MULTIPHYSICS ENGINEERING PROBLEMS IN MARINE RENEWABLE ENERGY

Challenges and Opportunities with SPH

Bonaventura Tagliafierro – June 16, 2025

btagliafierro@gmail.com

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No: 101109440.

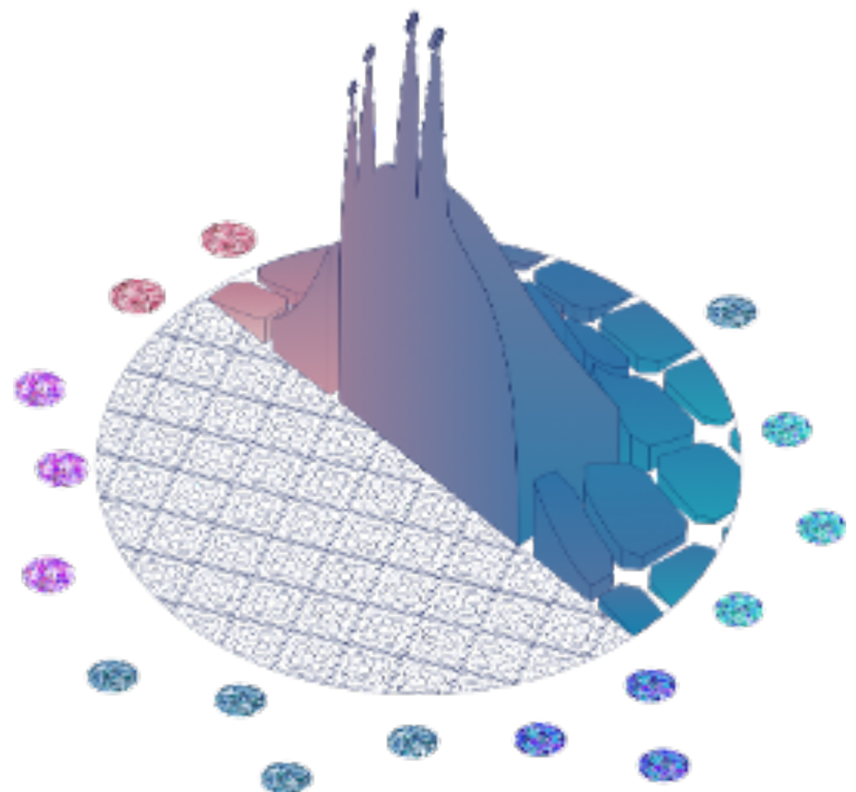
Funded by the European Union

MARIE SKŁODOWSKA-CURIE ACTIONS
Research Fellowship Programme

IM-POWER

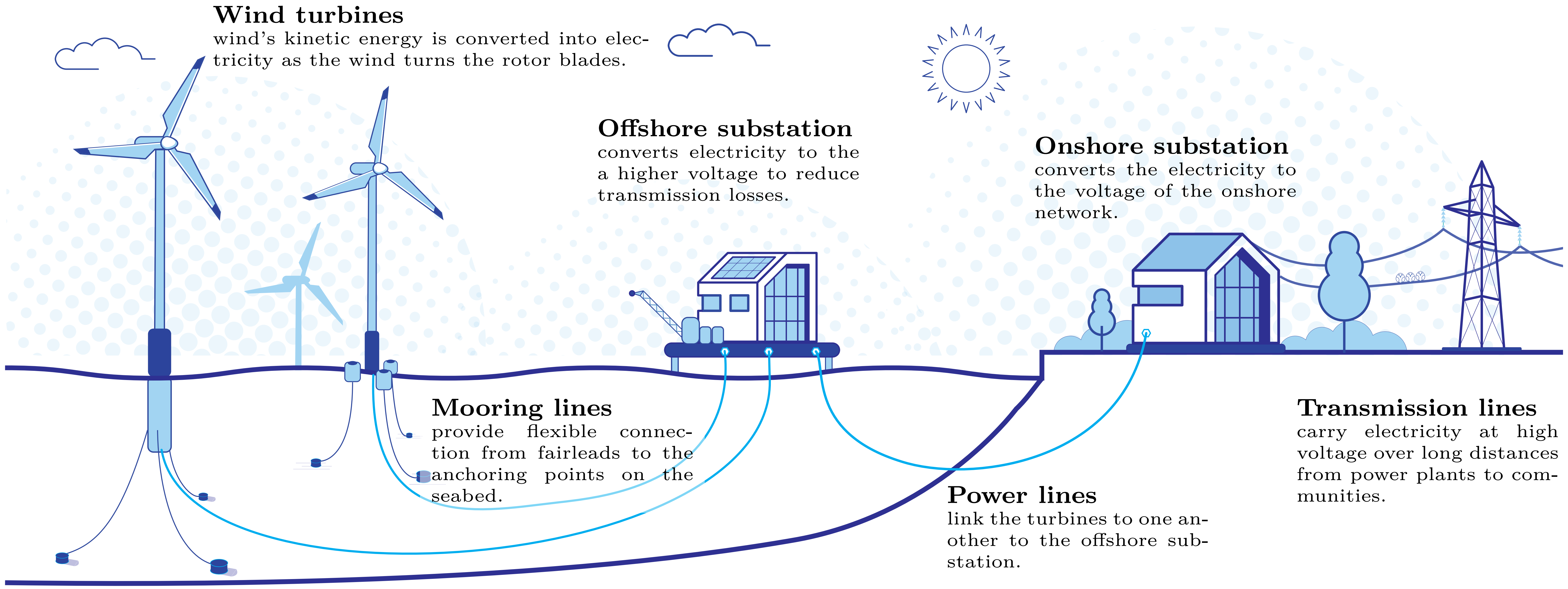
UPPSALA UNIVERSITET

hexicon



The IM-POWER project

Primary goal:
Power output of a floating wind farm under storm conditions



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No: 101109440.

Funded by the European Union

MARIE SKŁODOWSKA-CURIE ACTIONS
Research Fellowship Programme

IM-POWER

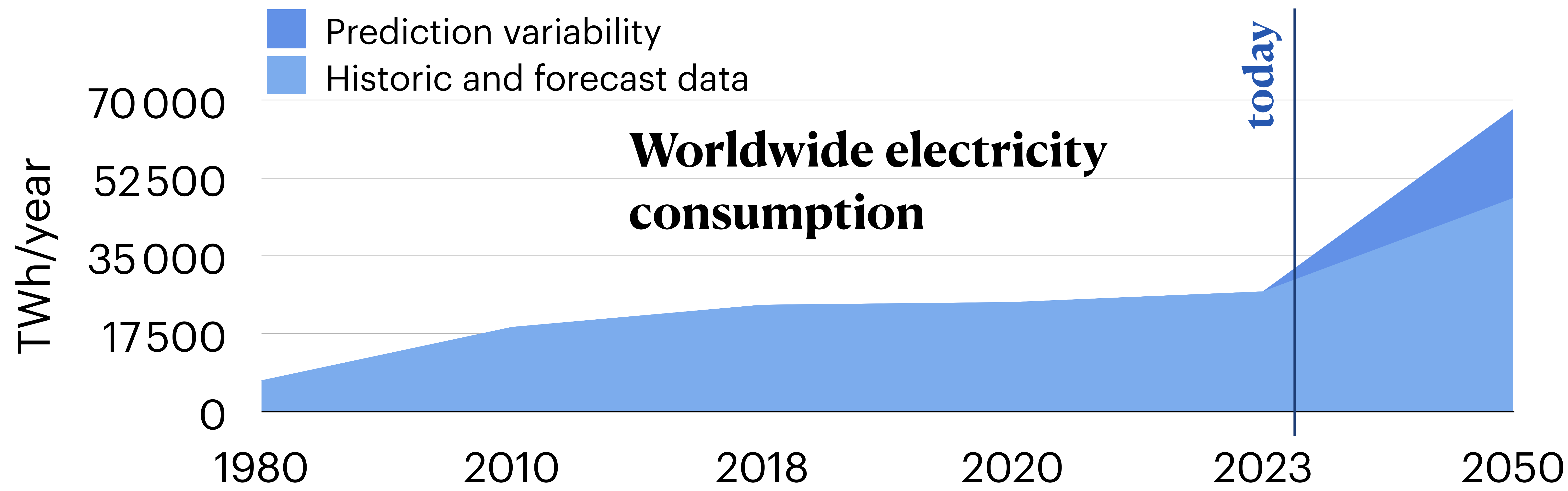
Our team

Prof Malin Göteman
Prof Hans Bernhoff

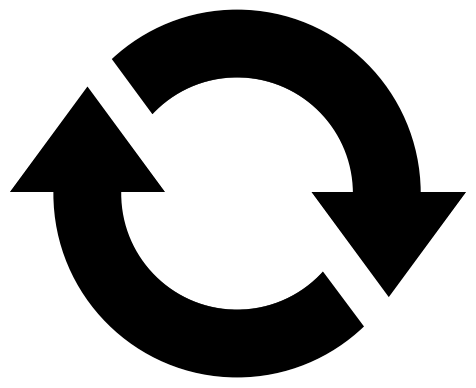
Dr Victor Mendoza
Guilherme Nunes

hexicon

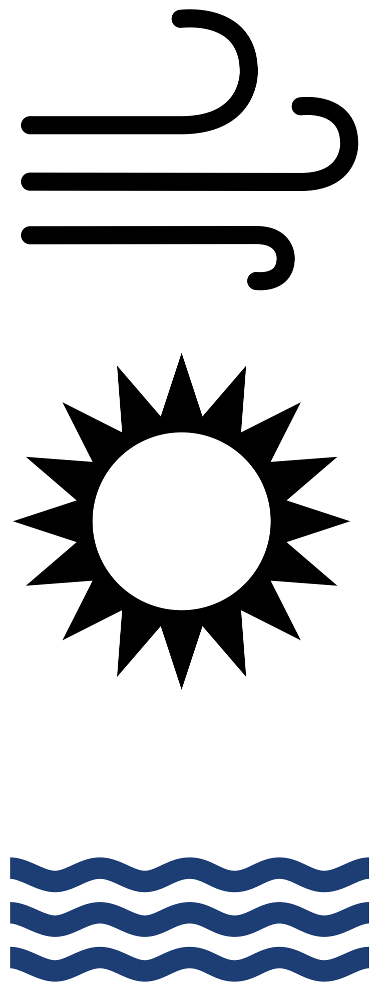
Outlook on Offshore Renewable Energy (ORE)



The Renewable Contribution?



80% by 2050



The largest part will be covered by onshore Wind and Solar

Ocean Renewable Energy sources can significantly contribute

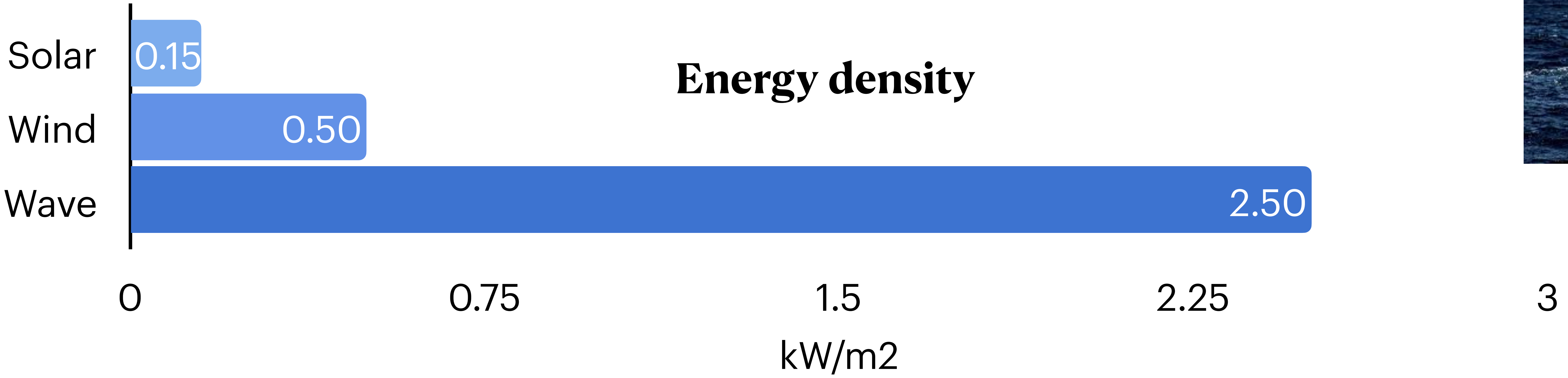
- **Diversification potential**
- **Grid stability**
- **Limit social challenges**
- **Off-grid distribution**

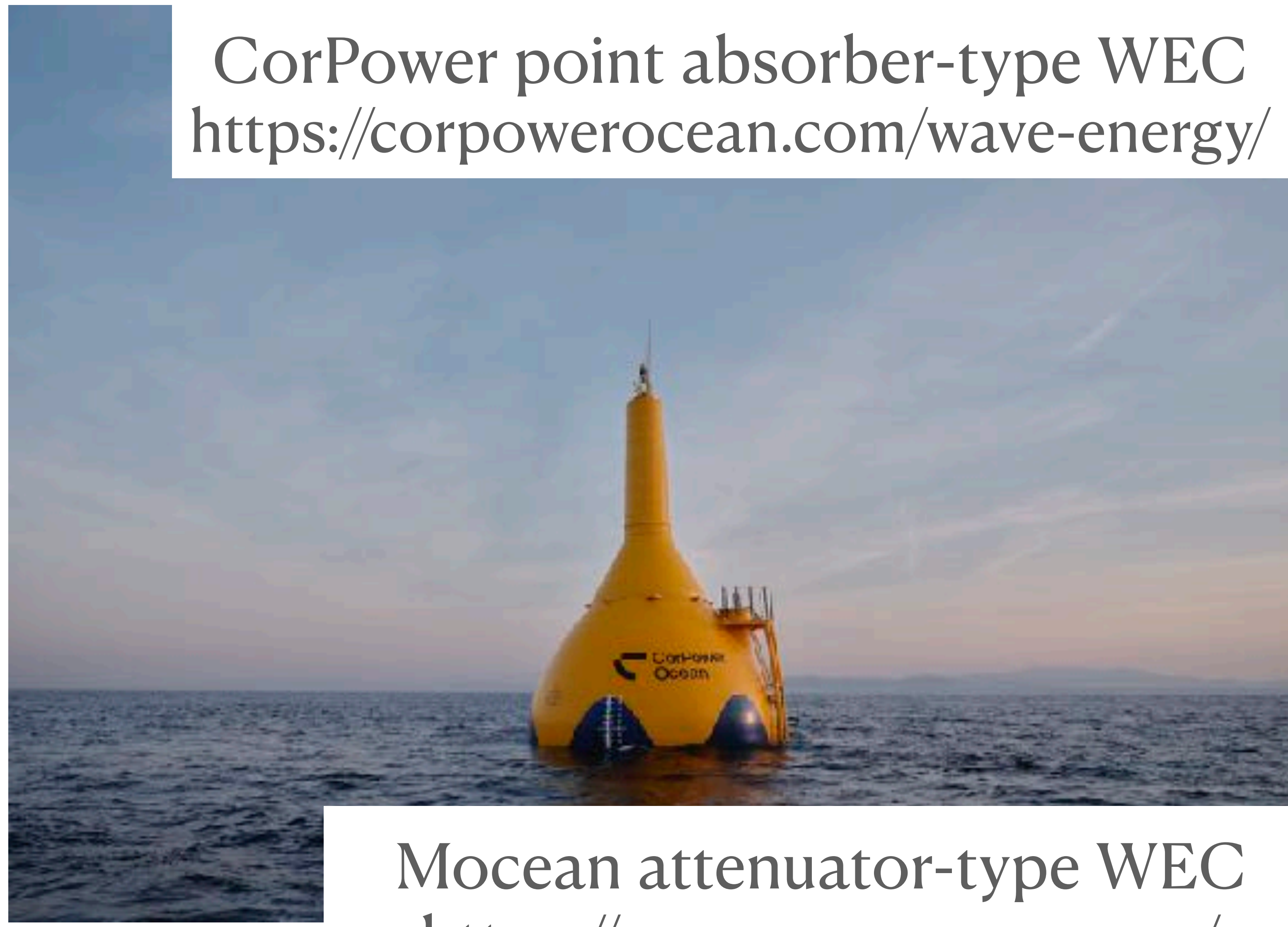
Outlook on Offshore Renewable Energy (ORE)

ORE devices:

- Tidal Current turbines
- Floating Photovoltaic panels
- **Floating Offshore Wind Turbines (FOWTs)**
- **Wave Energy Converters (WECs)**

- Abundant resource
- Low variability
- High predictability





CorPower point absorber-type WEC
https://corpowerocean.com/wave-energy/

Mocean attenuator-type WEC
https://www.mocean.energy/

Modeling dilemma

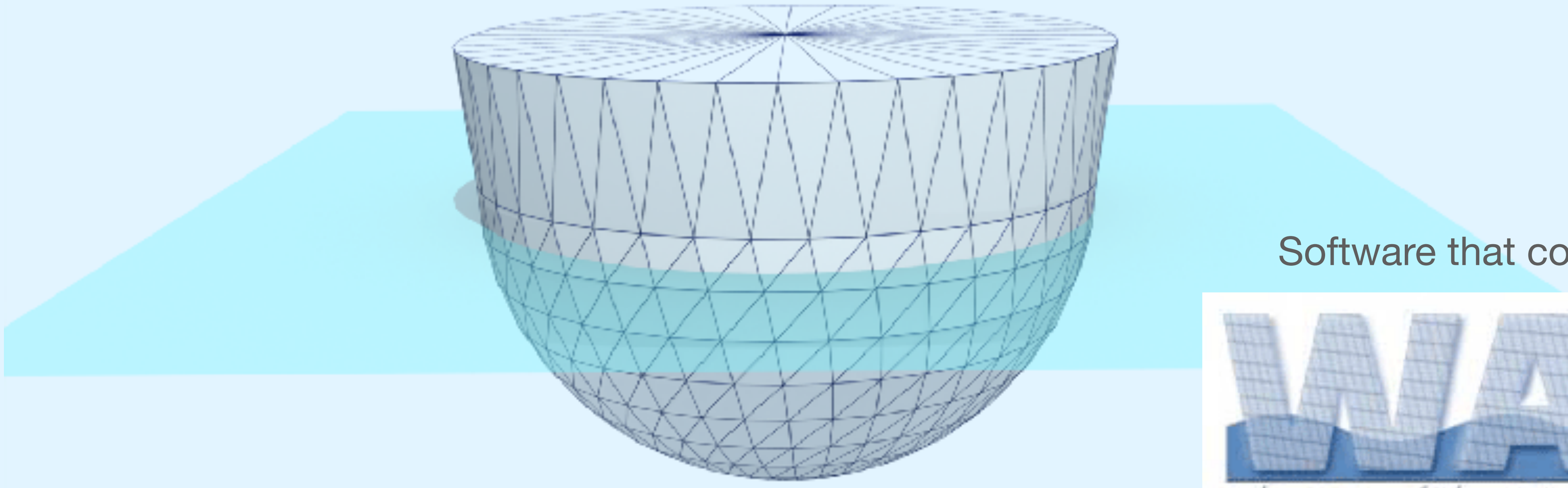
$$\mathbf{M}\,\ddot{\mathbf{x}}(t) = \mathbf{f}_{hydro}(t) + \mathbf{f}_{PTO}(t) + \mathbf{f}_{mooring}(t)$$

Equation of motion for a rigid body

Added mass — Retardation function — Restoring — Wave excitation

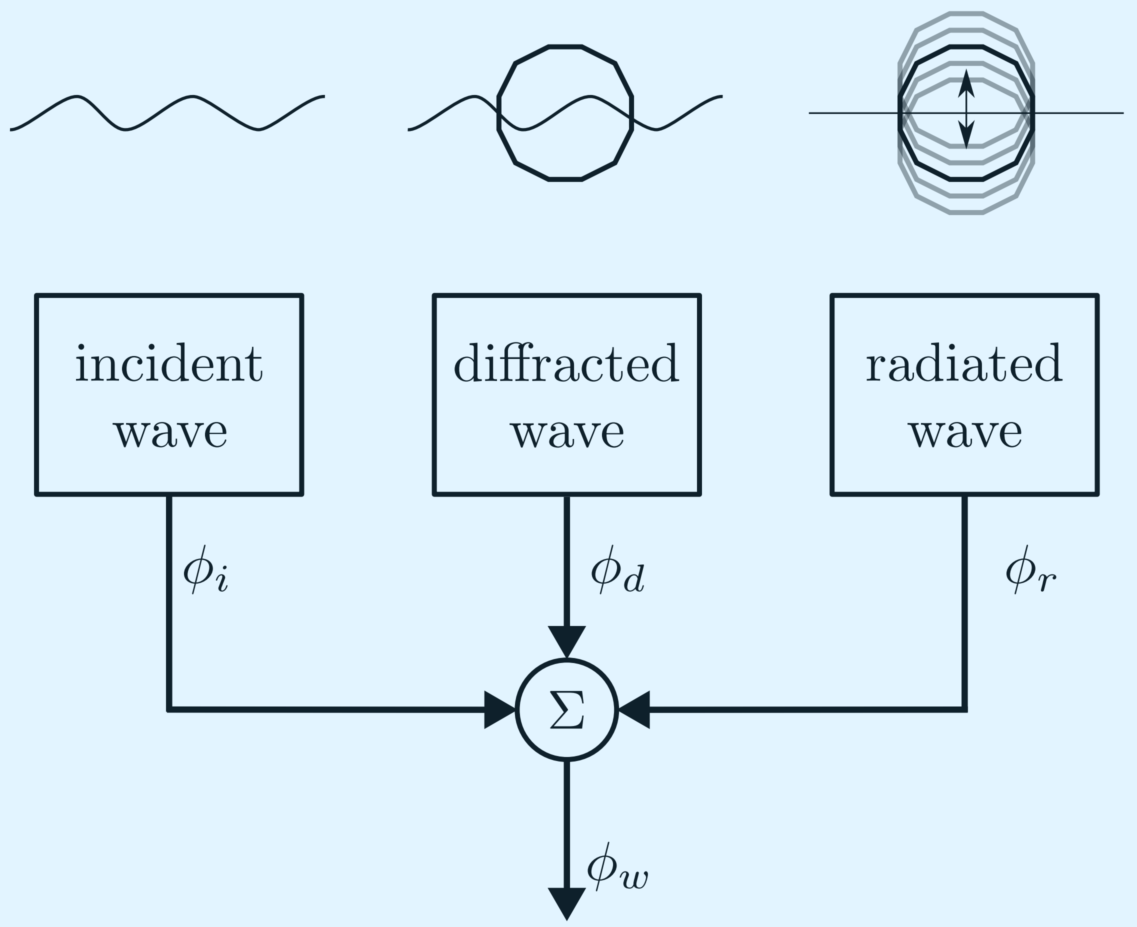
$$\left[\mathbf{M}+\mathbf{M}_a\right]\ \ddot{\mathbf{x}}(t)+\int_0^t \mathbf{K}(t-\tau)\,\dot{\mathbf{x}}(\tau)\,d\tau + \mathbf{R}\,\mathbf{x}(t) = \mathbf{f}_{exc}(t)+\mathbf{f}_{PTO}(t)+\mathbf{f}_{mooring}(t)$$

Cummins equation



Software that could be used, for example: WAMIT INC — The State of the Art in Wave Interaction Analysis

Courtesy Dr. Bruno Paduano @ Polito (Italy)



- Linear wave theory applies (small-amplitude waves)
- Fluid is inviscid, incompressible, and irrotational
- Small oscillations (linearized kinematics)

Cummins, W. E. (1962). *The impulse response function and ship motions* (DTMB Report No. 1661). David Taylor Model Basin, Department of the Navy, Washington, D.C.

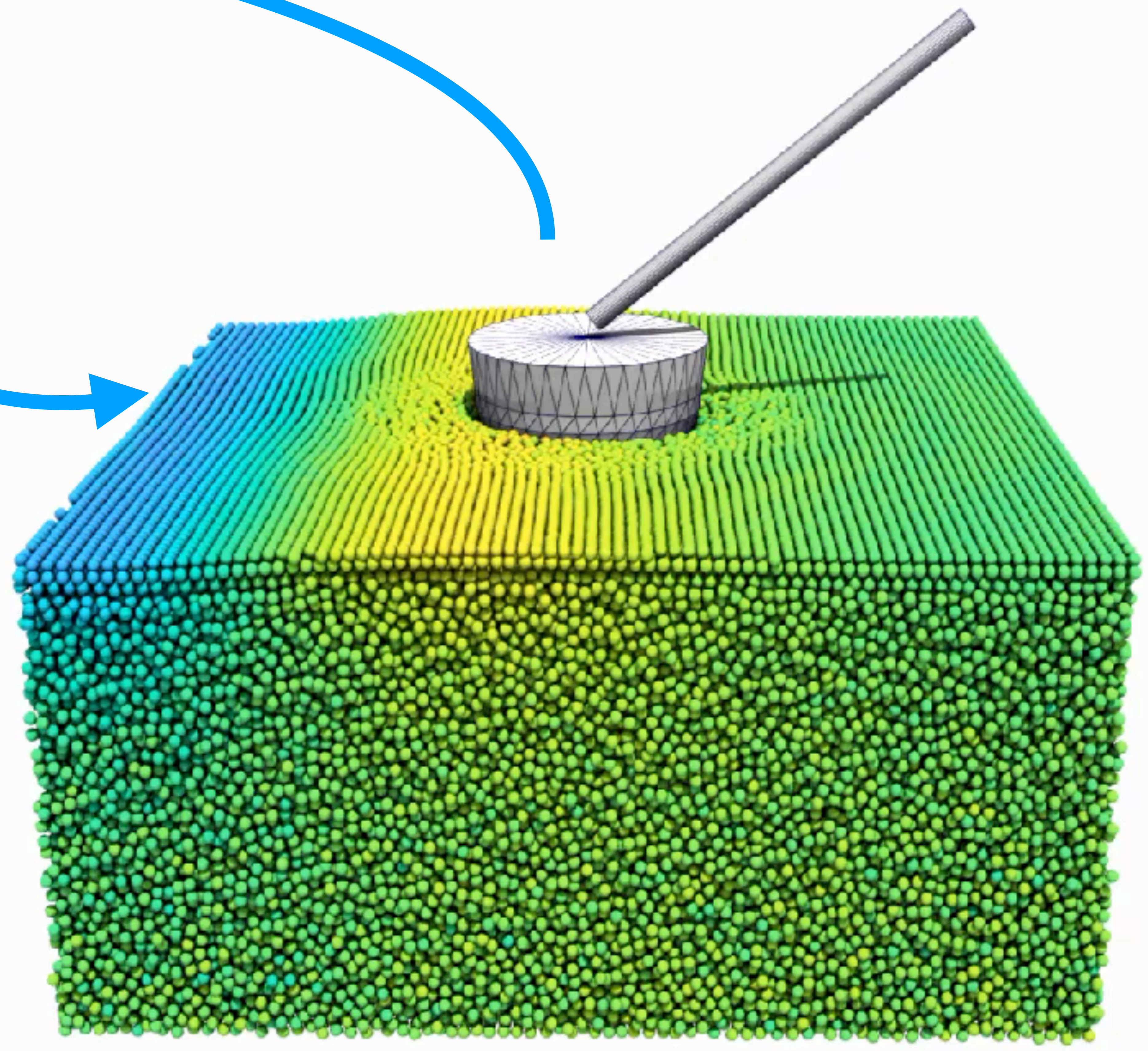
Modeling dilemma

$$\mathbf{M}\,\ddot{\mathbf{x}}(t) = \mathbf{f}_{hydro}(t) + \mathbf{f}_{PTO}(t) + \mathbf{f}_{mooring}(t)$$

Equation of motion for a rigid body

$$\begin{cases} \dfrac{D\rho}{Dt} + \rho\,\nabla\cdot\mathbf{u} = 0 \\[2ex] \dfrac{D\mathbf{u}}{Dt} = -\dfrac{1}{\rho}\nabla p + \nabla\cdot\boldsymbol{\tau} + \mathbf{f} \end{cases}$$

Navier–Stokes equations in the Lagrangian formalism on a fluid domain Ω



Fluid simulation with SPH of a Wavestar WEC under regular wave.

- Captures viscous and nonlinear effects
- Solved in time
- High computational cost

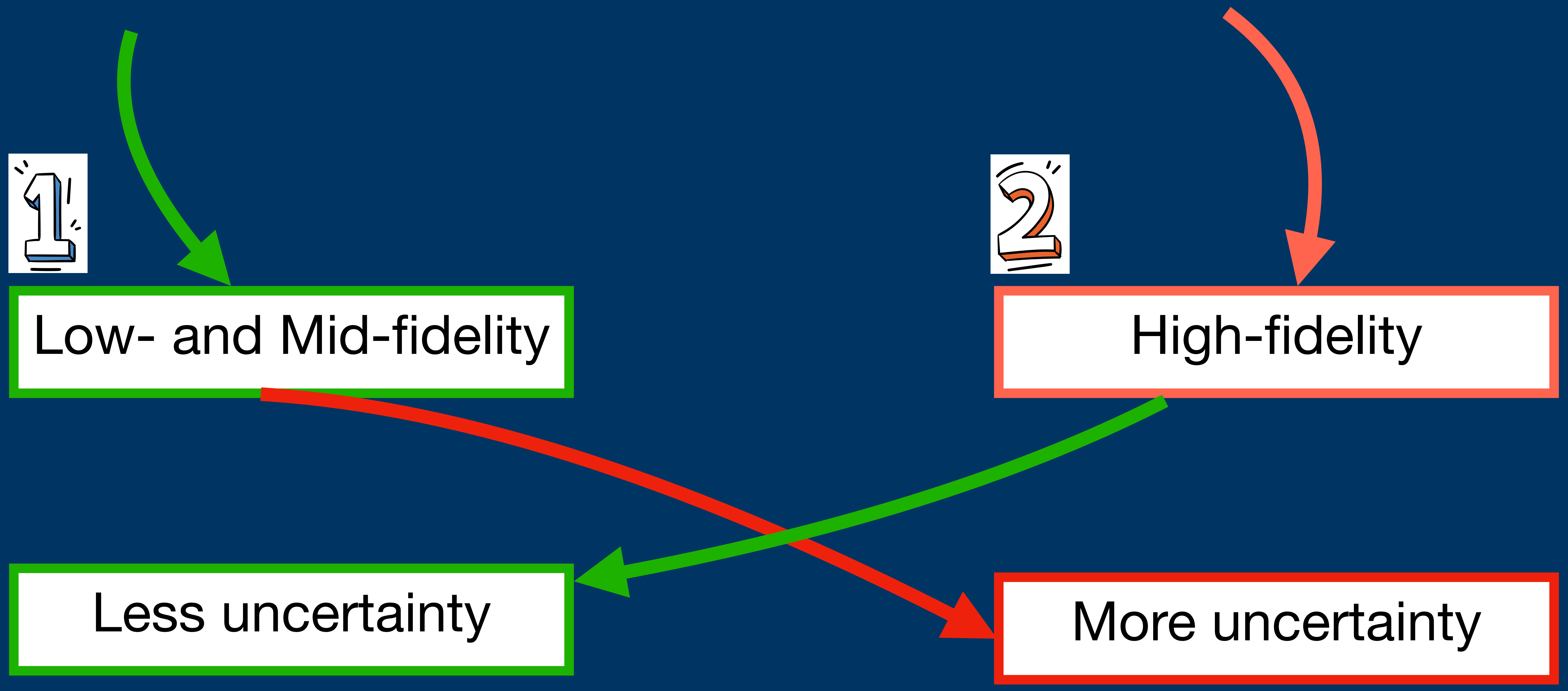
Design dilemma

Operational vs. Extreme (Ultimate) conditions

Design dilemma

Operational vs. Extreme (Ultimate) conditions

Basics on Semi-Probabilistic methods for structural design



Usually coped with bigger safety factors

There are conditions where high-fidelity may be the only way forward

Global variable

- The response amplitude operator RAO is computed as:

$$RAO(\omega) = \frac{S^*_{\xi\eta}(\omega)}{S_{\xi\xi}(\omega)}$$

$S^*_{\xi\eta}(\omega)$ → complex conjugate of the cross-spectral density between the wave elevation and the heave motion

$S_{\xi\xi}(\omega)$ → auto-spectral density of the wave elevation

- All the simulations are run using “NVIDIA H100” hardware.

The same you’ll be using this afternoon

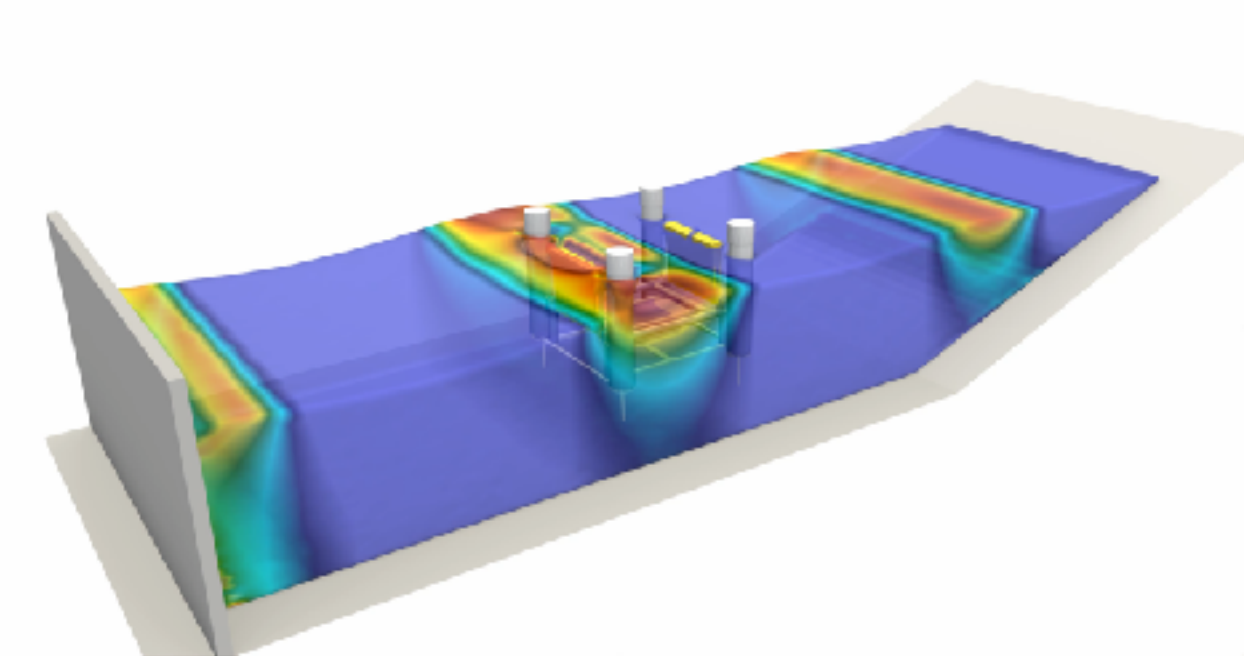
I acknowledge EuroHPC JU for awarding the project ID EHPC-REG-2024R02-084 (POW – Power from Offshore Wind) access to MareNostrum5 ACC hosted by the Barcelona Supercomputing Center (Spain)

Agenda

1. Software stack

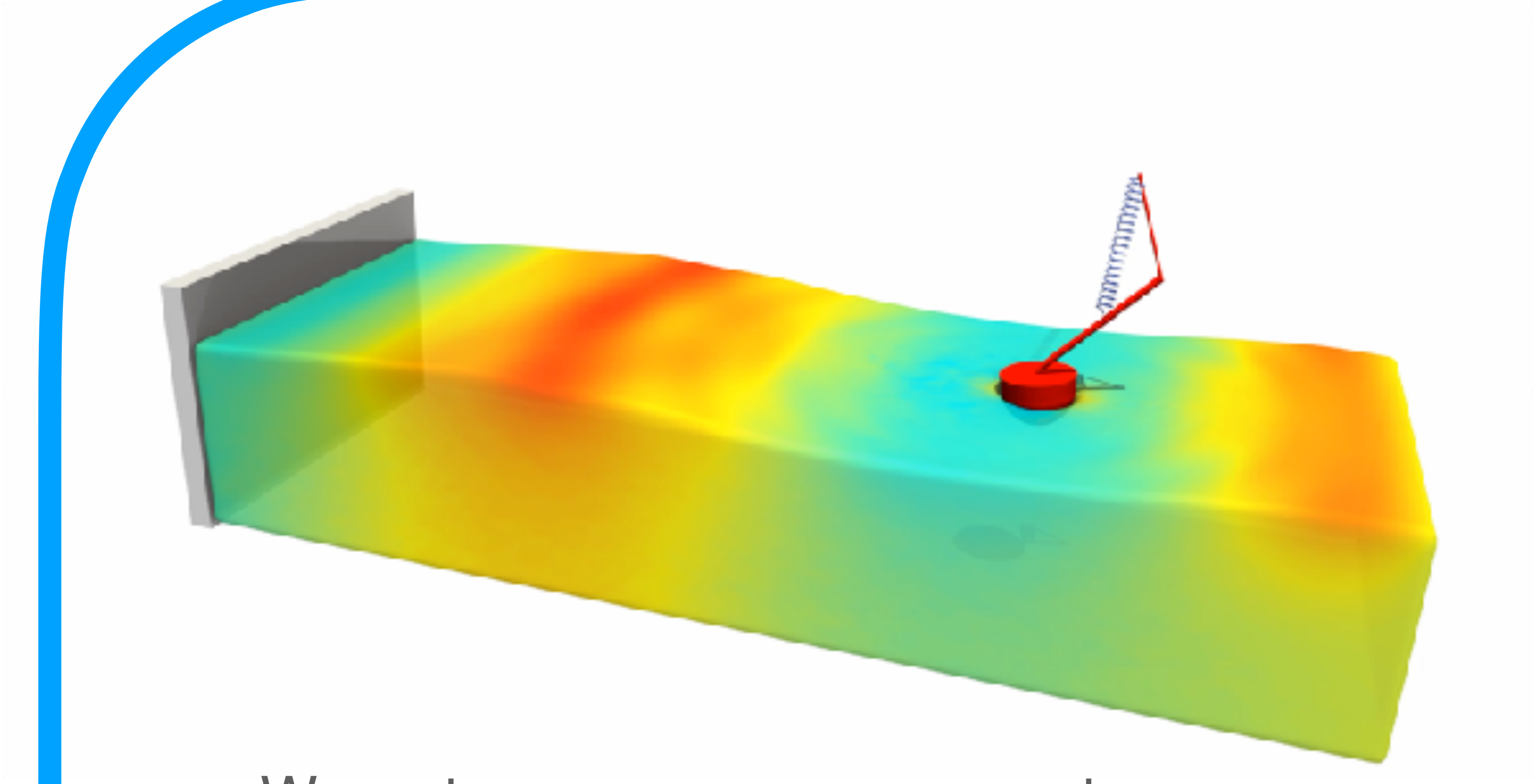
DualSPHysics, Project Chrono, MoorDyn+

2. FOSWEC

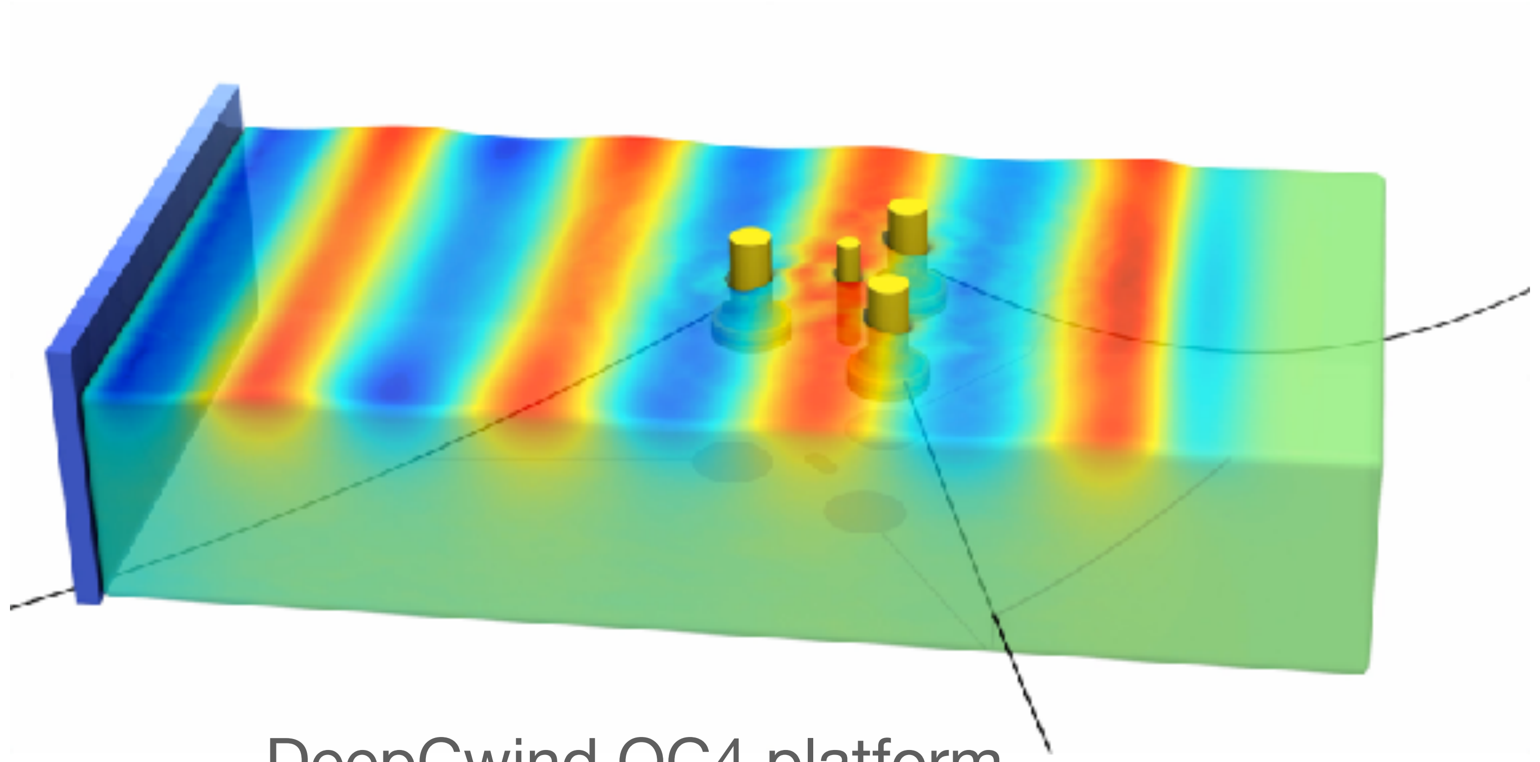


Floating Oscillating Surge WEC – a platform for wave energy.

3. Hybrid Wind–Wave platform



Wavestar wave energy converter



DeepCwind OC4 platform

Validation

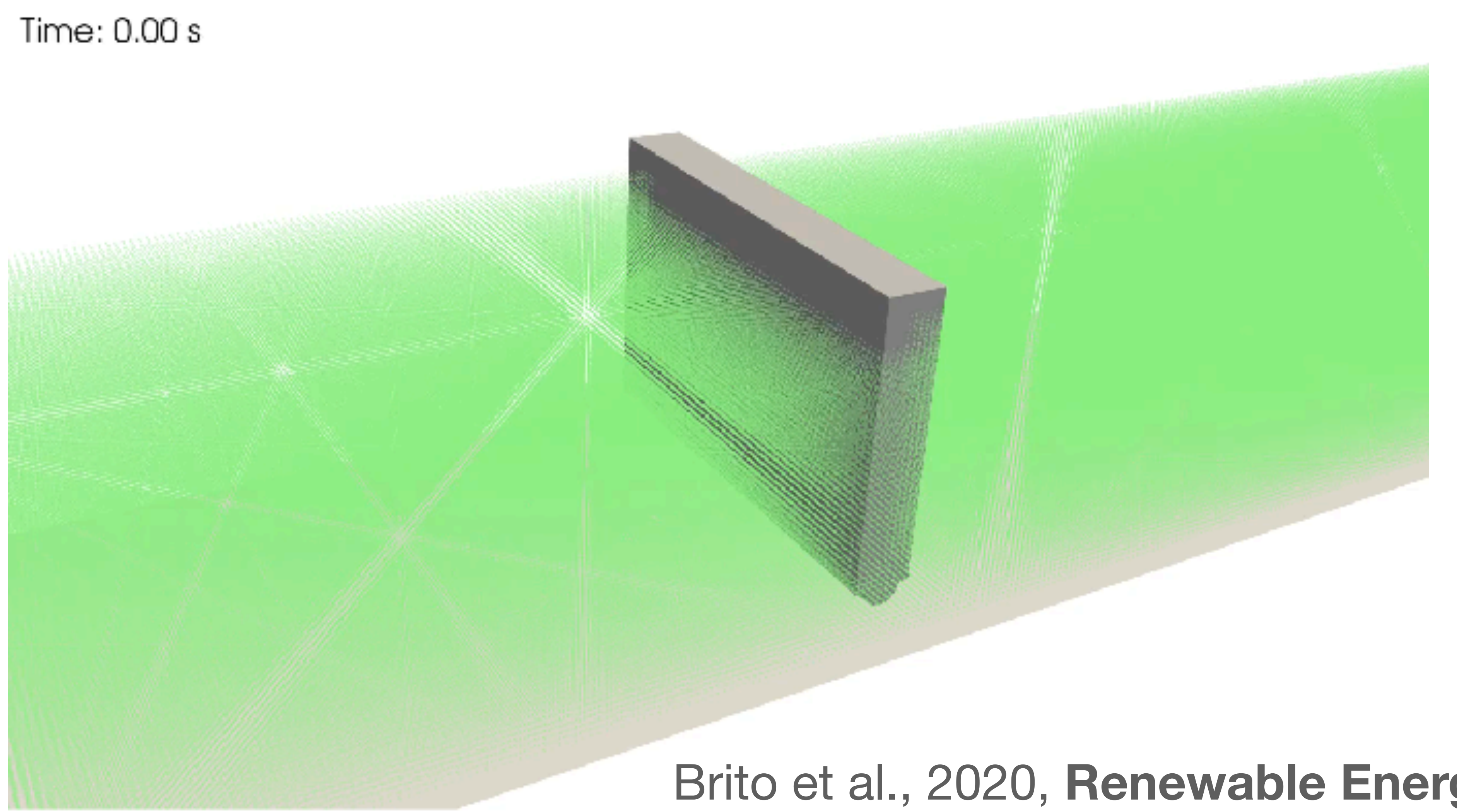
- Hydrodynamics
- Wave-induced motion

1. Software stack

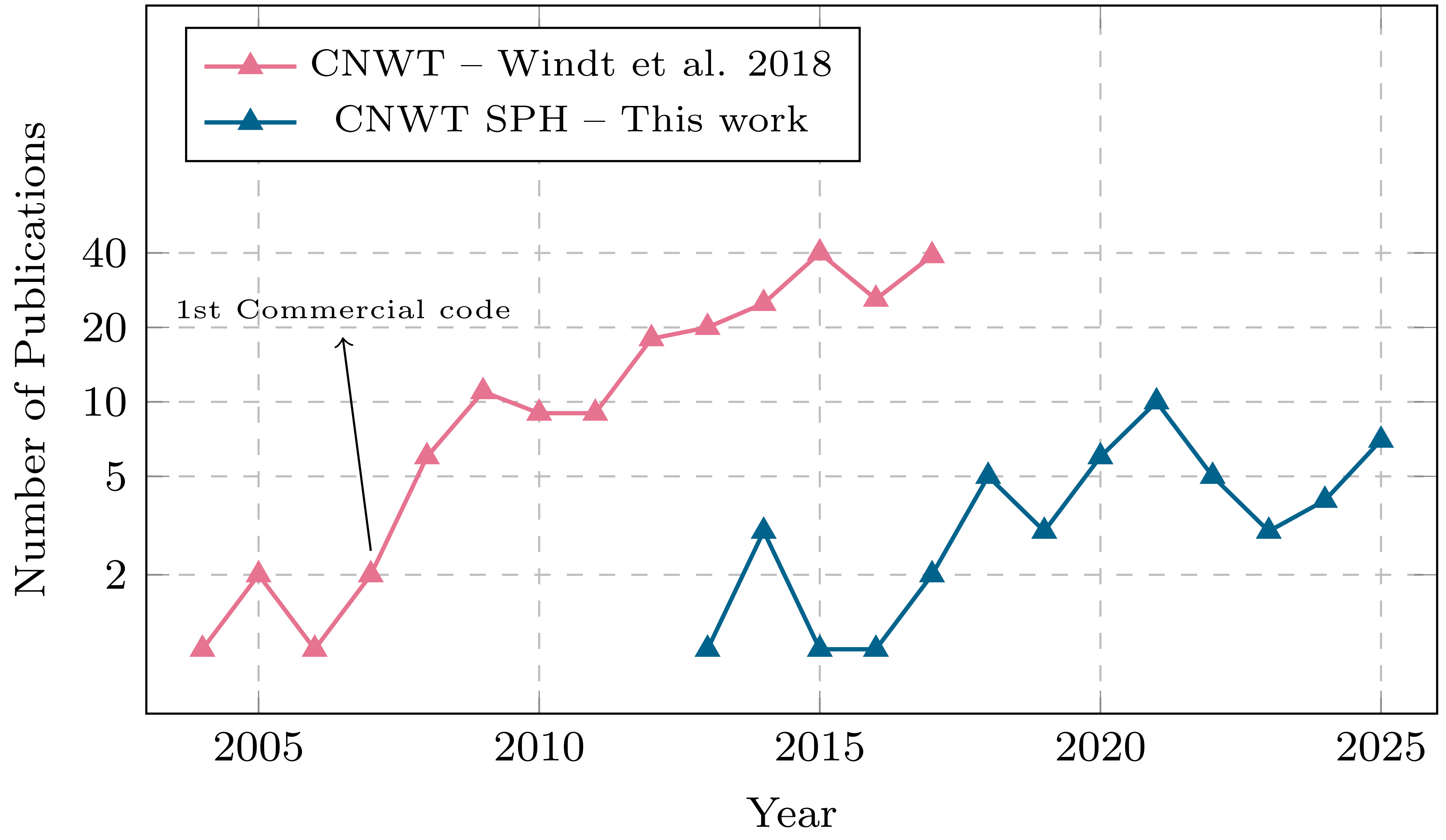
cpu gpu DualSPHysics

Wave energy

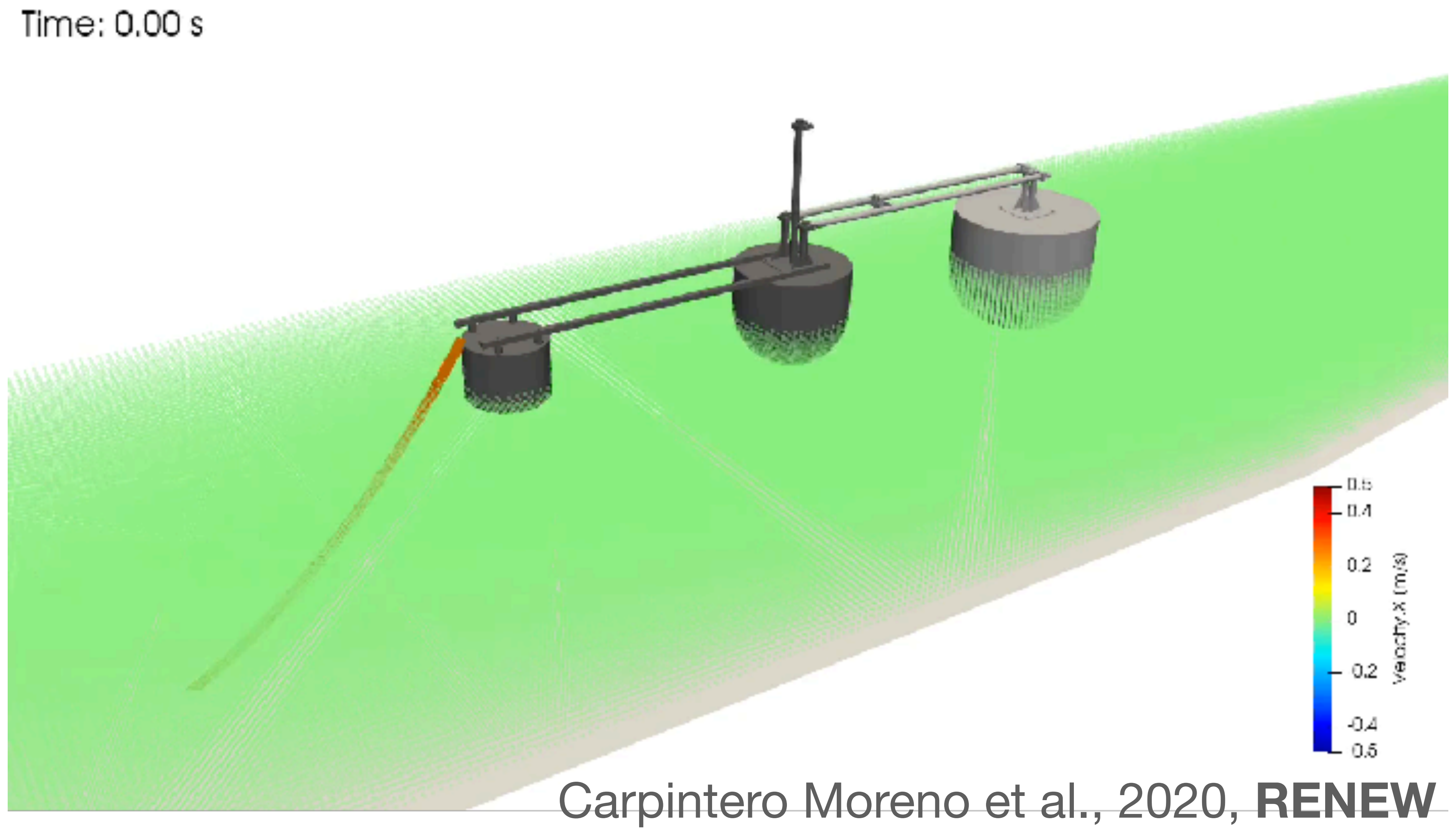
Overview on SPH



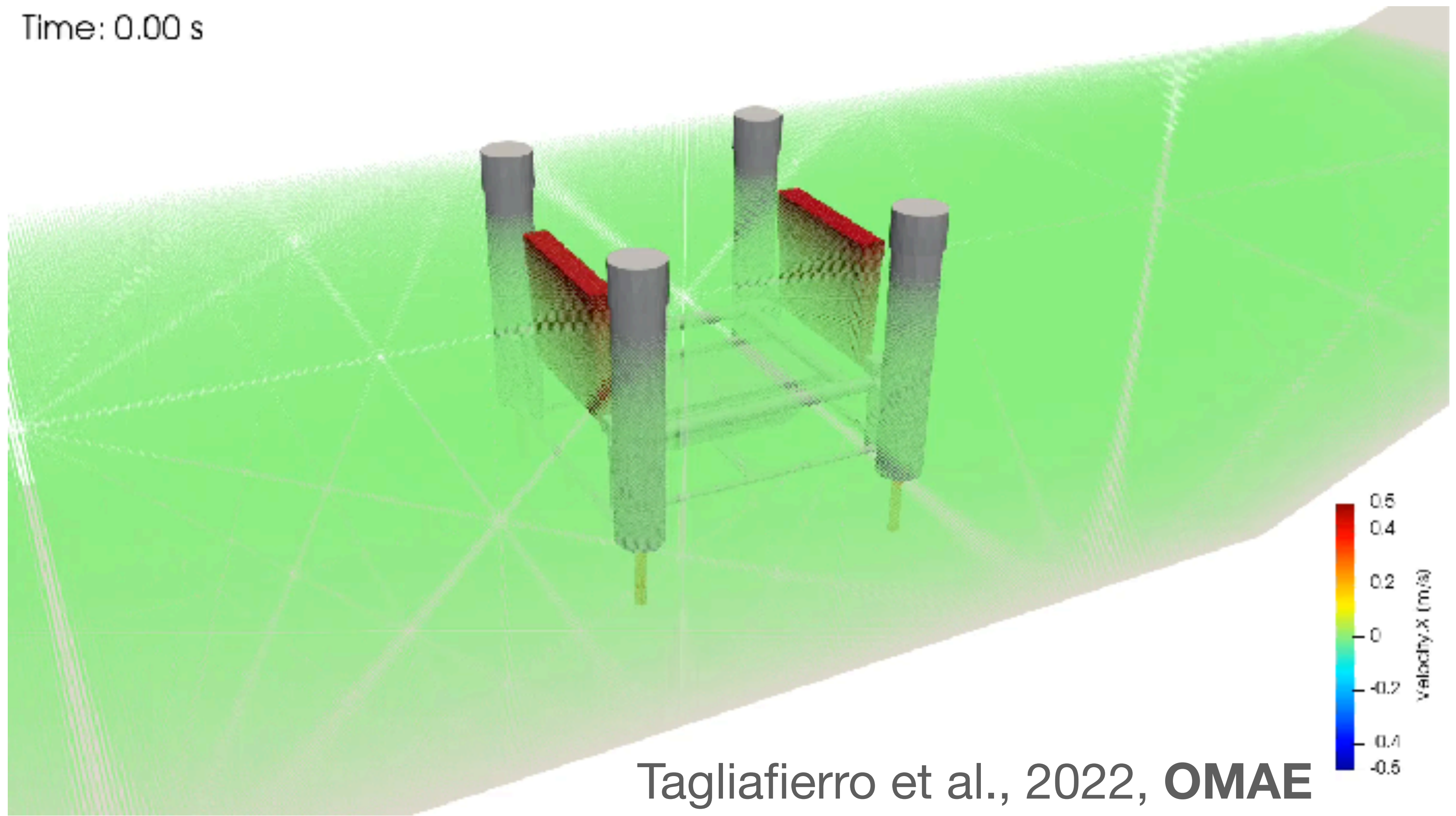
Brito et al., 2020, **Renewable Energy**



The chart illustrates the extent of research where the SPH method is employed in simulating Wave Energy Converters WECs.



Carpintero Moreno et al., 2020, **RENEW**

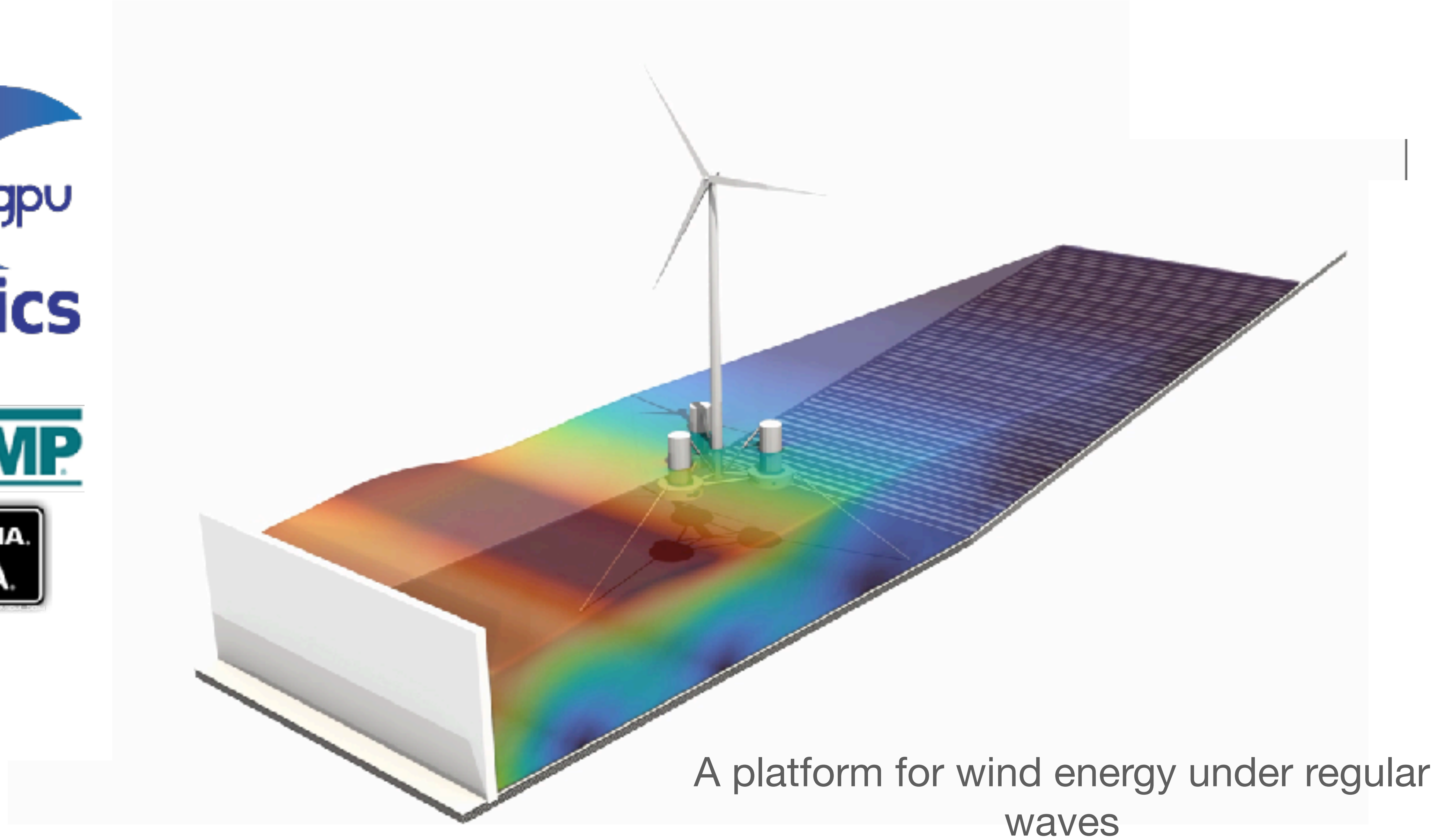


Tagliafierro et al., 2022, **OMAE**

The DualSPHysics code

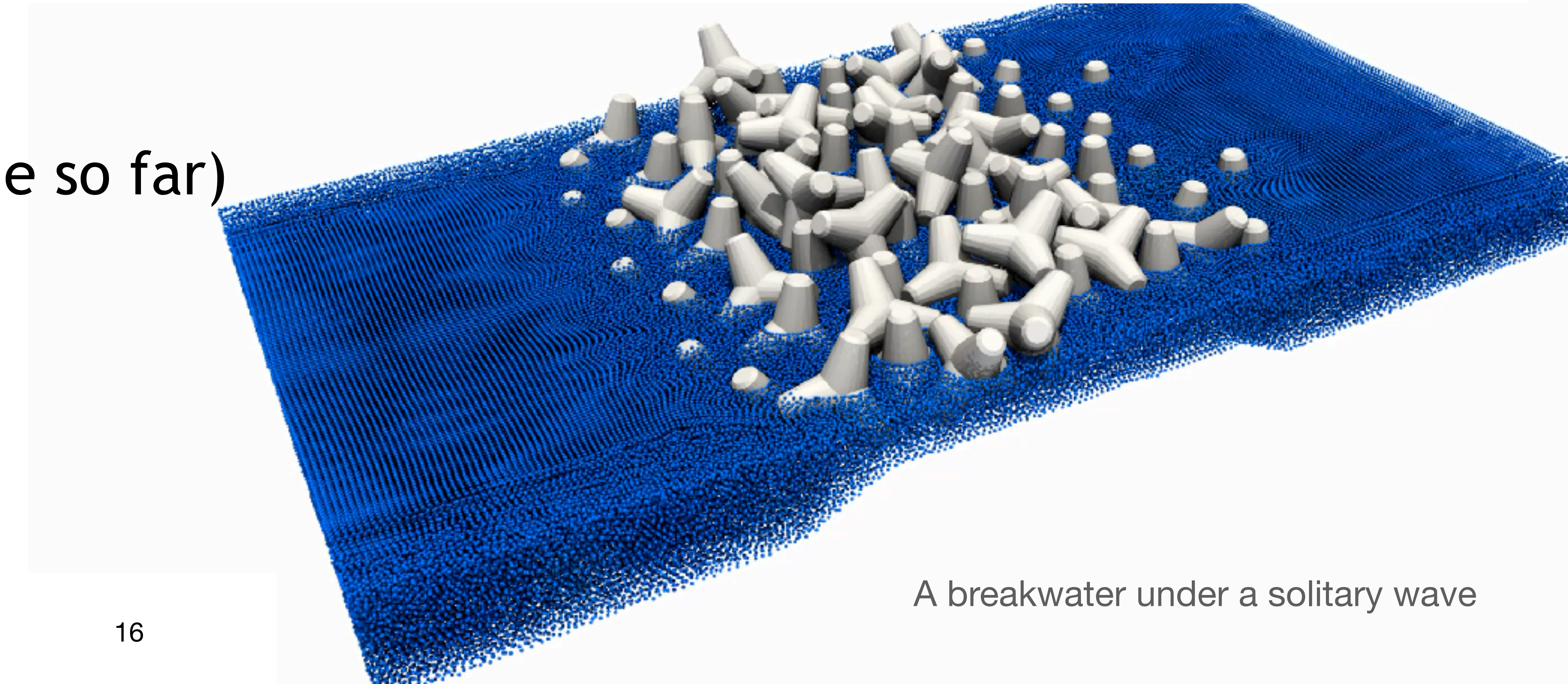
Open-source SPH solver

- Mono-dispersed SPH implementation
- Coupling to improve the physics
- Single phase


A platform for wind energy under regular waves

Features:

- CPU/GPU Implementation (C++/Cuda)
- Highly parallelized for GPU units (only one so far)
- Pre- and Post-processing tools
- Open source


A breakwater under a solitary wave

Domínguez et al., 2022, **CPM**

MoorDynPlus

Anchoring system solver

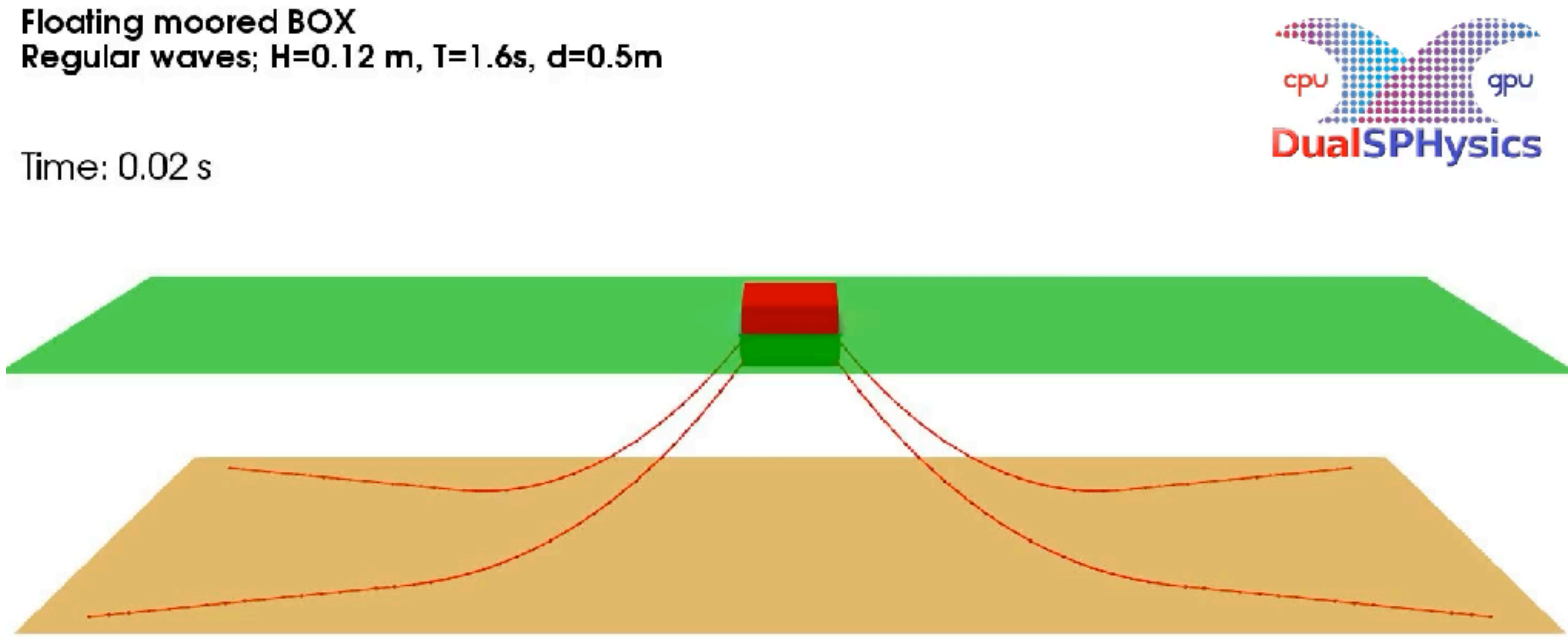
Based upon the original implementation "MoorDyn" by Dr. Matthew Hall

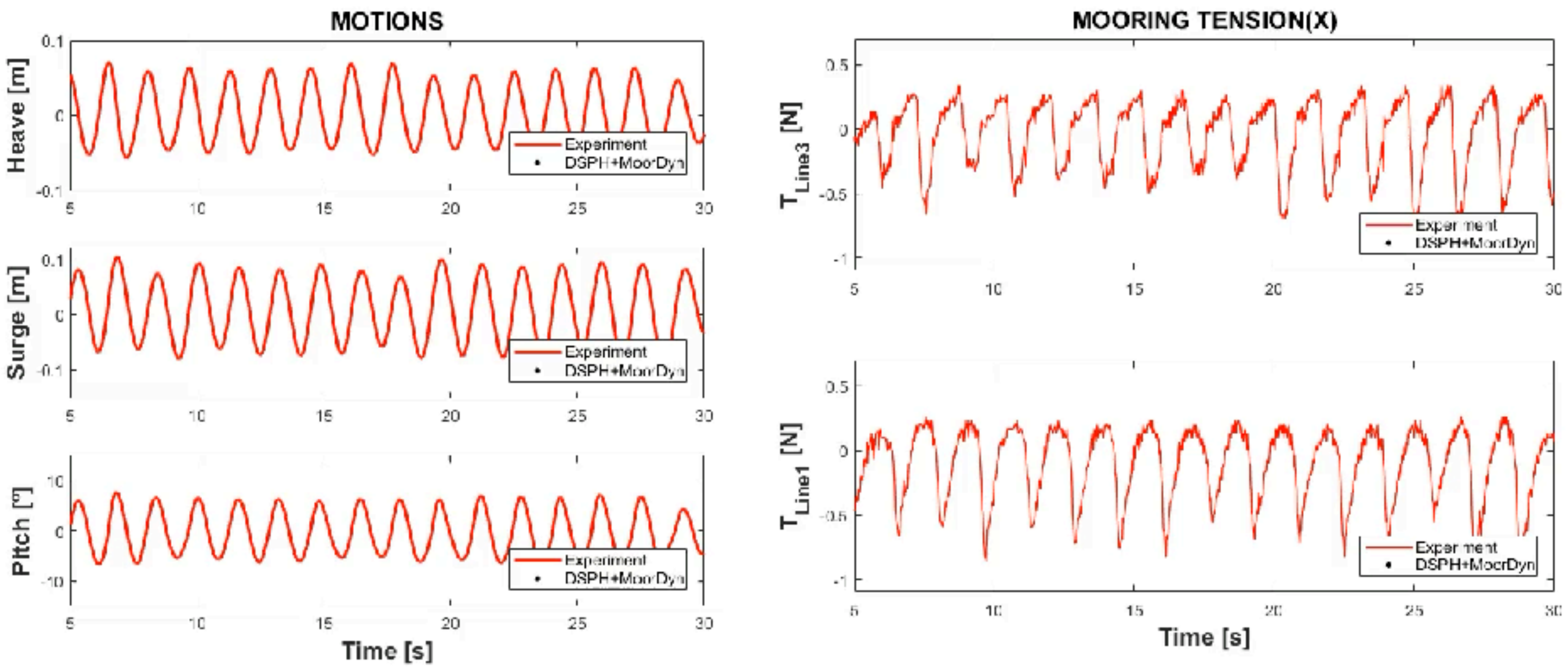
This lumped mass mooring line model is able to account for:

- Any sea-floor geometry
- Wave loads (also from CFD fluid)
- Solve interconnected floating bodies
- Assign different depths for catenary-like connections.

Development: Dr. Iván Martínez-Estévez

EPhysLab – Spain



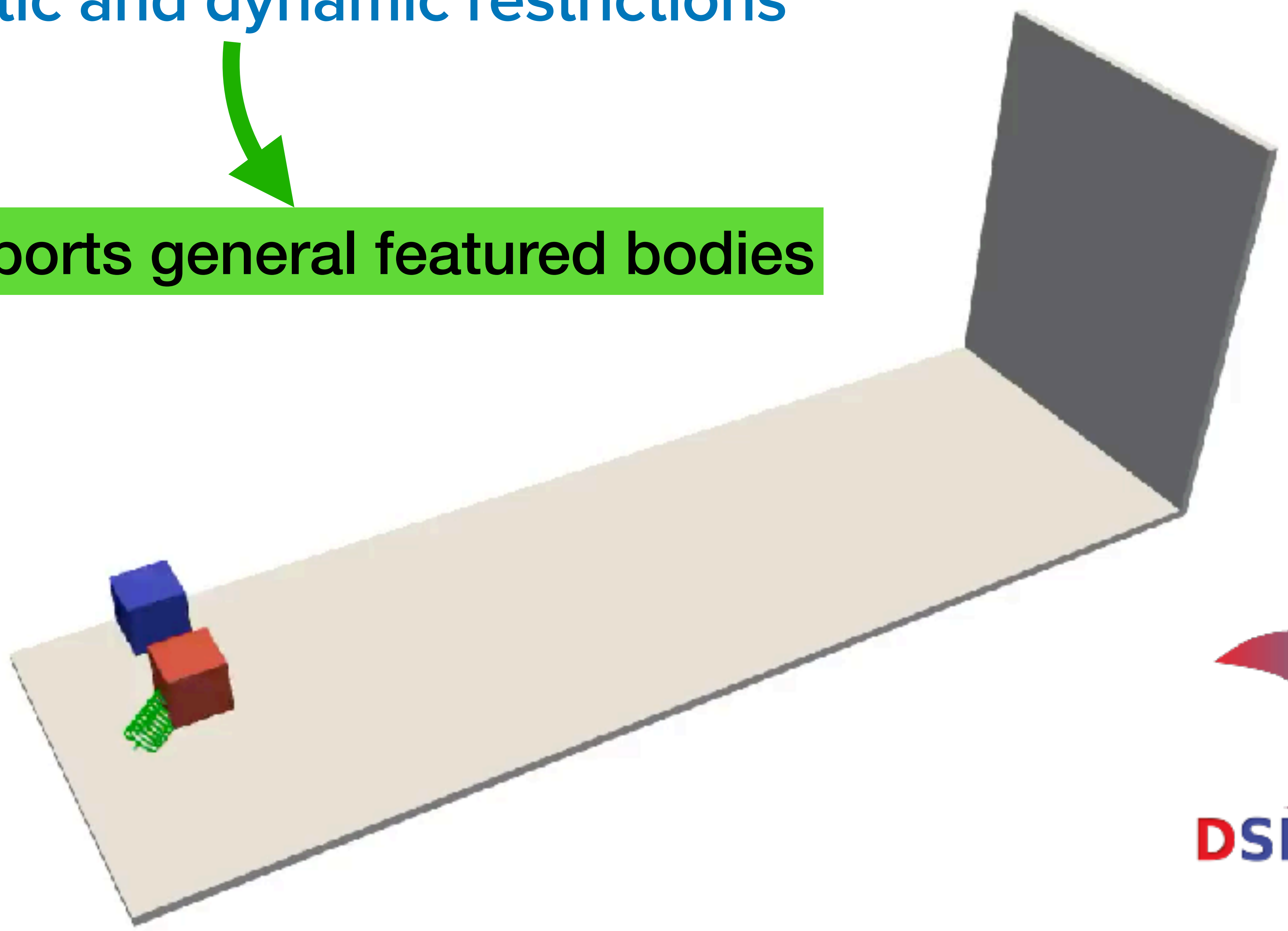


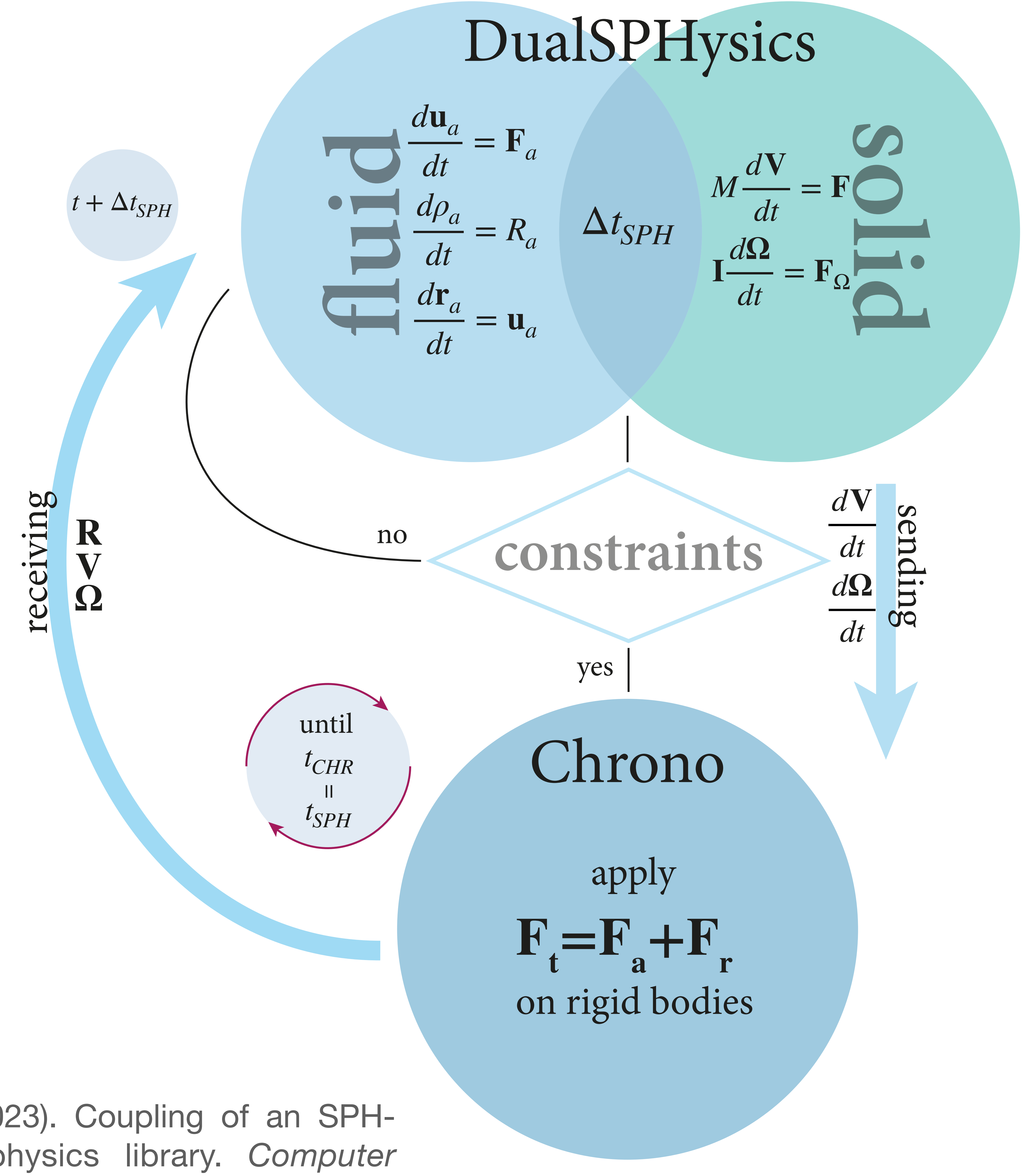
Chrono library

Open source multiphysics solver

Multi-body support
Smooth and non-smooth contacts
Kinematic and dynamic restrictions

Supports general featured bodies





Martínez-Estévez, I. et al. (2023). Coupling of an SPH-based solver with a multiphysics library. *Computer Physics Communications*, *283*, 108581. https://doi.org/10.1016/j.cpc.2022.108581

Courtesy of Salvatore Capasso

Rigid body

Usage

Open source multiphysics library

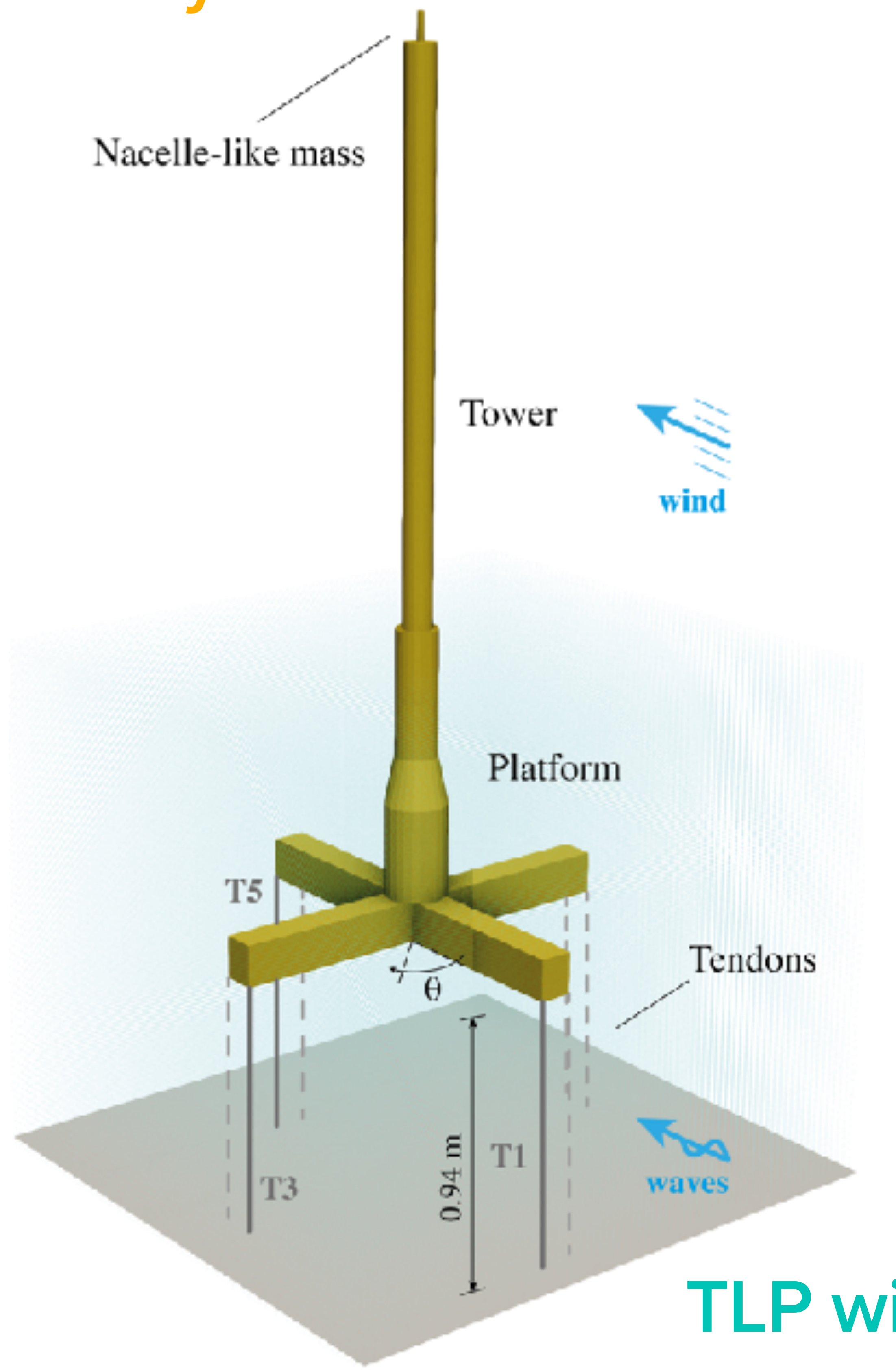
multi-body support

smooth and non-smooth contacts

kinematic and dynamic restrictions

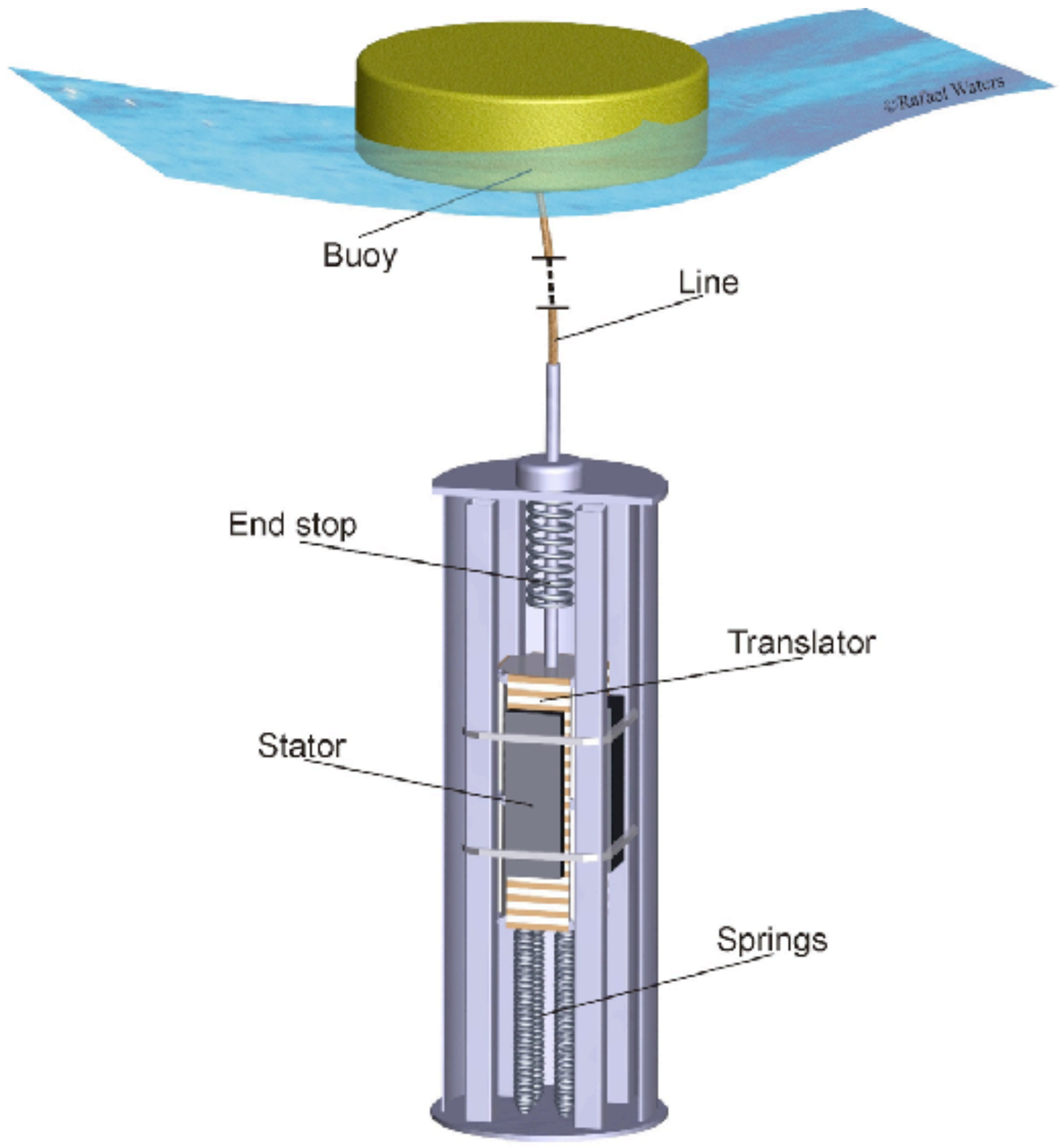
PROJECT CHRONO ⟷ DSPHChronoLib ⟷ DualSPHysics

Martínez-Estévez et al., 2023, **CPC**



Tension legs

TLP with 8 tendons



End-stoppers systems

Point-absorber WEC

2. Wave energy converters

FOSWEC

Challenges

1. Non-linear wave representation

2. Power Take-off systems

3. Mooring systems

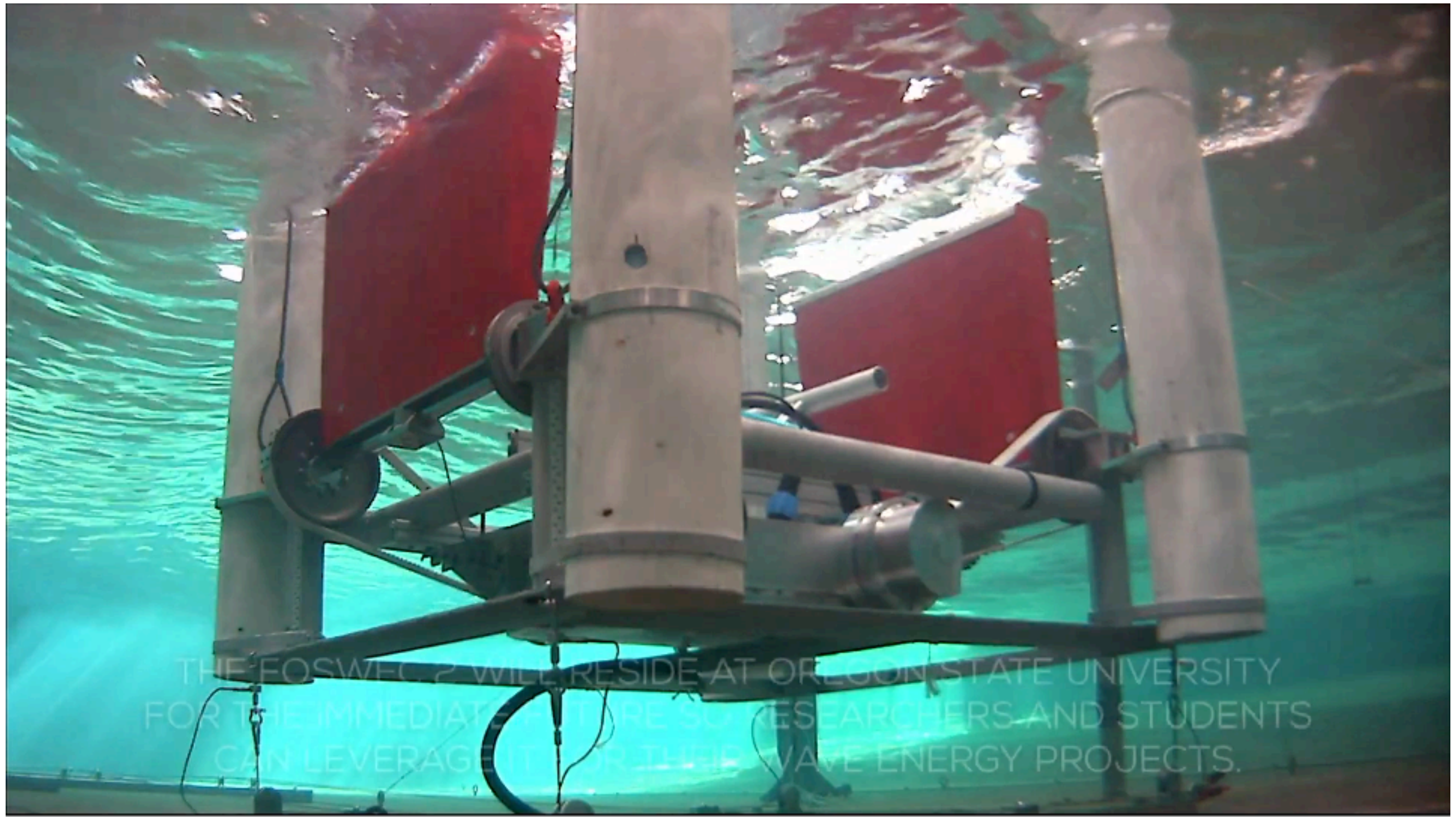
4.Simulation of fairly large domains

FOSWEC2

Experimental setup

- Floating Oscillating Surge WEC
- FOSWEC has two flaps attached to a submerged moored platform
- Platform includes a Power Take-Off (PTO) box

FOSWEC was engineered by Sandia National Labs as a tool to provide consistent and controlled data for software validation. It is represent a challenging device to simulate as it comprises a platform that hosts 2 flaps. Its multibody nature calls for the use of specific library for multibody dynamics.

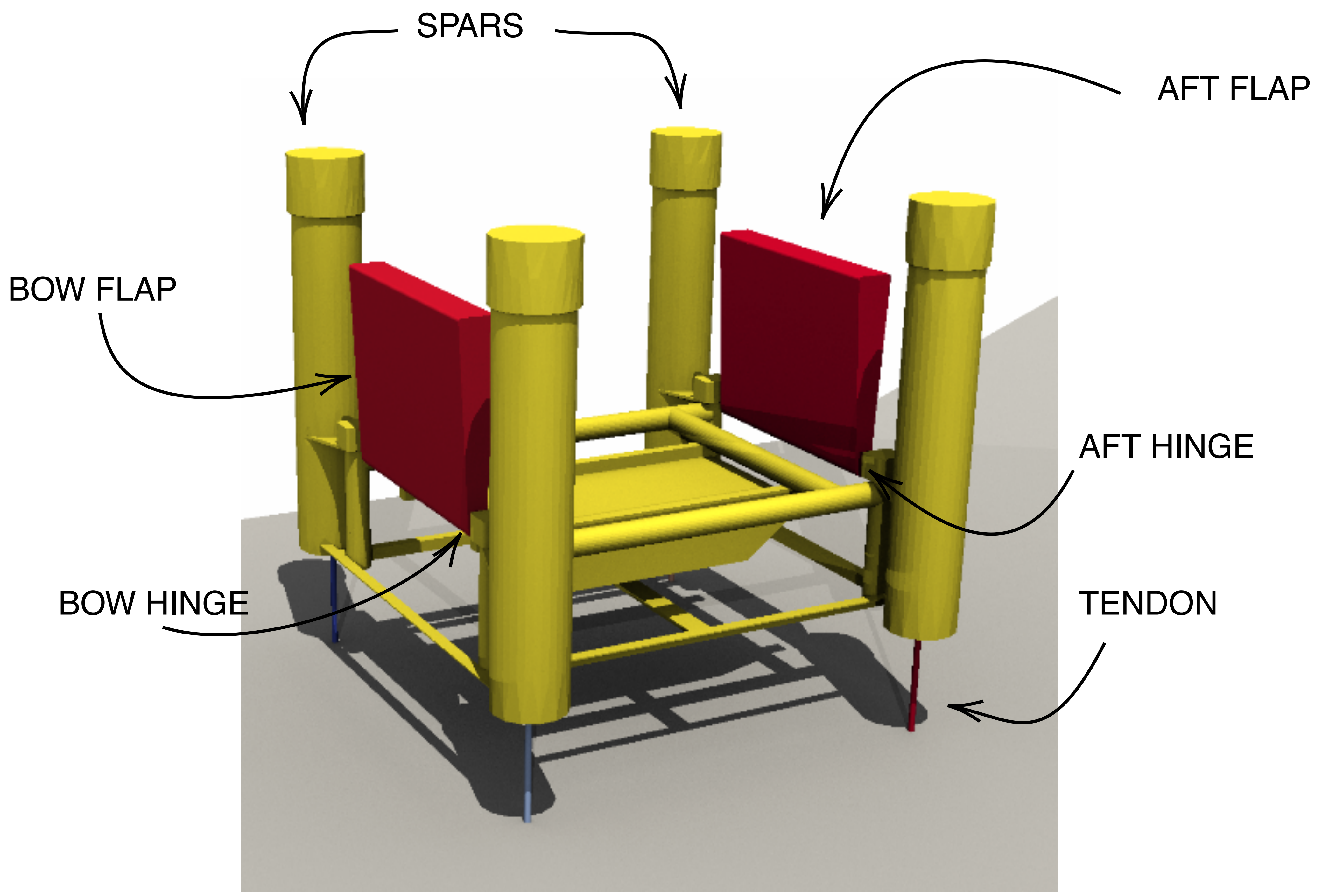


Forbush, D. D., Bacelli, G., Spencer, S. J., Coe, R. G., Bosma, B., & Lomonaco, P. (2022). Design and testing of a free floating dual flap wave energy converter. *Energy, 240*, 122485. https://doi.org/10.1016/j.energy.2021.122485

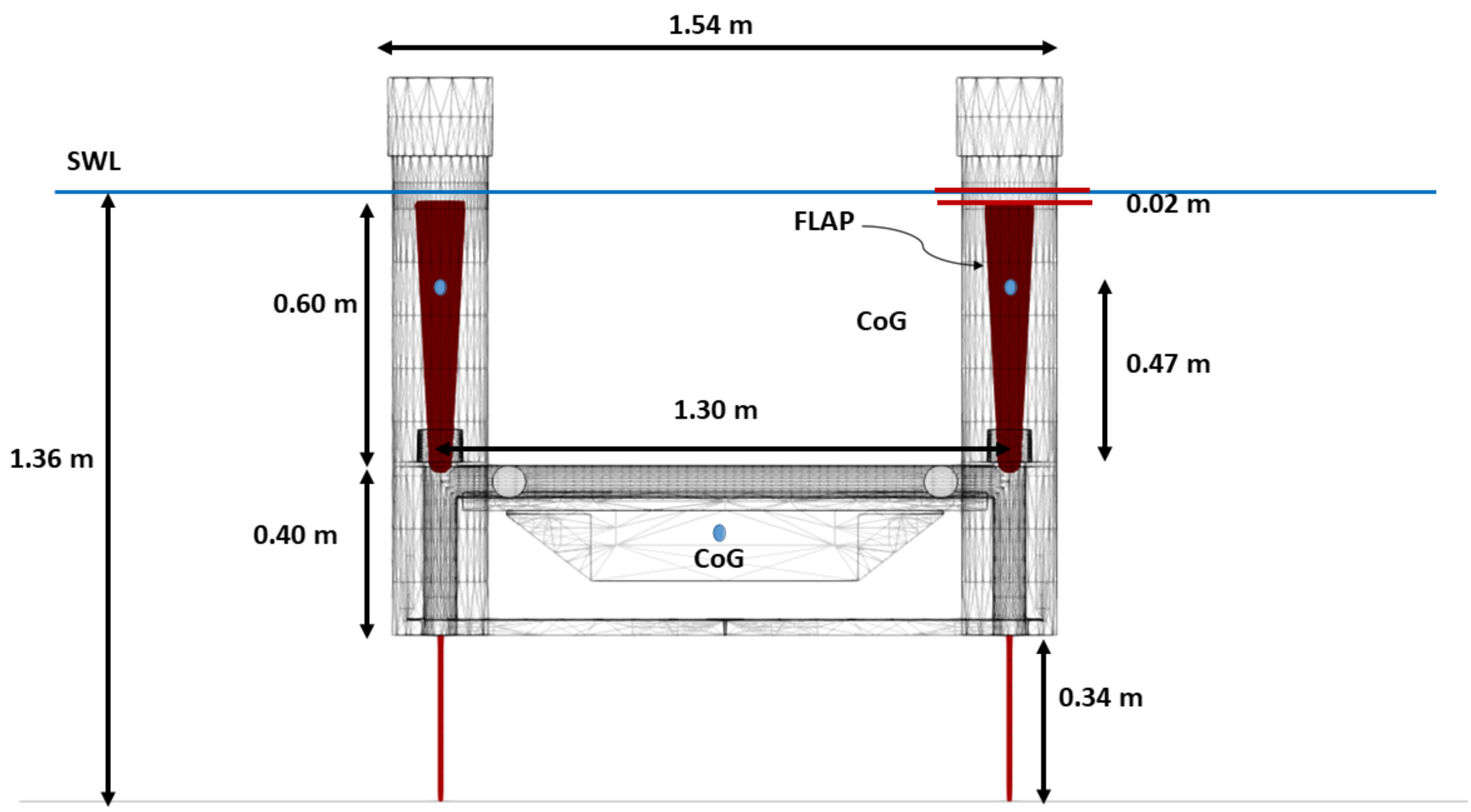
FOSWEC2

Experimental setup

$$\mathbf{M}\,\ddot{\mathbf{x}}(t) = \mathbf{f}_{hydro}(t) + \mathbf{f}_{PTO}(t) + \mathbf{f}_{mooring}(t)$$



Three dimensional view of the device.

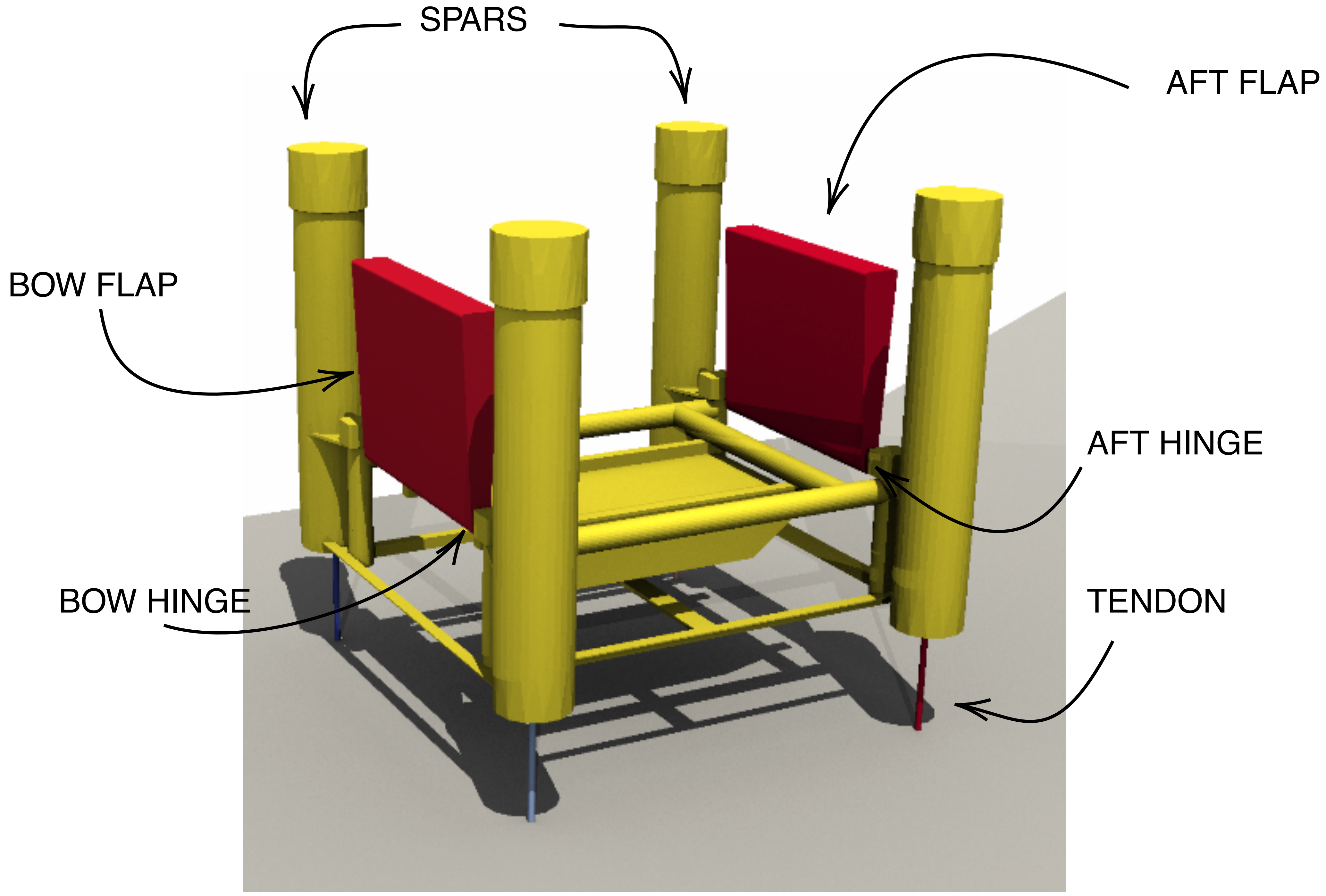


Lateral view with reference dimensions.

Forbush, D. D., Bacelli, G., Spencer, S. J., Coe, R. G., Bosma, B., & Lomonaco, P. (2022). Design and testing of a free floating dual flap wave energy converter. *Energy, 240*, 122485. https://doi.org/10.1016/j.energy.2021.122485

FOSWEC2

Experimental setup



Three dimensional view of the device.

Characteristics of the PTO system

Location	Parameter	Symbol	Quantity	Unit
Bow flap	Stiffness	$k_{p.b}$	-3.561	N·m/rad
Bow flap	Damping	$k_{d.b}$	1.762	N·m·s/rad
Aft flap	Stiffness	$k_{p.a}$	-2.800	N·m/rad
Aft flap	Damping	$k_{d.a}$	0.465	N·m·s/rad

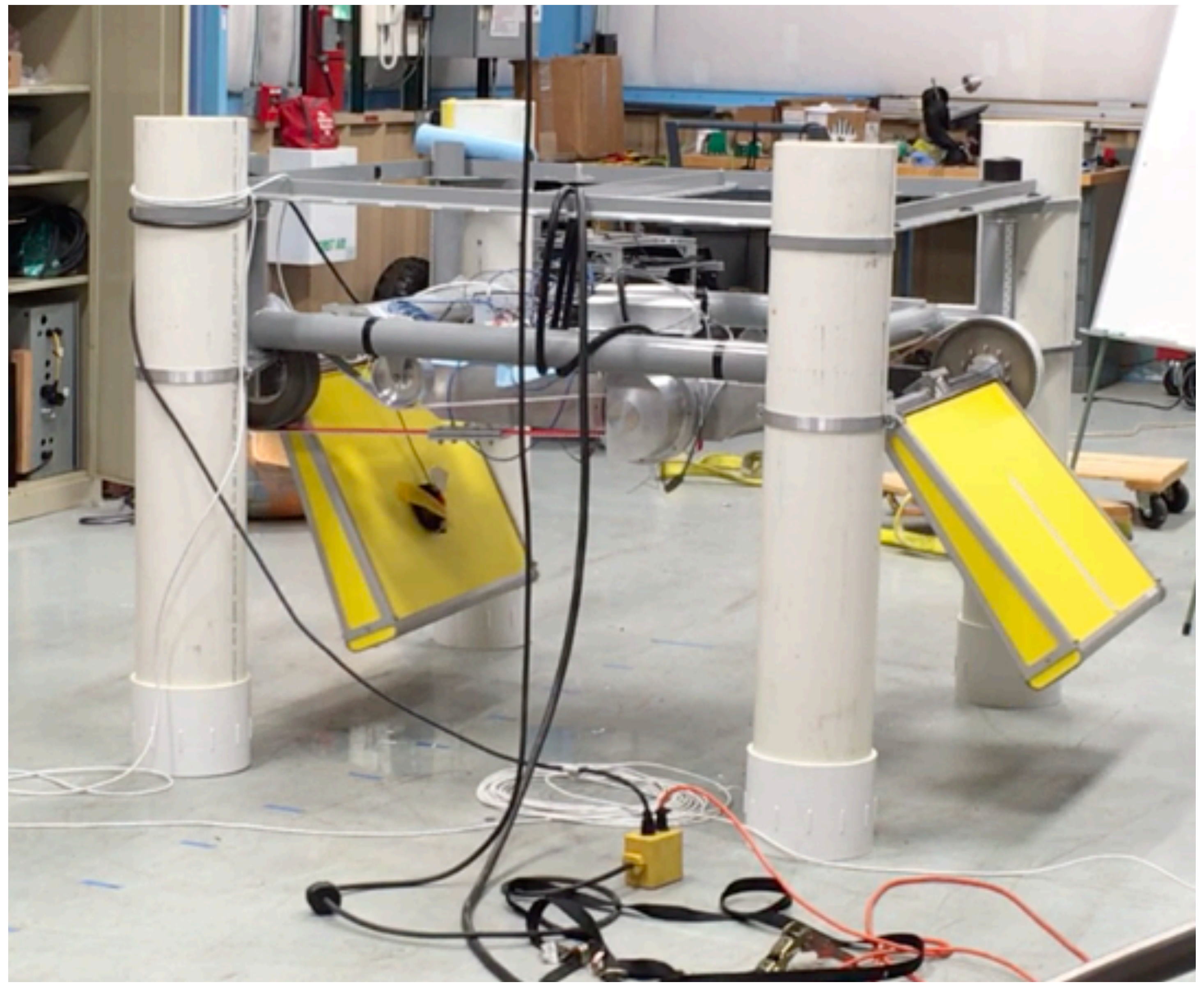
Characteristics of the tendons

Element	Symbol	Quantity	Unit
Cross sectional stiffness	EA_l	183	kN
Nominal diameter	D_N	3.50	mm
Segments	N	10	-
Density in air (steel)	ρ_s	7500	kg/m^3
Weight in fluid	W_l	0.40	N
Natural frequency	f_n	20.0	MHz
Model time step	dt_M	5e-07	s

Forbush, D. D., Bacelli, G., Spencer, S. J., Coe, R. G., Bosma, B., & Lomonaco, P. (2022). Design and testing of a free floating dual flap wave energy converter. *Energy, 240*, 122485. https://doi.org/10.1016/j.energy.2021.122485

Niosi et al. 2023. **ISOPE**

Dry tests - flap decay



Platform total dimension

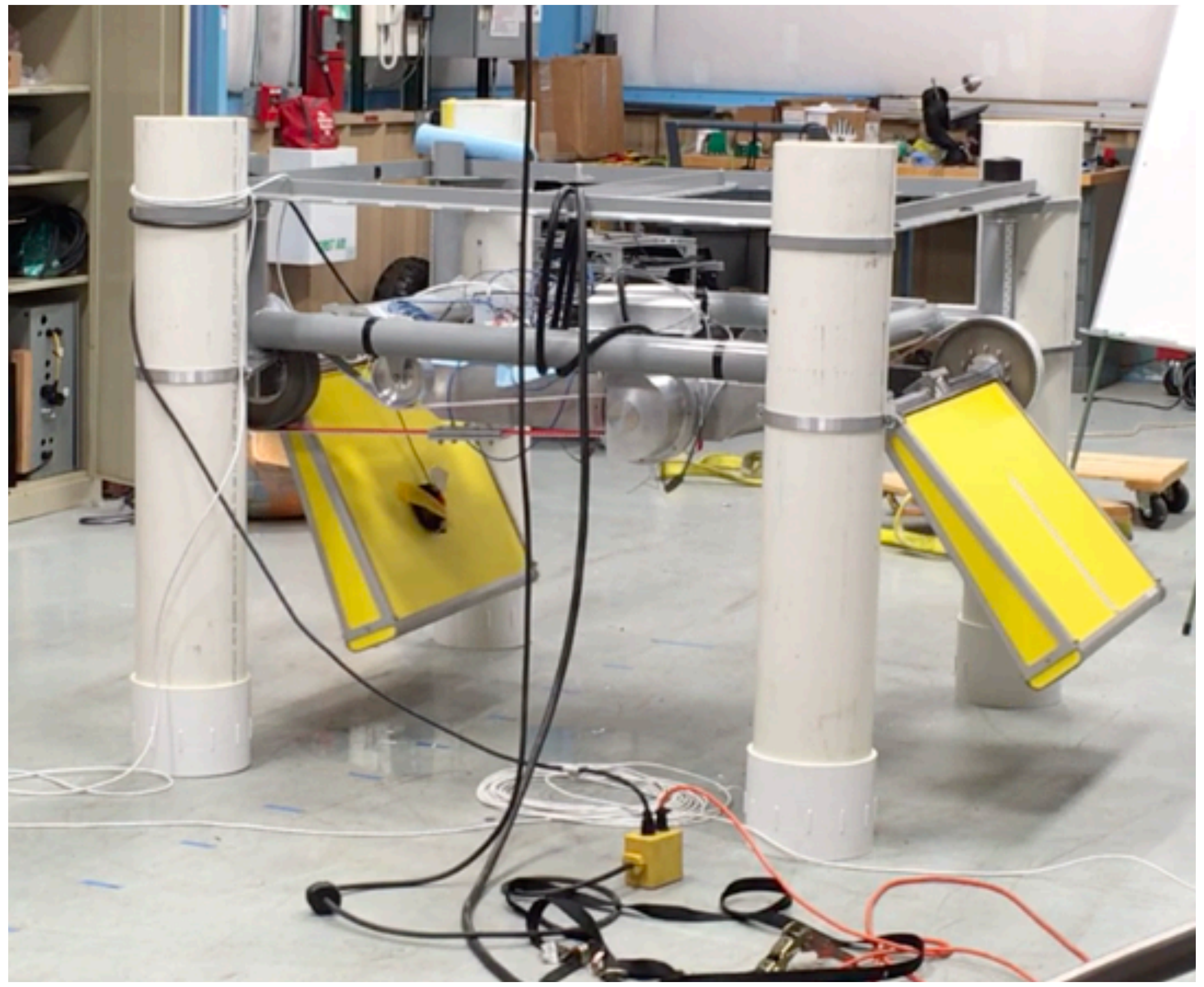
Element	Symbol	Quantity	Unit
Mass	m	263	kg
Length	L_{WEC}	1.44	m
Beam	W_{WEC}	1.63	m
Draft	D_{WEC}	¡1.24	m

Estimation of the flap CoG

$$\mathrm{CoG}_{Flap} = \frac{gT^2}{4\pi^2} = 0.466 \text{ m}$$

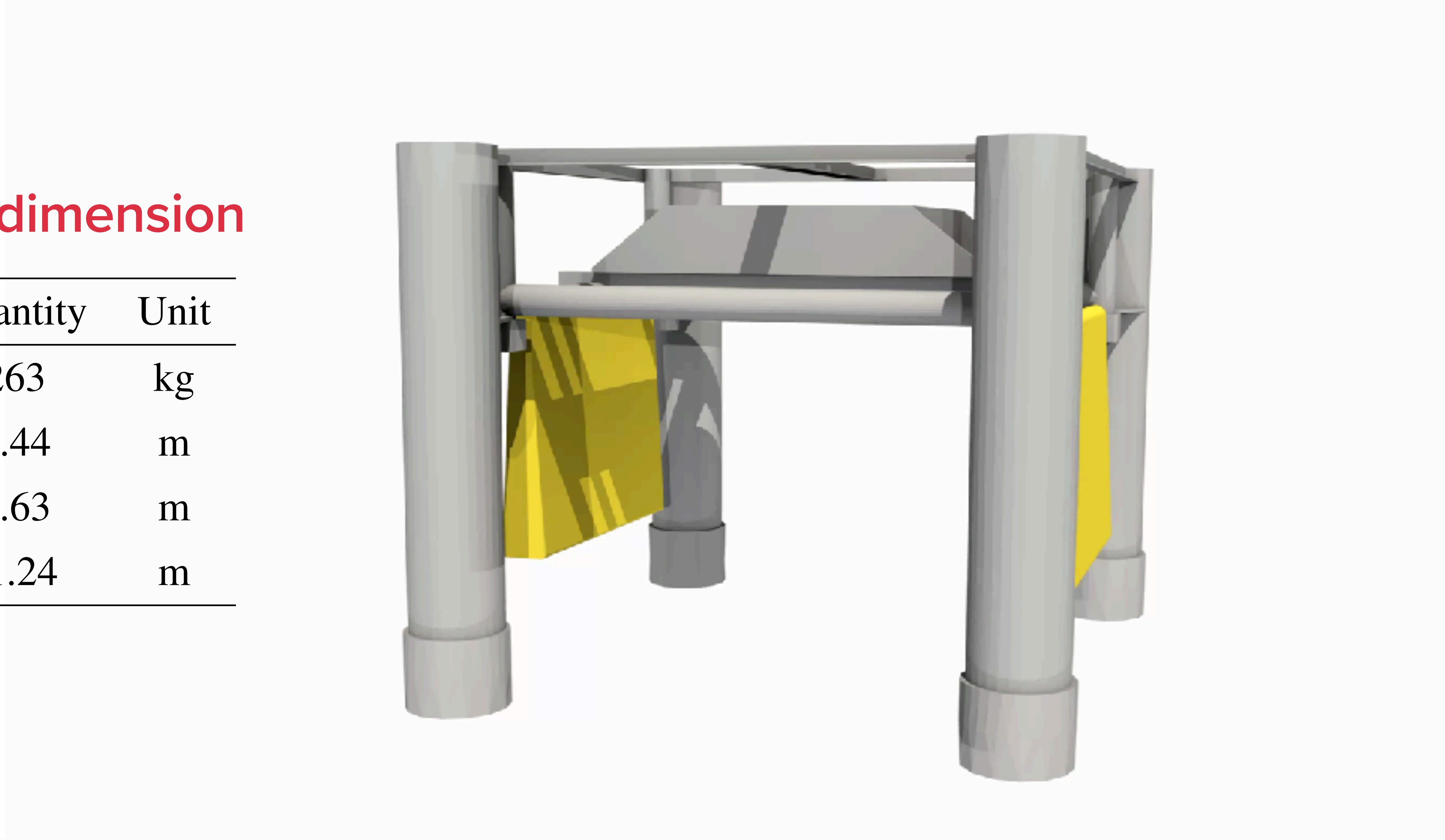
FOSWEC2

Dry tests - flap decay



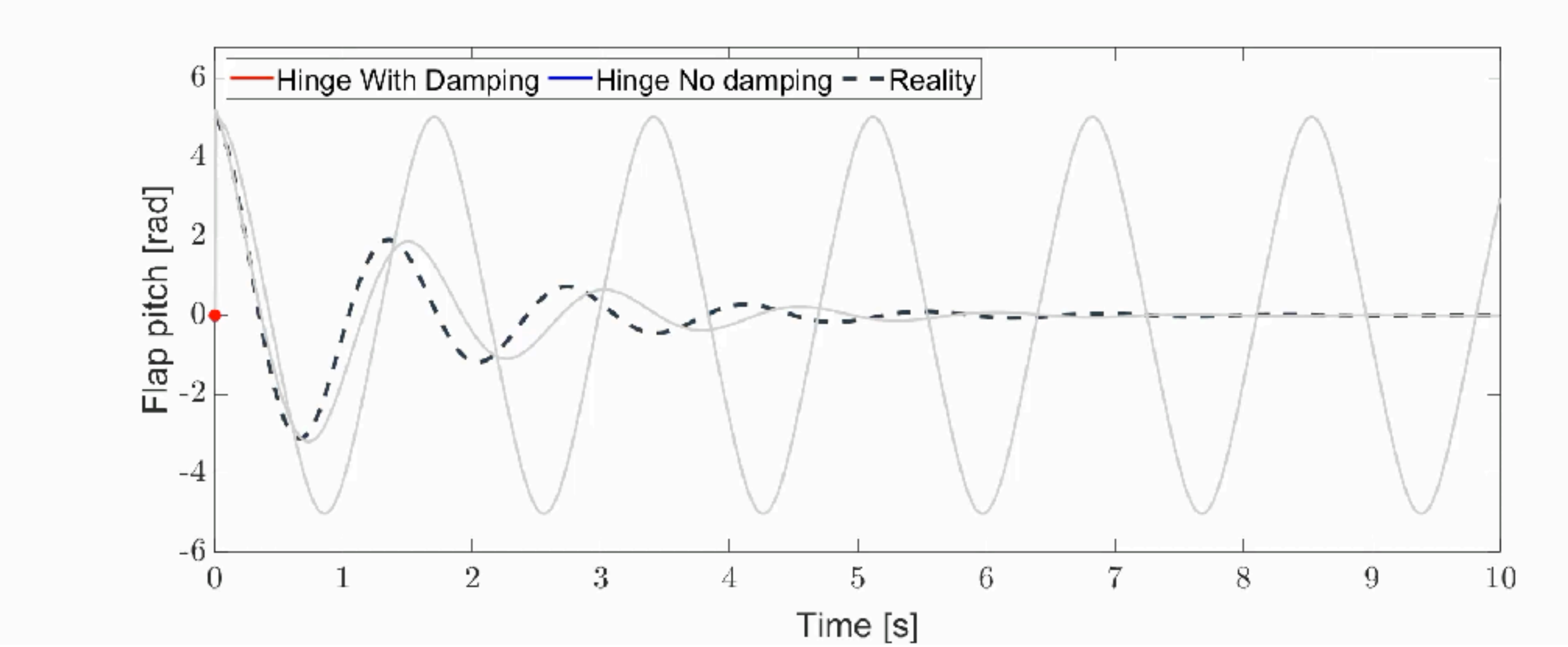
Platform total dimension

Element	Symbol	Quantity	Unit
Mass	m	263	kg
Length	L_{WEC}	1.44	m
Beam	W_{WEC}	1.63	m
Draft	D_{WEC}	¡1.24	m



Estimation of the flap CoG

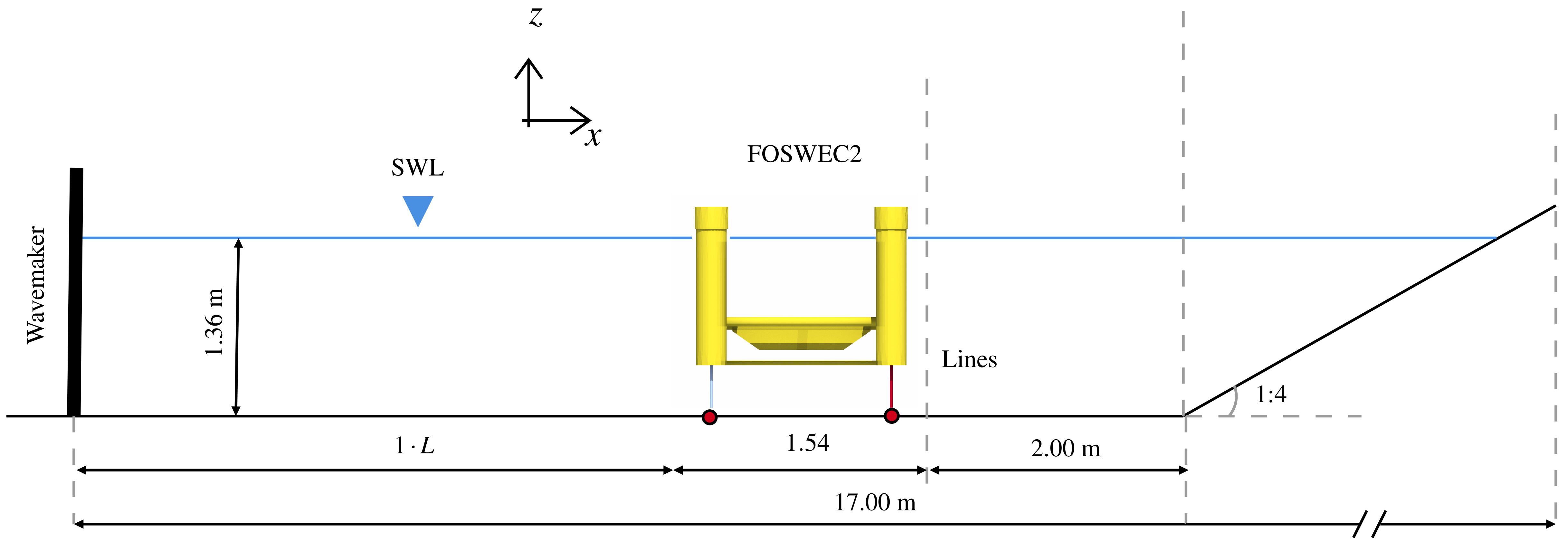
$$\text{CoG}_{Flap} = \frac{gT^2}{4\pi^2} = 0.466 \text{ m}$$



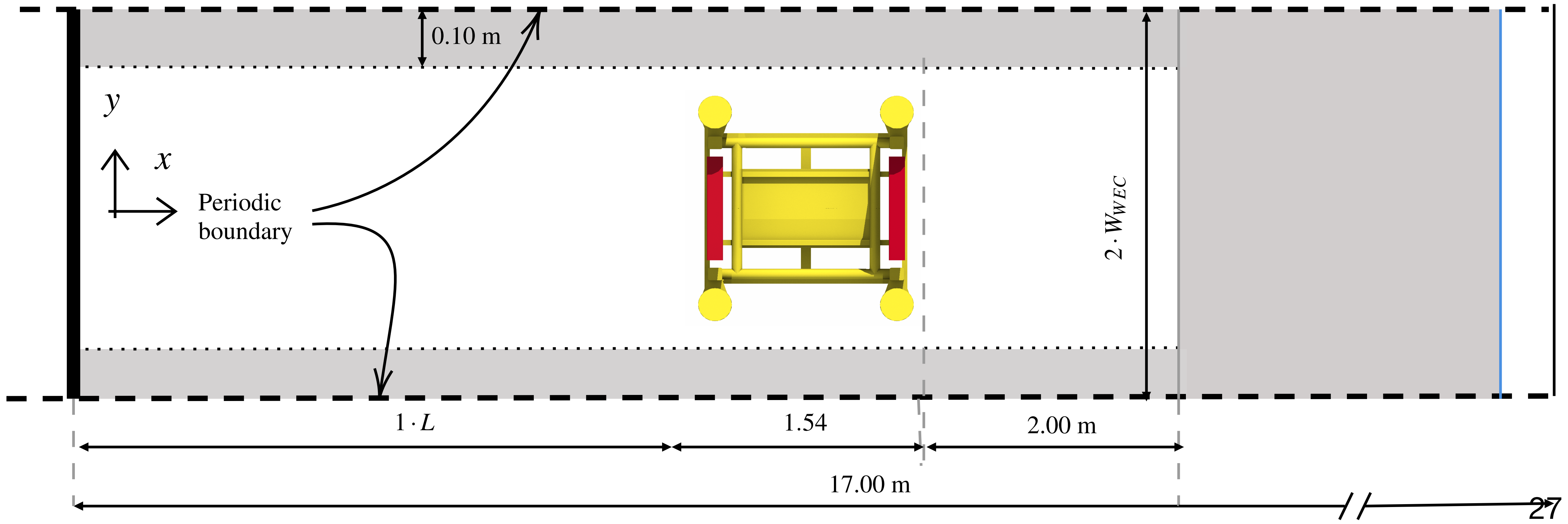
FOSWEC2

Regular wave validation

$$\mathbf{M}\,\ddot{\mathbf{x}}(t) = \mathbf{f}_{hydro}(t) + \mathbf{f}_{PTO}(t) + \mathbf{f}_{mooring}(t)$$



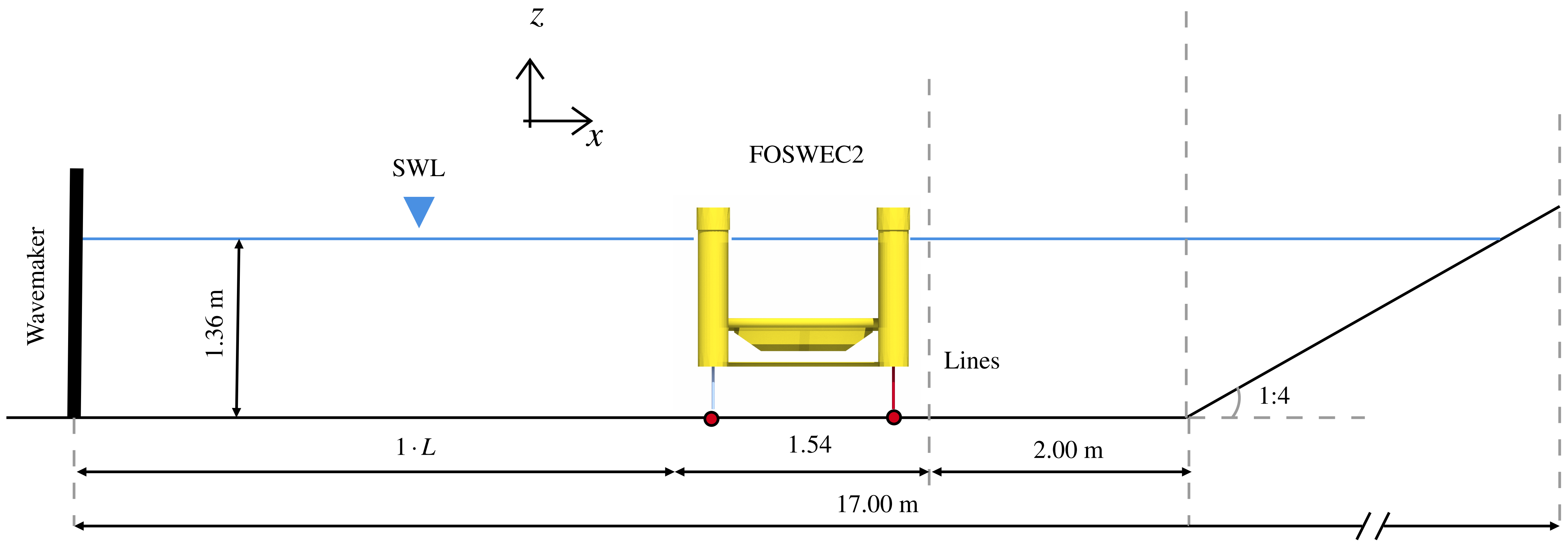
Parameter	Symbol	Quantity	Unit
Wave period	T	1.56	s
Wave height	H	0.136	m
Water depth	d	1.36	m
Wave length	L	3.73	m



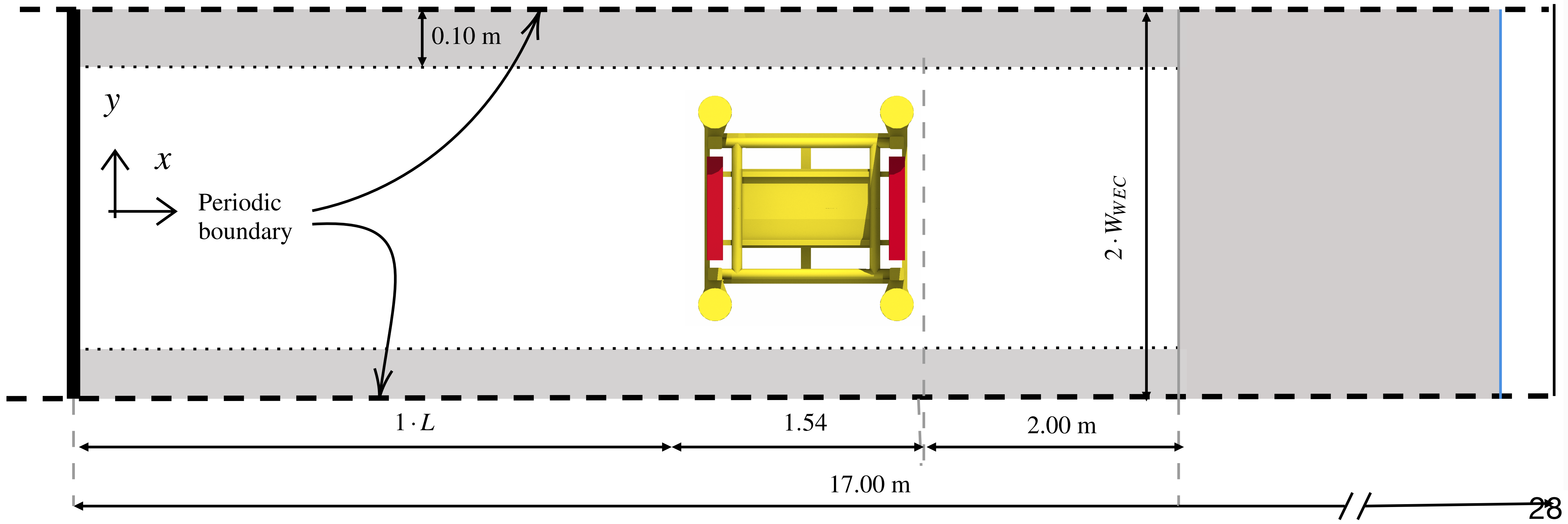
FOSWEC2

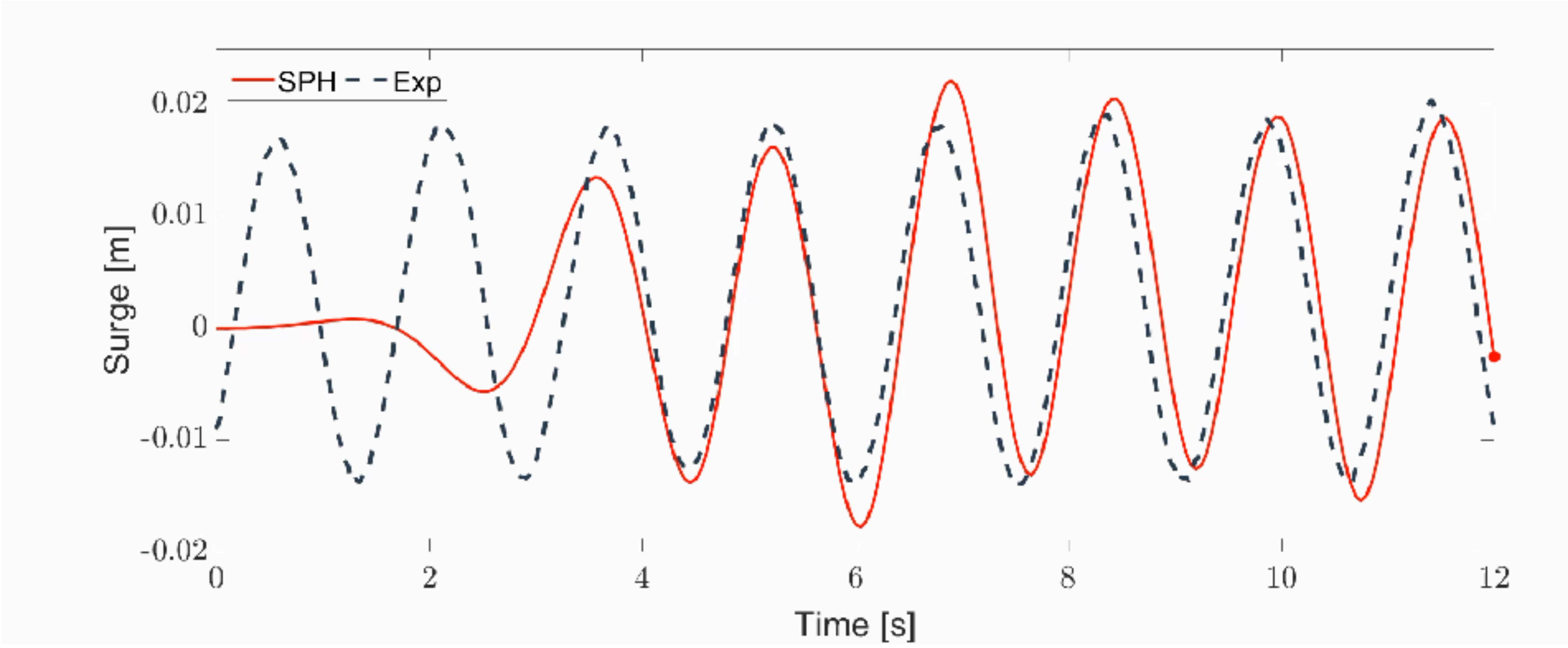
Regular wave validation

$$\mathbf{M}\,\ddot{\mathbf{x}}(t) = \mathbf{f}_{hydro}(t) + \mathbf{f}_{PTO}(t) + \mathbf{f}_{mooring}(t)$$



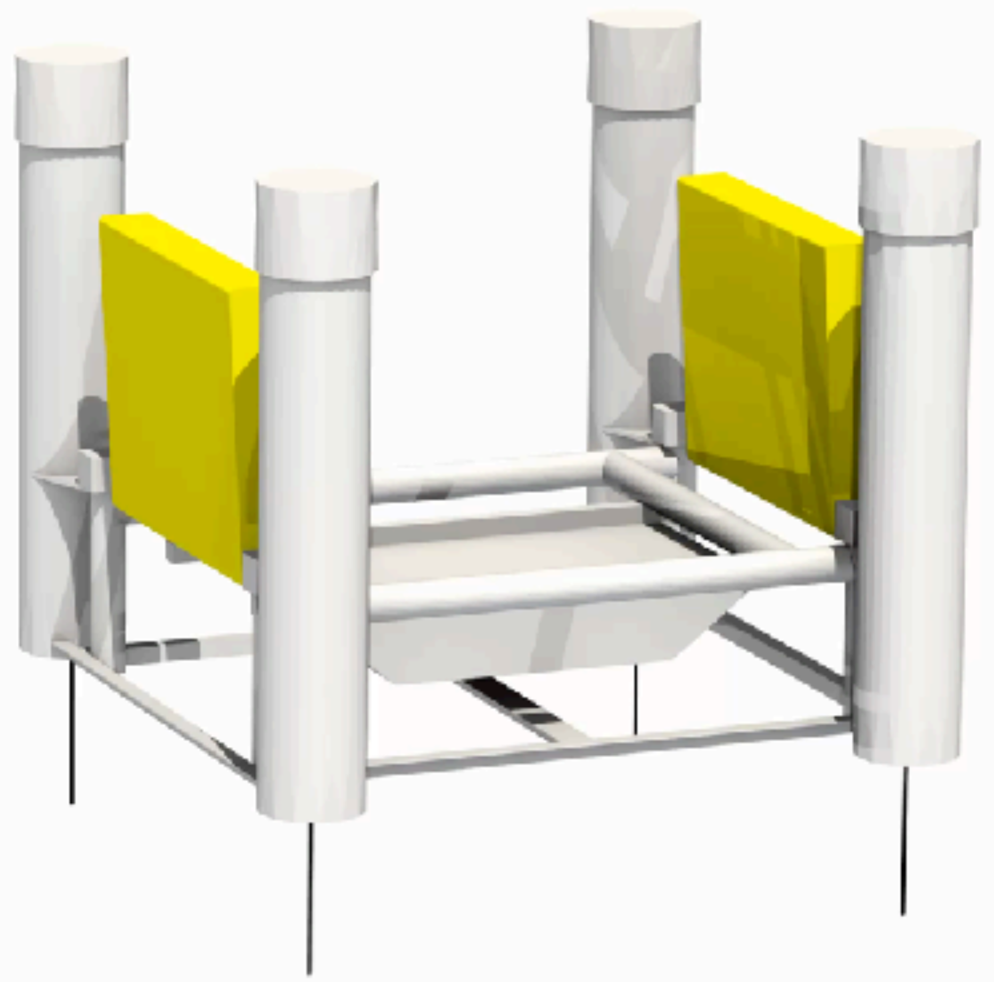
Parameter	Symbol	Quantity	Unit
Wave period	T	1.56	s
Wave height	H	0.136	m
Water depth	d	1.36	m
Wave length	L	3.73	m

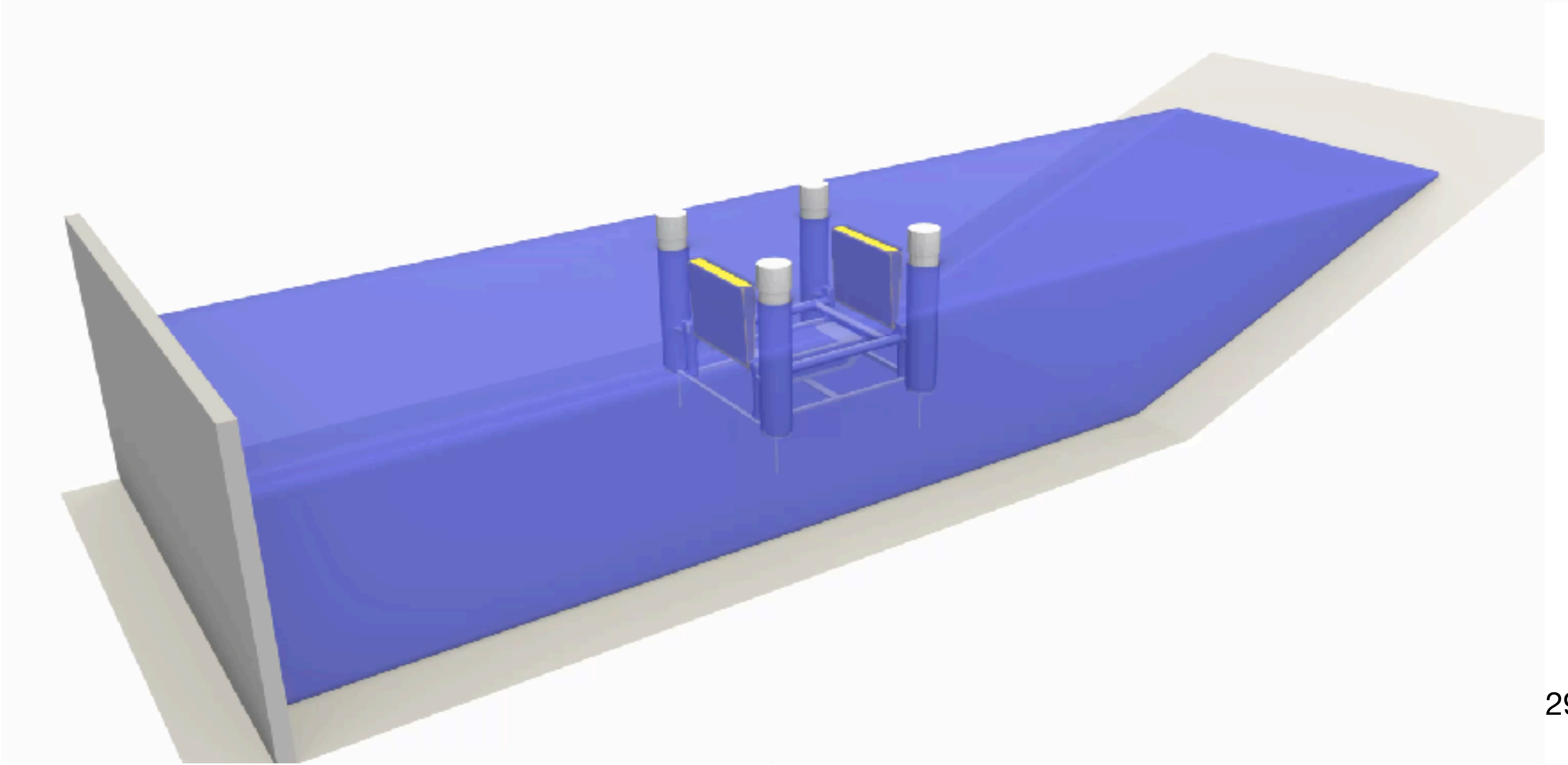


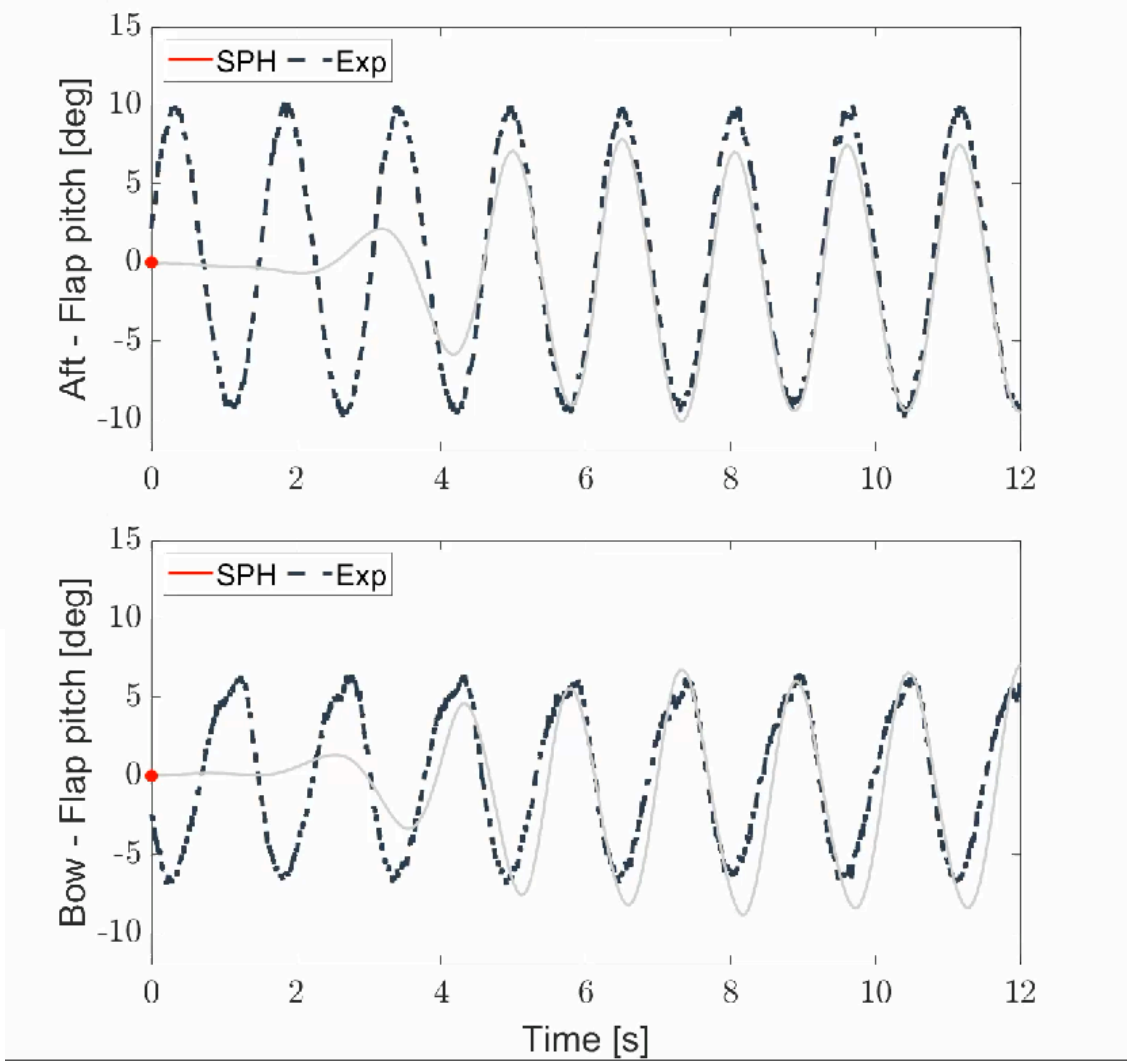


FOSWEC2

Regular wave validation







3. Hybrid platform configuration

Wave–wind power units

Hybrid Wind–wave platforms

Rendered view of a wave–wind farm and a 1/40 experimental model of a wind–wave power system.

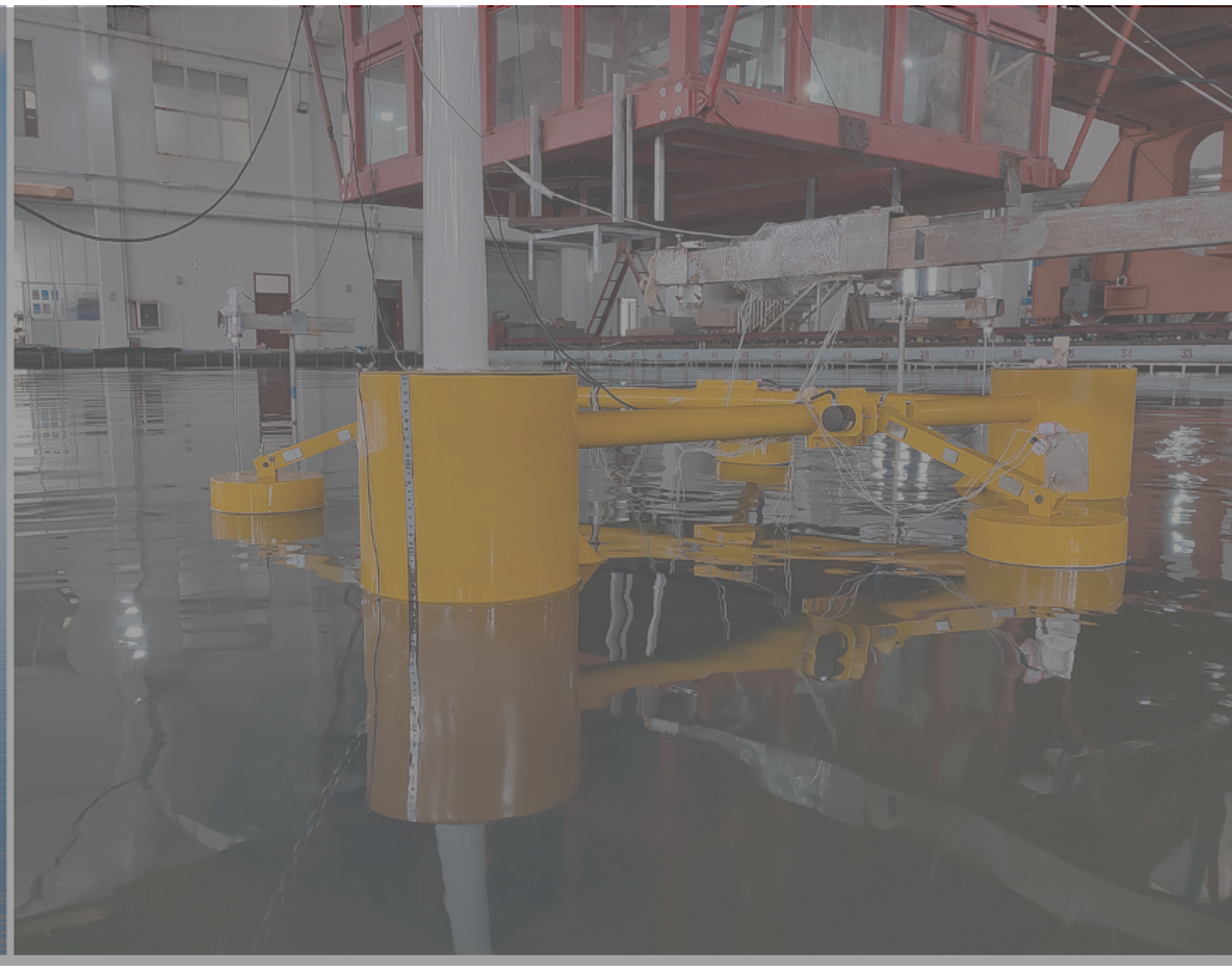
Wei, Z., Borthwick, A. G. L., Cao, F., Zhao, C., Han, M., Dai, M., & Shi, H. (2025). Power performance of an offshore floating hybrid wind and wave energy converter. *Energy Conversion and Management, 341*, 120023. https://doi.org/10.1016/j.enconman.2025.120023

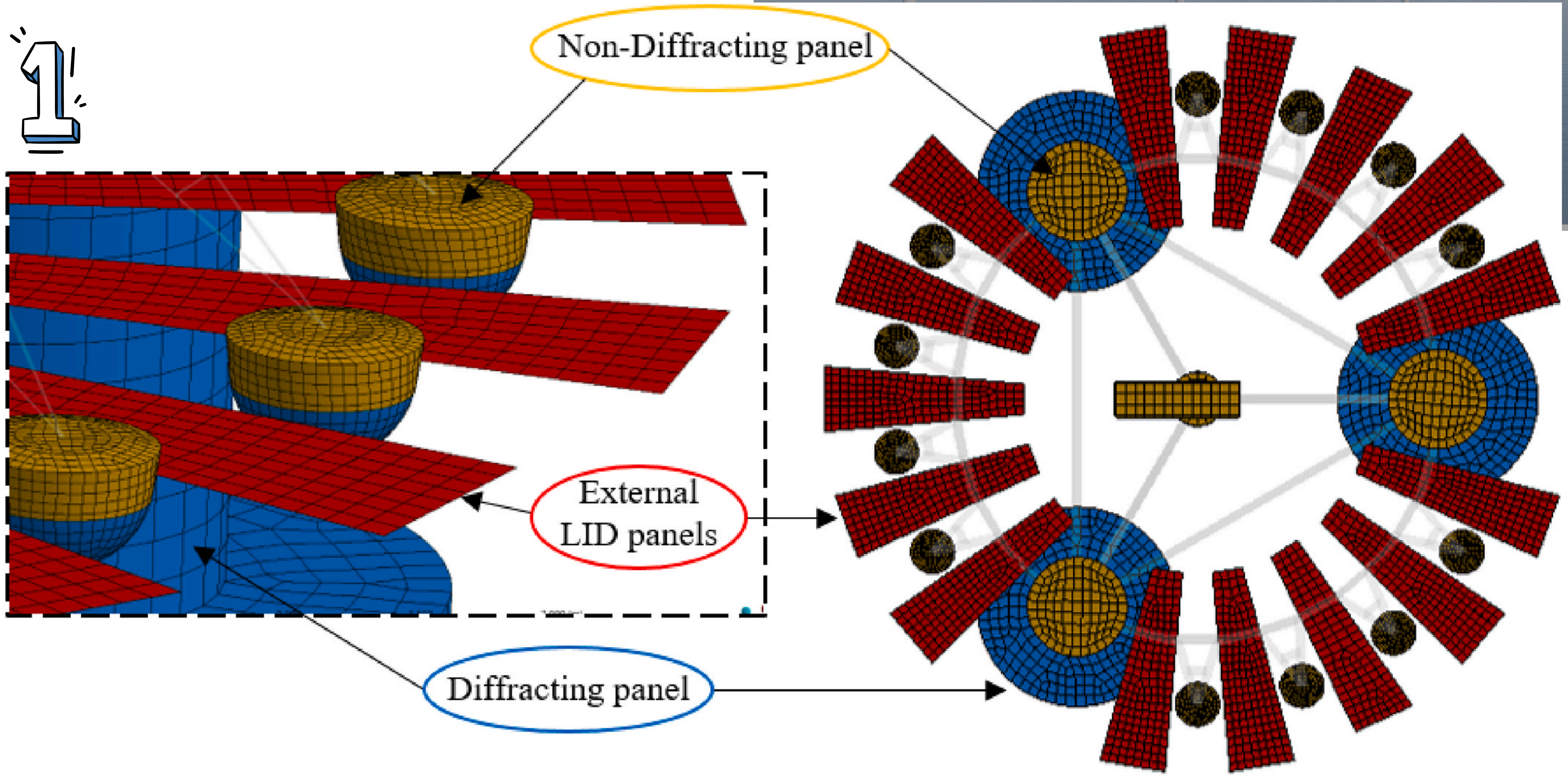
Wei, Z., Cao, F., Cao, C., Han, Z., Shi, H., & Ji, T. (2025). Experimental study on the effects of an array of concentric wave energy converters on the dynamic of semi-submersible floating wind turbine. *Renewable Energy, 242*, 122495. https://doi.org/10.1016/j.renene.2025.122495

Wave energy combined to wind

- Synergy for performance
- Synergy for infrastructure
- Benefits the power grid

Hybrid Wind–wave platforms

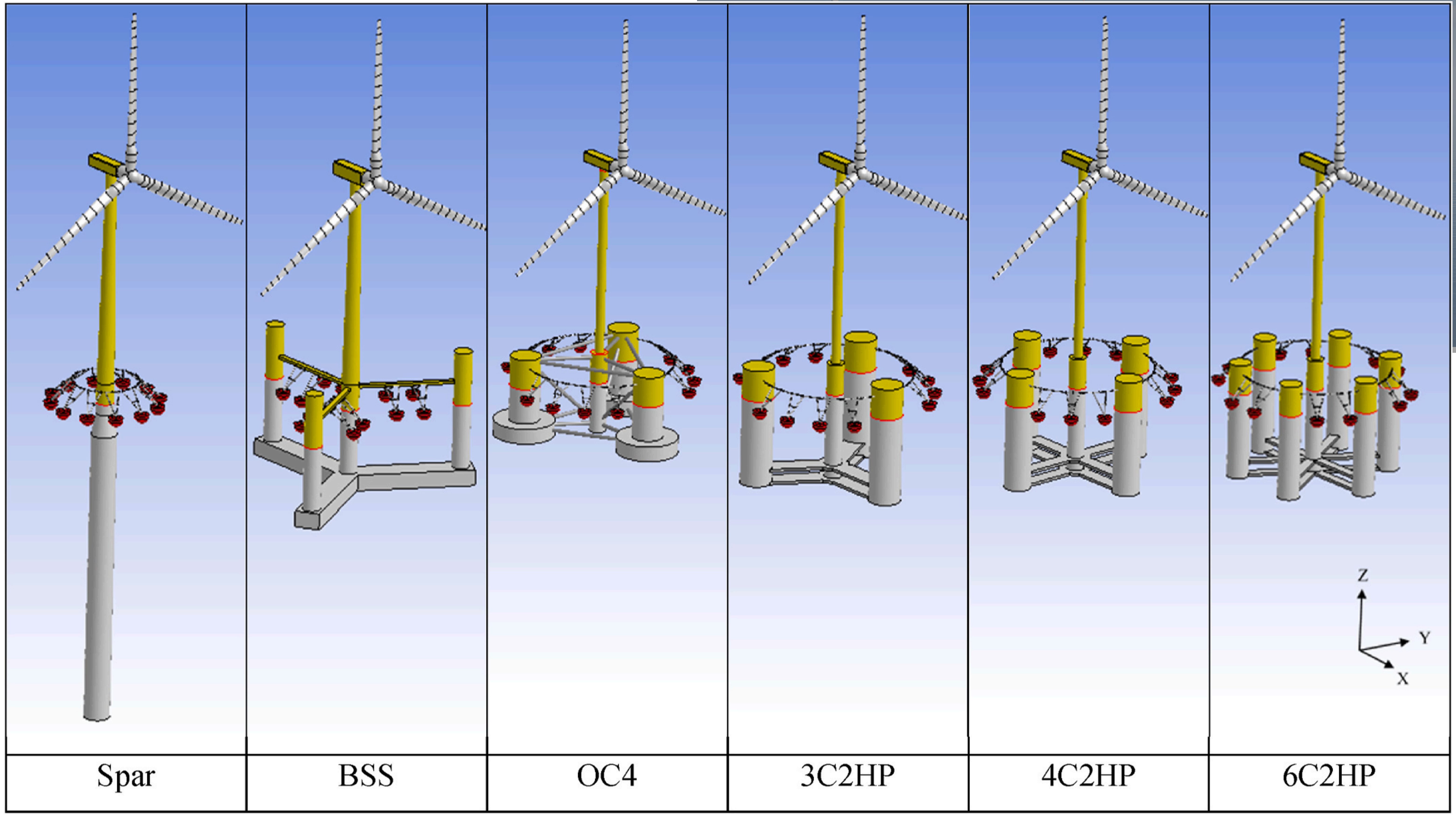




Panel models of the multibody system, including diffracting panels and external LID panels.

Ghafari, H. R., Ghassemi, H., & Akbari Vakilabadi, K. (2025). Hydrodynamic performance and power absorption of the hybrid wind-wave energy systems with different platform geometries. *Ocean Engineering, 332*, 121440. https://doi.org/10.1016/j.oceaneng.2025.121440

Hybrid Wind–wave platforms



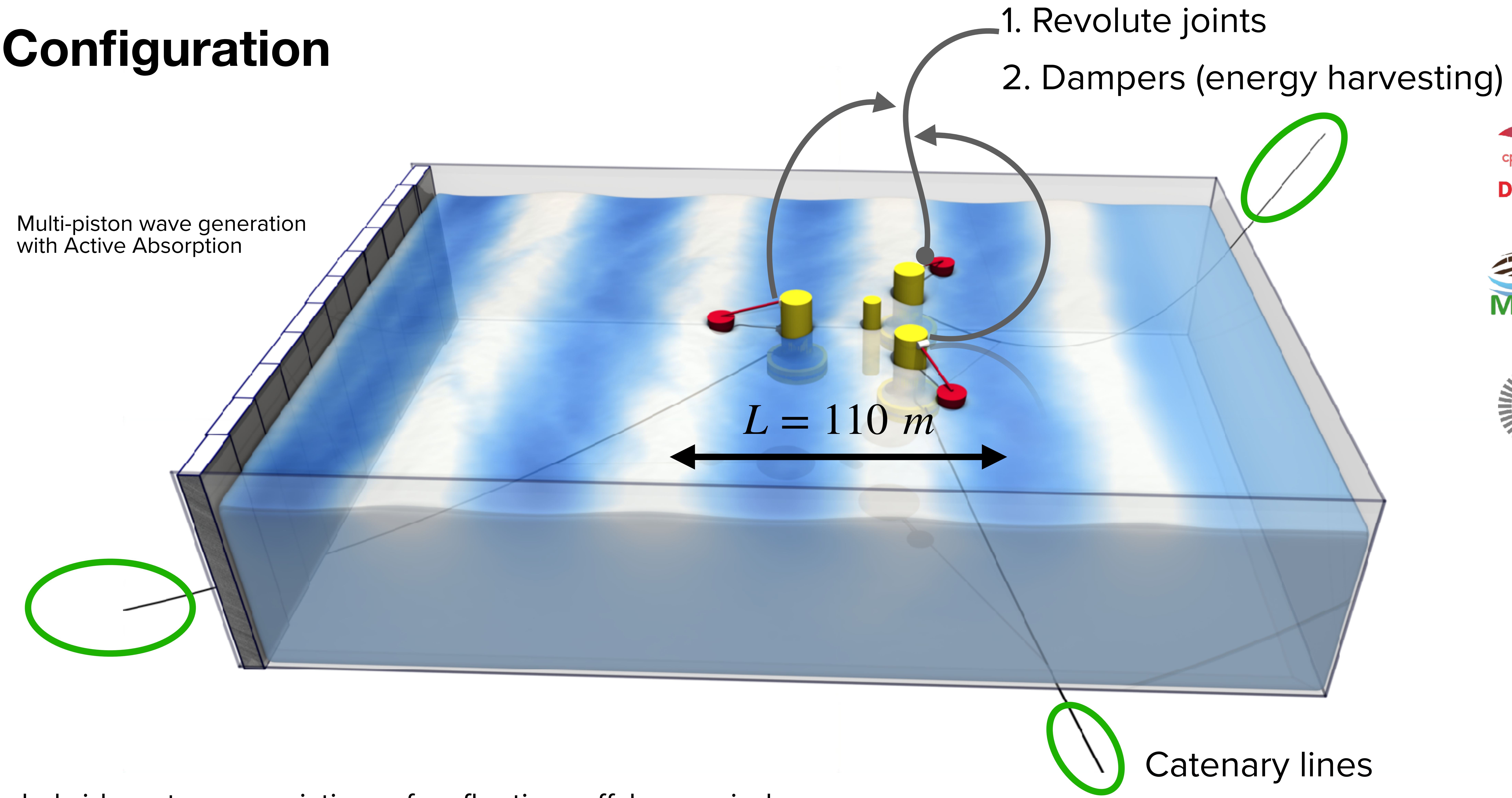
Ansys AQWA

Different types of floating platforms for hybrid wind-wave systems (Wavestar: N=12, D=5.00 m).

Ghafari, H. R., Ghassemi, H., & Akbari Vakilabadi, K. (2025). Hydrodynamic performance and power absorption of the hybrid wind-wave energy systems with different platform geometries. *Ocean Engineering, 332*, 121440. https://doi.org/10.1016/j.oceaneng.2025.121440

Semi-sub and Wavestar

Configuration



A hybrid system consisting of a floating offshore wind turbine and wave energy converters (WECs) is promising for multiple extractions of ocean renewable energy.

Jin, P., Zheng, Z., Zhou, Z., Zhou, B., Wang, L., Yang, Y., & Liu, Y. (2023). Optimization and evaluation of a semi-submersible wind turbine and oscillating body wave energy converters hybrid system. *Energy, 282*, 128889. https://doi.org/10.1016/j.energy.2023.128889

Challenge

1. Coexistence of very dissimilar structures (WECs and FOWTs)
2. Simulation of larger domains
3. Long simulations

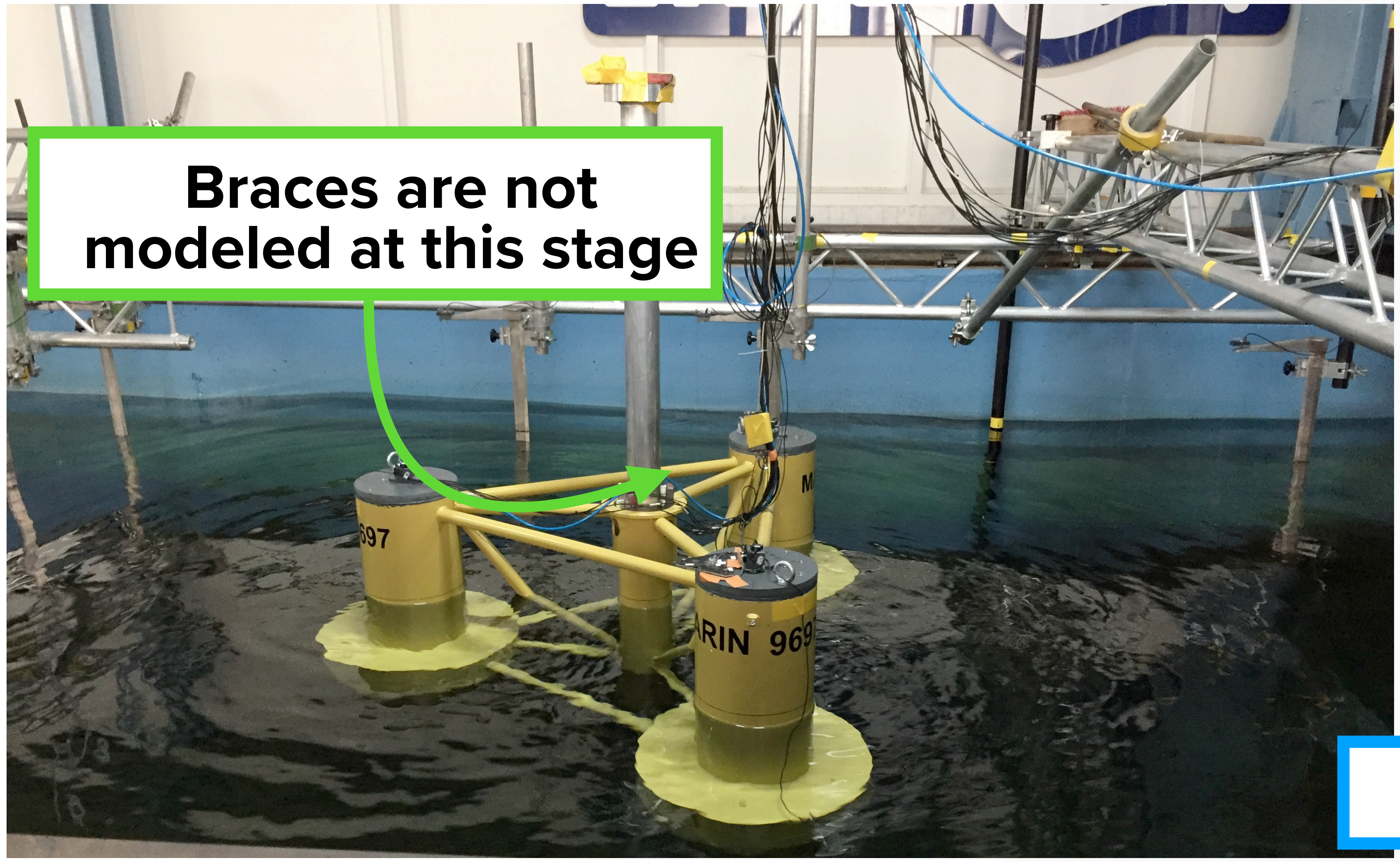
Floating offshore wind

DeepCwind Platform

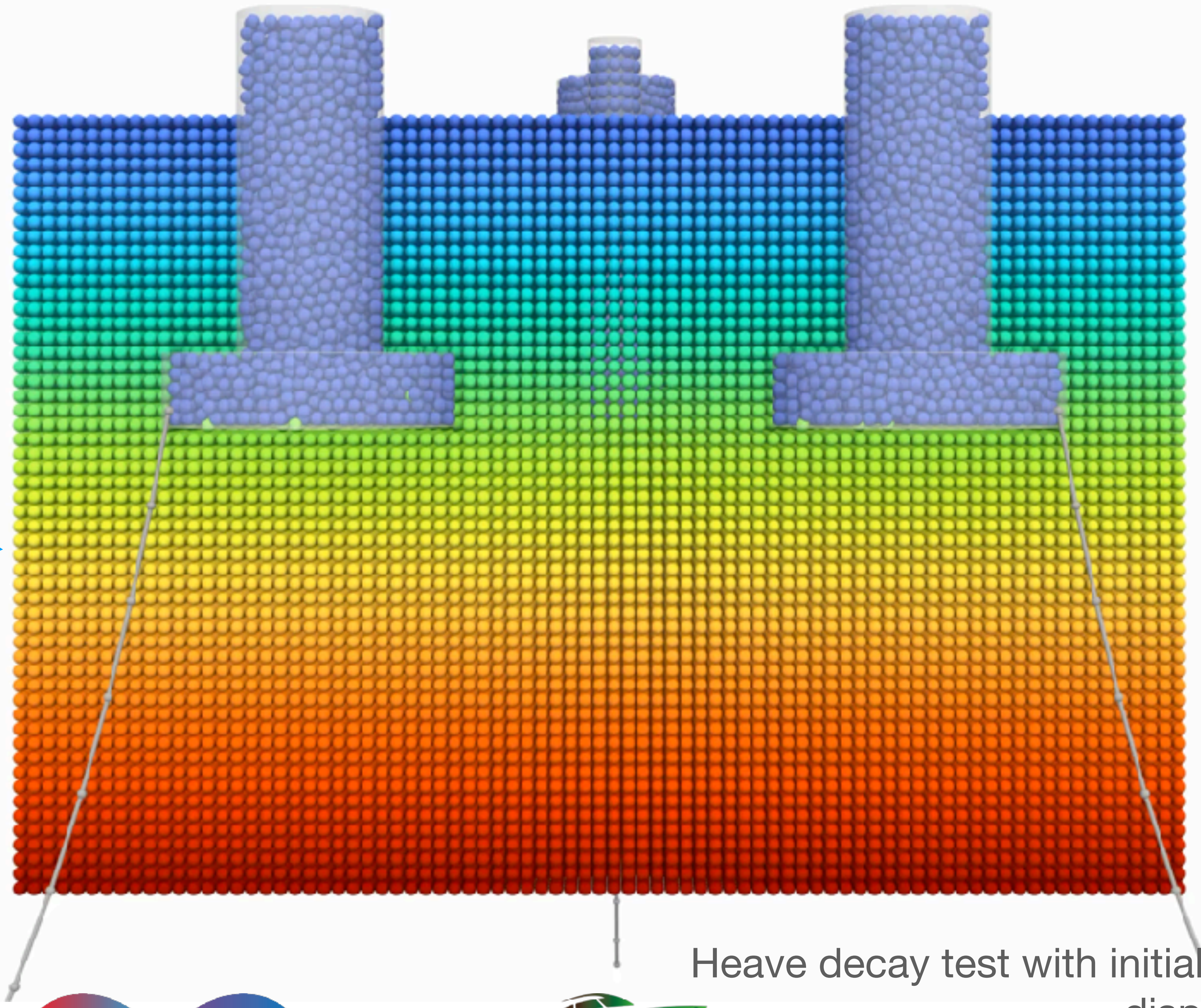
Packing algorithm for particle positioning

DEEPCWIND USED IN OC6-PHASE IA

	Particle size	Float Particles	Total Particles	Runtime
Dp=T/5	1.25 cm	22 k	3.6 M	2.3 h



Simulation time: 15 seconds



Heave decay test with initial negative displacement

Phase I of the OC6 project is focused on examining **why** offshore wind design tools underpredict the response (loads/motion) of the OC5-DeepCwind semisubmersible at its surge and pitch natural frequencies.

Niosi, F., Dell'edera, O., Glorioso, M., Paduano, B., Giorgi, G., & Schreier, S. (2025). Experimental investigation and dataset release of a taut-leg mooring system for a semi-sersible floating offshore wind turbine. *Ocean Engineering*, *328*, 121067. https://doi.org/10.1016/j.oceaneng.2025.121067

cpu gpu DualSPHysics

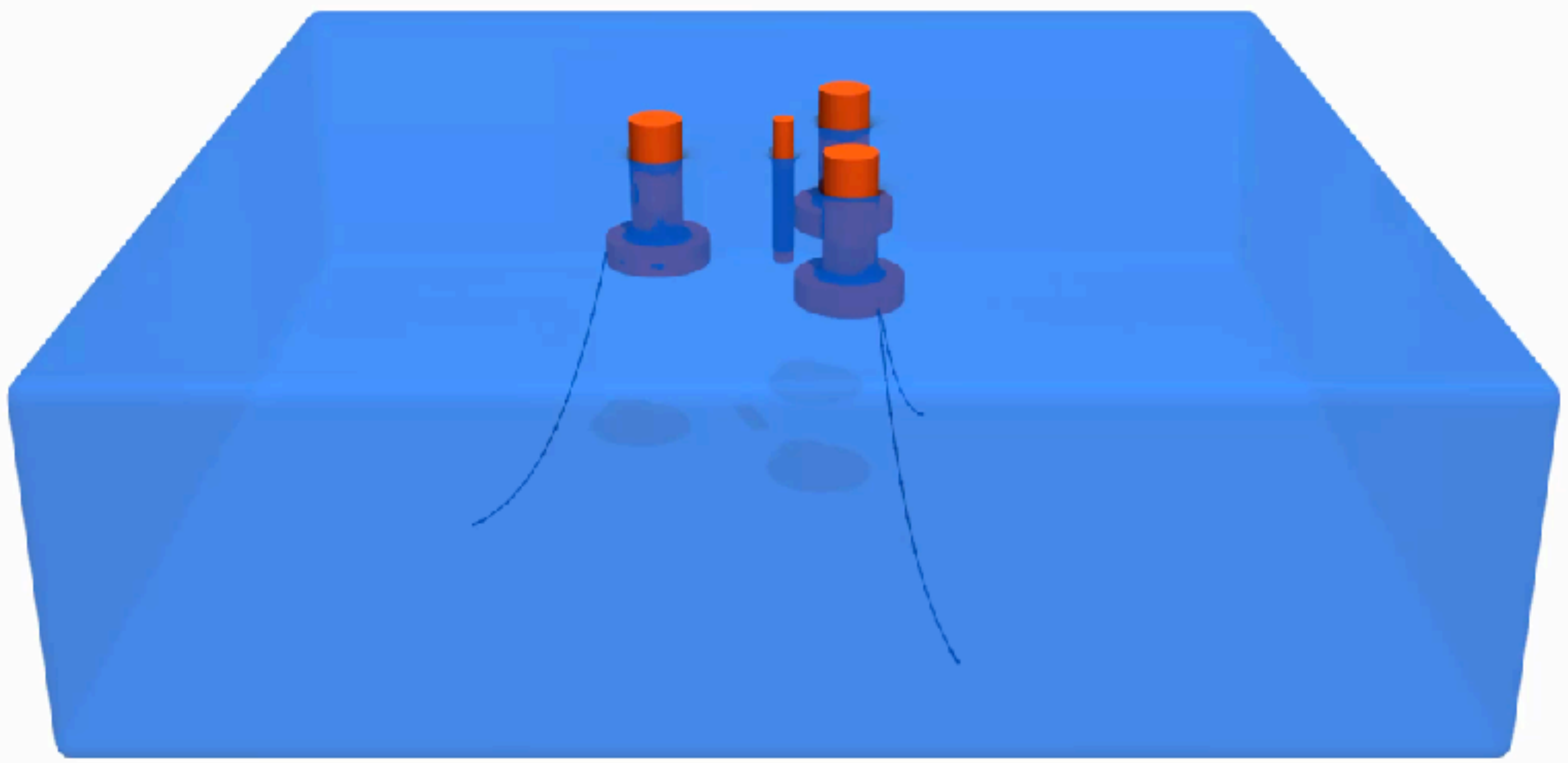
MoorDyn+

Decay test

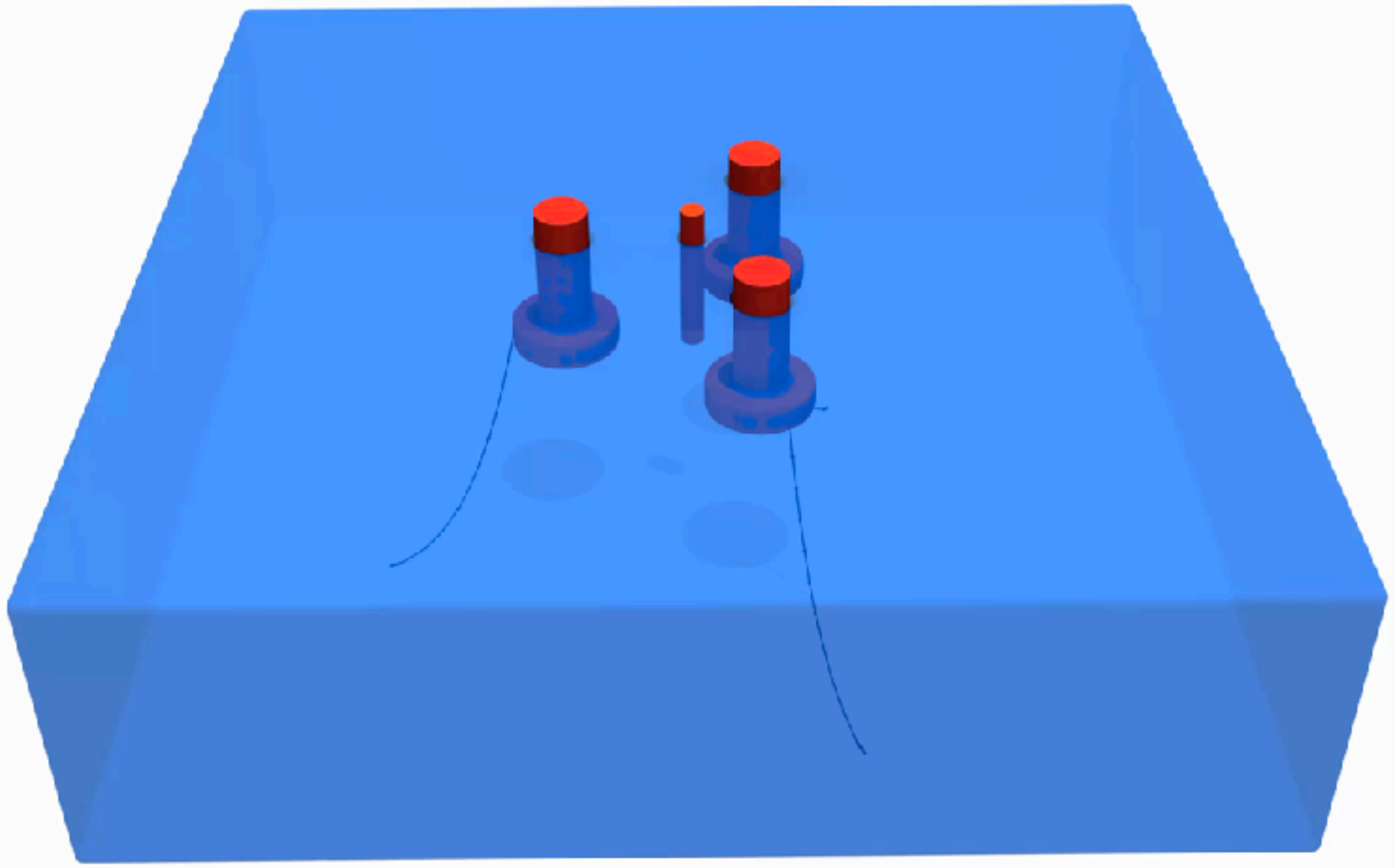
Heave

	Particle size	Float Particles	Total Particles	Runtime
Dp=T/5	1.25 cm	22 k	3.2 M	1.9 h
Dp=T/10	0.62 cm	100 k	20 M	23 h

Simulation time: 15 seconds



Coloring represents magnitude velocity



Coloring represents magnitude velocity

Heave decay test with initial negative displacement

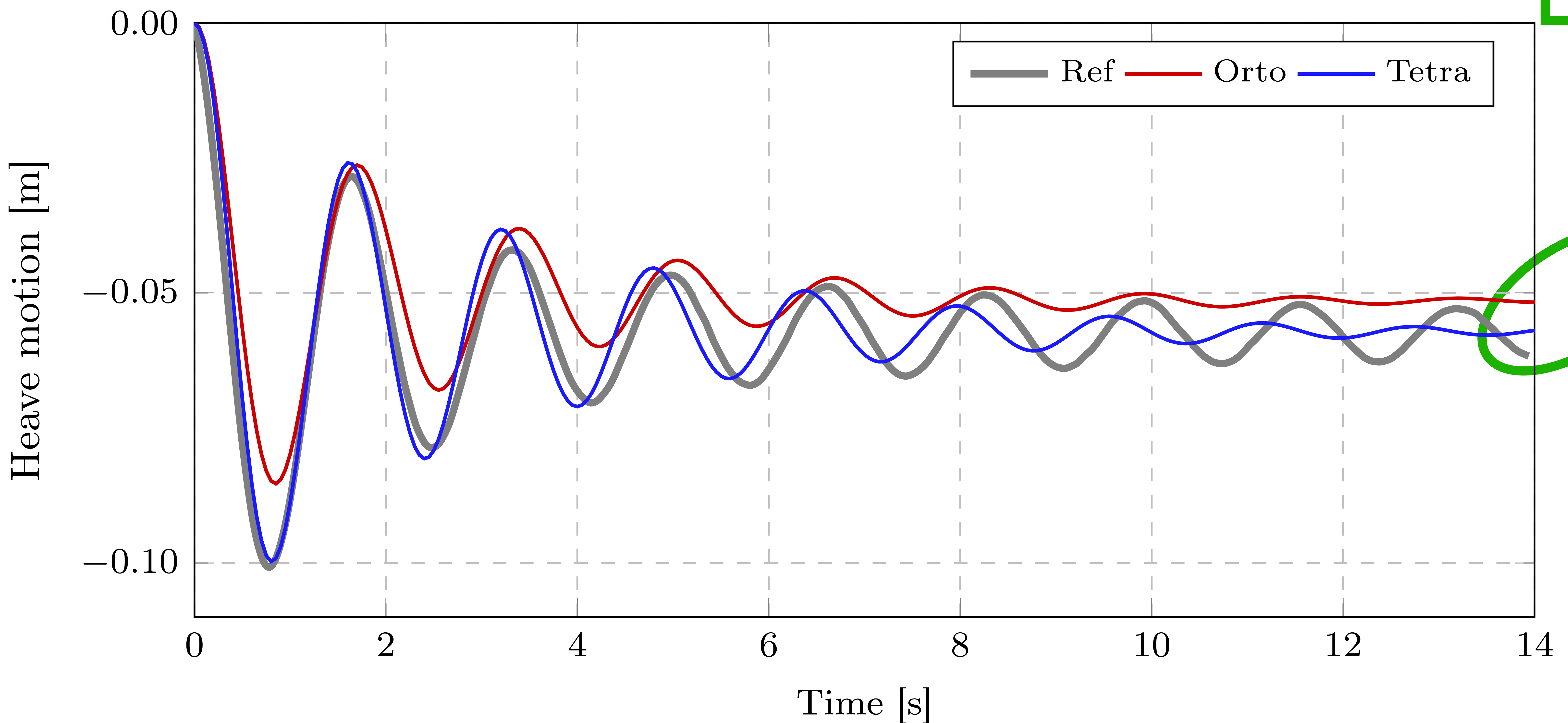
Packing algorithm for particle positioning

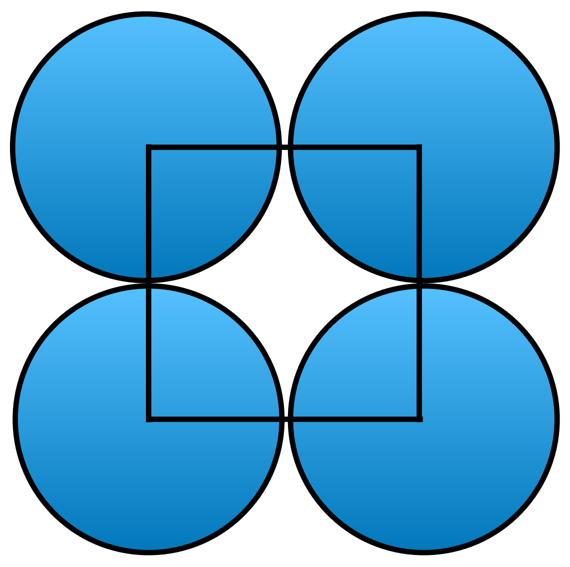
Comparison $Dp = T/5$

Laminar viscosity

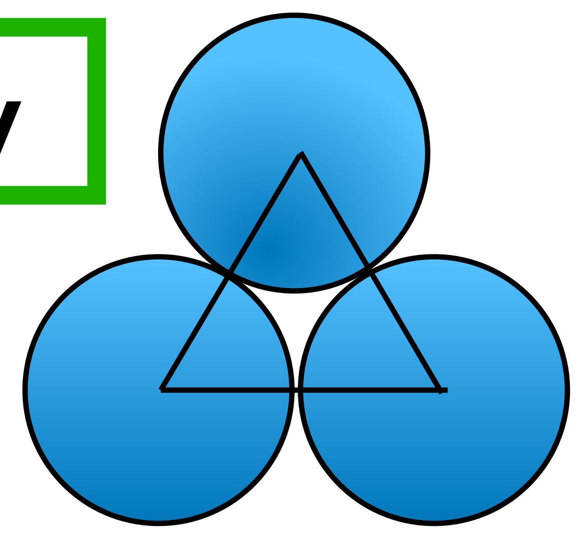
	Main frequency (s)	Damping ratio (δ_2)	Error
Orto	1.65	3.5%	7%
Tetra	1.60	3.0%	4%
Reference	1.64	2.0%	-

Better buoyancy





Orto Lattice



Triangular Lattice

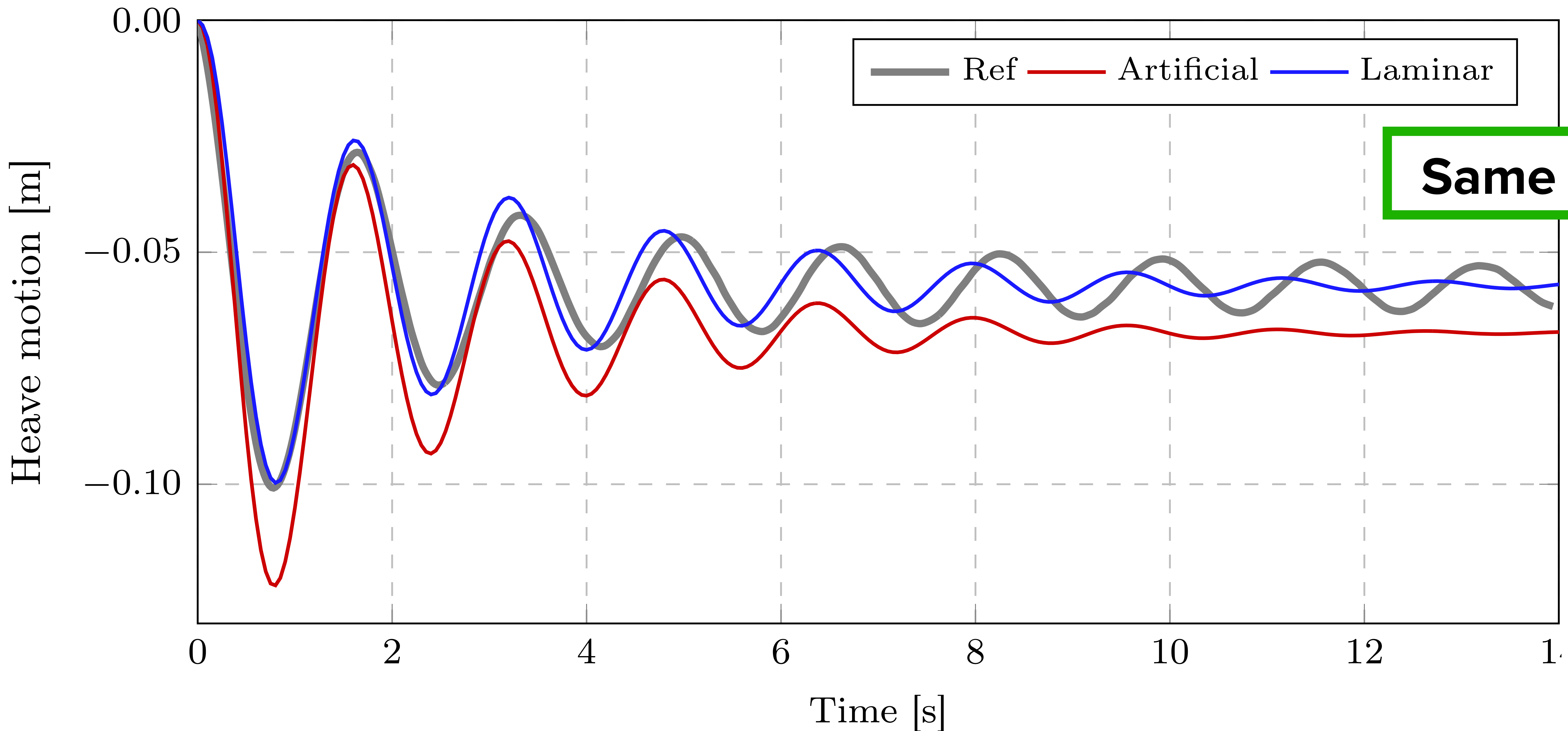
CHRONO DEM-Engine

DualSPHysics

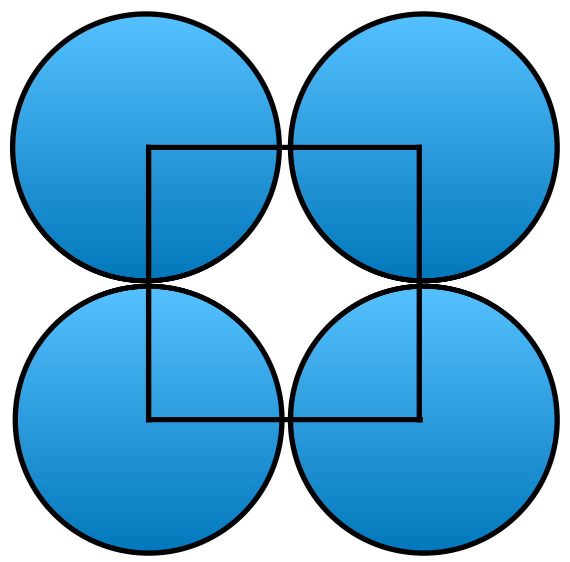
Packing algorithm for particle positioning

Viscosity model

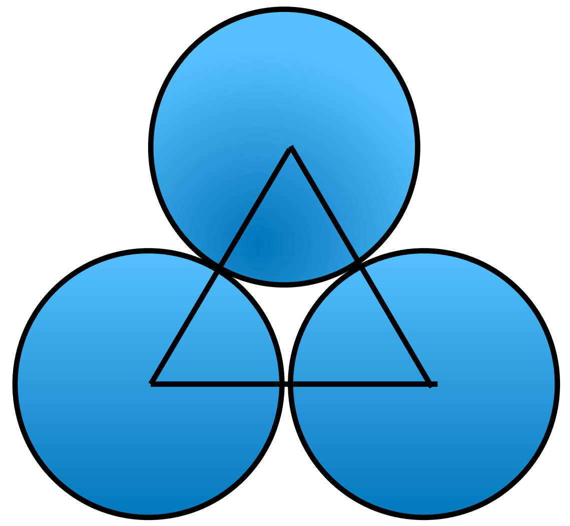
	Main frequency (s)	Damping ratio (δ_2)	Error
Orto	1.65	3.5%	7%
Tetra	1.60	3.0%	4%
Reference	1.64	2.0%	-



Same runtime!



Orto Lattice



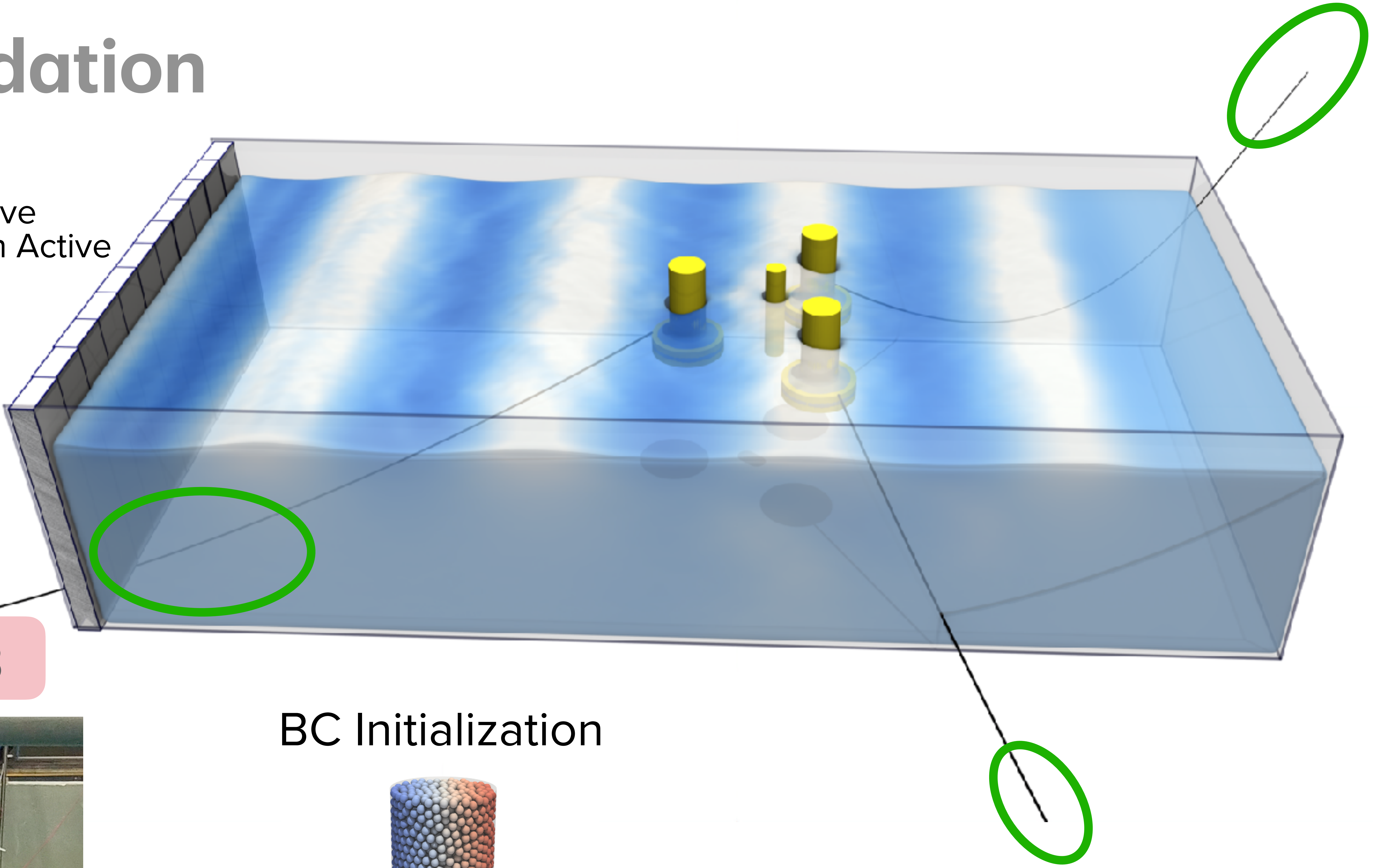
Triangular Lattice

CHRONO DEM-Engine

cpu gpu DualSPHysics

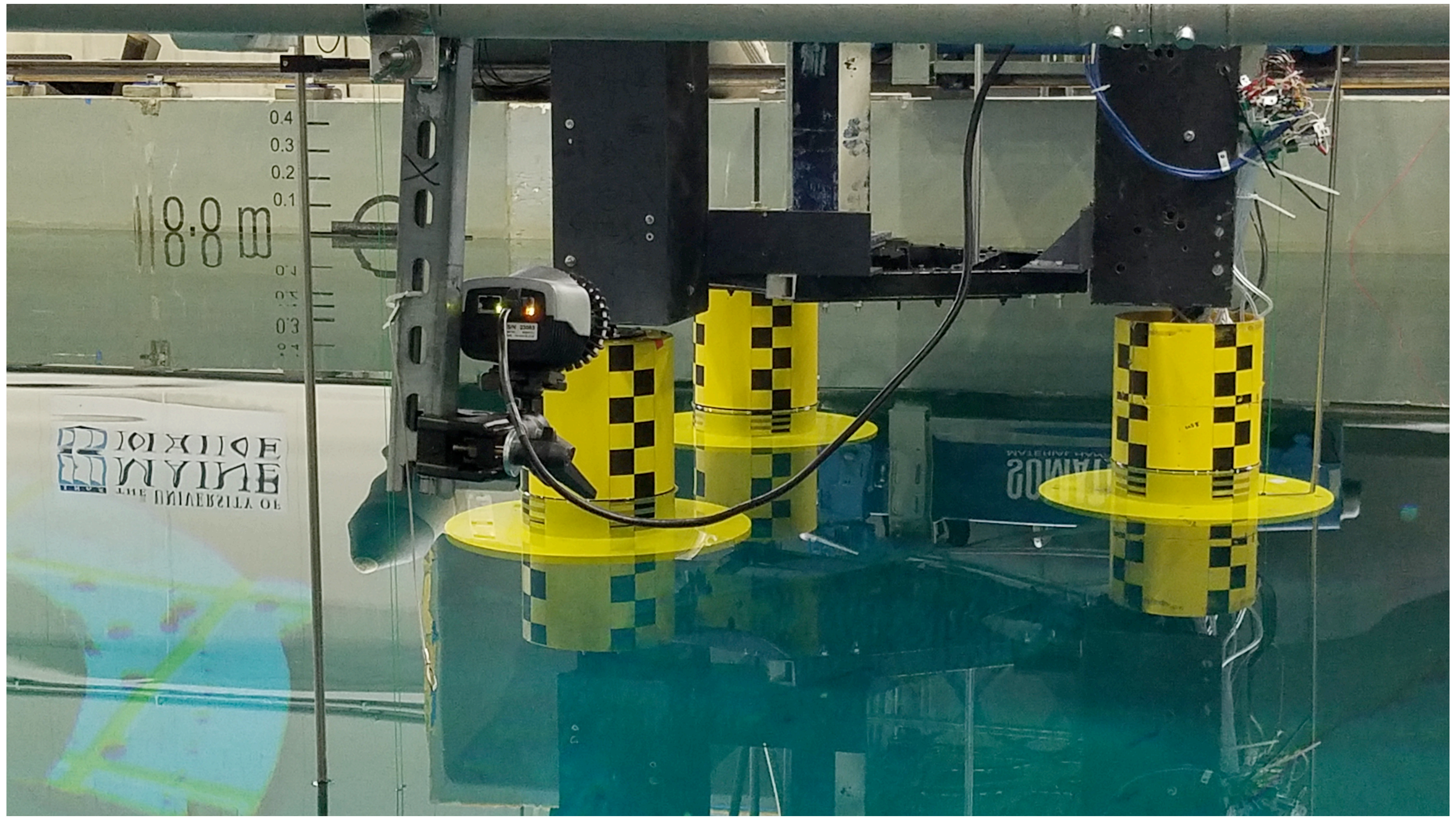
Hydrodynamic load validation

Multi-piston wave generation with Active Absorption

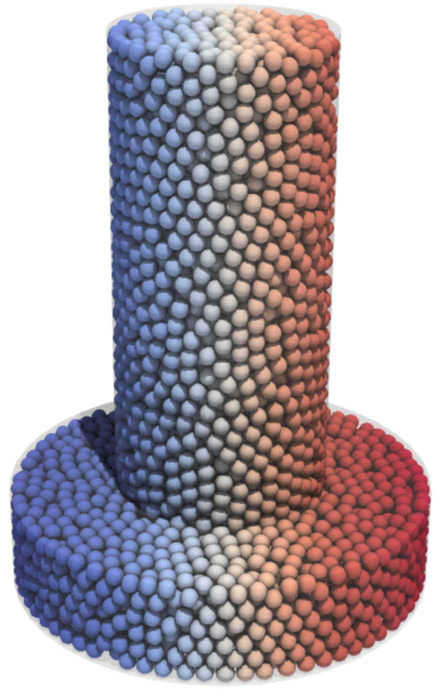


Images courtesy of Amy Robertson (NREL)

DEEPCWIND USED IN OC6-PHASE IB



BC Initialization

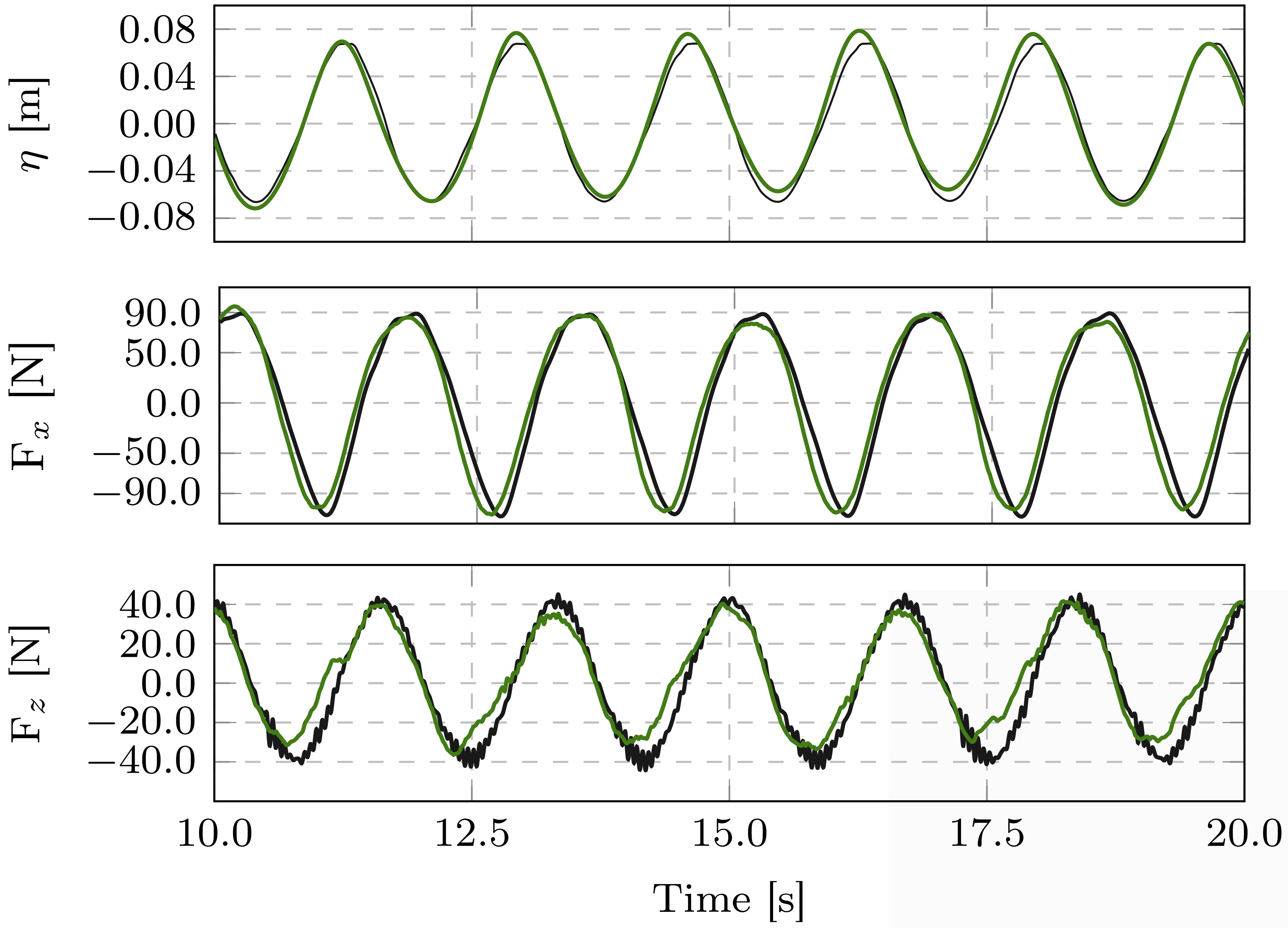


DualSPHysics MoorDyn+

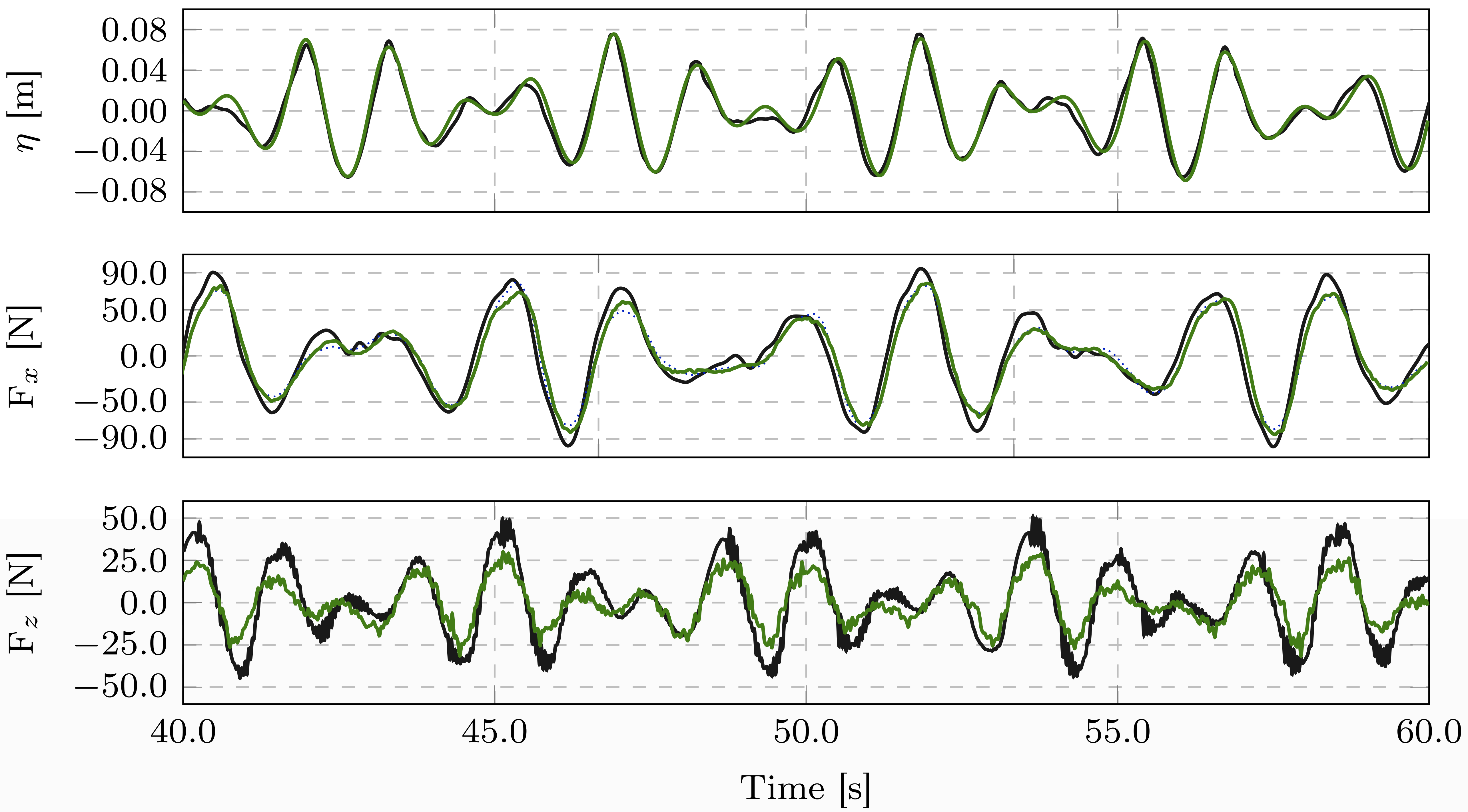
Tagliafierro, B., Karimirad, M., Altomare, C., Göteman, M., Martínez-Estévez, I., Capasso, S., Domínguez, J. M., Viccione, G., Gómez-Gesteira, M., & Crespo, A. J. C. (2023). Numerical validations and investigation of a semi-submersible floating offshore wind turbine platform interacting with ocean waves using an SPH framework. *Applied Ocean Research, 141*, 103757. https://doi.org/10.1016/j.apor.2023.103757

Validation

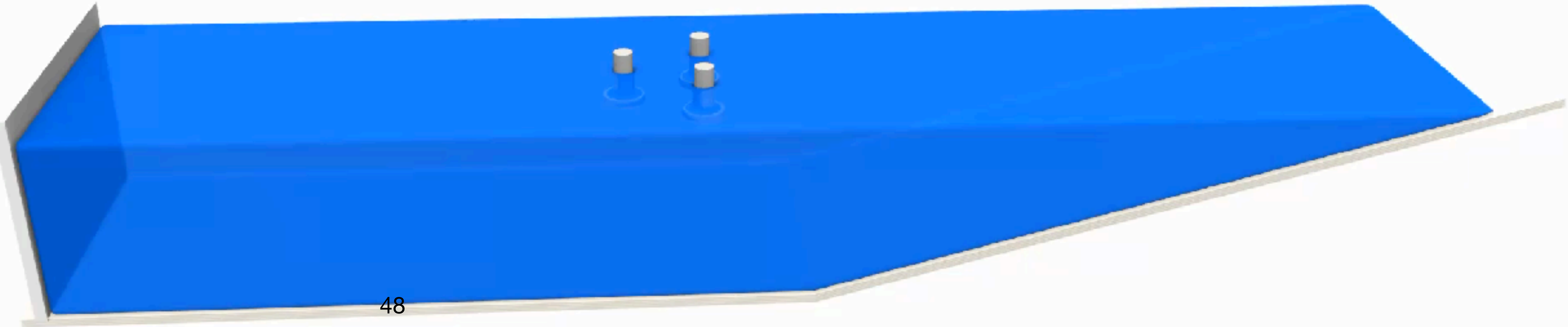
Regular waves



Bichromatic waves

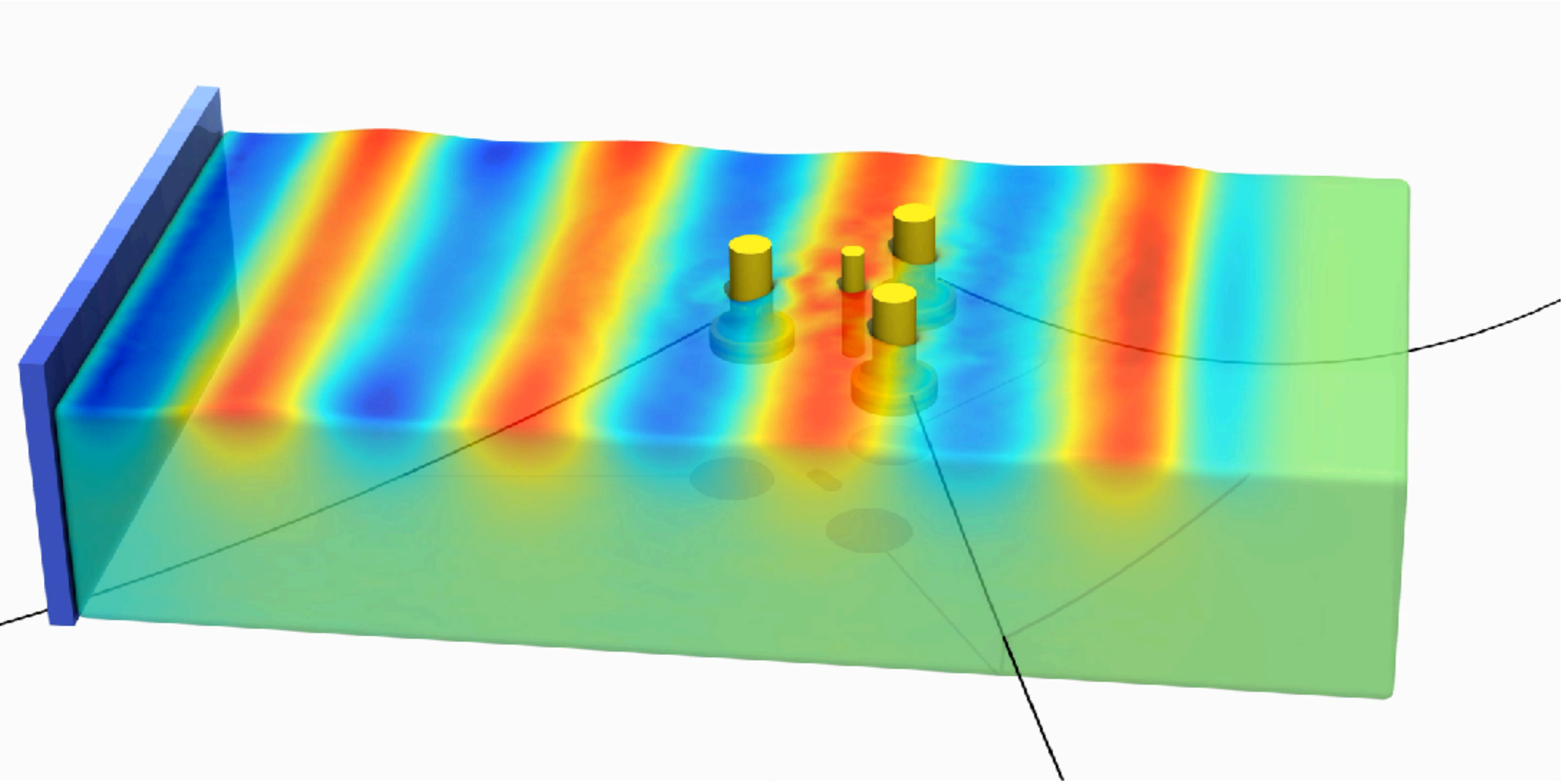


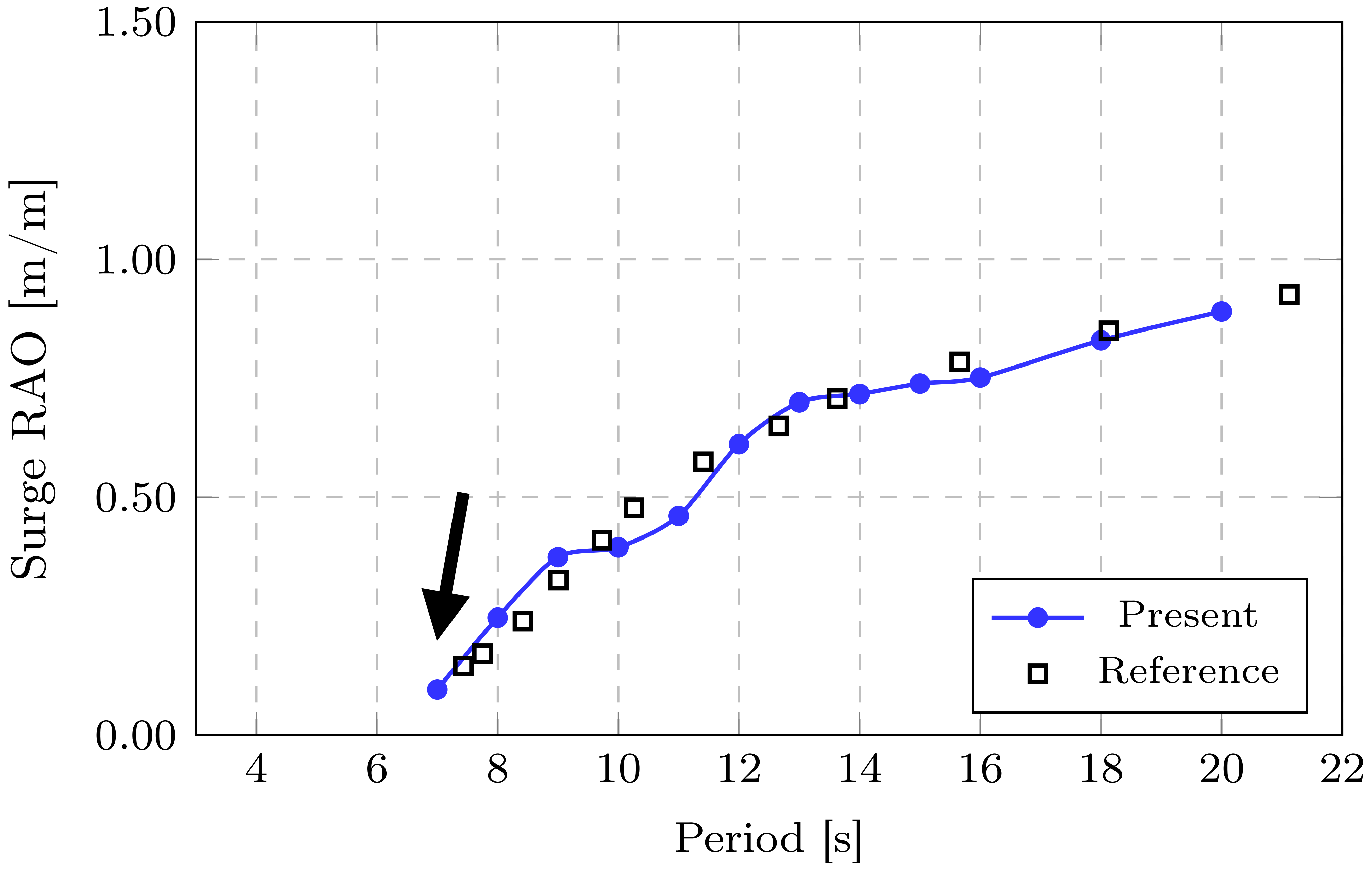
The platform is fixed, so these simulations do not include any external library.

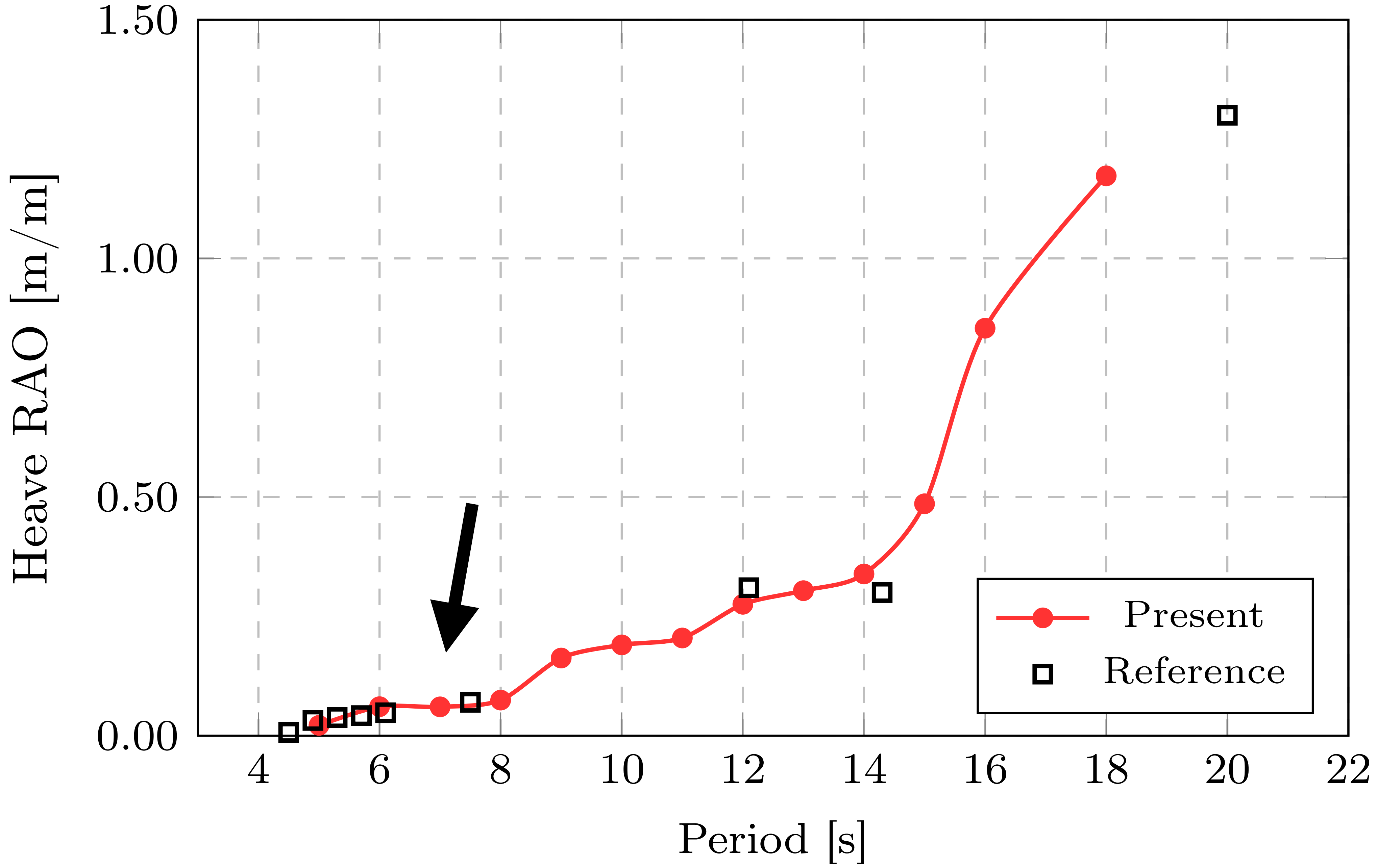


Spectral response

	H	T
R7	3.00 m	7.00 s







Wave energy converters

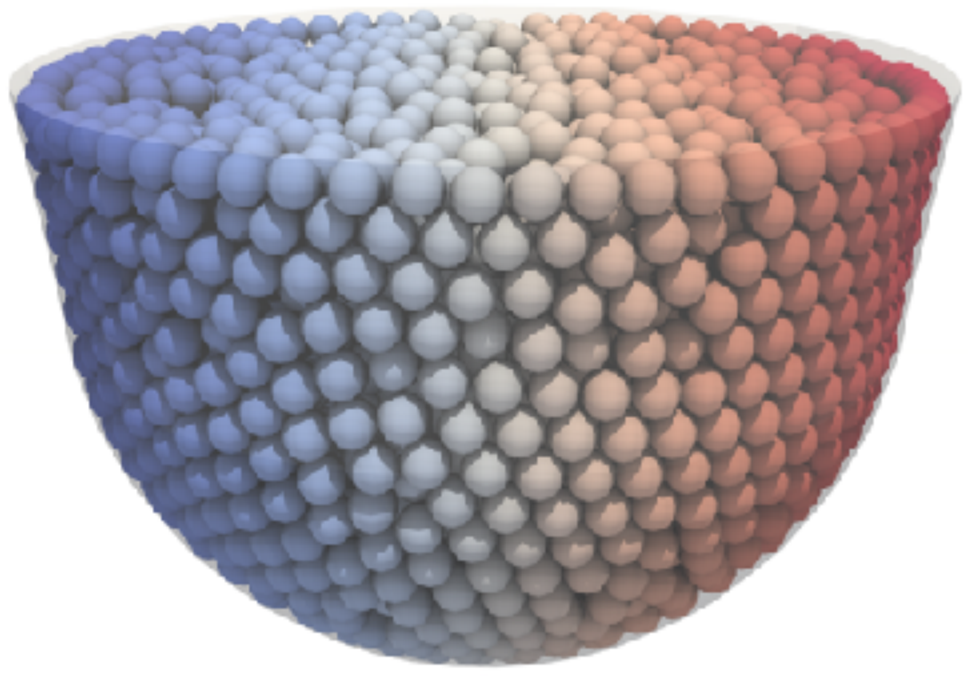
Wavestar

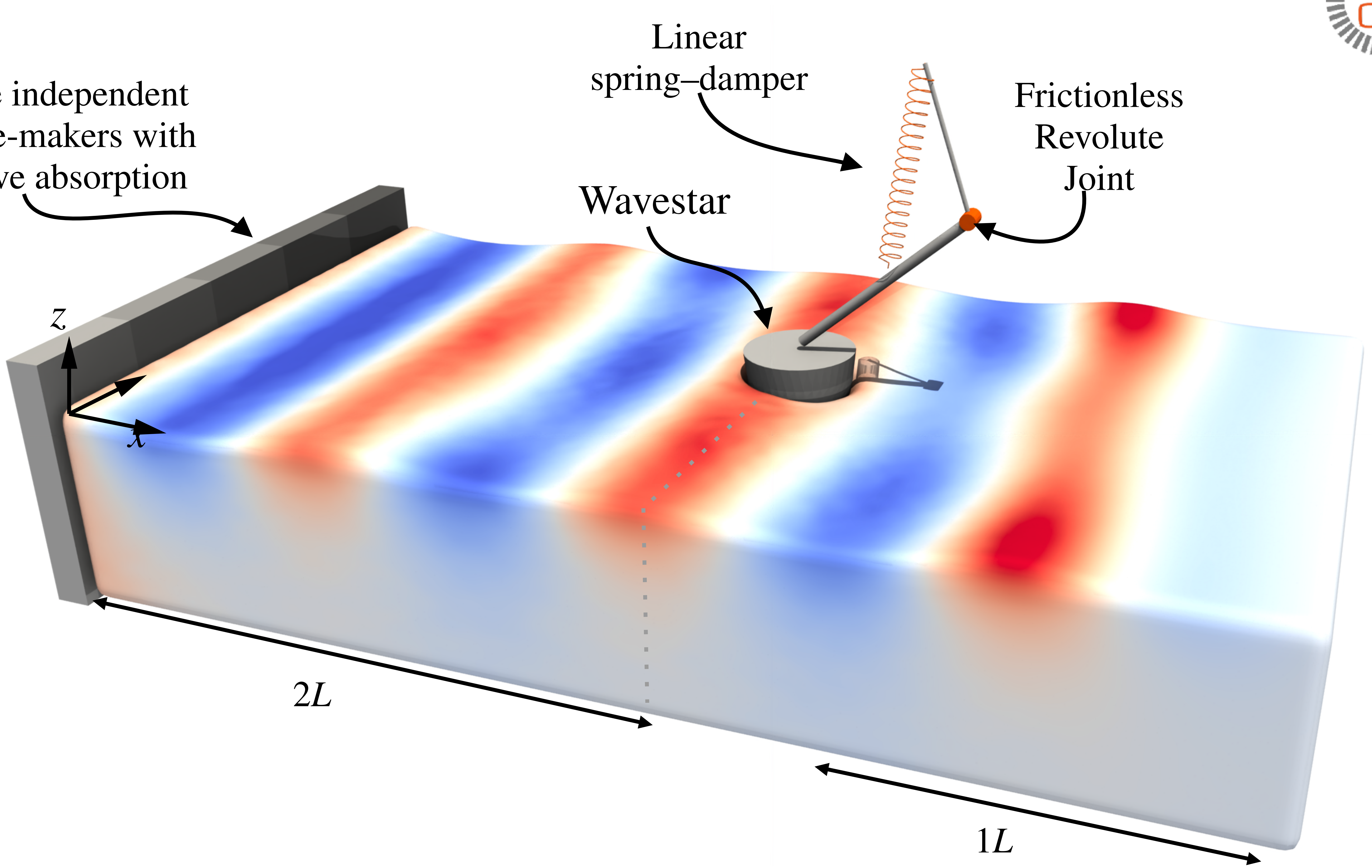
Wavestar

General overview

BC Initialization

$D = 9.80\ m$



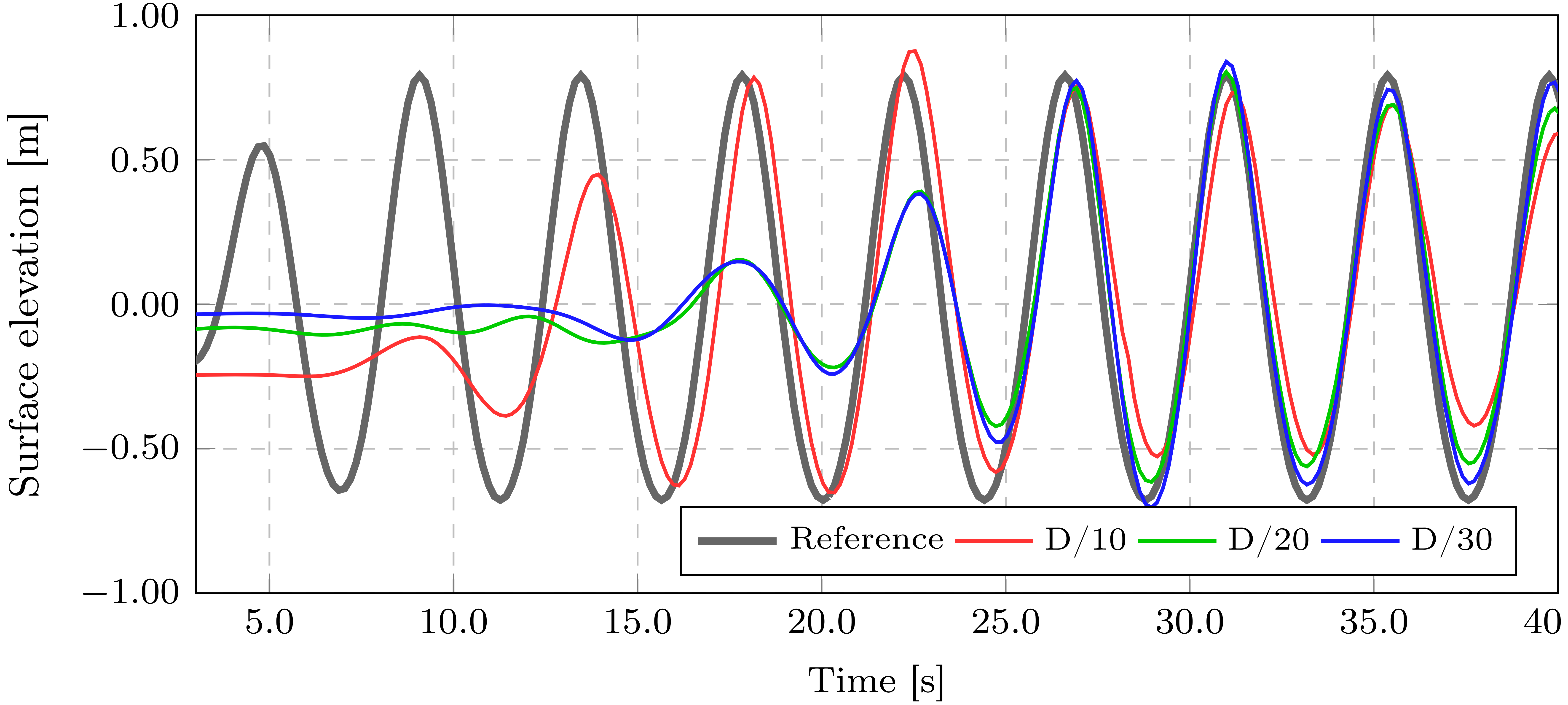


Windt et al. (2020). Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter. *Renewable Energy, 146*, 2499-2516. https://doi.org/10.1016/j.renene.2019.08.059

Wave validation

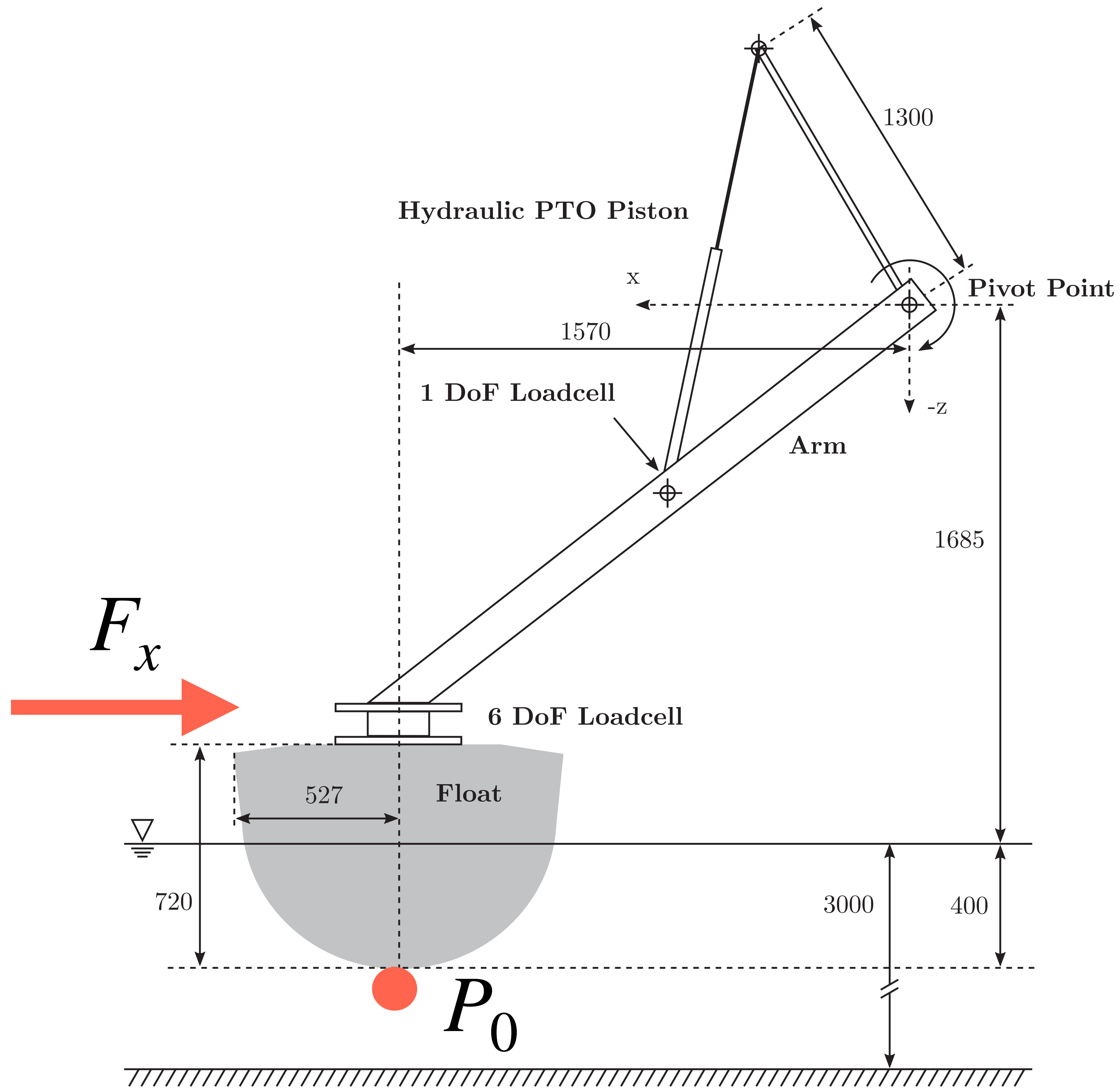
	Particle size	H/*dp*
Dp=D/10	1.00 m	1.50
Dp=D/20	0.50 m	3.00
Dp=D/30	0.33 m	5.00

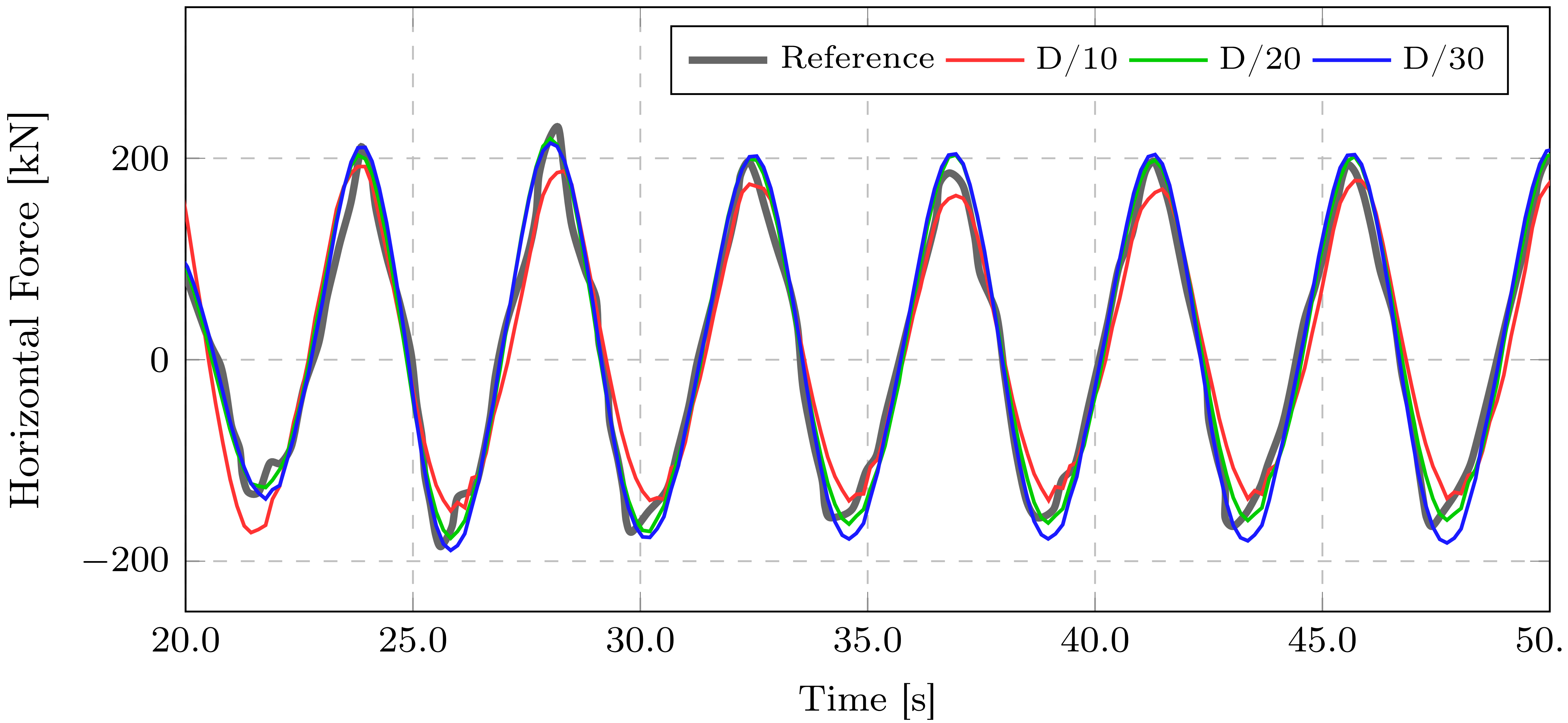
	Wave Height	Wave Period	Wave Length
MS02	1.50 m	4.40 s	30.92 m

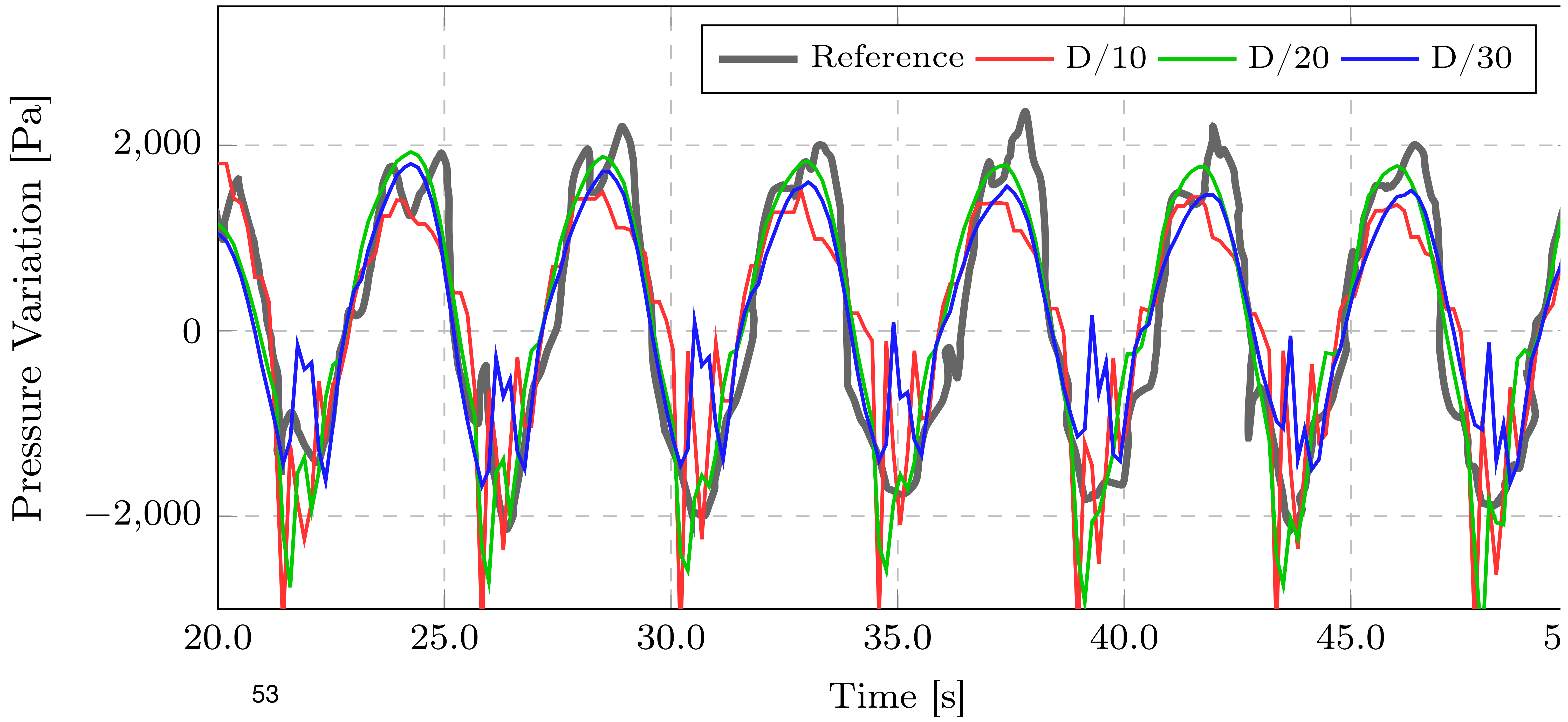


Fixed Float

Hydrodynamics





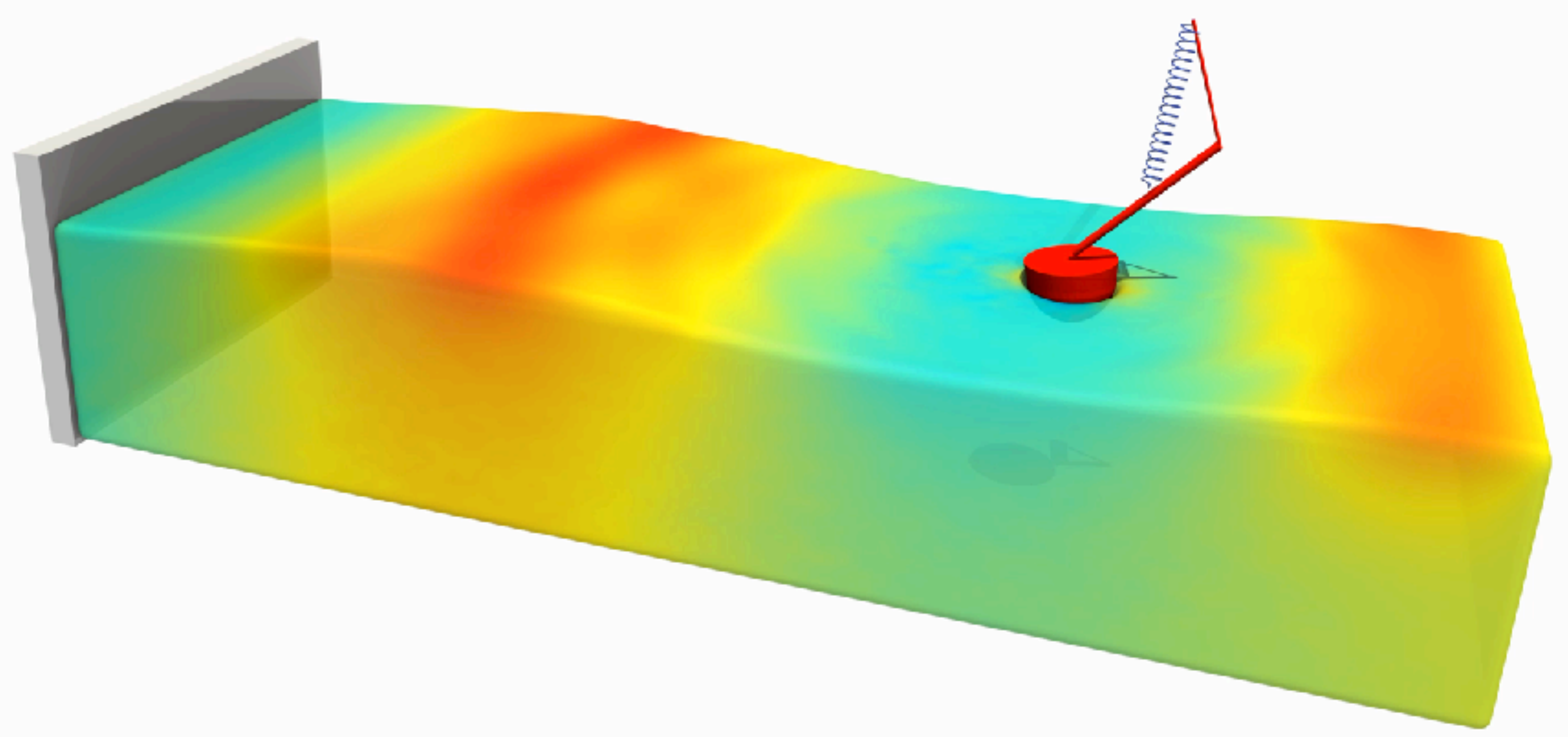


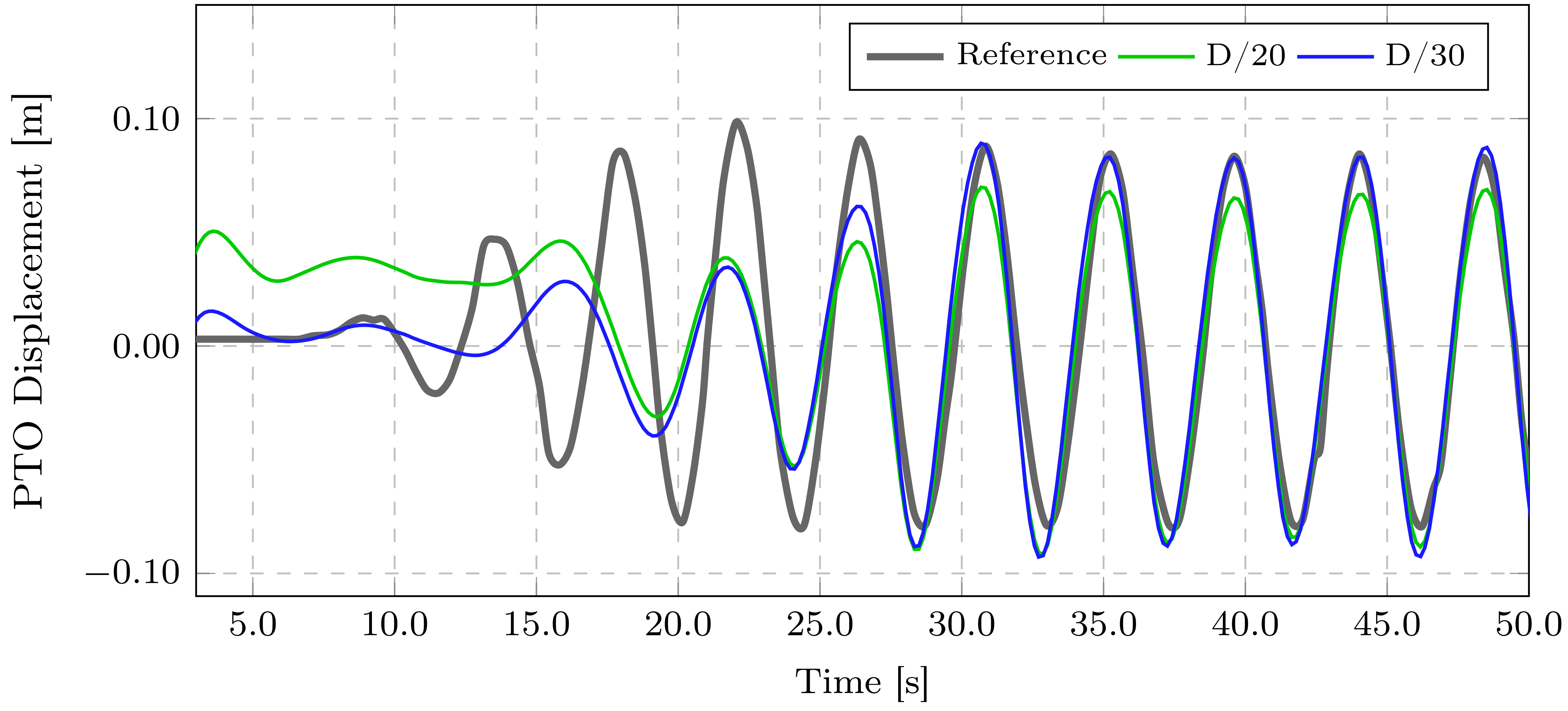
Windt et al. (2020). Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter. *Renewable Energy, 146*, 2499-2516. https://doi.org/10.1016/j.renene.2019.08.059

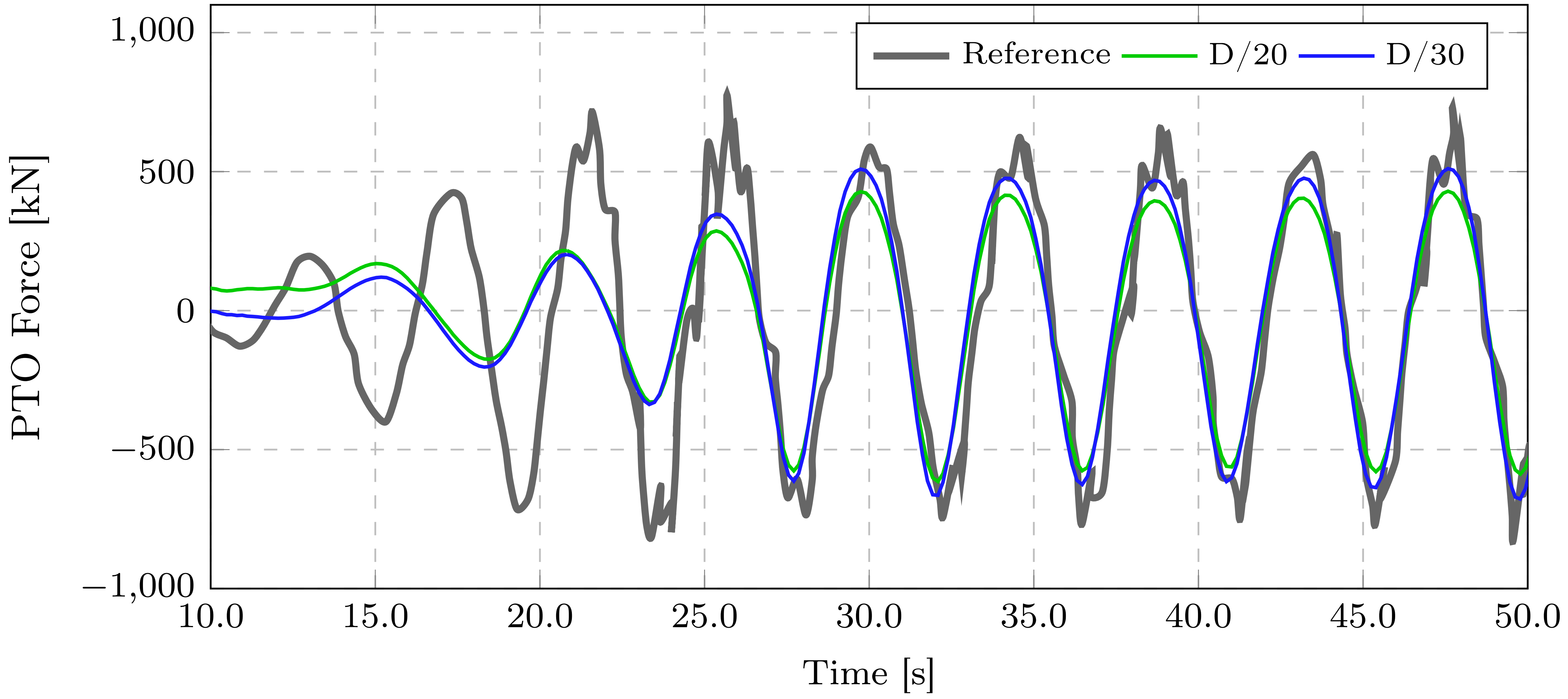
Wave energy conversion

PTO aggressive configuration

	Damping	Stiffness	Initial Length
PTO	21 MNs/m	3.80 MN/m	11.30 m

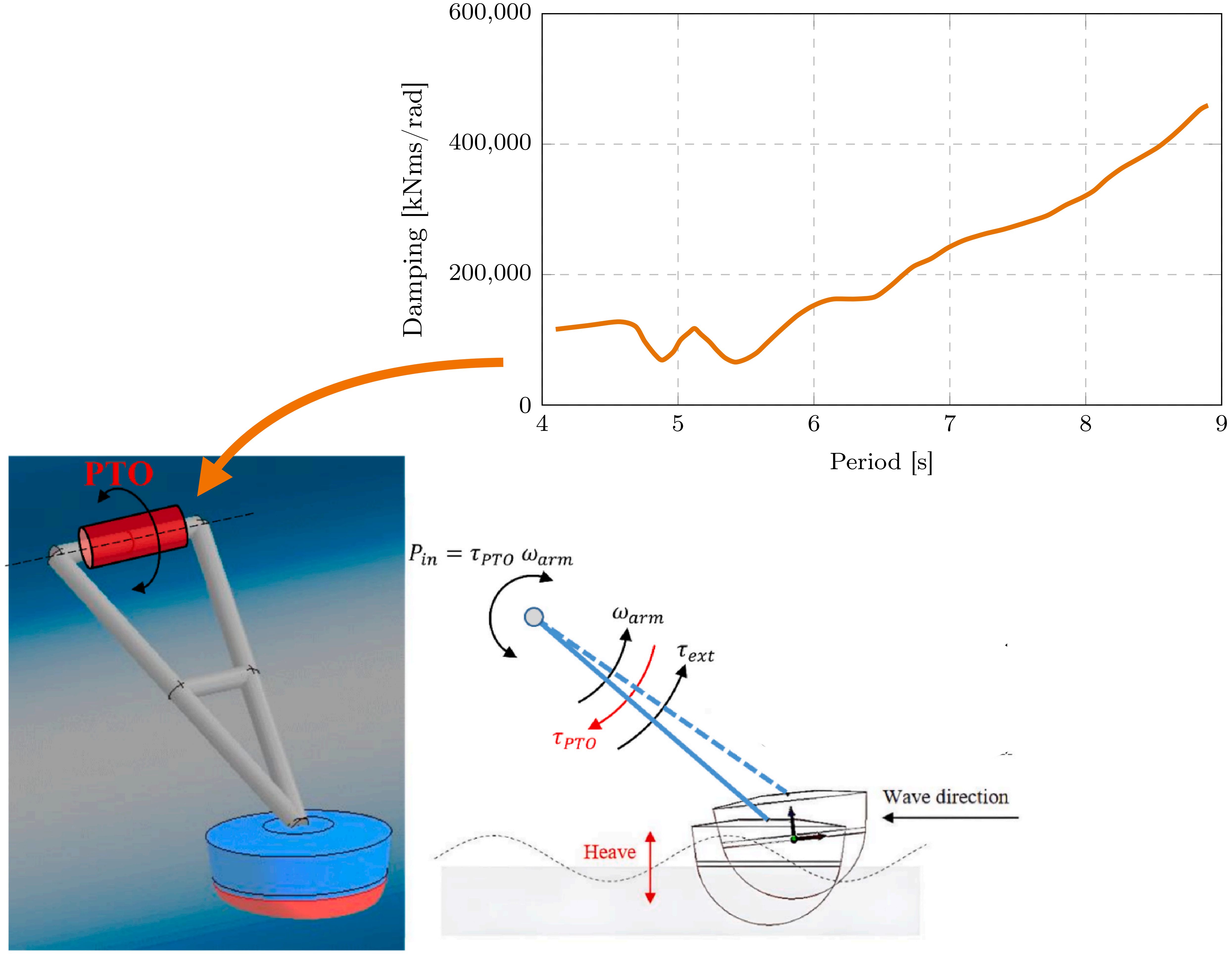




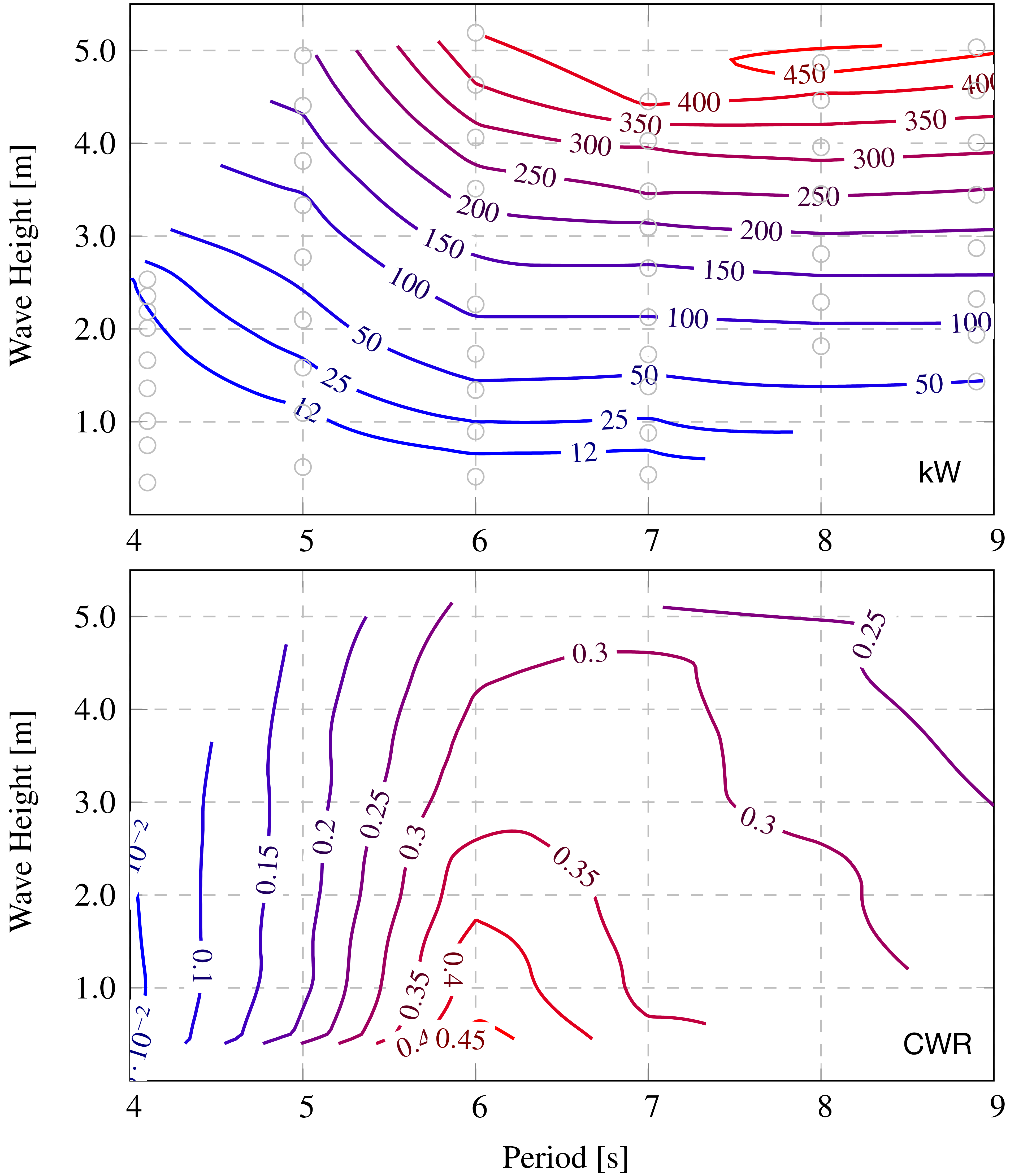


Wave energy conversion

Power matrix



Ghafari, H. R., Ghassemi, H., & Akbari Vakilabadi, K. (2025). Hydrodynamic performance and power absorption of the hybrid wind-wave energy systems with different platform geometries. *Ocean Engineering, 332*, 121440. https://doi.org/10.1016/j.oceaneng.2025.121440



Tagliafierro, B., Martínez-Estévez, I., Capasso, S., Domínguez, J. M., Karimirad, M., Viccione, G., Gómez-Gesteira, M., Crespo, A. J. C., & Göteman, M. (2025). Wave power extraction from semi-submersible hybrid platforms with multi-physics and high-fidelity simulations powered by SPH *(Paper No. OMAE2025-156719)*. Vancouver, Canada.

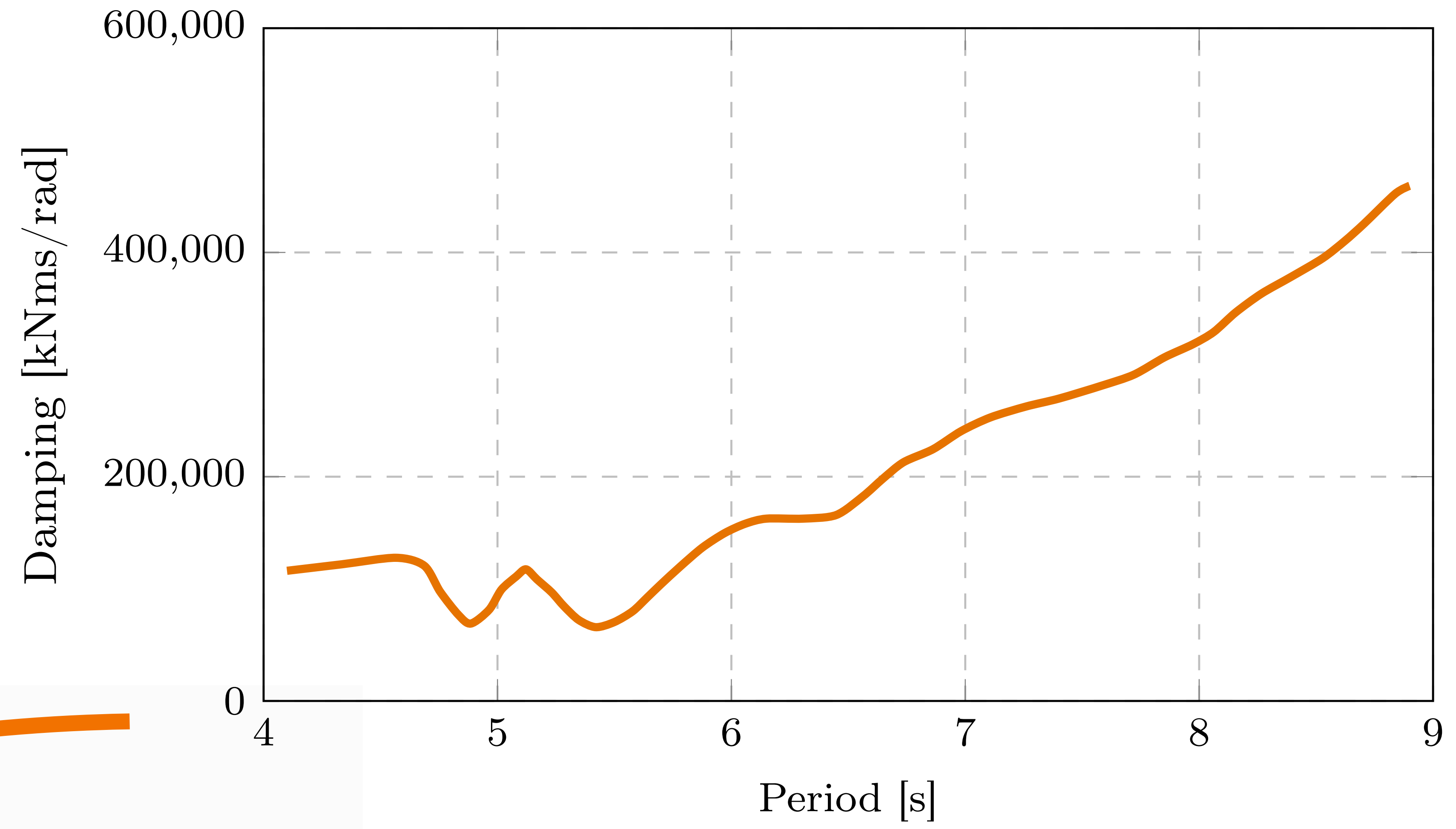
Hybrid platform configuration

DeepCwind Platform

UPPSALA
UNIVERSITET

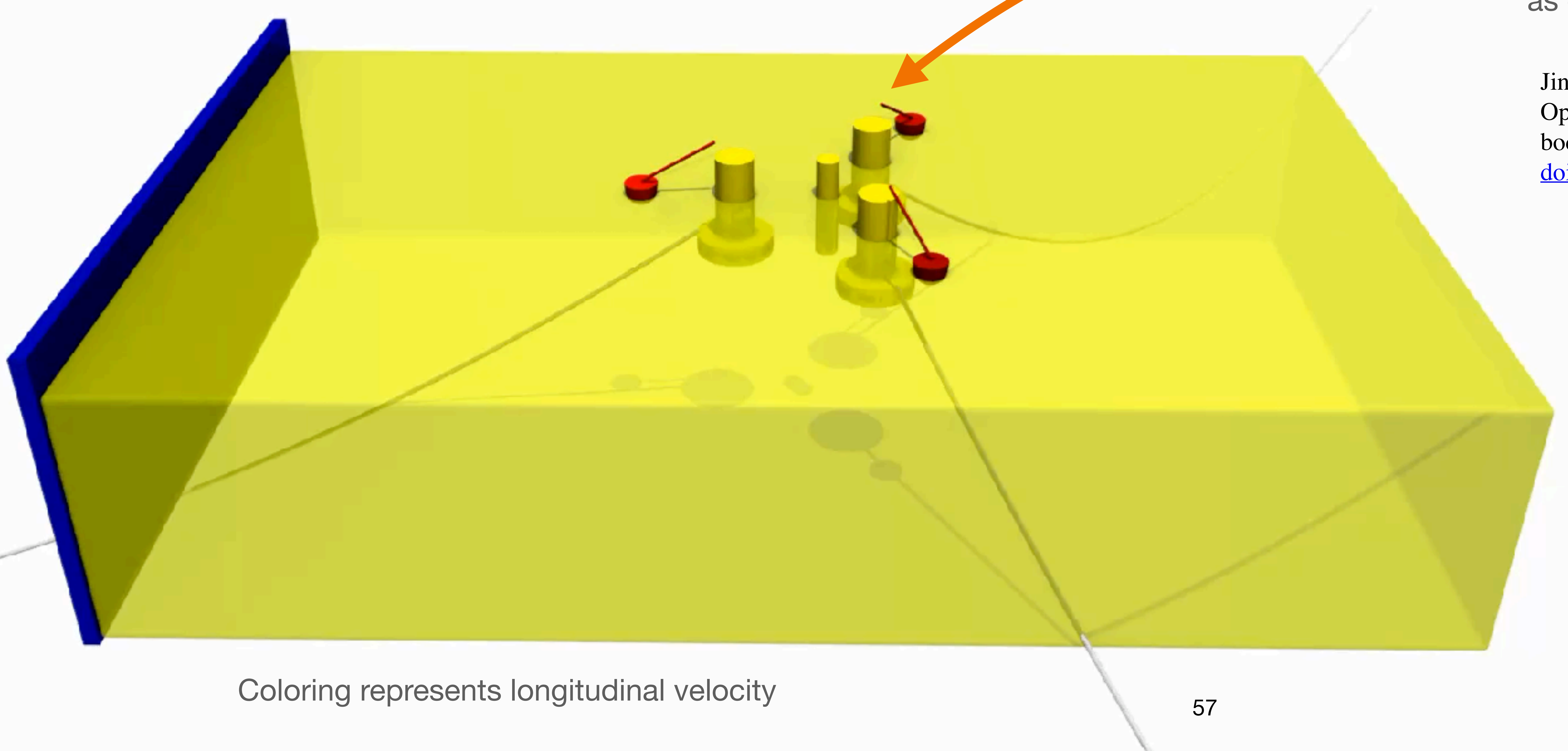
Hybrid Platform

	H	T	Wind
R8	2.00 m	8.00 s	0 m/s



Optimal damping function for passive PTO control as defined in Jin et al. (2023).

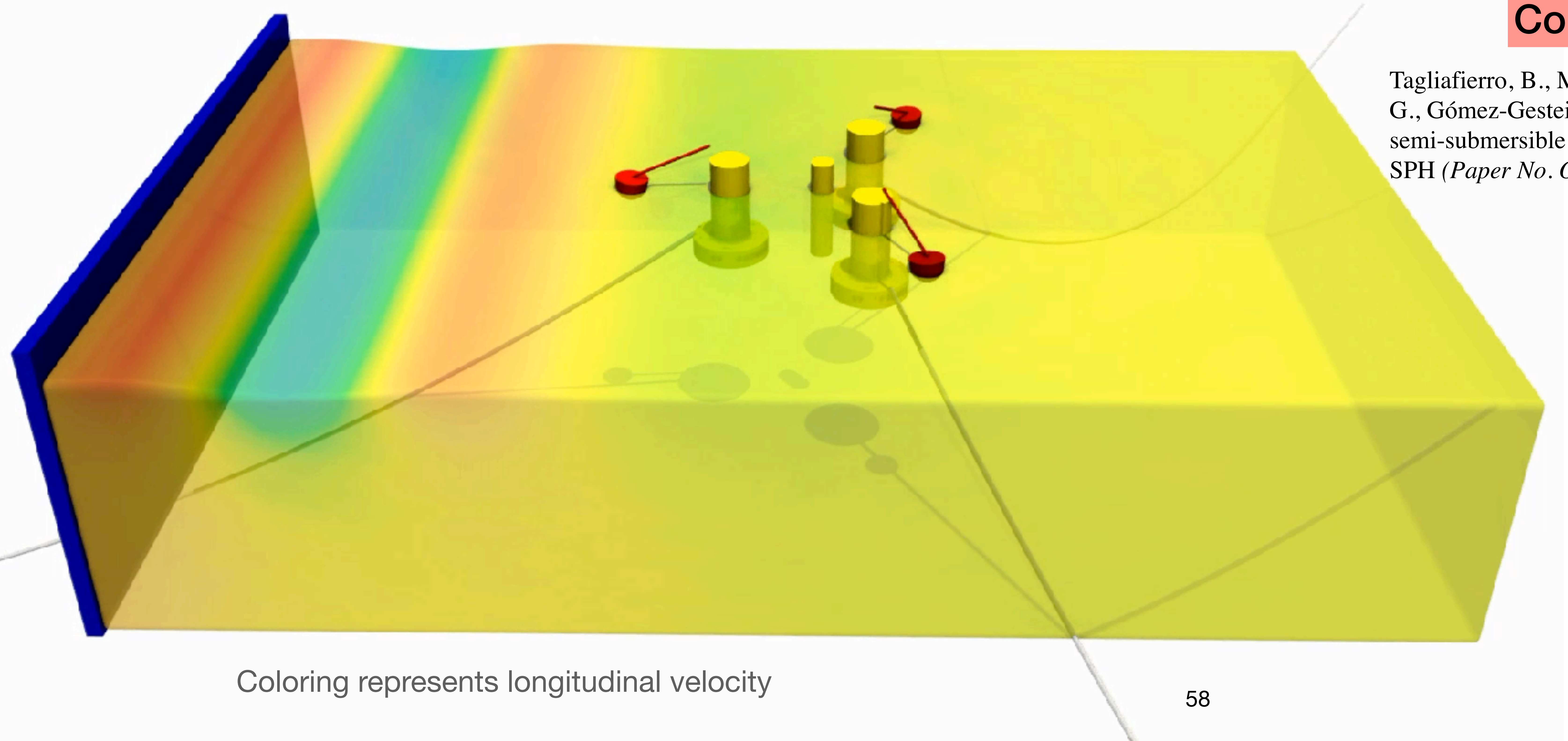
Jin, P., Zheng, Z., Zhou, Z., Zhou, B., Wang, L., Yang, Y., & Liu, Y. (2023). Optimization and evaluation of a semi-submersible wind turbine and oscillating body wave energy converters hybrid system. *Energy*, *282*, 128889. https://doi.org/10.1016/j.energy.2023.128889



Coloring represents longitudinal velocity

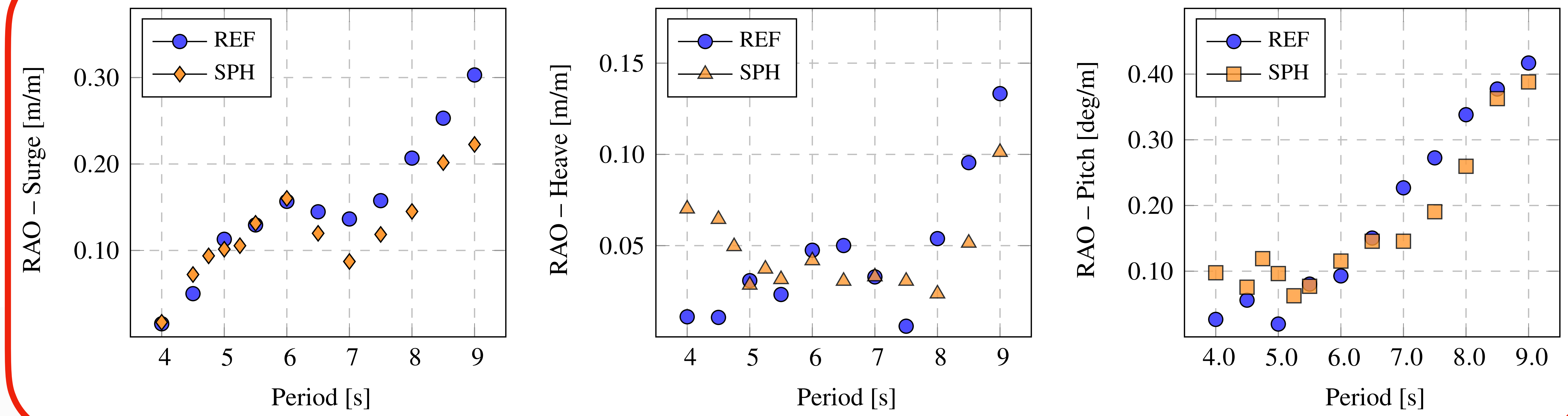
Hybrid Platform

	H	T	Wind
R	2.00 m	-	0 m/s



Coloring represents longitudinal velocity

Platform response



Comparison

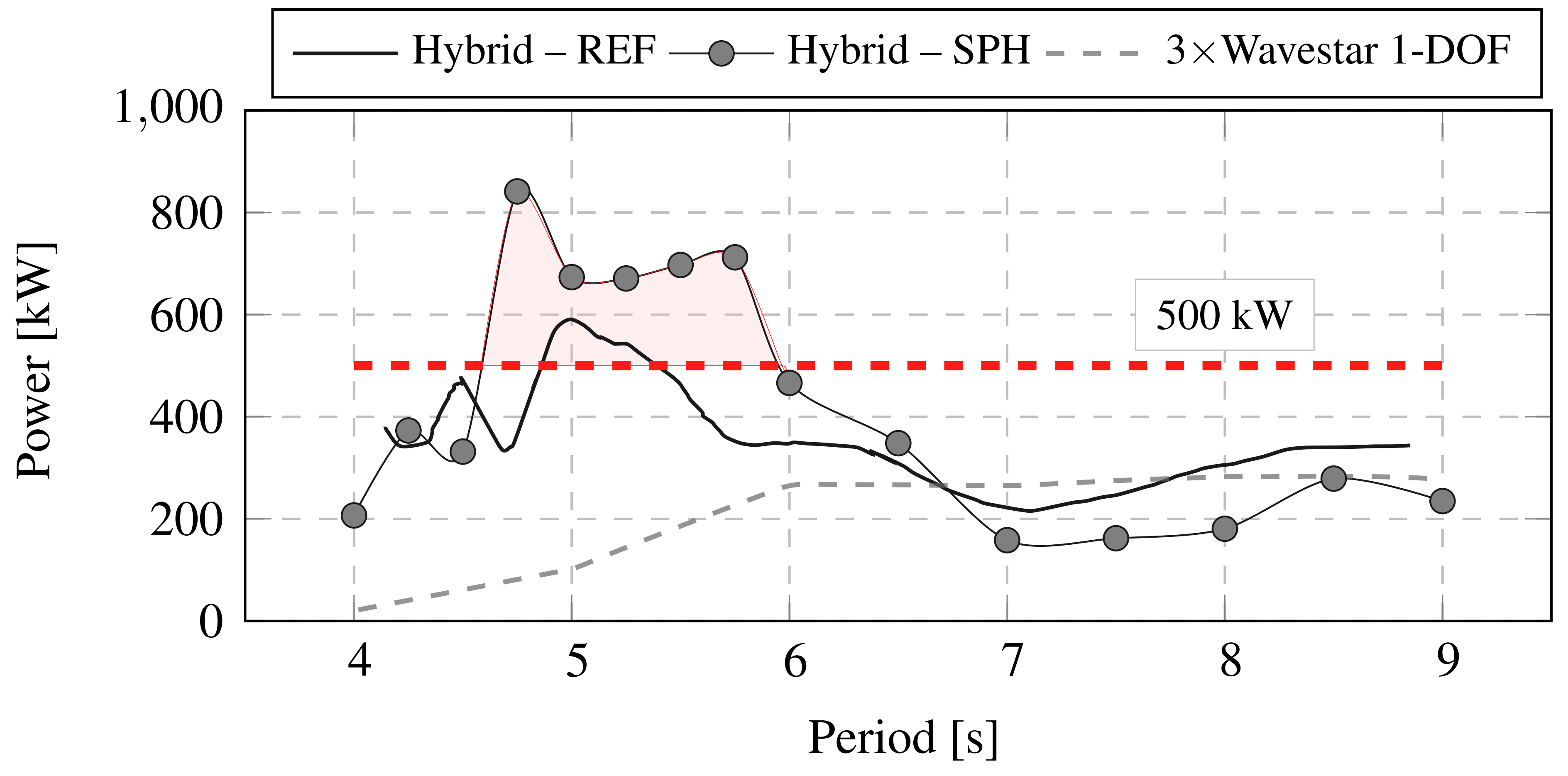
Tagliafierro, B., Martínez-Estévez, I., Capasso, S., Domínguez, J. M., Karimirad, M., Viccione, G., Gómez-Gesteira, M., Crespo, A. J. C., & Göteman, M. (2025). Wave power extraction from semi-submersible hybrid platforms with multi-physics and high-fidelity simulations powered by SPH *(Paper No. OMAE2025-156719)*. Vancouver, Canada.

PROJECT CHRONO DualSPHysics MoorDyn+

Hybrid Platform

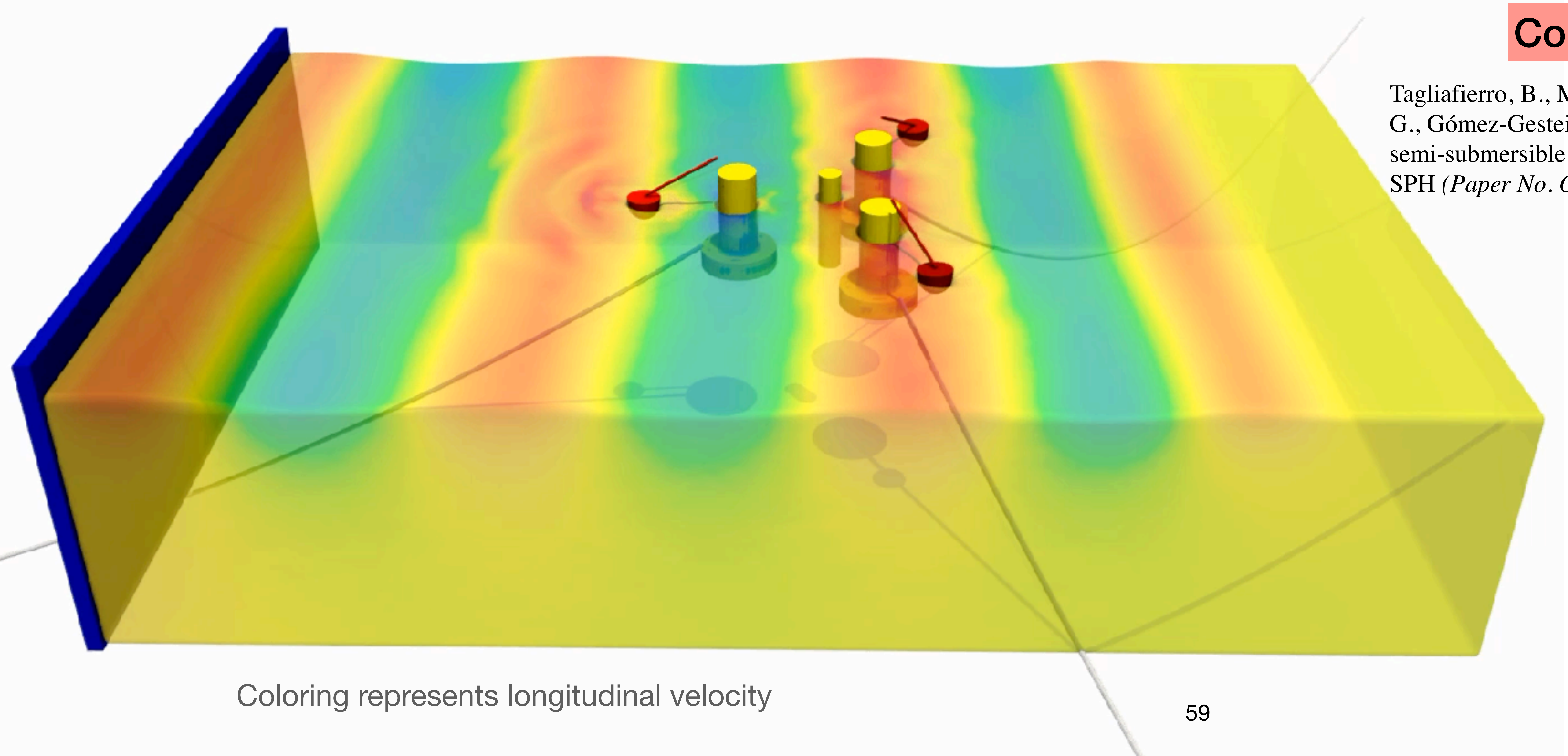
Total wave power

	H	T	Wind
R	2.00 m	-	0 m/s



Comparison

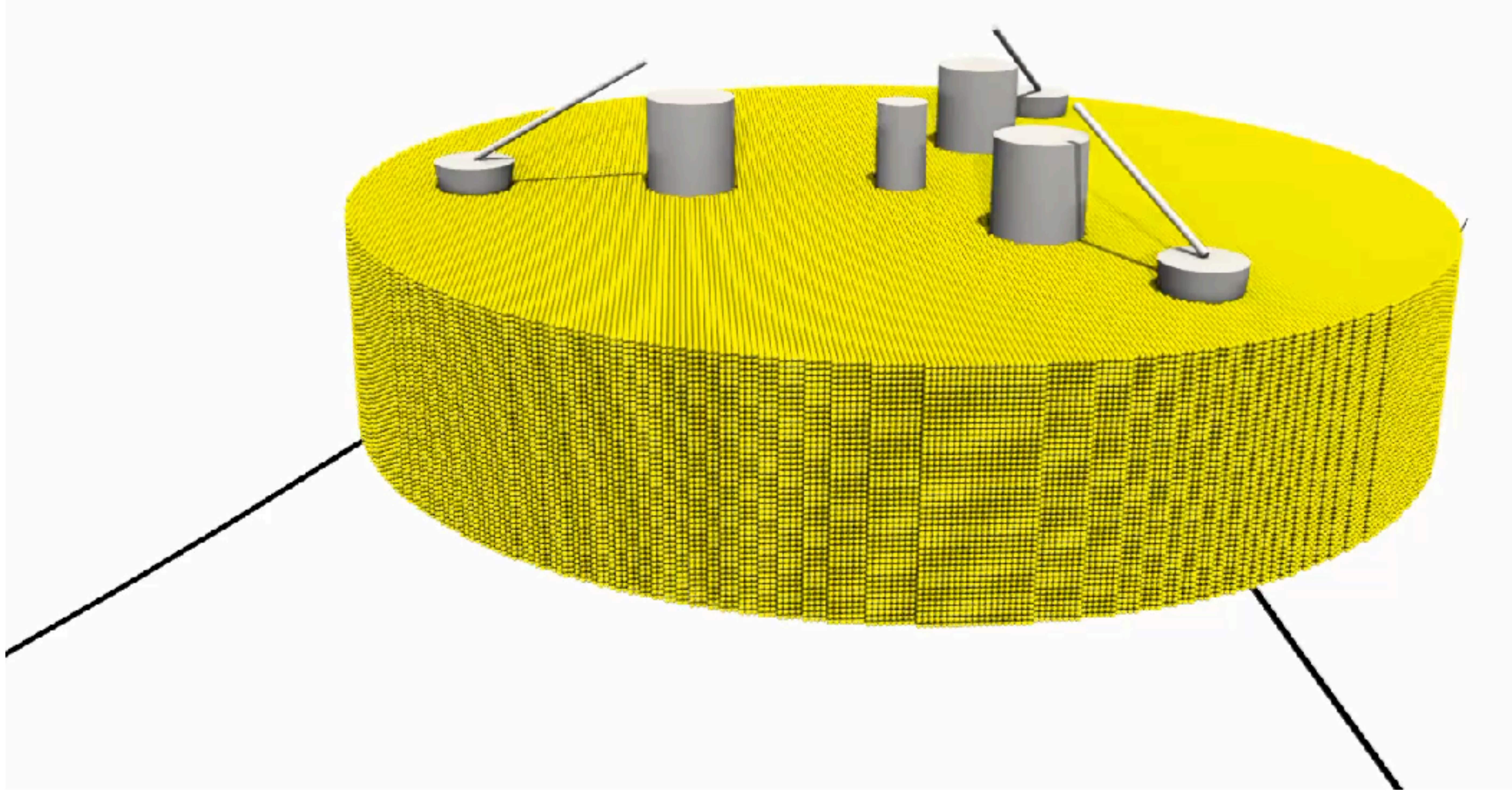
Tagliafierro, B., Martínez-Estévez, I., Capasso, S., Domínguez, J. M., Karimirad, M., Viccione, G., Gómez-Gesteira, M., Crespo, A. J. C., & Göteman, M. (2025). Wave power extraction from semi-submersible hybrid platforms with multi-physics and high-fidelity simulations powered by SPH *(Paper No. OMAE2025-156719)*. Vancouver, Canada.



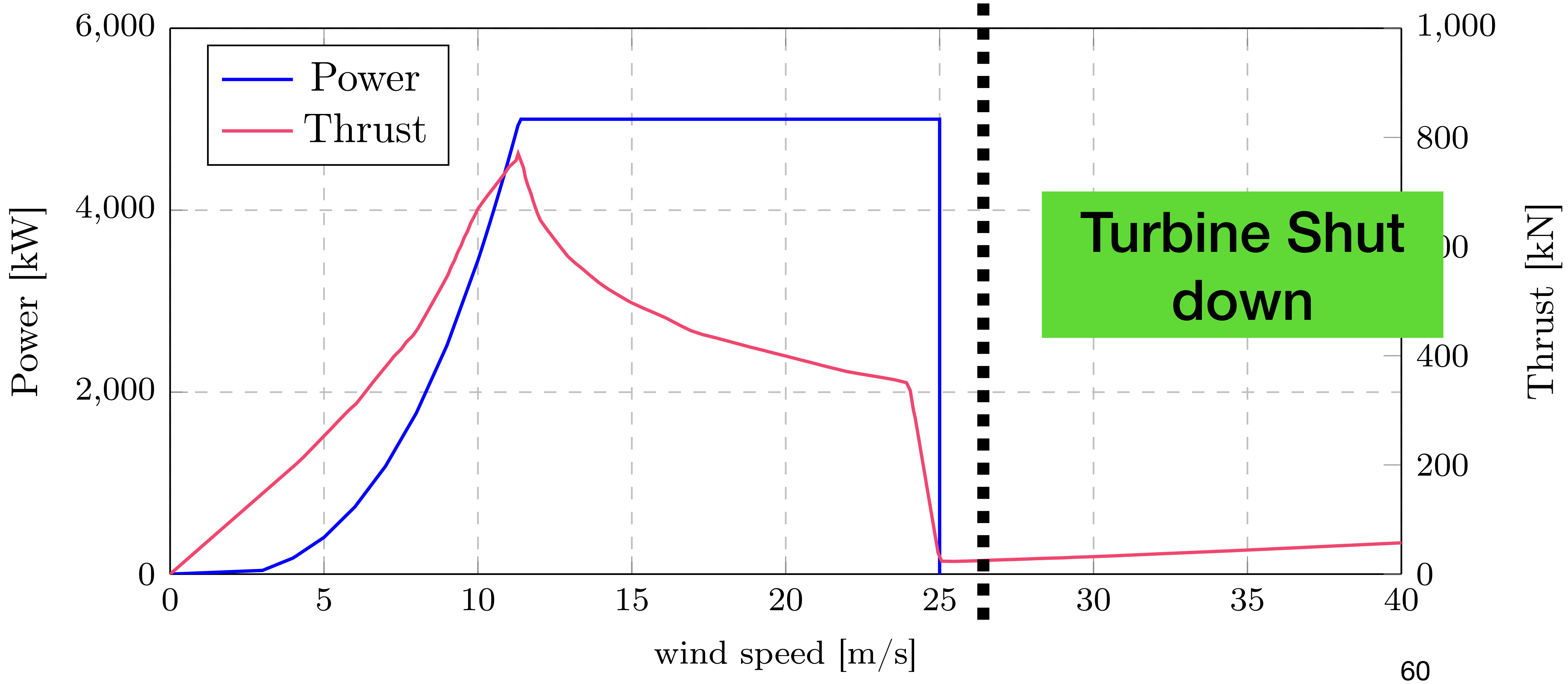
Coloring represents longitudinal velocity

Power performance

	Hs	Tp	Wind
Random	3.20 m	7.70 s	25 kN



Wind speed at 26 m/s – turbine parked



Turbine Shut down

Most critical event for power grid stability

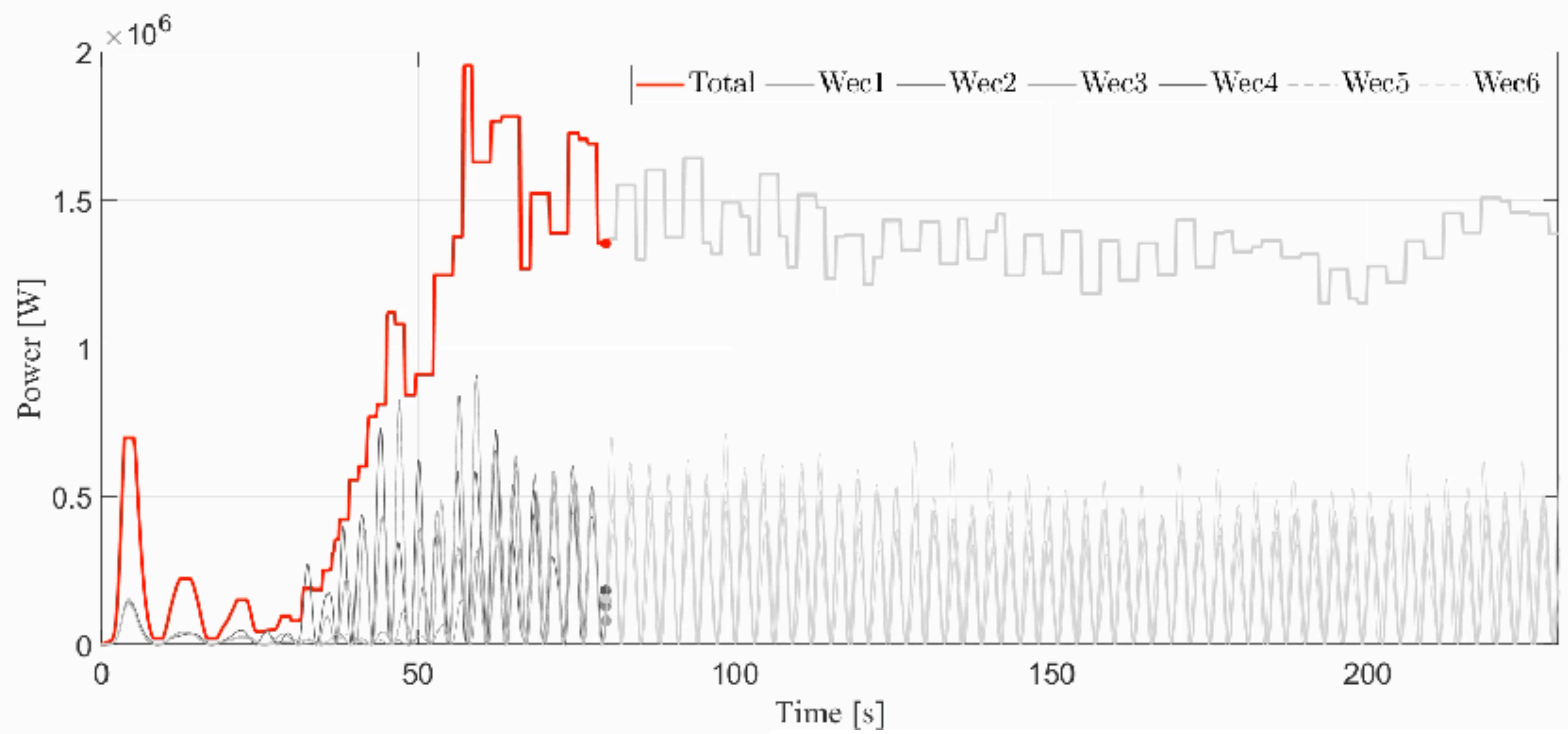
PROJECT CHRONO

DualSPHysics

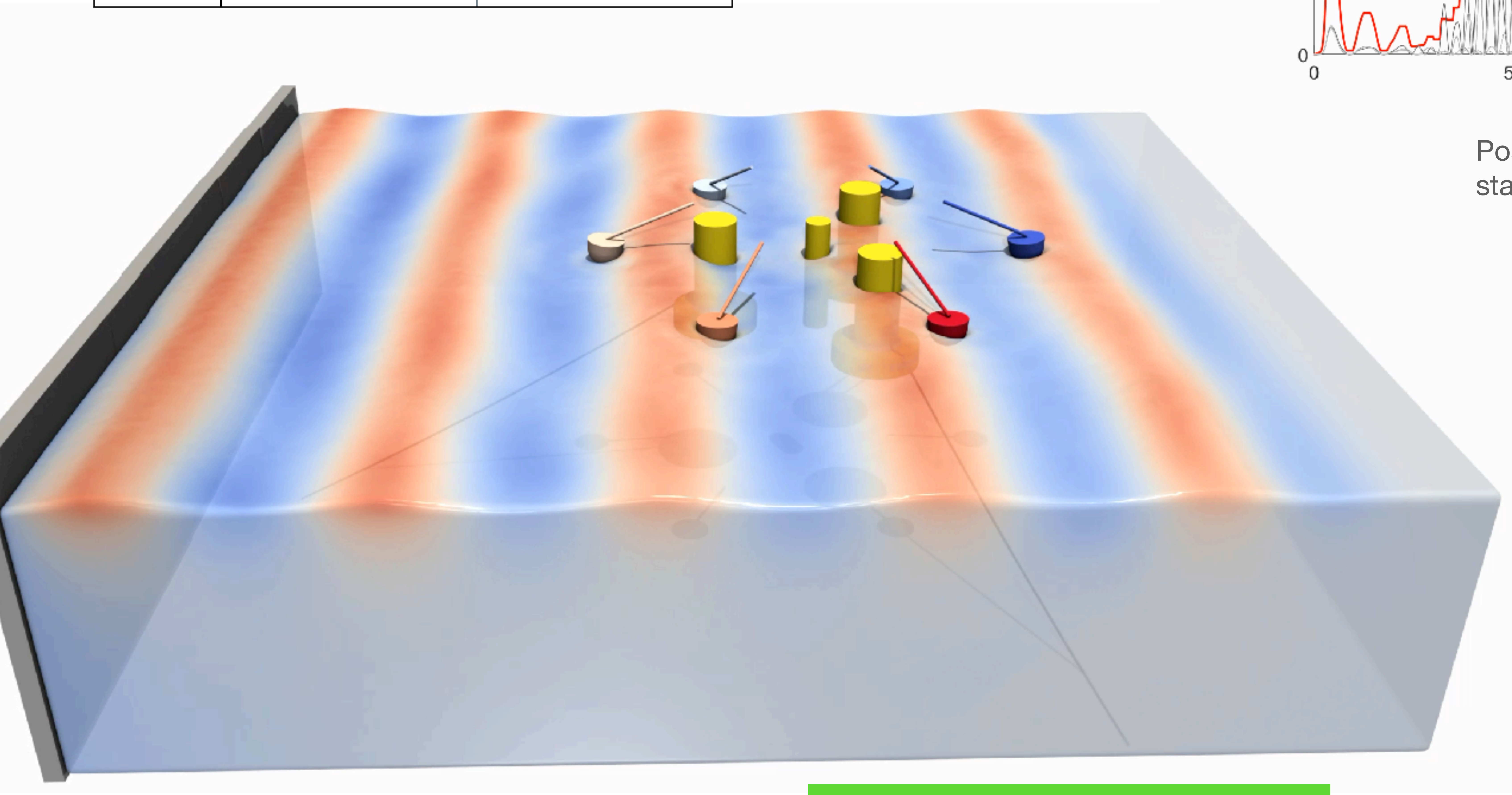
MoorDyn+

Hybrid Platform (6 WECs)

	H [m]	T [s]
R6	2.50 m	6.00 s



Possible on-board flywheel for 10-15 seconds stabilized output.



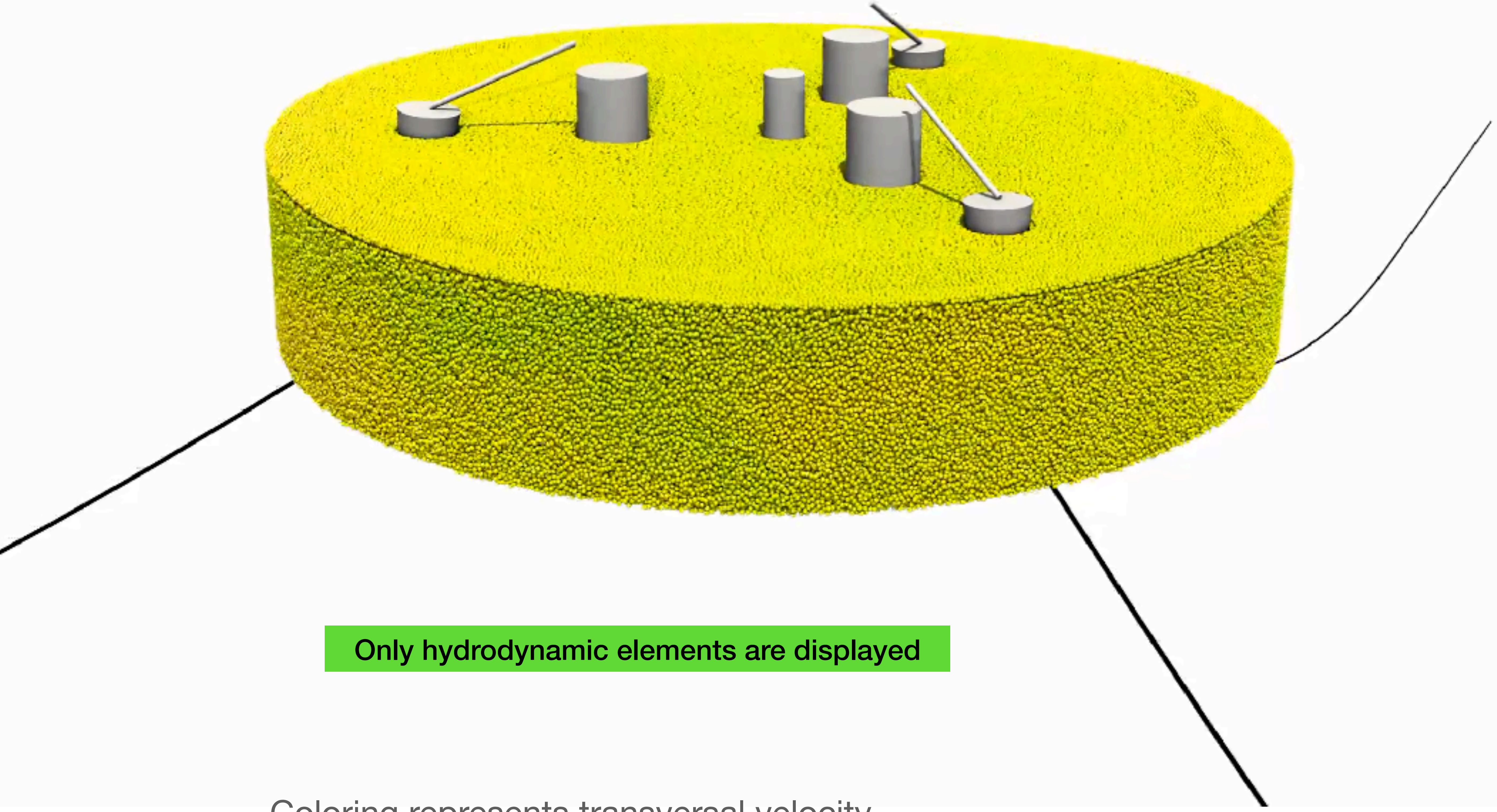
Only hydrodynamic elements are displayed

Coloring represents transversal velocity

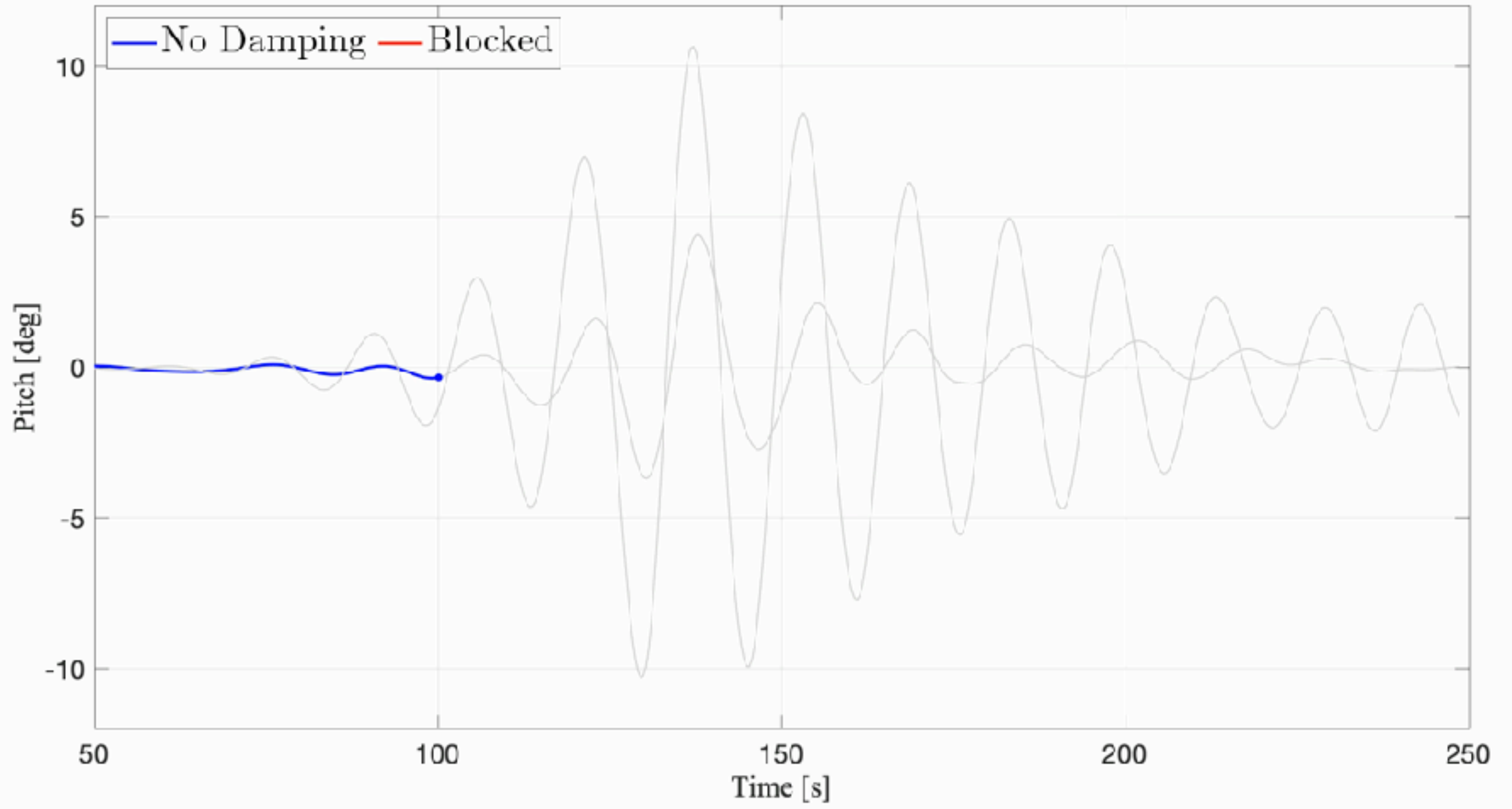
PROJECT CHRONO DualSPHysics MoorDyn+

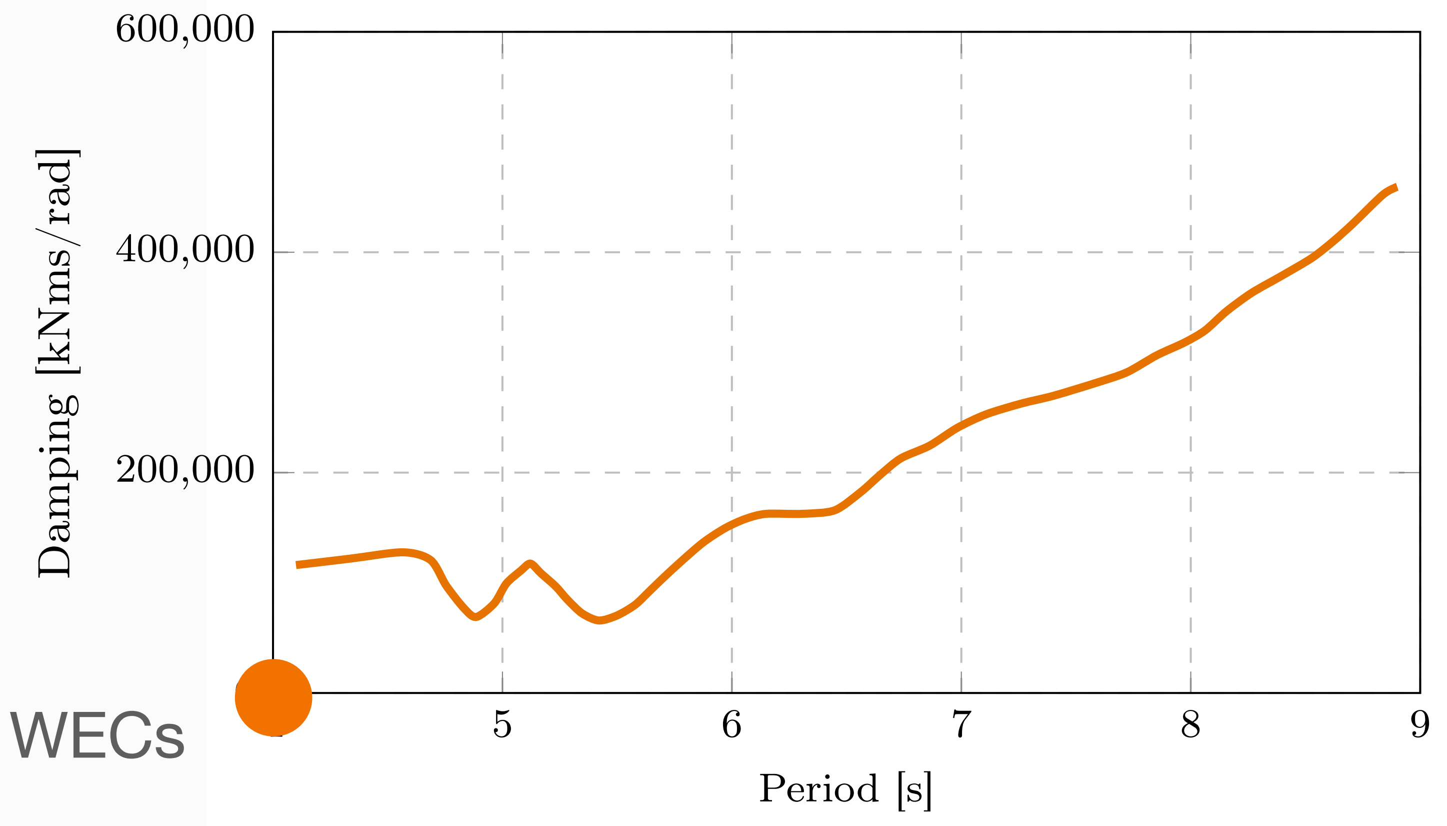
Extreme conditions (Free)

	Hs	Tp
Focused wave	14 m	15 s



Coloring represents transversal velocity

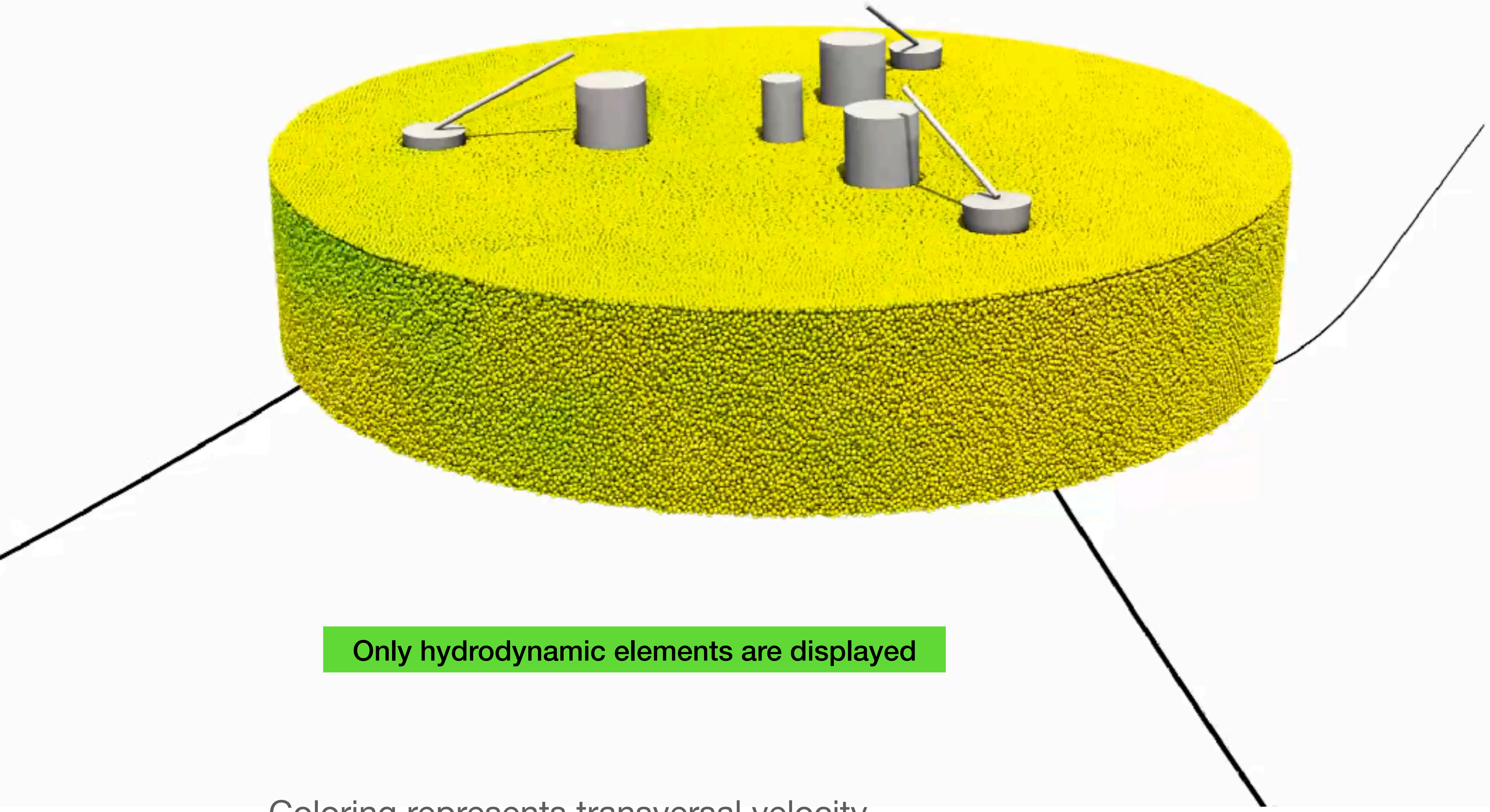




Working point for WECs

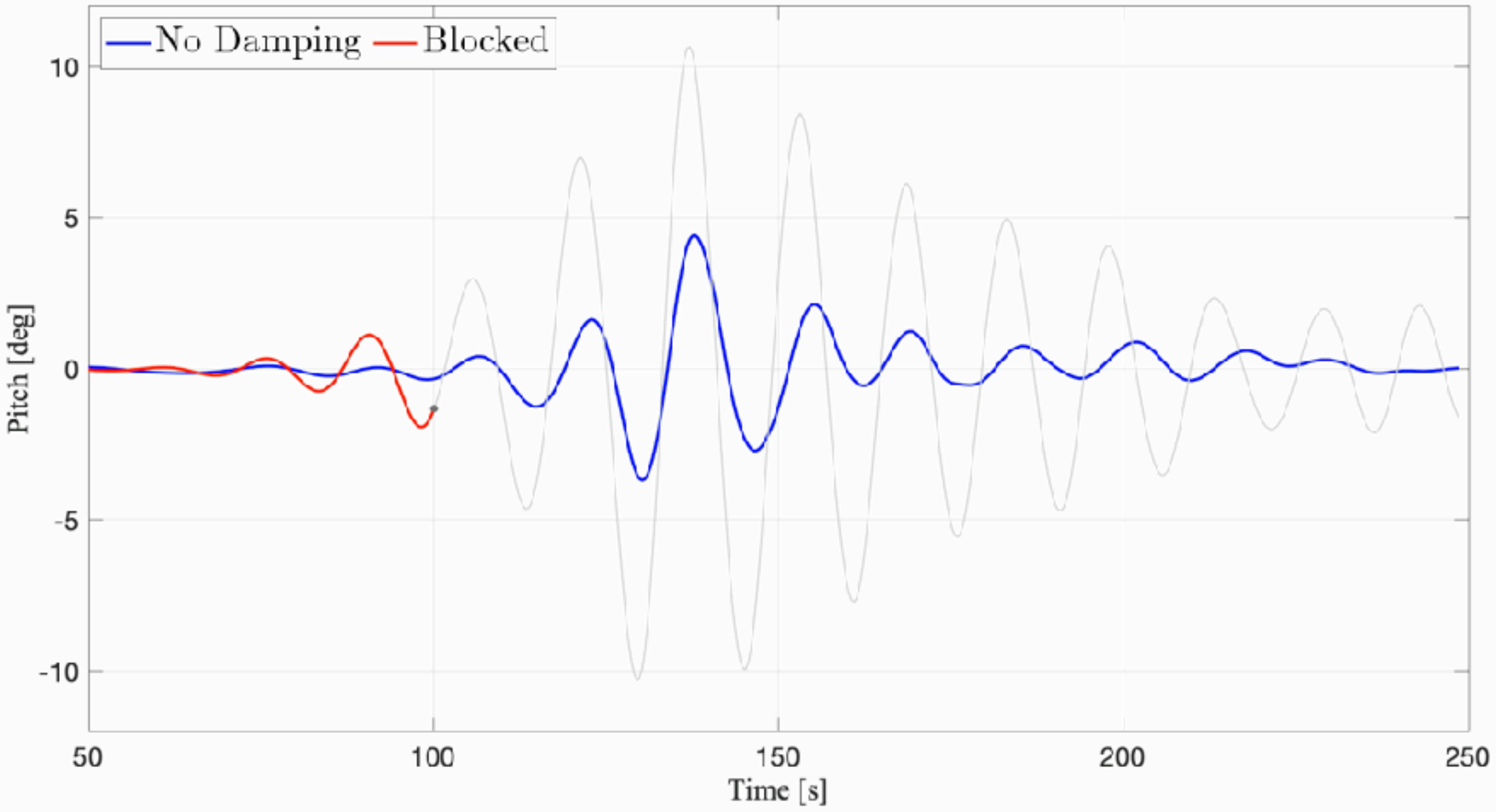
Extreme conditions (Locked)

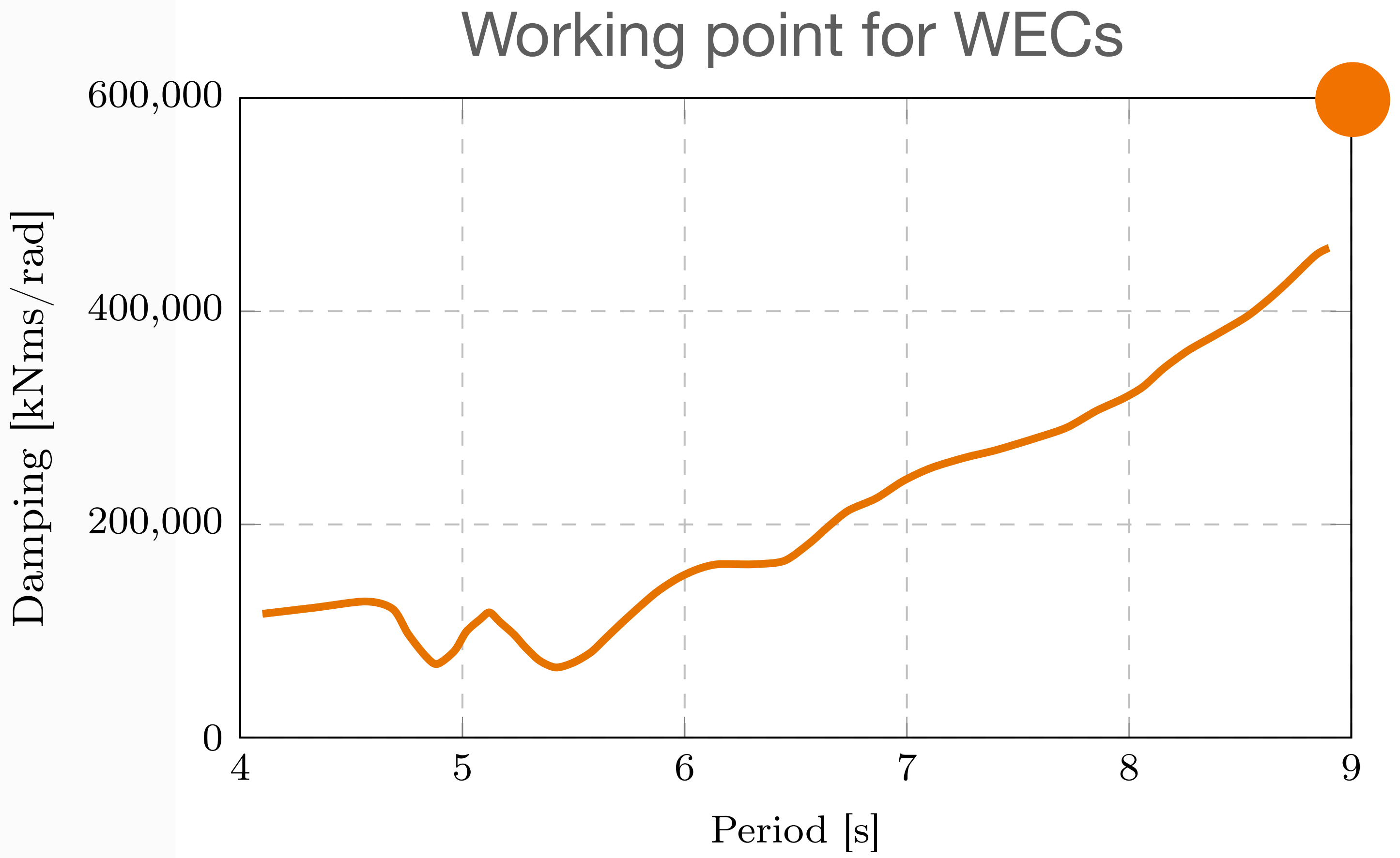
	Hs	Tp
Focused wave	14 m	15 s



Only hydrodynamic elements are displayed

Coloring represents transversal velocity





PROJECT CHRONO

cpu gpu DualSPHysics

MoorDyn+

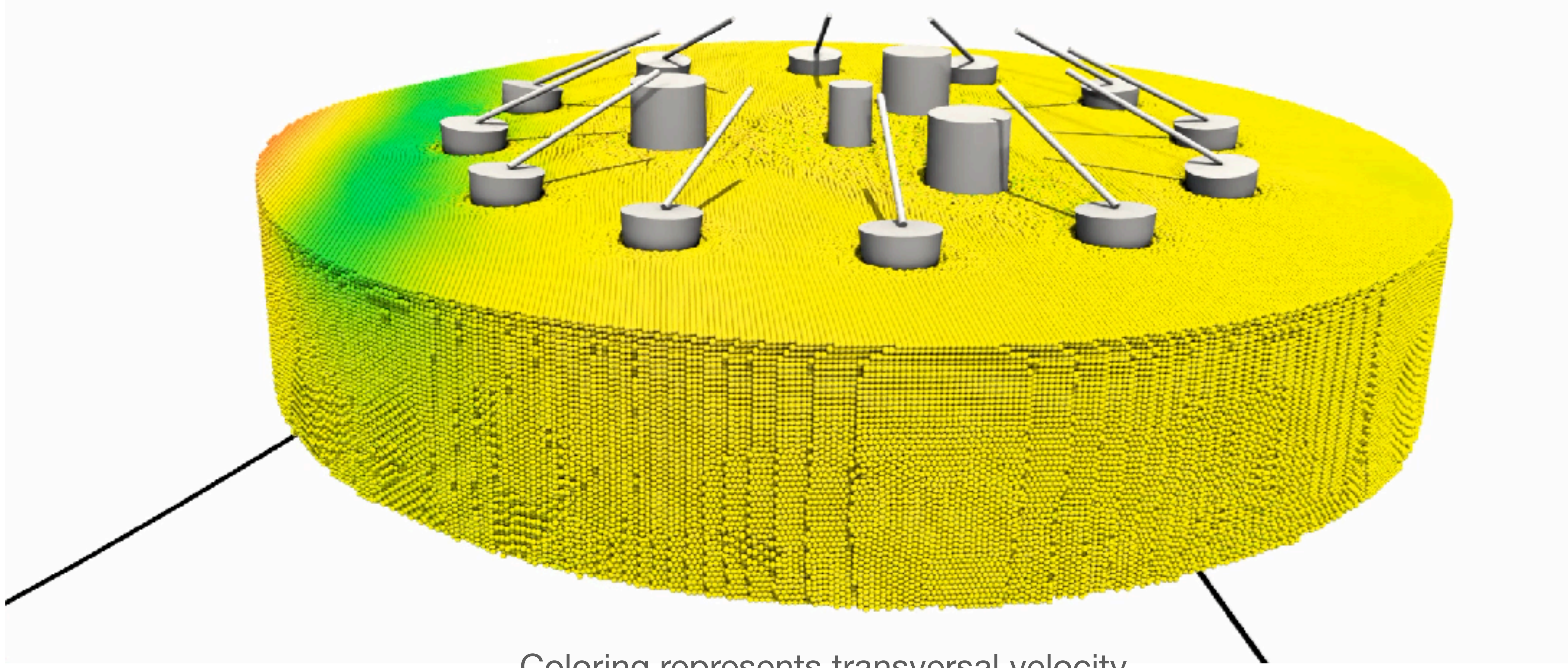
Discussion

1. High-fidelity has found its niche for marine renewable energy
2. SPH is catching up with (applicability is key)
3. Combined validation are deemed reliable for most applications
4. We can do engineering!

THANK YOU!

Bonaventura Tagliafierro – June 16, 2025

btagliafierro@gmail.com



Coloring represents transversal velocity

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No: 101109440.

Funded by the European Union

MARIE SKŁODOWSKA-CURIE ACTIONS

Research Fellowship Programme

UPPSALA UNIVERSITET

IM-POWER