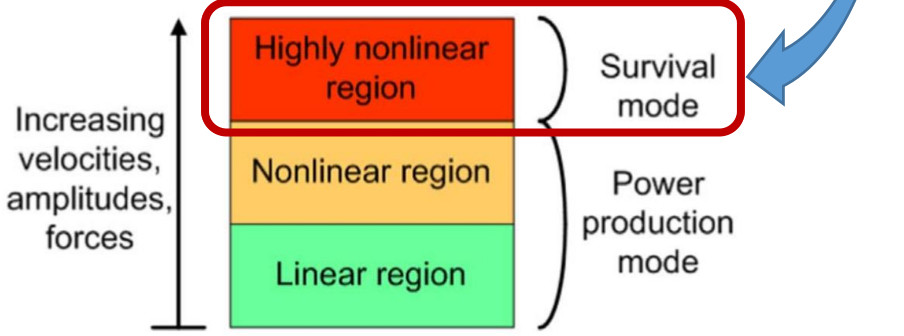
L: linear
P-NL: partially-nonlinear
W-NL: weekly-nonlinear
F-NL: fully-nonlinear.



Source: *Penalba et al., 2017*

Smoothed **P**article **H**ydrodynamics
high fidelity
time consuming

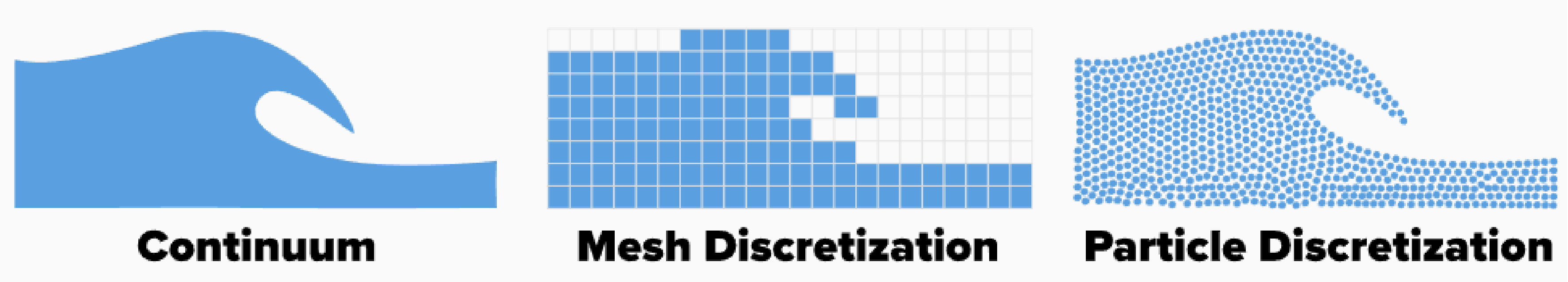
Different operating regions for wave energy devices



1.1 Meshless CFD and SPH

Smoothed Particle Hydrodynamics

Meshless Our computation points are **particles** that now **move** according to governing dynamics



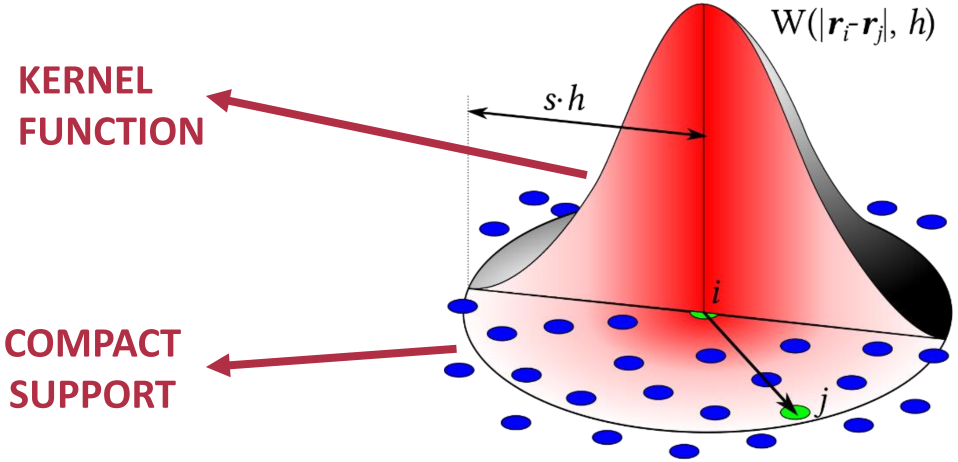
Source: *https://www.dive-solutions.de/blog/sph-basics*

Particles possess **fluid properties** that travel with them, e.g., density, pressure; these can change with time

Local Interpolation (summation) with a **weighting function** (**Kernel**) around each particle to obtain fluid properties

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

KERNEL FUNCTION



Source: *Wikipedia (CC BY-SA 4.0)*

1.1 Meshless CFD and SPH

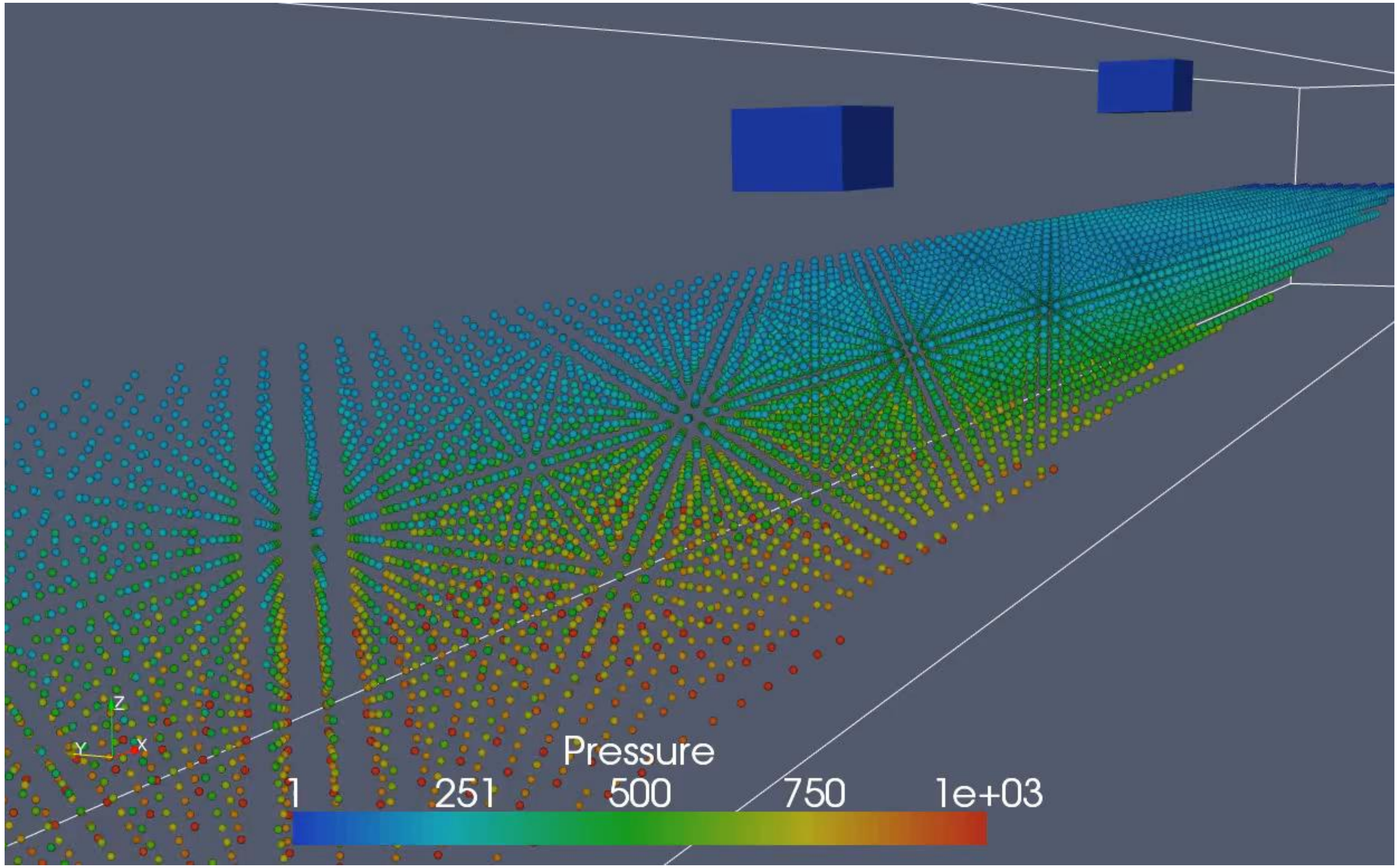
Smoothed **P**article **H**ydrodynamics

Navier-Stokes momentum equation

Continuity equation + density diffusion terms

WCSPH: equation of state

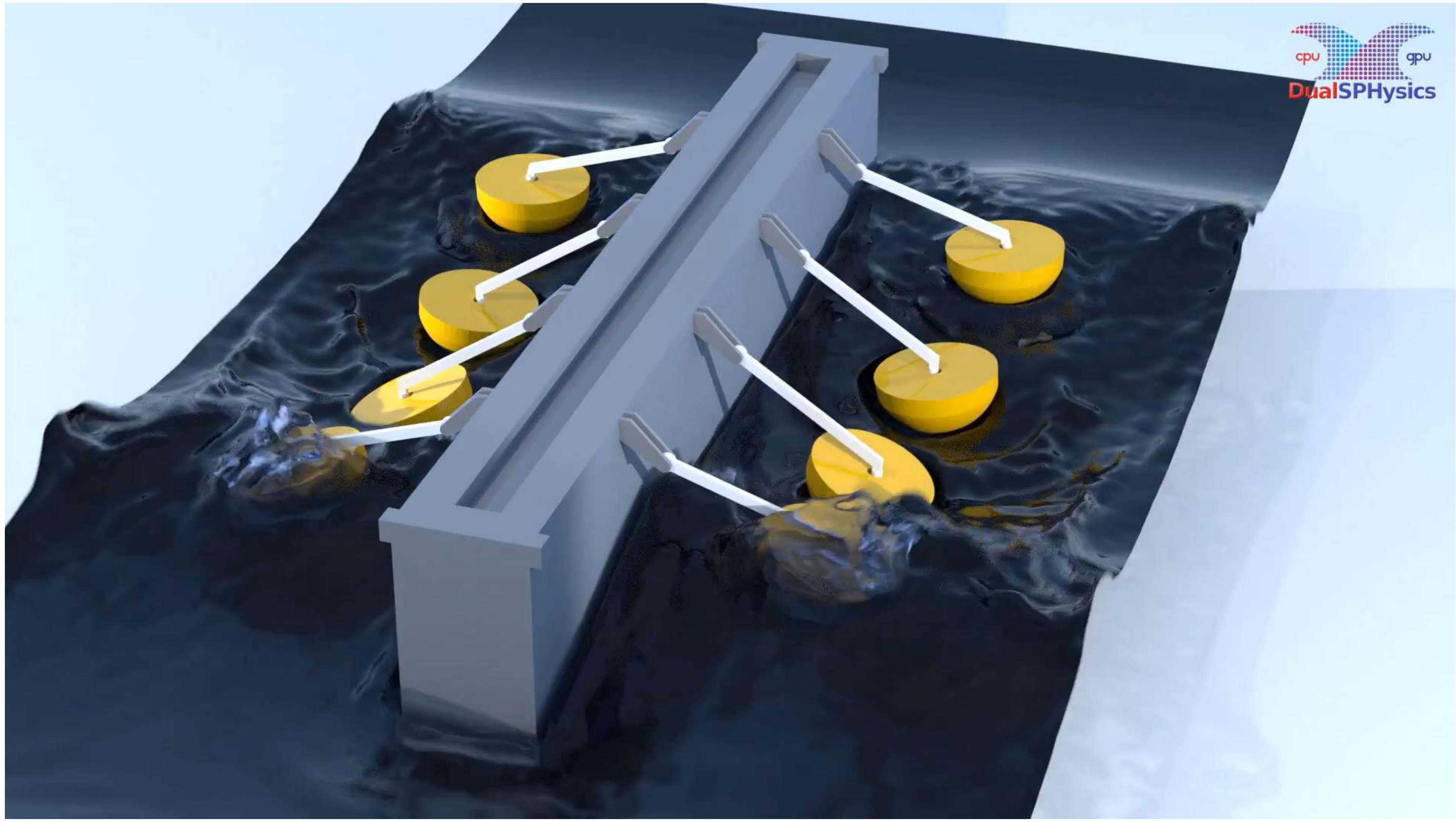
particles = moving computational nodes



1.1 Meshless CFD and SPH

Smoothed **P**article **H**ydrodynamics

- **Easy to set up**, no mesh, particles conform to body in still water automatically
- Efficient treatment of the **large deformation of free surfaces** (no mesh distortion)
- **Avoids** computation of the **nonlinear advection terms** thanks to its Lagrangian formulation
- **Waves and currents easy to input**, as mesh methods
- Method inherently **stable and robust**



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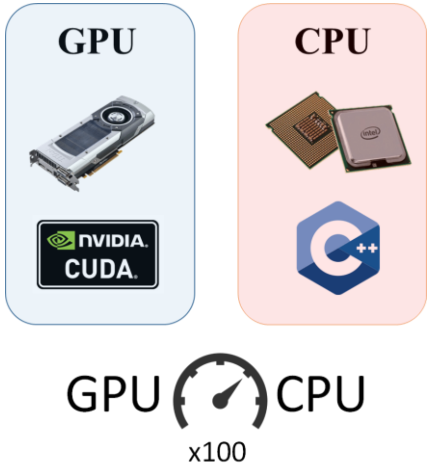
DISADVANTAGES comparing with mesh-based CFD codes:

- There is still **no unanimity** to choose the best **solid boundary** conditions
- **Turbulence** treatment is still an **open field** and more research is needed
- Time **computation is expensive** comparing with other methods

1.2 DualSPHysics open-source code

DualSPHysics Code on GitHub
https://github.com/DualSPHysics/DualSPHysics
+120.000 downloads

Universidade de Vigo, Spain
The University of Manchester, UK
Università degli studi di Parma, Italy
Universitat Politècnica de Catalunya
New Jersey Institute of Technology, USA



OPEN-SOURCE CODE

COLLABORATIVE PROJECT

LGPL LICENSE

RIGOROUSLY VALIDATED

HIGHLY PARALLELISED

PRE- & POST-PROCESSING

APPLIED TO REAL PROBLEMS

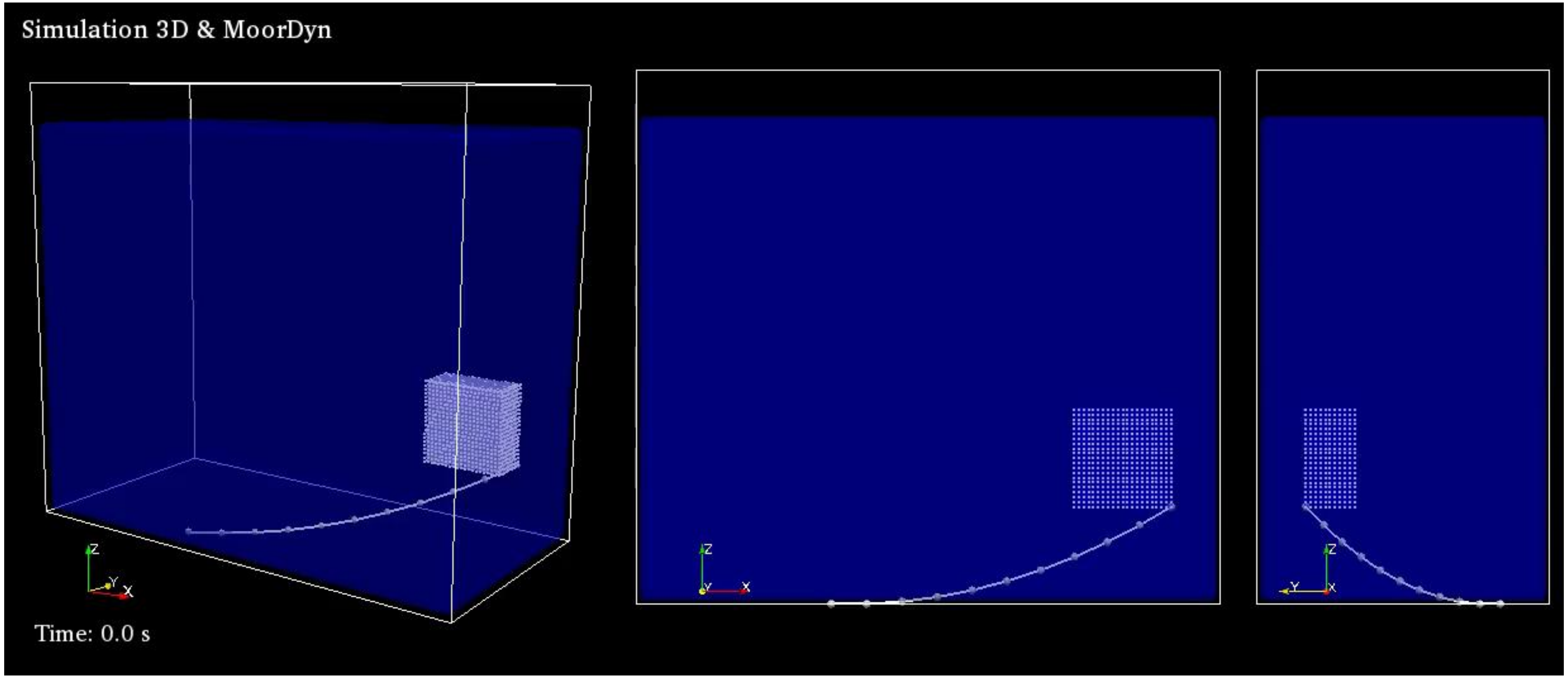
*Domínguez JM, Fourtakas G, Altomare C, Canelas RB, Tafuni A, García-Feal O, Martínez-Estévez I, Mokos A, Vacondio R, **Crespo AJC**, Rogers BD, Stansby PK, Gómez-Gesteira M. 2022. DualSPHysics: from fluid dynamics to multiphysics problems. **Computational Particle Mechanics**, 9(5), 867-895.*

1.3 Coupling with other solvers

https://github.com/imestevez/MoorDynPlus

Coupling with MoorDyn+ solver

MoorDyn+ (based on **MoorDyn**) is a dynamic mooring line model that uses a lumped-mass formulation:
- *Solves **catenary equation***
- *Considers **axial stiffness** and friction with the bottom*
- *Use of **different water depths** in the same simulation*
- *Mooring **connected to more than one floating** object*



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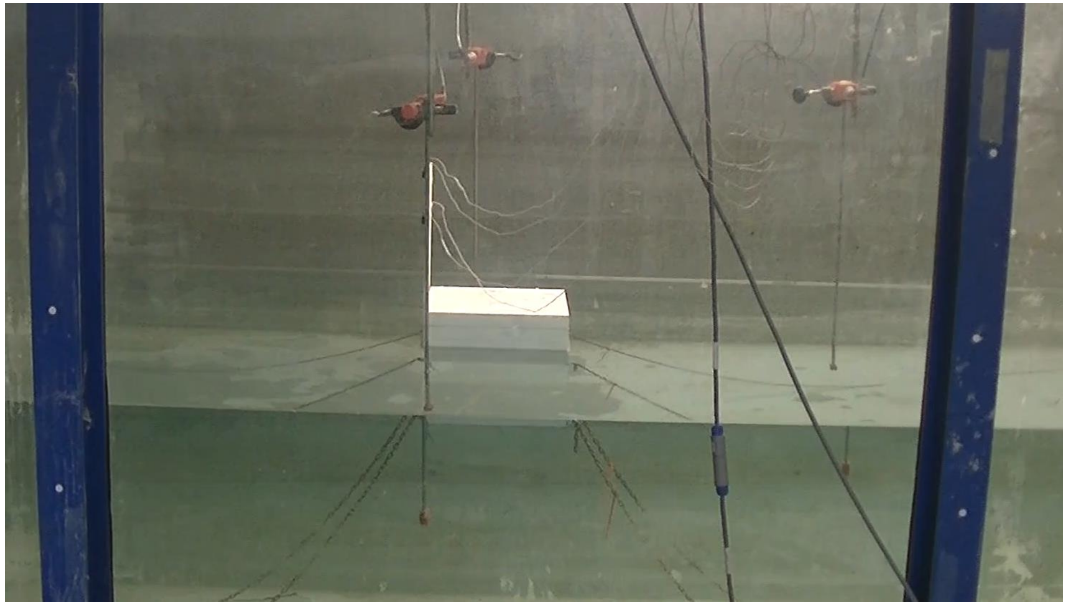
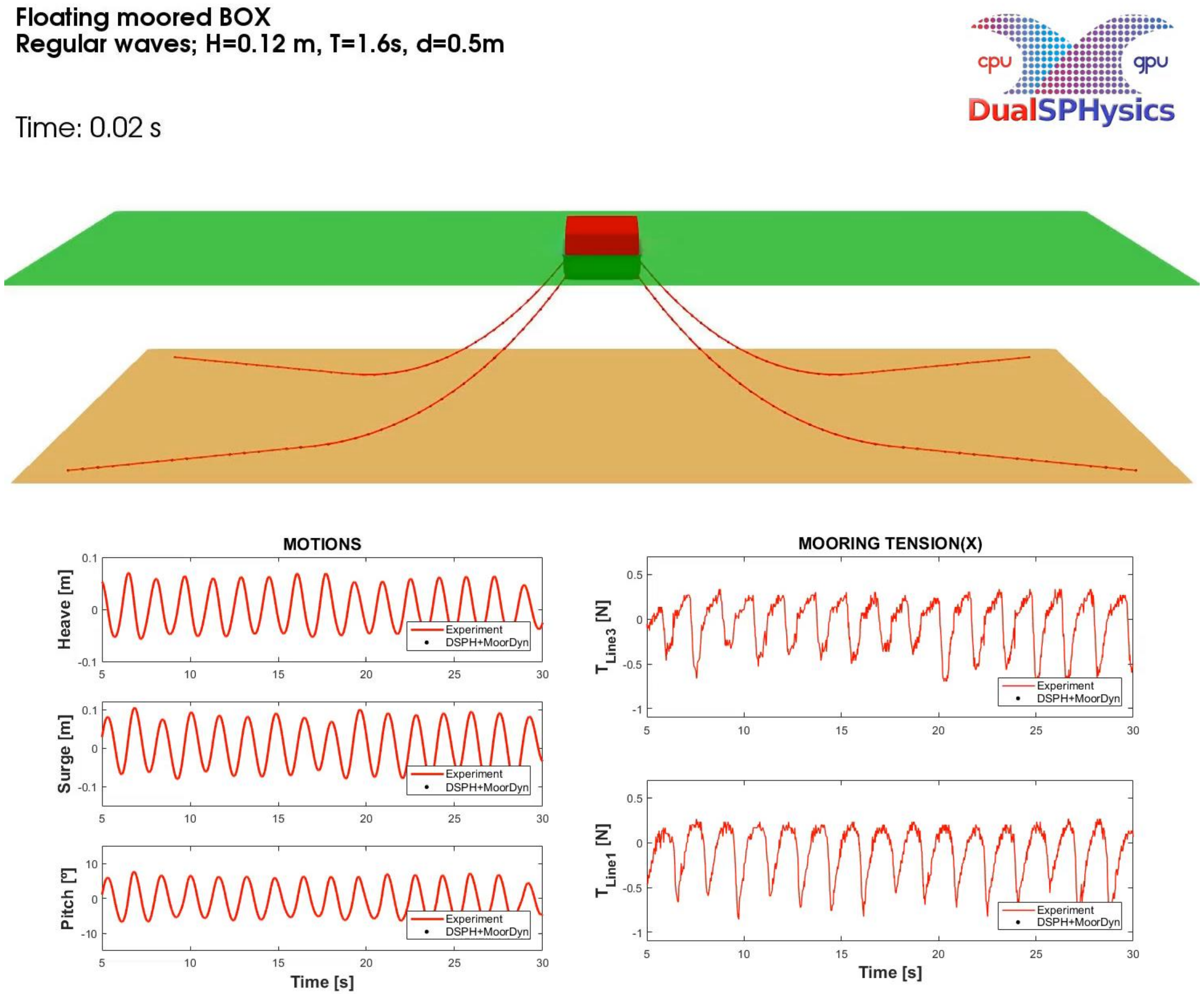
Coupling with MoorDyn+ solver



Parameter	Value
box length	20 cm
box width	20 cm
box height	13.2 cm
box weight (+ connections)	3.6 kg
centre of gravity of the box (X,Y,Z)	(0, 0, -1.26) cm
box lip draught	7.86 cm
mooring diameter	3.656 mm
mooring weight (per length)	0.607 g/cm
mooring length	145.5 cm

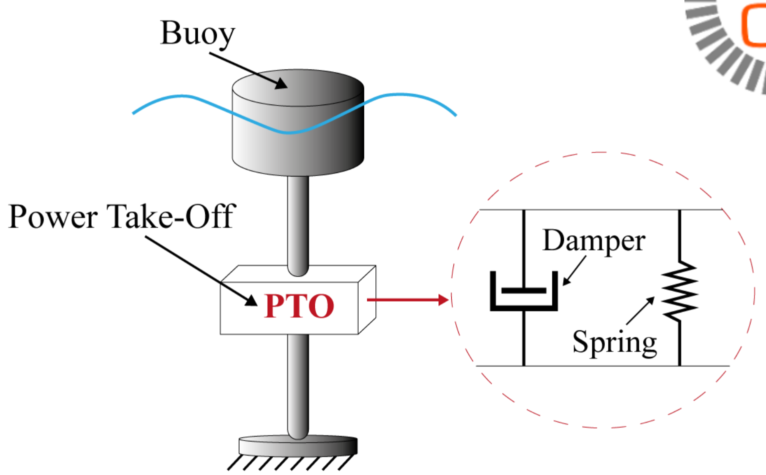


*Domínguez JM, **Crespo AJC**, Hall M, Altomare C, Wu M, Stratigaki V, Troch P, Cappietti L, Gómez-Gesteira M. 2019. SPH simulation of floating structures with moorings. **Coastal Engineering**, 153, 103560.*

1.3 Coupling with other solvers

http://projectchrono.org

Coupling with Project Chrono library



MULTIBODY DYNAMICS

Mechanical constraints between rigid and flexible objects
Add motors, linear actuators, springs and dampers.
Apply forces and torques.

COLLISION DETECTION

Define collision shapes using meshes or primitives.
Compute frictional contact forces using state-of-the-art collision detection algorithms.
Define surface/material properties.

FINITE ELEMENTS

Use the FEA module to create finite elements and model flexible parts.
Beams, cables, shells, solid tetrahedrons and hexahedrons.

1.3 Coupling with other solvers

http://projectchrono.org

Coupling with Project Chrono library

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Mechanical constraints between rigid and flexible objects
Add motors, linear actuators, springs and dampers.
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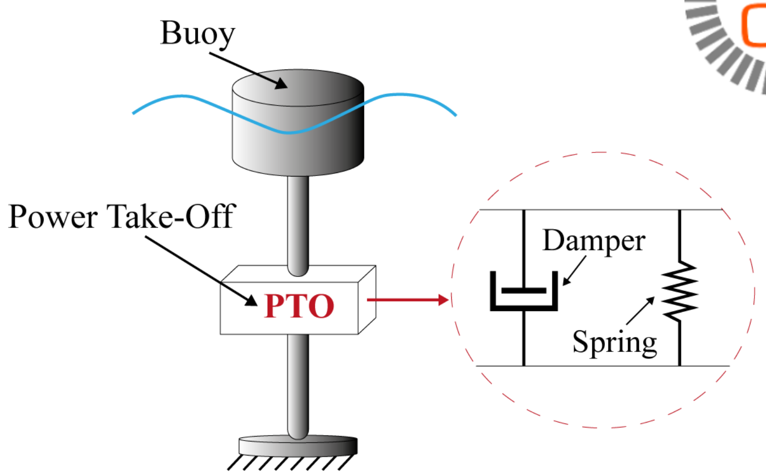


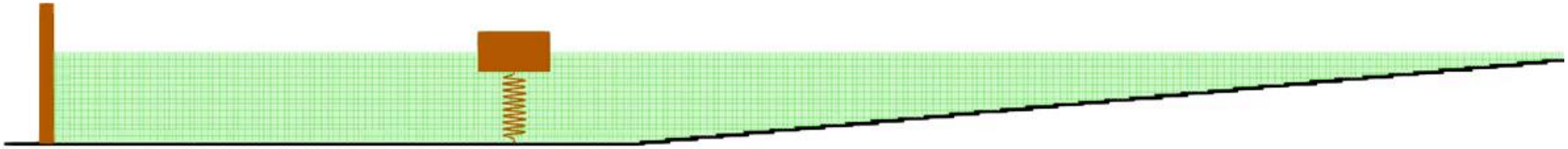
Translational Spring-Damper-Actuator (TSDA)

Spring with stiffness and damping in CHRONO:

$$F_{PTO} = \boldsymbol{k}(d - l) + \boldsymbol{c} \cdot v$$

d: distance between the two origins
l: equilibrium length
v: velocity experienced by spring
k: stiffness coefficient
c: damping coefficient

CasePointAbsorberSpring



*Martínez-Estévez I, Domínguez JM, Tagliafierro B, Canelas RB, García-Feal O, **Crespo AJC**, Gómez-Gesteira M. 2023. Coupling of an SPH-based solver with a multiphysics library. **Computer Physics Communications**, 283, 108581*

1.1 Meshless CFD and SPH

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- Time **computation is expensive** comparing with other methods

USING the open-source DualSPHysics package:

- Coupling with Chrono for structural constraints and MoorDyn available, so flexible
- Speeds on GPU similar to mesh methods

cpu gpu DualSPHysics

OUTLINE

1. Numerical modelling of WECs

- **1.1 Meshless CFD and SPH**
- **1.2 DualSPHysics open-source code**
- **1.3 Coupling with other solvers**

2. Simulation of different WEC technologies

- **2.1 Uppsala Point Absorber**
- **2.2 Oscillating Wave Surge Converter**
- **2.3 Floating Oscillating Surge Wave Energy Converter**
- **2.4 Multi-float M4**

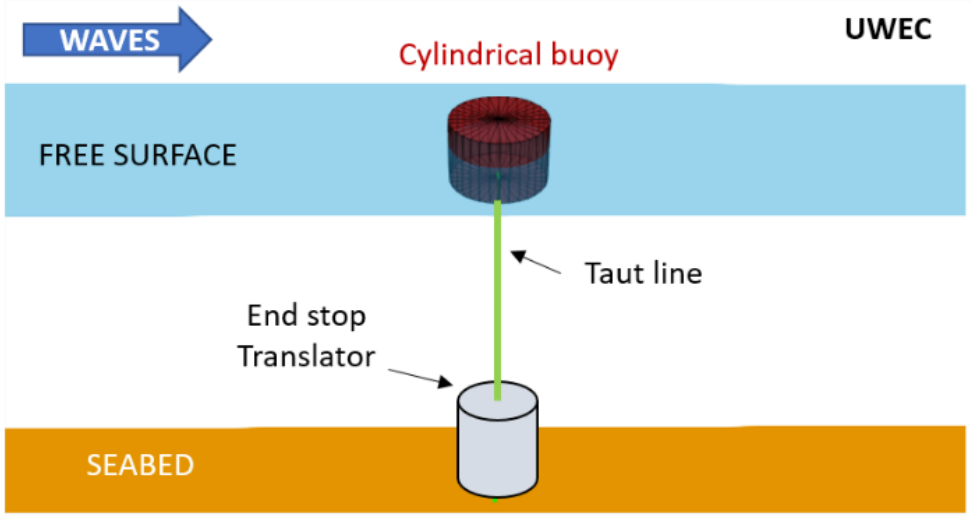
3. Work undergoing

- **3.1 More WEC technologies**
- **3.2 Active control systems**
- **3.3 Flexible WECs**

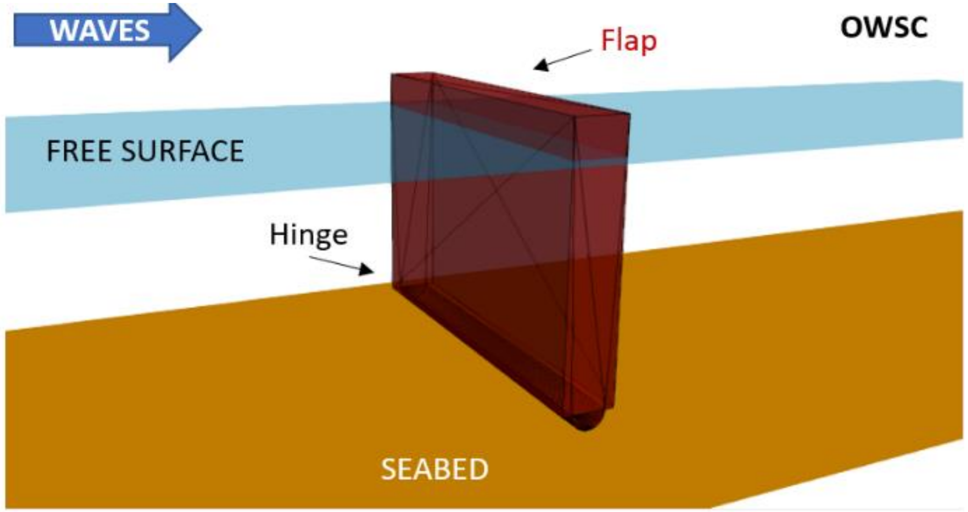
4. Conclusions

2. Simulation of different WEC technologies

Uppsala Point Absorber

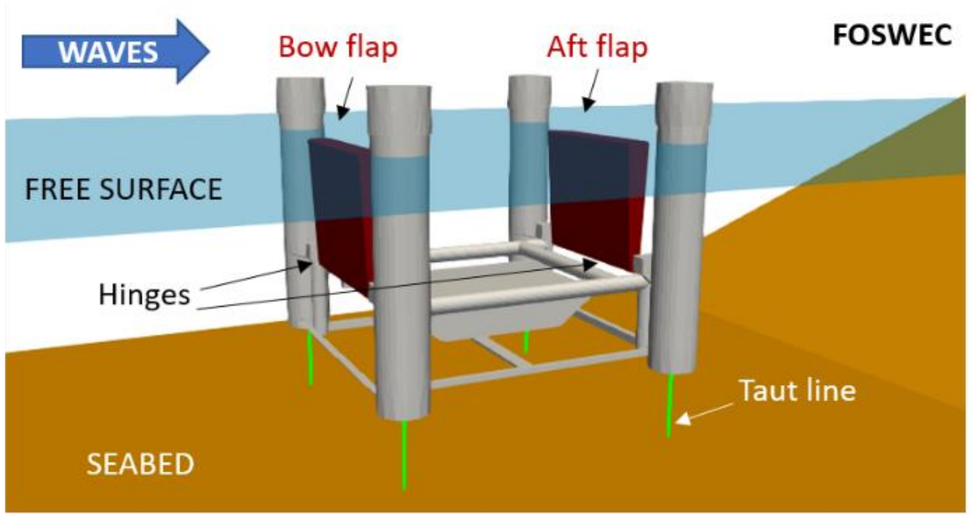


Oscillating Wave Surge Converter

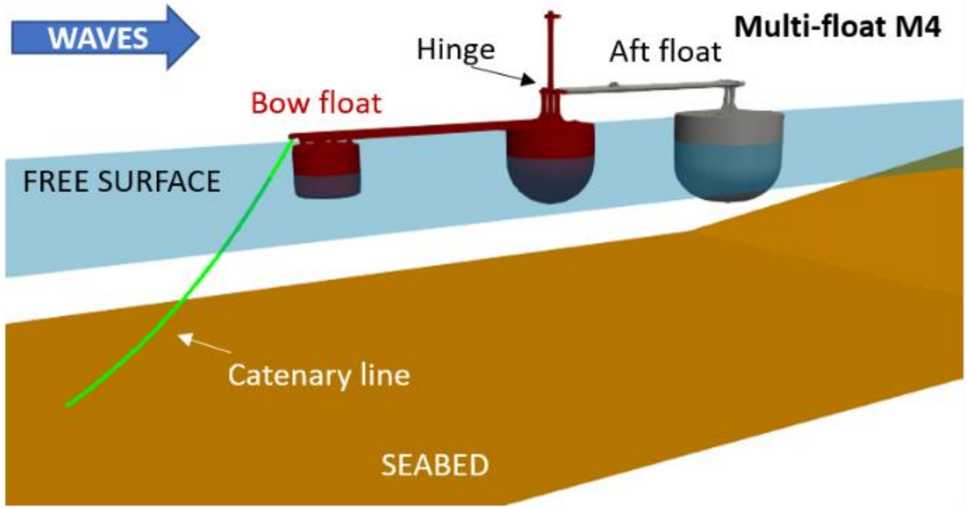


cpu gpu
DualSPHysics

Floating Oscillating Surge WEC



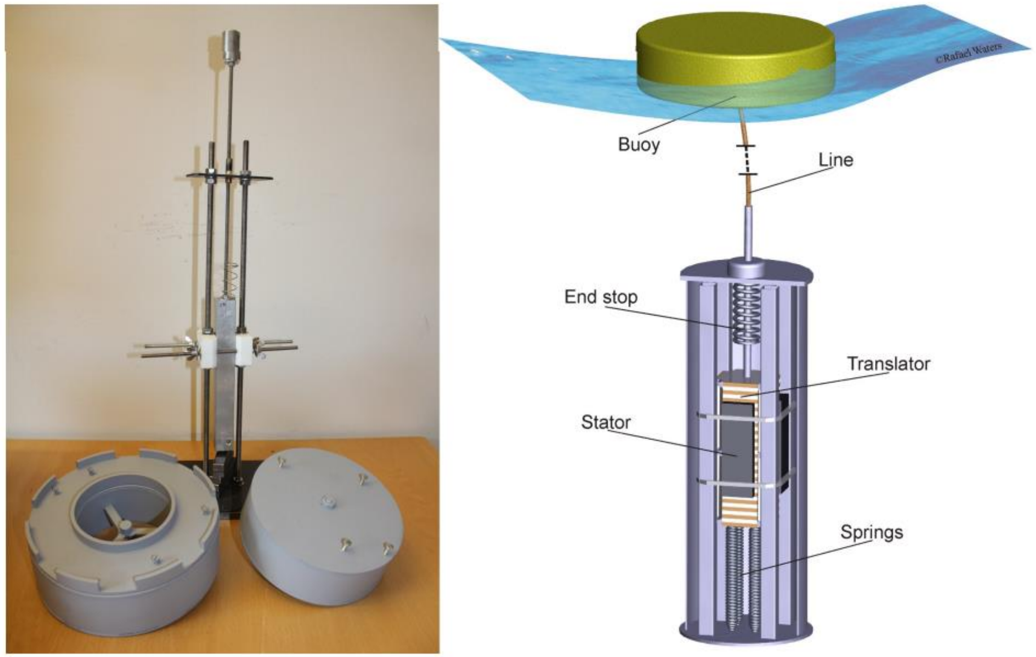
Multi-float M4



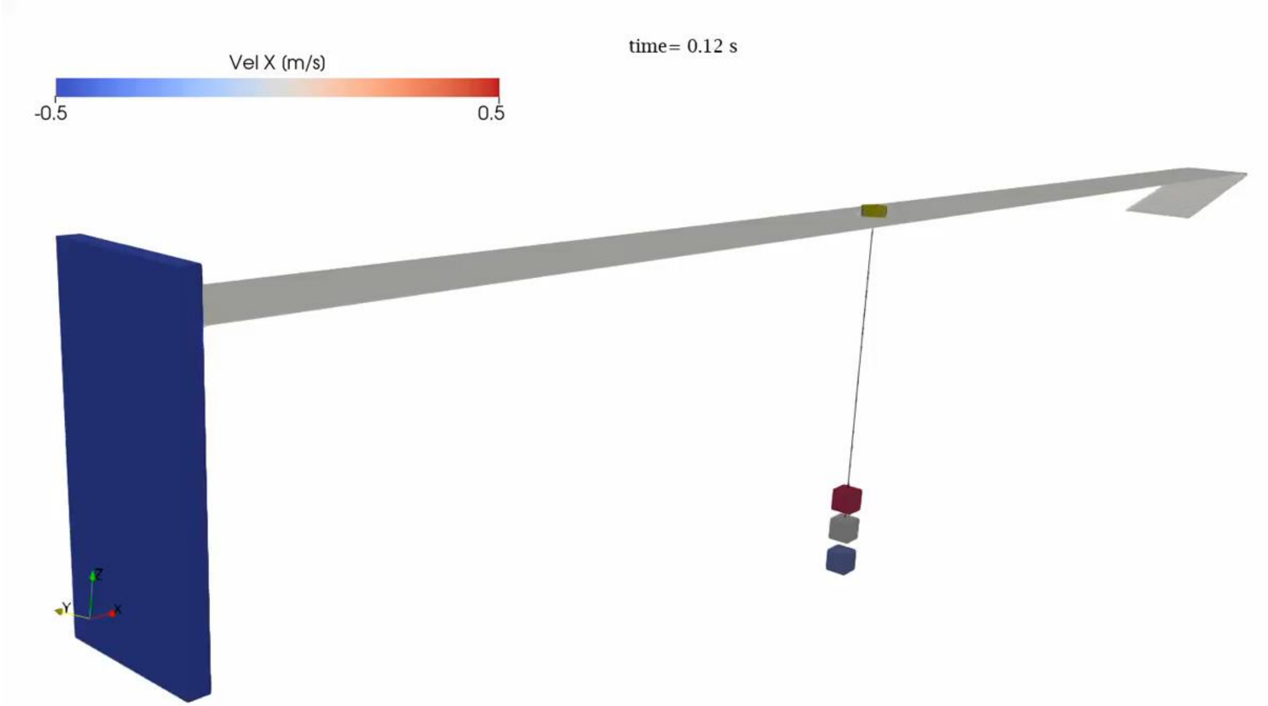
2.1 Uppsala Point Absorber

WEC concept and experiments

- **Floating buoy** and a linear magnet generator (PTO) **connected via a line**.
- The generator is attached on a **ballasted platform** fixed at the seabed.



Source: *Göteman et al., 2015*

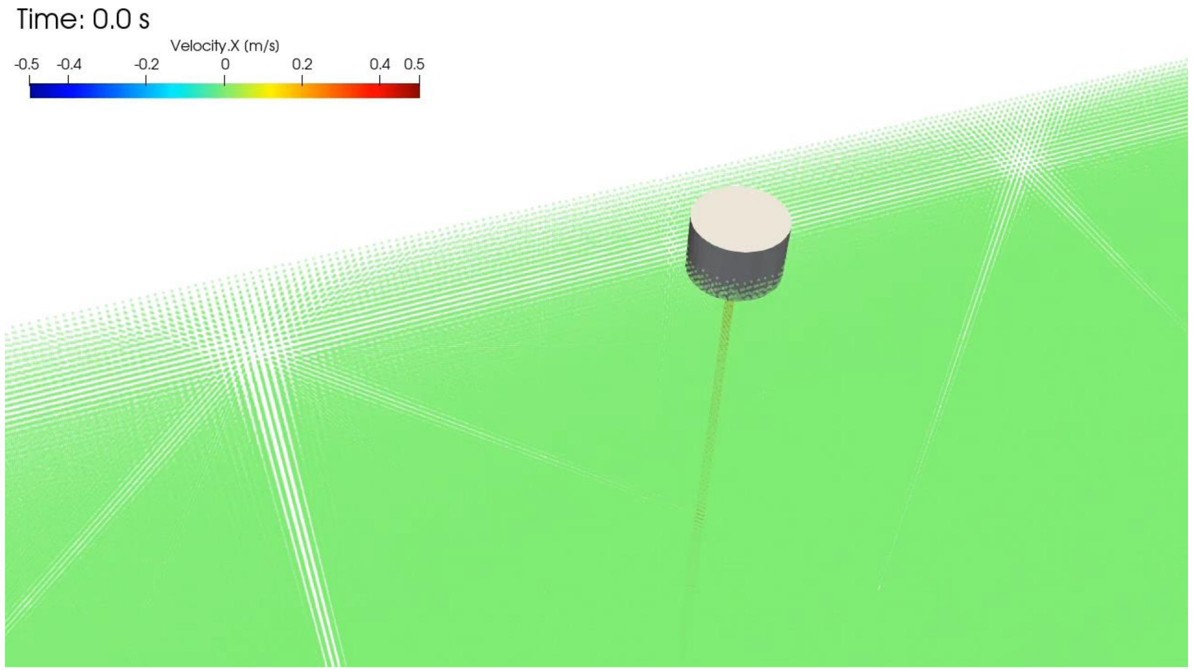


The model is asserted by friction brakes acting on the translator → PROJECT CHRONO

A taut mooring line transmits the rectified motion of the buoy to the translator → MoorDyn+

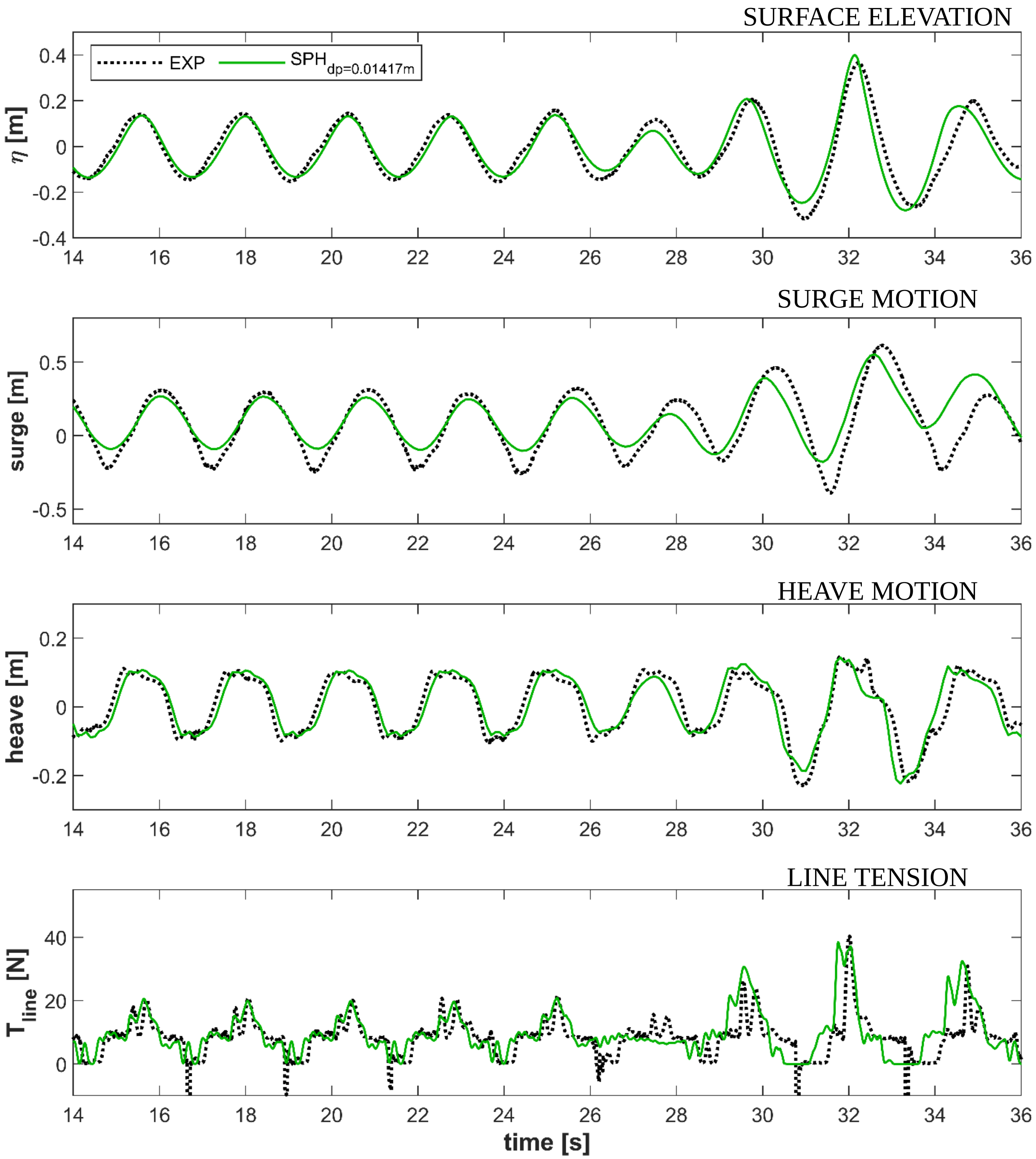
2.1 Uppsala Point Absorber

Validation using DualSPHysics v5.2



Focused wave train (H_{focus}**=0.38 m**, T_{focus}**=2.604 s**)
embedded into regular wave background (***H*****=0.27 m**, ***T*****=2.4 s**)
PTO configuration with only internal **damping (2.79 Ns/m)**

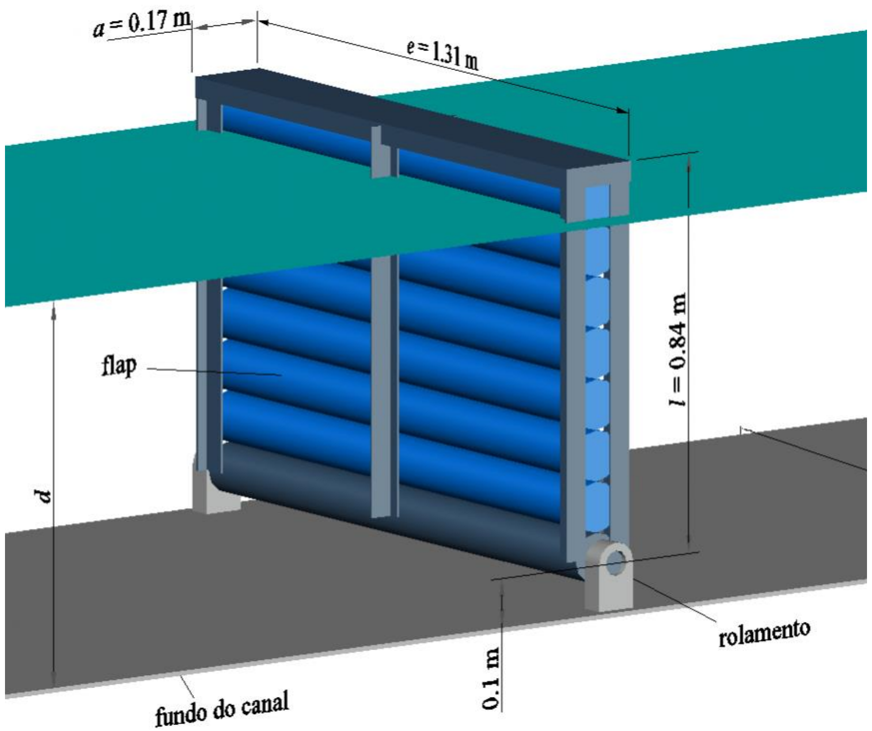
dp [m]	**0.0425**	**0.02125**	**0.01417**
H/dp	8.47	16.94	25.41
particles	$2.03\cdot10^5$	$1.89\cdot10^6$	$6.43\cdot10^6$
runtime	1.0 h	10.6 h	48.3 h
runtime/second	1.5 min	16.8 min	1.3 h



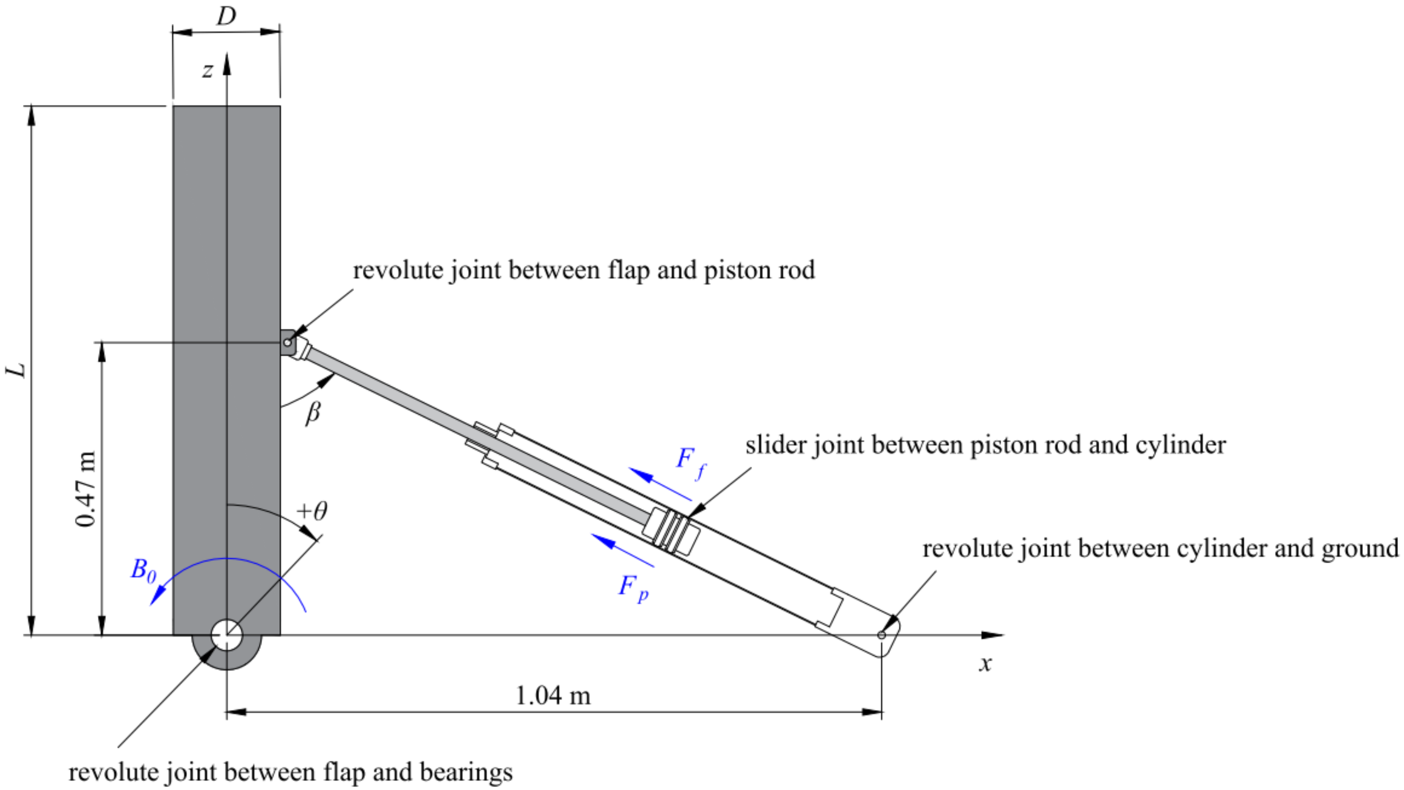
2.2 Oscillating Wave Surge Converter

WEC concept and experiments

- OWSCs are designed to **harness wave energy** nearshore through the **oscillatory pitch motion of a flap**.
- The **flap** consists of PVC tubes joined by a stainless steel frame, and a bearing, and it is **hinged width-wise above the bed**.



Source: *Brito et al., 2017*

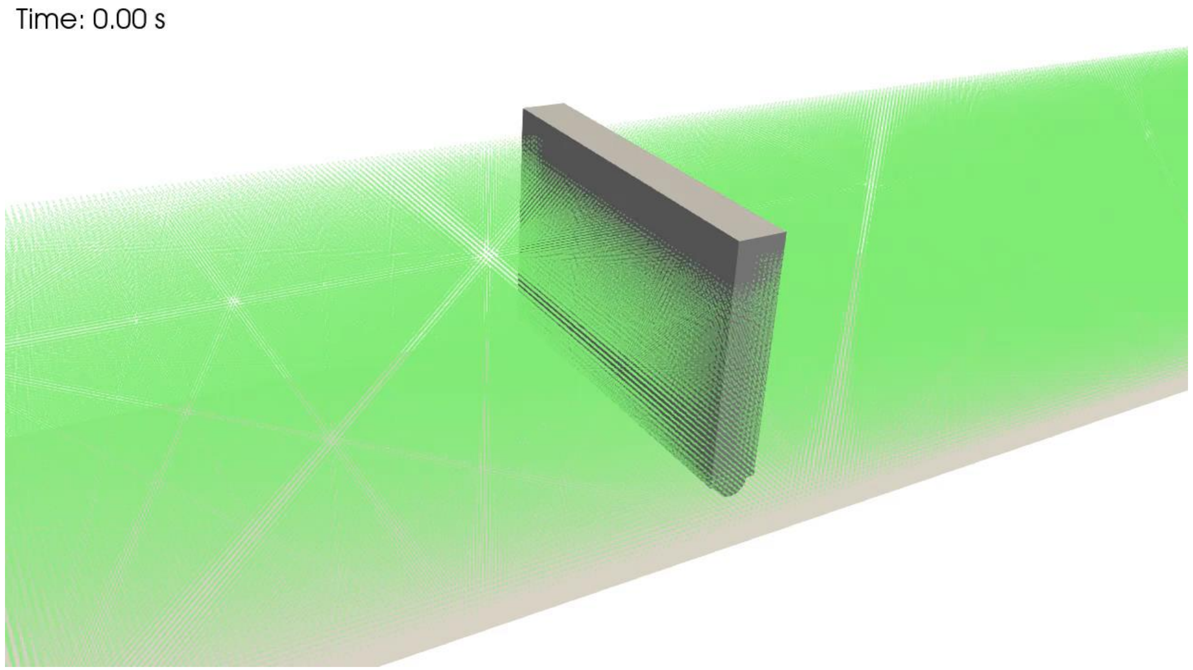


The PTO system: equivalent torque (to the one on the revolute joint) generated by a linear force following a Coulomb damping behaviour

PROJECT CHRONO

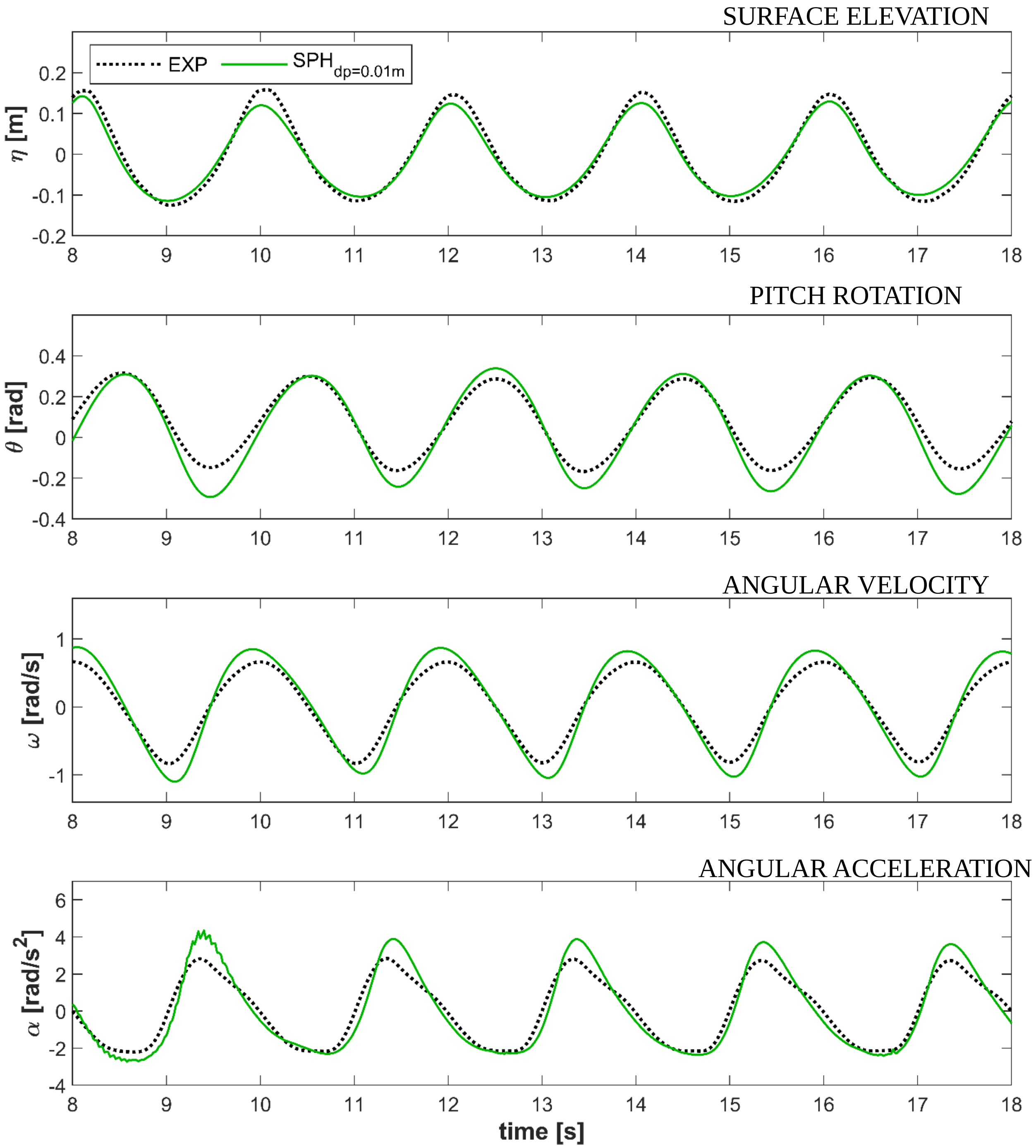
2.2 Oscillating Wave Surge Converter

Validation using DualSPHysics v5.2



Regular wave (***H*=0.25 m, *T*=2 s, depth=0.825 m)**

dp [m]	**0.03**	**0.02**	**0.01**
H/dp	8.33	12.50	25.00
particles	$1.20 \cdot 10^6$	$3.87 \cdot 10^6$	$2.92 \cdot 10^7$
runtime [h]	1.4 h	6.4 h	91.2 h
runtime/second	4.2 min	16.9 min	4.6 h

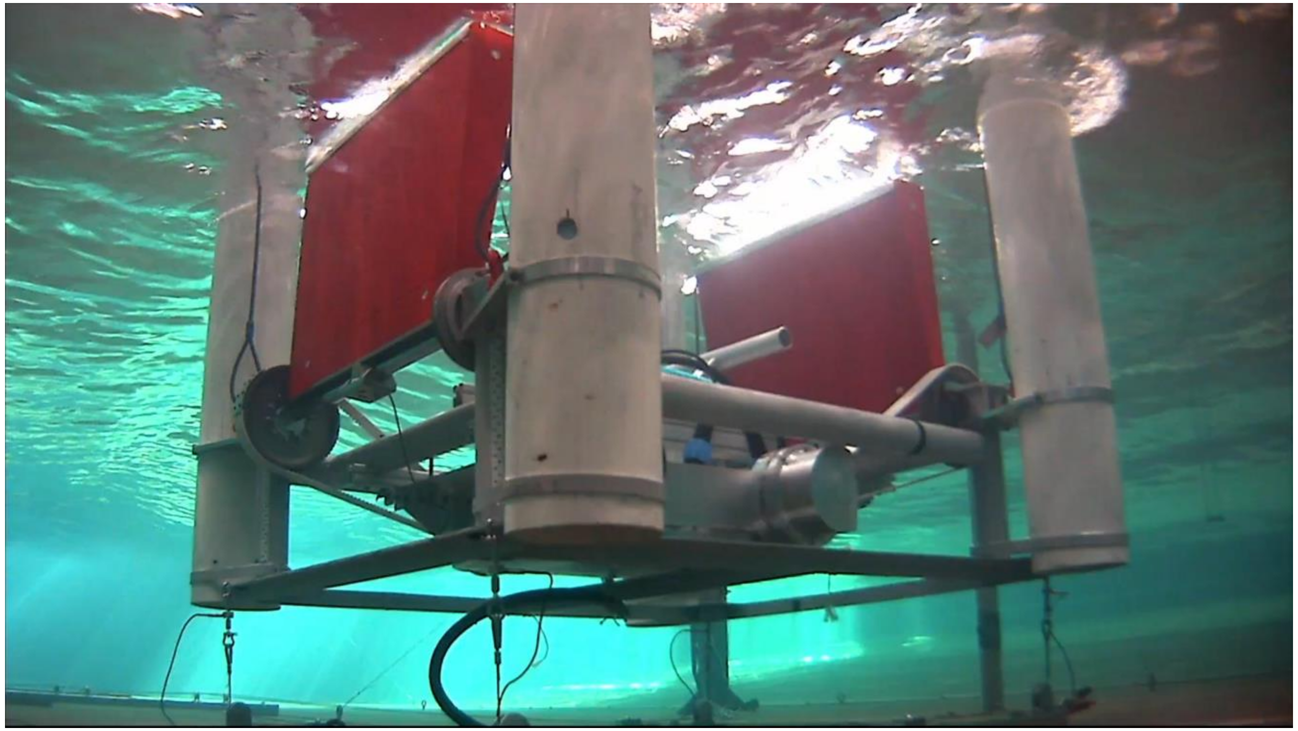


2.3 Floating Oscillating Surge Wave Energy Converter

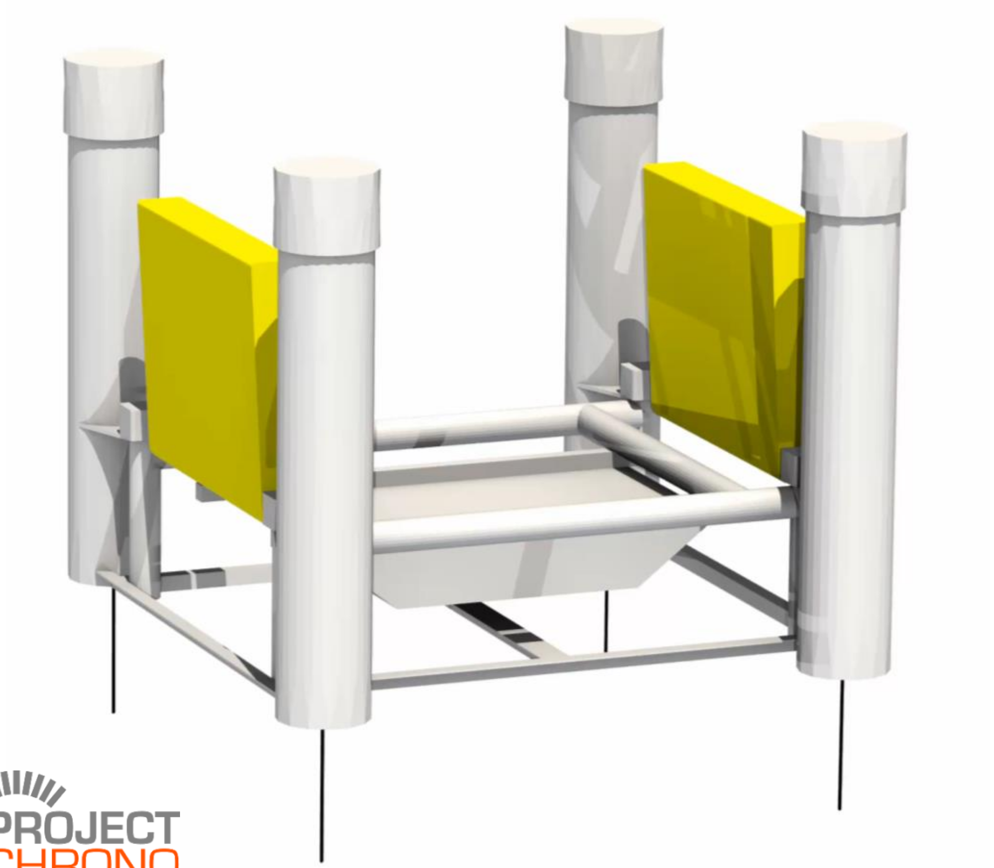
Sandia National Laboratories

WEC concept and experiments

- FOSWEC is a **dualflap** device with a submerged central platform serving as the host for the two flaps.
- The flaps are hinged **to pivot around shafts** mounted to the hull and are controlled by independent motors (PTO).



https://youtu.be/OUxbaEC2K6Y

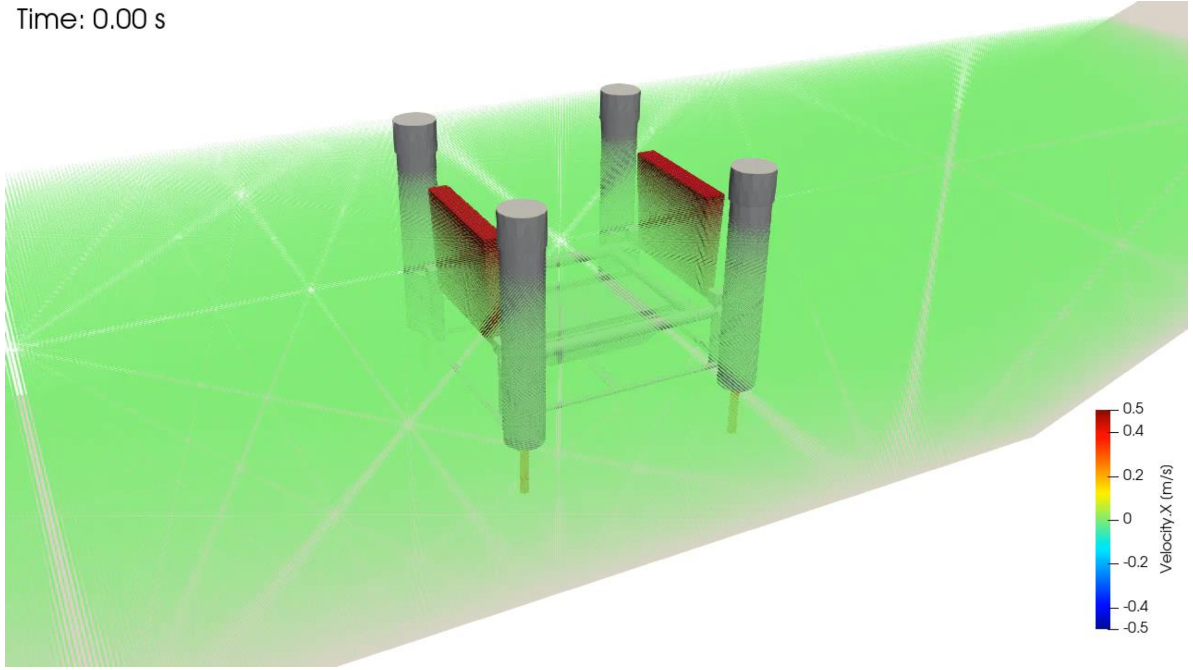


Stiffness and damping coefficients of the PTO system → PROJECT CHRONO

The hull is anchored by 4 mooring taut vertical lines → MoorDyn+

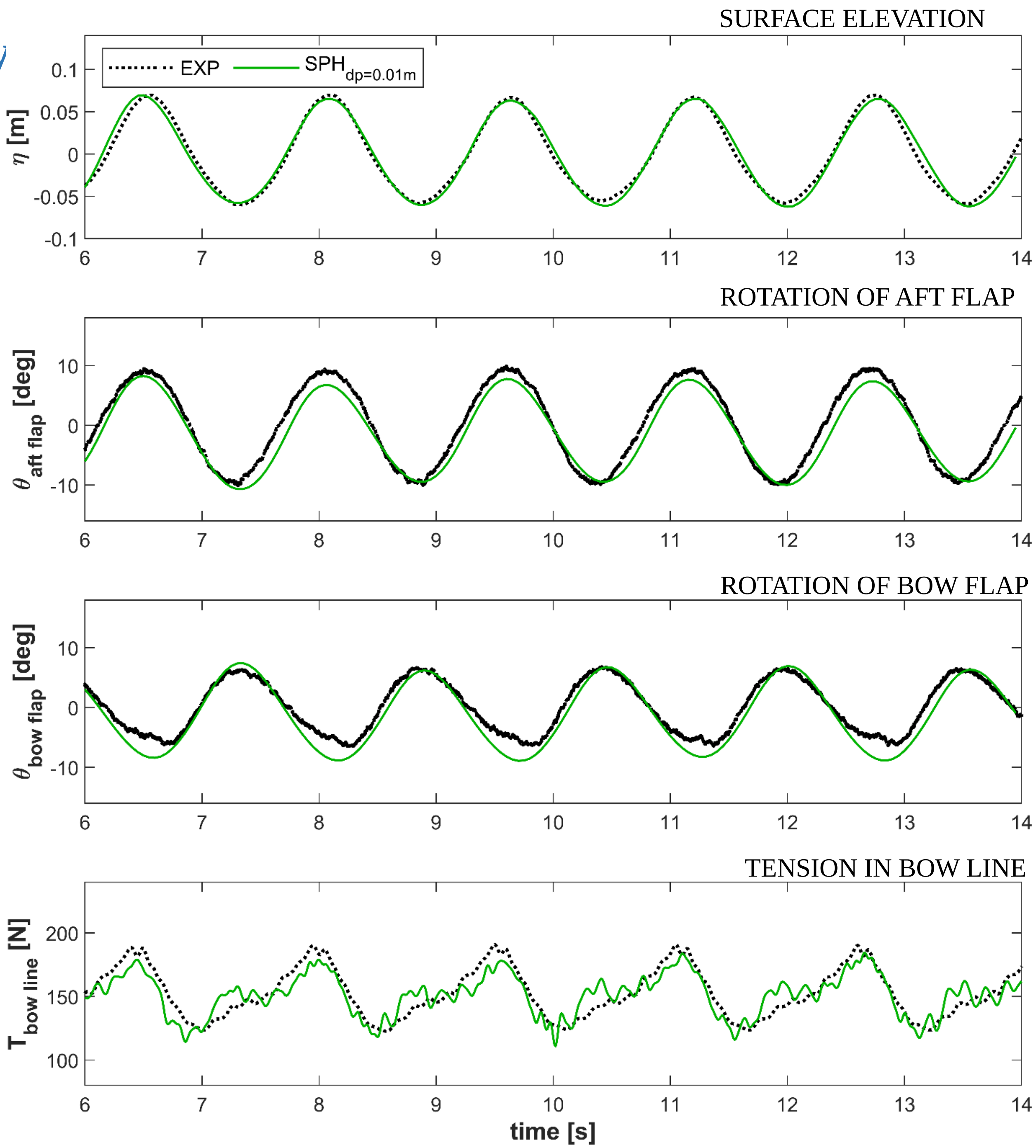
2.3 Floating Oscillating Surge Wave Energy

Validation using DualSPHysics v5.2



Regular wave (***H*=0.136 m, *T*=1.5625 s, depth=1.36 m**)

dp [m]	**0.03**	**0.02**	**0.01**
H/dp	4.53	6.80	13.60
particles	$1.45 \cdot 10^5$	$4.78 \cdot 10^6$	$3.68 \cdot 10^7$
runtime	1.4 h	6.5 h	100.9 h
runtime/second	6.1 min	28.0 min	7.2 h

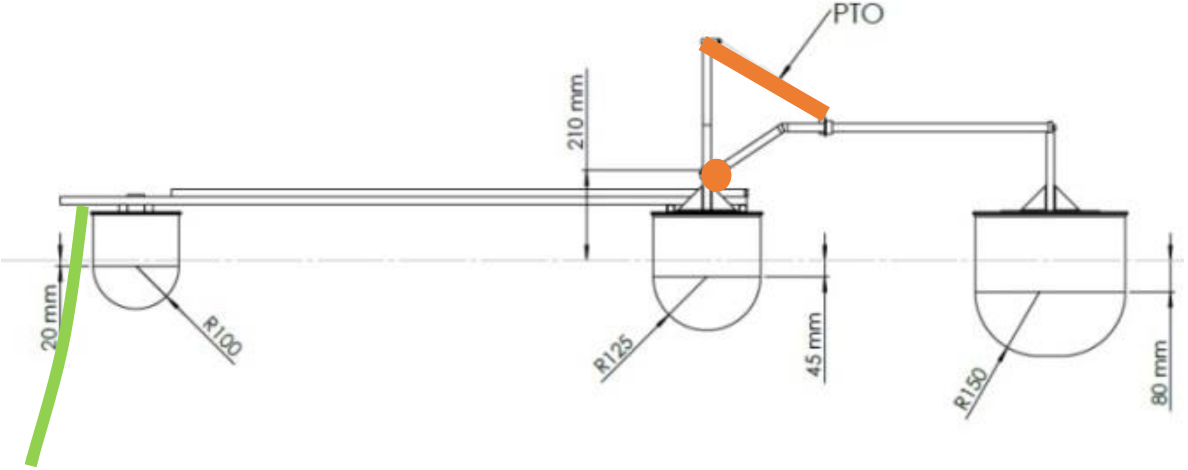


2.4 Multi-float M4

WEC concept and experiments

- The multi-float M4 comprises several floats with **multi-mode forcing**.
- The cylindrical **floats have different diameters and drafts** with hemispherical bases.
- The diameters of the floats and their drafts **increase from bow to aft to facilitate the alignment** with the wave direction.

Source: *Santo et al., 2017*

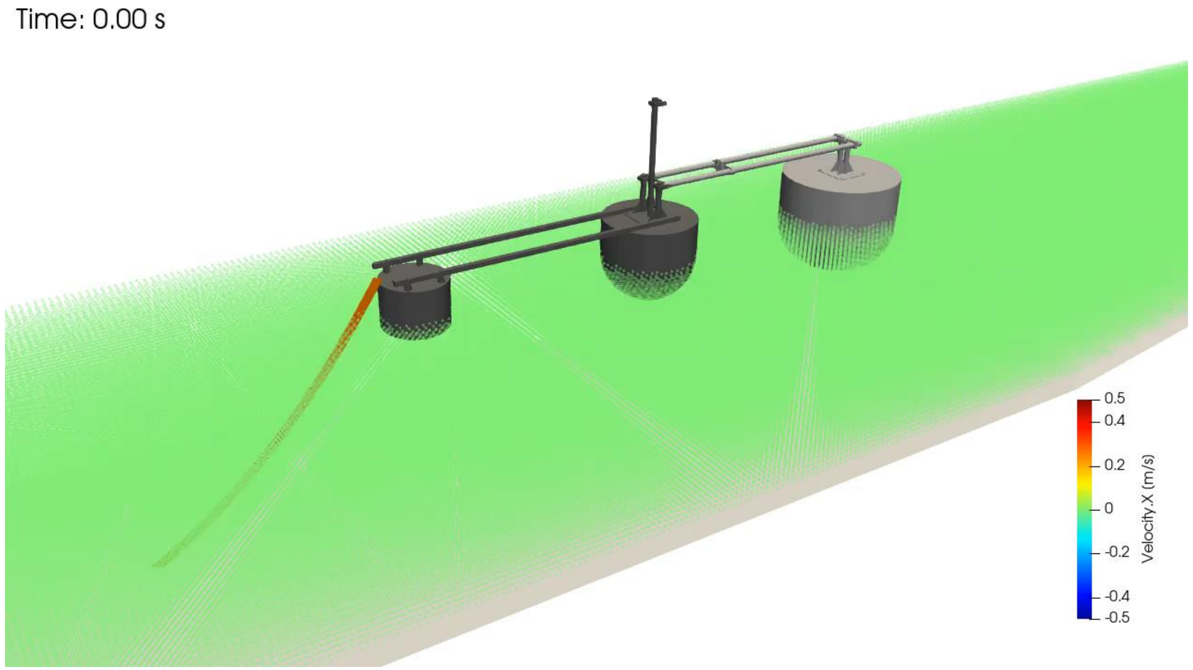


Interaction wave-WEC — **SPH**
Mooring line — **MoorDyn+**
Mechanical constraint "hinge"
Pneumatic actuator or damper

PROJECT CHRONO

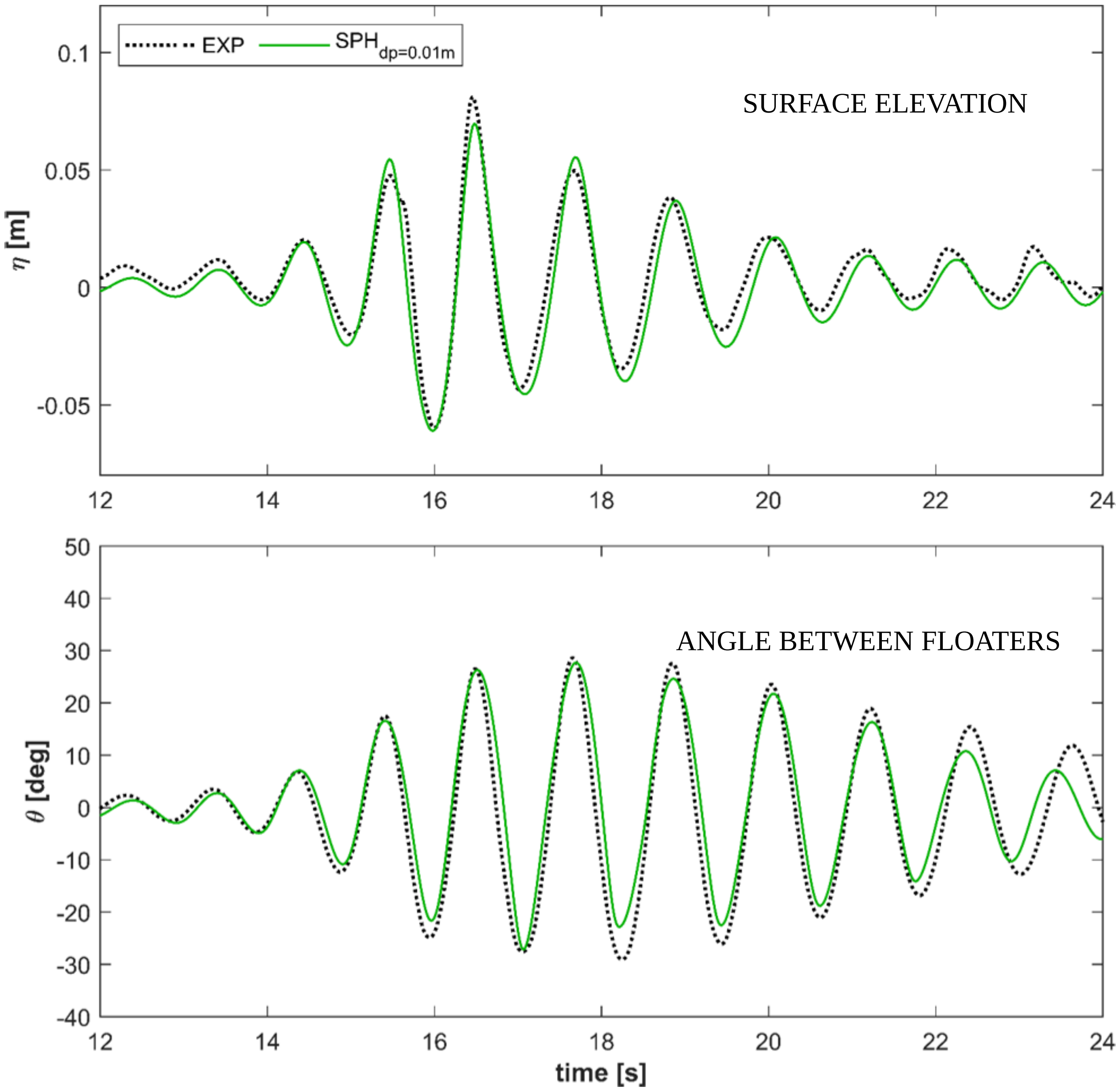
2.4 Multi-float M4

Validation using DualSPHysics v5.2



Focused wave (**H_{focus}=0.16 m, T_{focus}=1.1 s, depth=0.6 m)**

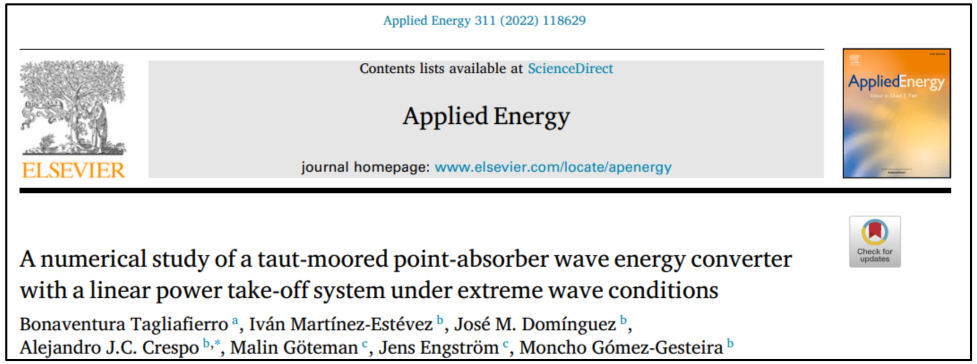
dp [m]	0.03	0.02	0.01
H/dp	5.33	8.00	16.00
particles	$3.30 \cdot 10^5$	$1.20 \cdot 10^6$	$7.46 \cdot 10^6$
runtime	0.6 h	2.1 h	24.9 h
runtime/second	1.4 min	4.9 min	59.6 min



Previous published work

2.1 Uppsala Point Absorber

*Tagliafierro B, Martínez-Estévez I, Domínguez JM, **Crespo AJC**, 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, 118629.*


Applied Energy 311 (2022) 118629

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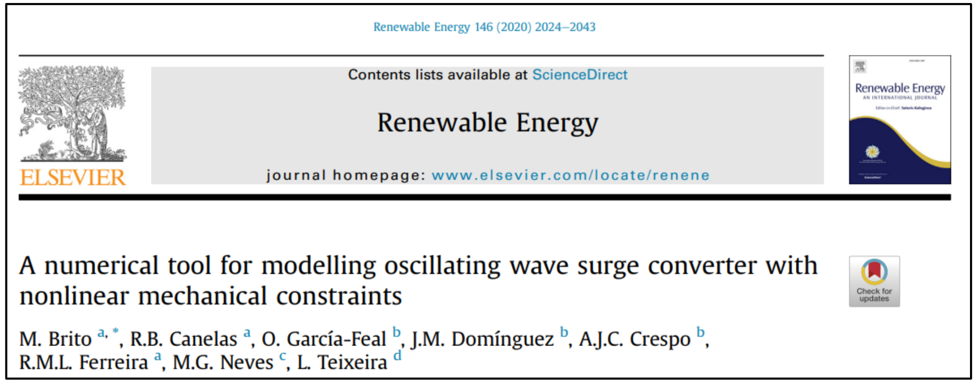
ELSEVIER

A numerical study of a taut-moored point-absorber wave energy converter with a linear power take-off system under extreme wave conditions

Bonaventura Tagliafierro [a], Iván Martínez-Estévez [b], José M. Domínguez [b], Alejandro J.C. Crespo [b,*], Malin Göteman [c], Jens Engström [c], Moncho Gómez-Gesteira [b]

2.2 Oscillating Wave Surge Converter

*Brito M, Canelas RB, García-Feal O, Domínguez JM, **Crespo AJC**, Ferreira RML, Neves MG, Teixeira L. 2020. A numerical tool for modelling oscillating wave surge converter with nonlinear mechanical constraints. **Renewable Energy**, 146, 2024-2043.*


Renewable Energy 146 (2020) 2024–2043

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A numerical tool for modelling oscillating wave surge converter with nonlinear mechanical constraints

M. Brito [a,*], R.B. Canelas [a], O. García-Feal [b], J.M. Domínguez [b], A.J.C. Crespo [b], R.M.L. Ferreira [a], M.G. Neves [c], L. Teixeira [d]

2.3 Floating Oscillating Surge Wave Energy Converter

*Tagliafierro B, Martínez-Estévez I, Crego-Loureiro C, Domínguez JM, **Crespo AJC**, Coe R, Bacelli G, Gómez Gesteira M, Viccione G. 2022. Numerical modeling of moored floating platforms for wave energy converters using DualSPHysics. In: Proceedings of the 41st International Conference on Ocean, Offshore & Arctic Engineering, Hamburg, Germany. **OMAE 2022***

2.4 Multi-float M4

*Carpintero Moreno E, Fourtakas G, **Crespo AJC**, Stansby PK. 2020. Response of the multi-float WEC M4 in focussed waves using SPH. In: 4th International Conference on Renewable Energies Offshore, Lisbon, Portugal. **RENEW 2020.***

OUTLINE

1. Numerical modelling of WECs
    1.1 Meshless CFD and SPH
    1.2 DualSPHysics open-source code
    1.3 Coupling with other solvers

2. Simulation of different WEC technologies
    2.1 Uppsala Point Absorber
    2.2 Oscillating Wave Surge Converter
    2.3 Floating Oscillating Surge Wave Energy Converter
    2.4 Multi-float M4

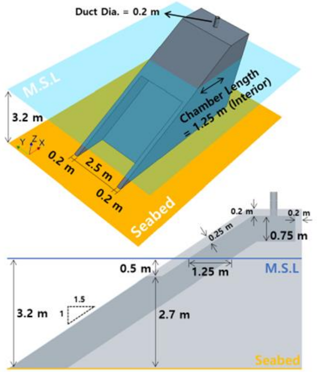
3. Work undergoing
    3.1 More WEC technologies
    3.2 Active control systems
    3.3 Flexible WECs

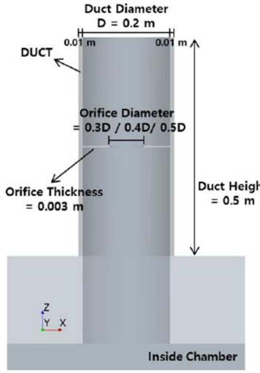
4. Conclusions

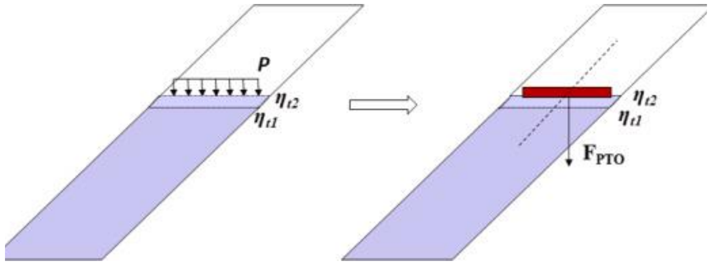
3.1 More WEC technologies

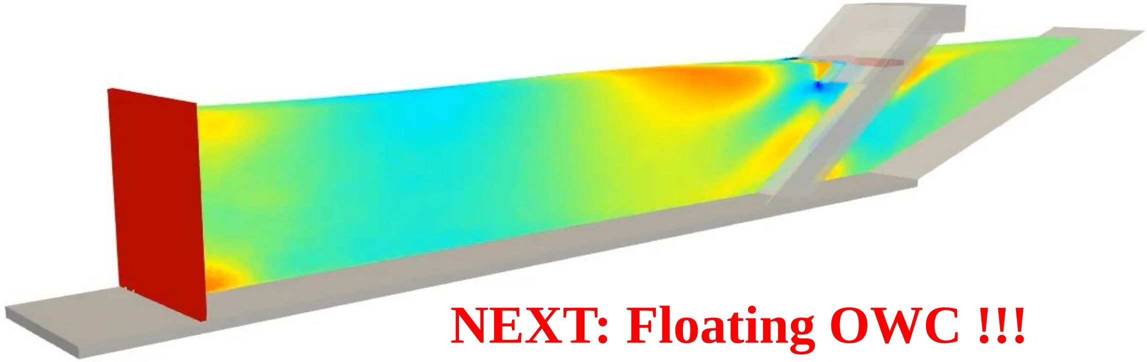
OWC

*Quartier N, **Crespo AJC**, Domínguez JM, Stratigaki V, Troch P. 2021. Efficient response of an onshore Oscillating Water Column Wave Energy Converter using a one-phase SPH model coupled with a multiphysics library. **Applied Ocean Research**, 115, 102856.*





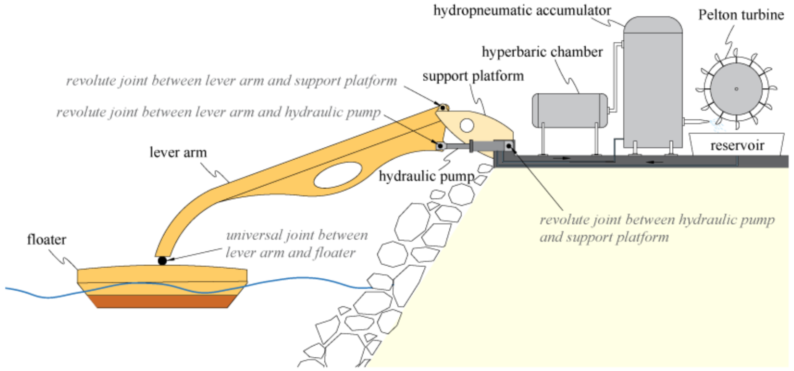


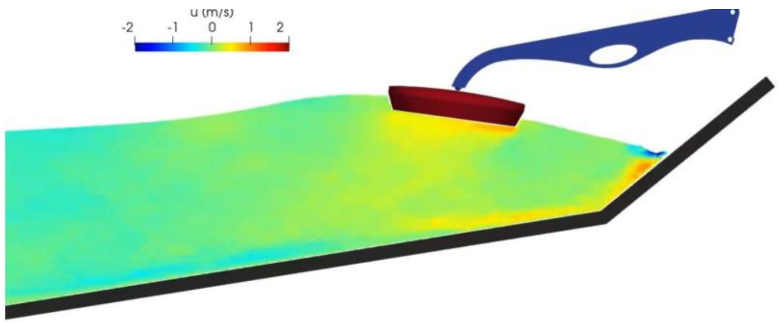


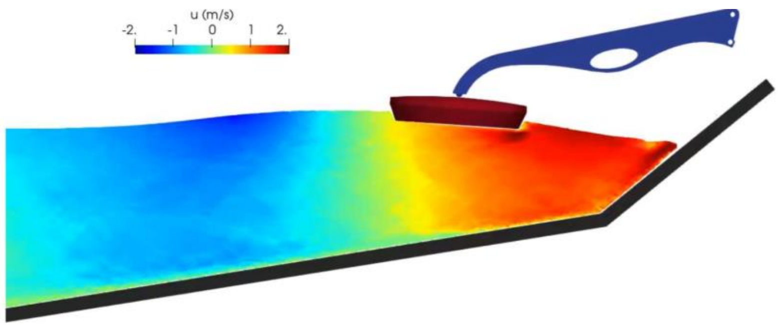
NEXT: Floating OWC !!!

WaveStar

*Brito M, Bernardo F, Neves MG, Neves DRCB, **Crespo AJC**, Domínguez JM. 2022. Numerical Model of Constrained Wave Energy Hyperbaric Converter under Full-Scale Sea Wave Conditions. **Journal of Marine Science and Engineering**, 10(10), 1489.*







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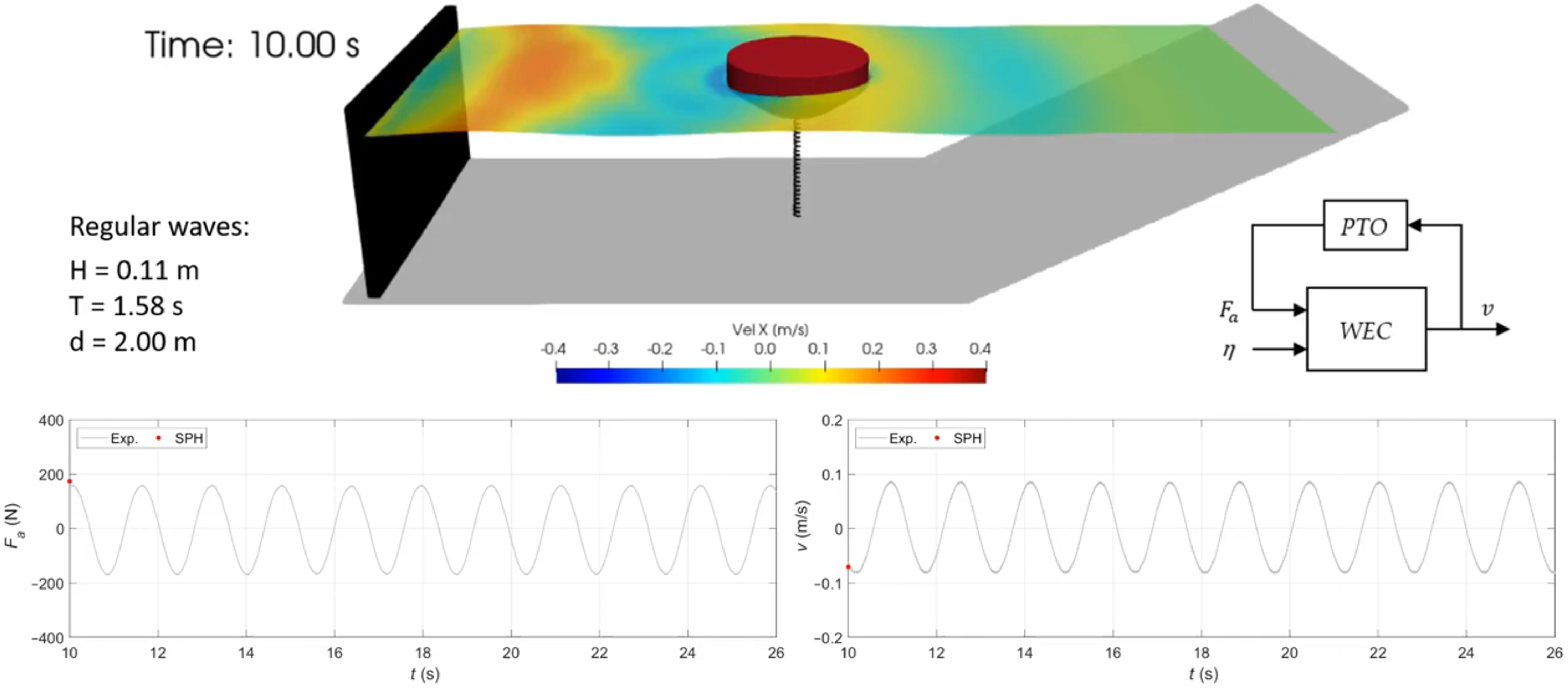
CLOSED-LOOP SYSTEM CONTROLLER

Point absorber with a closed-loop system defining the **PTO force as function of the WEC's position and velocity**



*Ropero-Giralda P, **Crespo AJC**, Coe RG, Tagliafierro B, Domínguez JM, Bacelli G, Gómez-Gesteira M. 2021. Modelling a heaving point-absorber with a closed-loop control system using the DualSPHysics code. **Energies** 14(3), 760.*

3.3 Flexible WECs

Numerical implementation of flexible-structure interaction (FSI)

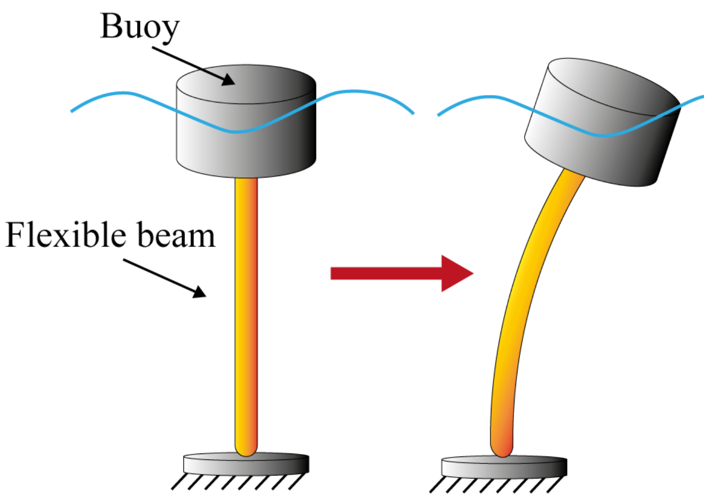
OPTION 1: Fully Lagrangian: SPH for fluid and total Lagrangian SPH for the solid solver

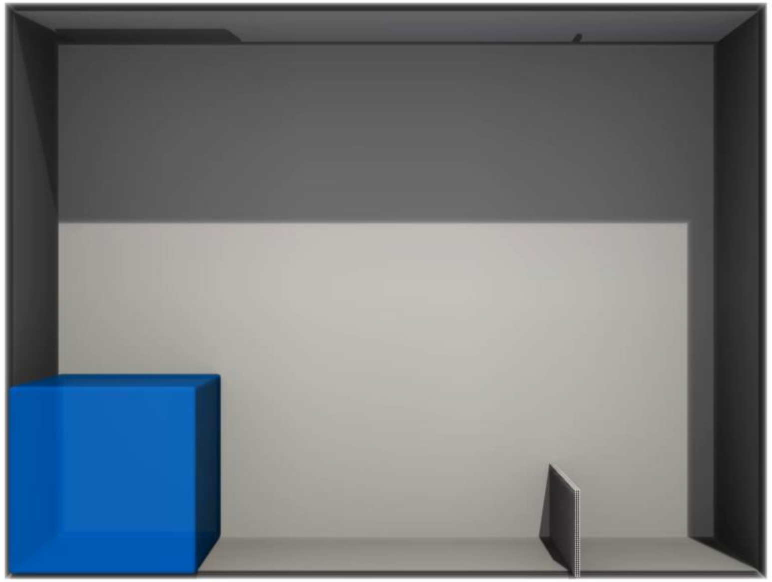
*O'Connor J, Rogers BD. 2021. A fluid-structure interaction model for free-surface flows and flexible structures using smoothed particle hydrodynamics on a GPU, **Journal of Fluids and Structures**, 104, 103312.*

OPTION 1 already in DualSPHysics v5.2

OPTION 2: Fully Lagrangian: SPH for fluid coupled with FEA module of Project Chrono

*Martínez-Estévez I, Tagliafierro B, El Rahi J, Domínguez JM, **Crespo AJC**, Troch P, Gómez-Gesteira M. 2023. Coupling an SPH-based solver with an FEA structural solver to simulate free surface flows interacting with flexible structures. **Computer Methods in Applied Mechanics and Engineering**, 410, 115989.*





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4. Conclusions

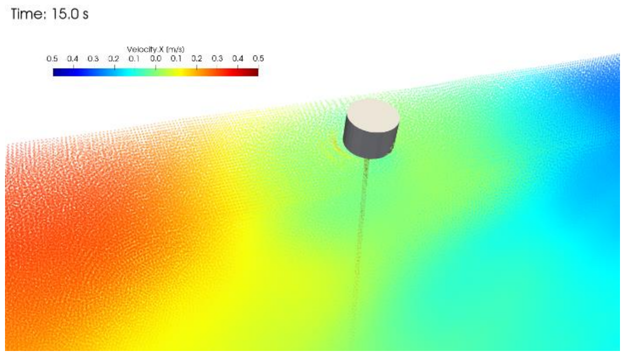
OUR APPROACH

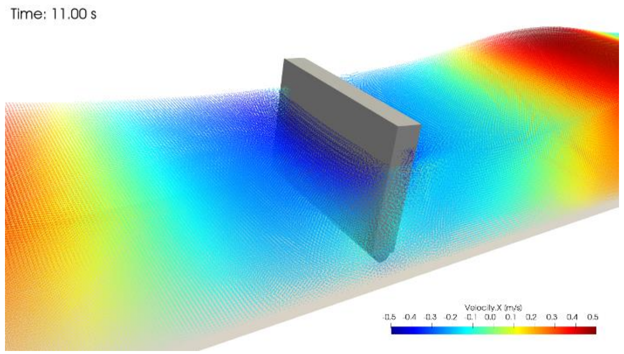
Meshless **SPH** method for **violent flows** with rapidly moving or **fluid-driven devices**

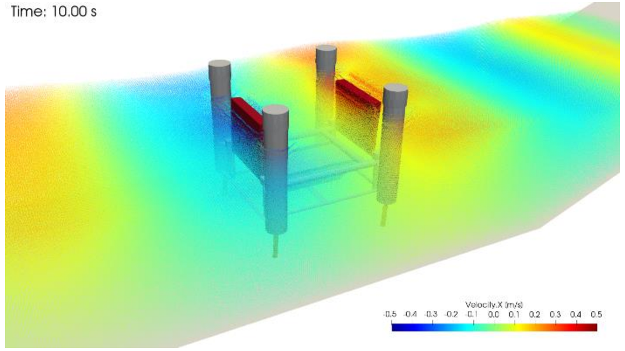
DualSPHysics v5.2 is applied to **four well-established WEC concepts**

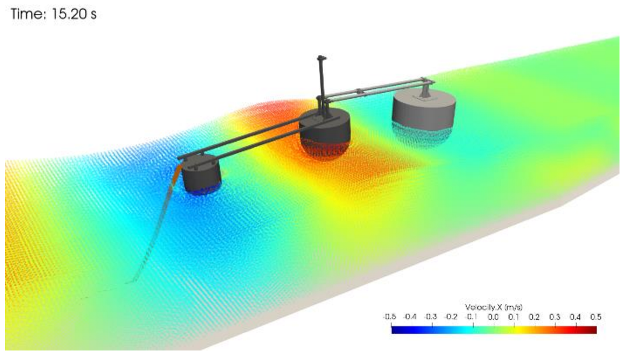
Study of not only the **efficiency but also the survivability** of WECs.

We provide a **free numerical tool** into simulating **other novel WEC** devices









<u>Our message:</u>

- We have a mature technology to cope with any kind of device, no matter how complex it may be
- This numerical tool is capable of simulating devices under extreme waves including active control systems
- We want you to collaborate with us! Please feel free to contact us!

WORK TEAM

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Salvatore Capasso, Giacomo Viccione,

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Georgios Fourtakas, Benedict D. Rogers, Peter K. Stansby

MARINE, CIVIL AND MECHANICAL ENGINEERS

COMPUTERS SCIENCE ENGINEERS

PHYSICISTS

THANKS A LOT FOR YOUR ATTENTION

ESKERRIK ASKO

MORE INFORMATION:

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