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Capturing wave energy converter's extreme response: experimental validation of DualSPHysics and STAR CCM+

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ABSTRACT: Validating numerical models against their physical realizations is an integral aspect, very essential for their development and a reliable assessment of their accuracy. This study focuses on comparing two different approaches: the open-source DualSPHysics, and the commercial software STAR CCM+, which have emerged as high-fidelity tools in evaluating wave energy converters' (WEC) performance. Notably, they belong to opposite ends of the modelling spectrum, with the former relying on a Lagrangian approach, and the latter employing a Eulerian one. As ground through, our validation is performed using an experimental investigation of the Pendulum Wave Energy Converter (PeWEC), focusing on its kinematic and mooring forces. In addition to rigours validations, this comparative analysis provides an overview of the advantages and short-comings of each employed numerical model, discussing pre-processing time, computational performance, and overall code platform flexibility for end-users. The aim of this comprehensive assessment is to under-line and compare performance and accuracy of these models when employed to capture the extreme response of resonant devices, such as WECs.

1 INTRODUCTION

Wave energy converters (WECs) represent a promising technology for sustainable energy generation, tapping into the vast and renewable resource of marine energy (Taveira-Pinto et al., 2020). As efforts intensify to transition towards clean energy sources, the development of efficient WEC technologies becomes increasingly crucial aligning with the European agenda for the decarbonization of our society (European Commission and Directorate-General for Maritime Affairs and Fisheries, 2014). However, the complex dynamics of wave interactions pose significant challenges in accurately predicting the performance of these devices (Paduano et al., 2024).

In the pursuit of reliable performance assessments, numerical modeling has become indispensable. Various techniques have been employed, ranging from frequency domain approaches (Niosi et al., 2021) to time domain simulations performed with potential flow methods or employing Navier-Stokes equations (Penalba Retes et al., 2015). Each model offers different trade-offs between computational cost and accuracy (Folley, 2016; Niosi et al., 2023b).

This study focuses on comparing two numerical modeling approaches based on Navier-Stokes equations: the open-source DualSPHysics (Domínguez et al., 2022) and the commercial software STAR CCM+. DualSPHysics utilizes a Lagrangian approach, tracking individual fluid particles, while STAR CCM+ employs an Eulerian framework, modeling fluid flow through a fixed connectivity.

Extensive validation of WECs' dynamics with both tools has been carried out in previous work by the authors (Dell'Edera et al., 2024). This research aims to provide a comprehensive understanding of their respective strengths and limitations in capturing the extreme response of WECs, assessing both the computational and economic costs.

The case study for this comparative analysis is the Pendulum Wave Energy Converter (PeWEC), developed by Polytechnic of Turin in collaboration with ENEA, the National Agency for new technologies, energy and sustainable economic development. The study focuses on an extreme regular wave, tested during the experimental campaign performed in 2021 at University of Naples Federico II.

In this paper, we present a brief description of the PeWEC experimental setup, followed by an in-depth discussion of the DualSPHysics and STAR CCM+ numerical models. Subsequently, we present and analyze the results obtained from both experimental and numerical investigations, focusing on the kinematics and mooring tensions of the device. Finally, we discuss the current status of both approach and analyze their respective strengths and weaknesses.

2 CASE STUDY: PEWEC

The subject of this investigation is PeWEC, a self-referenced inertial-based floating WEC, comprising a sealed hull housing a pendulum and the power take-off (PTO) mechanism, as depicted in Figure 1.

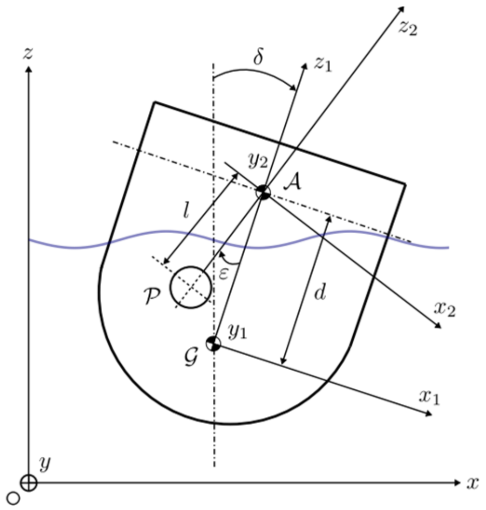

Figure 1: Scheme of PEWEC device. Adapted from (Niosi et al., 2023a)

Originating in 2012, PeWEC has undergone constant development thanks to a collaboration with ENEA, leading to a 1:12 scale testing in Rome in 2016 (Pozzi et al., 2018) to validate numerical models in operational conditions, and a 1:25 experimental campaign in Naples in October 2021 to investigate survivability and mooring layout during extreme events. It is now considered to have reached TRL 5.

2.1 *Experimental setup*

The experimental campaign for the PeWEC device, conducted in Naples, Italy in 2021, utilized a spread catenary mooring system. This configuration features four mooring lines symmetrically arranged, as depicted in Figure 2. Load cells are positioned at the fairlead, with LC1 and LC2 at the stern and LC3 and LC4 at the aft of the device.

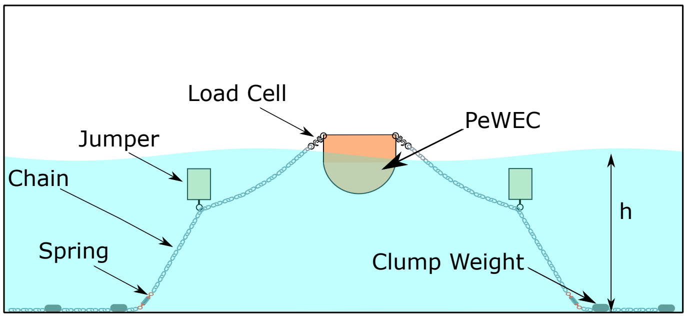

Figure 2: The sketch of PeWEC mooring system. Adapted from (Niosi et al., 2023a)

Each mooring line comprises a catenary, nine clump weights, and a jumper, with detailed parameters outlined in (Fenu et al., 2022). The clump weights are strategically employed to bolster the restoring force of the mooring line, crucial for the device's resilience in extreme environmental conditions. Moreover, the jumper assumes a critical role in supporting the catenary line weight, granting PeWEC the freedom of movement essential for its operation (Niosi et al., 2021). In terms of experimental tests, the device's kinematics was recorded using an in-board MTi and an optical Qualisys motion tracking unit. For a comprehensive overview of the experimental campaign and associated tests, please refer to (Niosi et al., 2023a). Table 1 reports the characteristics of the extreme regular wave selected for this study.

Table 1: Wave characteristic in full scale and model scale

Full scale		Model scale	
H [m]	T [s]	H [m]	T [s]
4.36	6.00	0.174	1.20

3 NUMERICAL MODELS

In this section, we will delve into the detailed development and implementation of both STAR CCM+ and DualSPHysics models for simulating the extreme response of WECs.

3.1 *STAR CCM+*

STAR CCM+ is a commercially-available software renowned for its Eulerian framework, which facilitates the modeling of fluid flow using a grid, usually referred to as mesh. The governing equations for STAR CCM+ are the Navier–Stokes equations, considering an incompressible flow. The mass conservation equation is represented as:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

and the momentum conservation equation is:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u}, \tag{2}$$

where $\mathbf{u}$ is the velocity vector, t is time, p is pressure, ρ is fluid density, ν is kinematic viscosity.

The model employed in this study is based on the unsteady Reynolds-Averaged Navier-Stokes (URANS) equations, utilizing the realizable k-epsilon turbulence model (Shih et al., 1994). The turbulence model is coupled with a wall function for treating high-gradient regions near walls (Wilcox et al., 1998). The model operates within a bi-phase framework, wherein the fluid medium consists of water while the gas phase comprises air. To define the two phases present in the model, the Volume Of Fluid (VOF) module is employed (Hirt & Nichols, 1981; Muzaferija, 1999), wherein the volume fraction, denoted by α, delineates whether a given cell contains water ($\alpha = 1$) or air ($\alpha = 0$) as depicted in Figure 3.

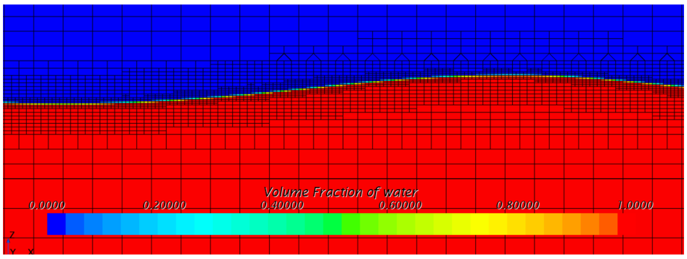

Figure 3: Volume fraction of water in the numerical tank

Wave generation is facilitated through the VOF waves module, employing a fifth-order Stokes wave formulation (Fenton, 1985) generated directly at the boundary, imposing the wave elevation and the velocity of the field. To ensure the correct propagation of the wave, a forcing zone is defined, where the solution is partially substituted with the analytical solution (Perić & Abdel-Maksoud, 2017). Unfortunately, the intrinsic instability of the coupling between the VOF model and the turbulence model results in an exponential increase in turbulent viscosity (Larsen & Fuhrman, 2018). This phenomenon causes excessive wave damping over an extended time series. Because of this, the approach described in (Casalone et al., 2022) has been used to restrict the maximum turbulent viscosity in the domain and avoid a non-physical growth of turbulence viscosity.

The movement of the floating body is managed by the Dynamic Fluid Body Interaction (DFBI) approach. Notably, the computational domain comprises two distinct regions: the numerical tank, which has a trimmed mesh, and the overset, which has a polyhedral mesh, depicted in Figure 4. The tank is 6λ (wavelength) long in the x direction (which is the direction of the wave propagation), and 2λ long in y direction. The overset region, rigidly connected to the body in both translation and rotation, ensures consistent and accurate modeling of the system dynamics.

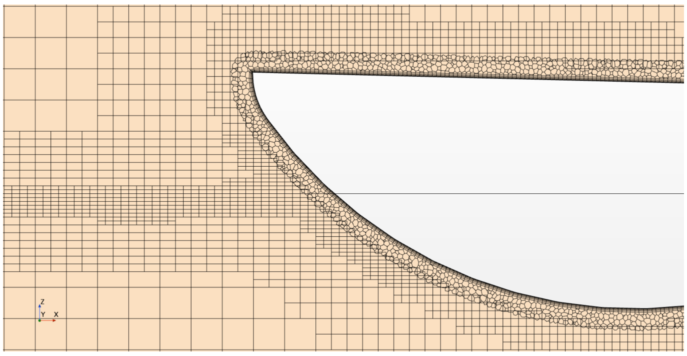

Figure 4: In the background is the numerical tank. The body is surrounded by an overset region that follows the body motion.

The simulation encompasses three degrees of freedom (DOF), namely pitch, heave, and surge, with a symmetry plane established at y=0. The mooring system is integrated into the model through an external coupling with MoorDyn, which has been developed and validated in previous studies (Dell'Edera et al., 2022; Dell'Edera et al., 2024). Time discretization is achieved at the second order, and Adaptive Mesh Refinement (AMR) techniques are employed to optimize computational efficiency. Refinement occurs every 15 time steps, focusing on areas near the free surface (defined by $\alpha = 0.5$) and the overset region to maintain interface integrity. The overall number of cells after the refinement has been performed is 3.5M cells. For further elucidation on the model, detailed insights can be gleaned from prior work (Dell'Edera et al., 2024).

3.2 *DualSPHysics*

DualSPHysics (Domínguez et al., 2022) is an open-source Lagrangian code, distributed under GNU license at *dual.sphysics.org*. DualSPHysics stands out in the offshore renewable energy modeling panorama for its relevant multi-physics features, boosted by couplings with external libraries, such as Chrono (Martínez-Estévez et al., 2023) or MoorDynPlus (Domínguez et al., 2019b). Its highly parallelized implementation for Graphic Processing Units (GPUs) (Domínguez et al., 2013) makes it a competitive option for common workstations.

The DualSPHysics implementation is based on the Smoothed Particle Hydrodynamics (SPH) method, within which the physical domain (fluid and solid phases) is discretized using moving computational nodes (particles), carrying individual properties. Physical quantities are locally interpolated among surrounding nodes, with this interaction being weighted by a smoothing kernel function (Liu & Liu, 2003). The governing Navier-Stokes equations are considered in Lagrangian form:

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla P + \nu \nabla^2 \mathbf{v}, \tag{3}$$

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \mathbf{v}, \tag{4}$$

where $\mathbf{v}$ is the velocity of a fluid particle, P is the pressure, and ρ is the fluid density. Differently from the incompressible approach of the mesh-based counterpart, the fluid in DualSPHysics is treated as weakly compressible, employing an equation of state to close out the system, relating fluctuations in density with changes in fluid pressure:

$$P = \frac{c_s^2 \rho_0}{\gamma} \left(\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right), \tag{5}$$

where $\rho_0 = 1000$ kg/m^3 is the reference fluid density, $\gamma = 7$ is the polytropic constant, c$_s$ is the numerical speed of sound. Further details about the SPH implementation are to be found in (Domínguez et al., 2022).

Solid objects are discretized as set of SPH boundary particles with assigned physical properties; they obey Newton's equations according to the fluid force experienced by each solid particle. Within this fully Lagrangian environment, the treatment of fluid driven floating objects and interfaces is straightforward. For details on boundary conditions and their application to floating bodies please refer to (English et al., 2022) and (Capasso et al., 2023c), (Capasso et al., 2023b), respectively. In the same fashion as STAR CCM+, the anchoring system is solved via the MoordynPlus coupling, which has been widely and successfully adopted for WECs and FOWTs simulations (Tagliafierro et al., 2022b; Tagliafierro et al., 2022a; Pribadi et al., 2023; Tagliafierro et al., 2023; Tan et al., 2023). MoorDynPlus, a C++ reimplementation of MoorDyn with minor changes, retains the same core implementation, including the marching time algorithm and lumped mass approach theory.

Wave generation is achieved using a piston-type wavemaker, made up of moving boundary particle much like physical wave flumes and basins. Piston's motion is imposed according to 2^{nd} order wave theory-generated solution for regular and random waves (Altomare et al., 2017). Other wave generation methods for solitary or focused waves (Domínguez et al., 2019a), or suitable open boundaries implementations (Tafuni et al., 2018), (Verbrugghe et al., 2019) for wave–current fields (Yang et al., 2023; Capasso et al., 2023a), are also available in DualSPHysics. The paddle is located at 2λ from the device, followed by a physical beach positioned at 1λ with 1/2 steepness and numerical dissipation. The domain is 1.5λ wide, resulting in a total number of particles of 31M.

4 RESULTS

In this section, we analyze the kinematic behavior and mooring tension of the PeWEC subjected to extreme regular waves, as defined in section 2, while also considering the cost comparison of the hardware used for running this simulation, the time required for computation, and the power consumption of the hardware. Empty wave tank tests were performed for both numerical models to ensure that the correct wave is exciting the device.

4.1 *Kinematic and mooring tension of PeWEC*

Figure 5 reports the surge, heave and pitch motions of PeWEC for the experimental campaign and for both numerical models. Upon analyzing the surge kinematics, we observe a slight deviation in the mean surge between the experimental data and the numerical model developed in STAR CCM+ (Table 2). This disparity may stem from differences in the initial condition of the mooring line, impacting the transient phase of the device. Note that during the experimental campaign, the mooring lines of the device were laid back on the seabed manually after each test, which makes it difficult to precisely replicate the setup in the numerical environment. Furthermore, a slight discrepancy between STAR CCM+ and DualSPHysics results may arise from artificial numerical damping in the STAR CCM+ model caused by the discretization. Despite these discrepancies, the results from both models are comparable, as shown in Table 3 where the standard deviation of the signals after the transient phase is reported. For pitch and heave, both numerical models faithfully represent the experimental campaign, accurately capturing the dynamic behavior and response of the wave energy converter under extreme regular wave conditions.

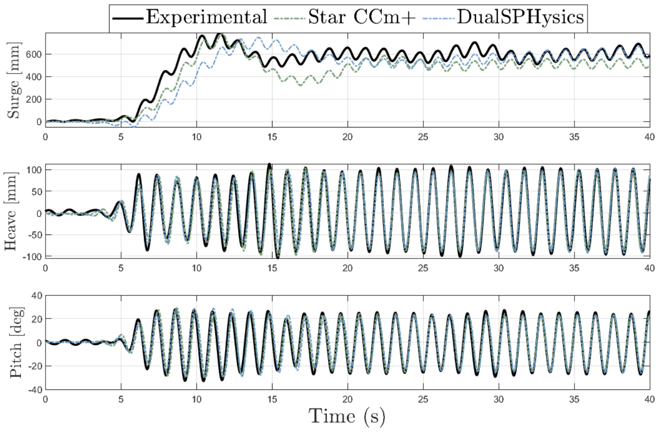

Figure 5: Comparison of the kinematic of PeWEC

Figure 7 reports the mooring tension. From the comparison we notice that both numerical models accurately describe the mooring tensions for the bow mooring lines (LC3 and LC4). This result was anticipated, given that STAR CCM+ and DualSPHysics rely on MoorDyn and MoorDynPlus, respectively, for evaluating mooring tensions. The bow lines play a critical role as they provide the restoring forces in surge and significantly contribute to the device's kinematics. Additionally, the standard deviation of the forces in the bow lines are one order of magnitude higher compared to the aft mooring lines (LC1 and LC2). However, the aft mooring lines experience con-

Figure 6: On the left the model developed with STAR CCM+ (the mooring is not visible but it is present in the model). In the middle the experimental campaign performed in 2021. On the Right the model developed with DualSPHysics

siderable noise in both numerical models and the experimental campaign. It must be noted that the stern lines only apply the weight forces of the chain itself to the device, with the chain links vibrating relative to each other, introducing noise. Despite this, the mean value and the standard deviation of the tensions are comparable for both numerical models and the experimental campaign as shown in table 3. Since this comparison is limited to an extreme regular wave, further works will include a comparison in short time series of irregular waves (such as focused waves or multisine waves), that represent a much more realistic test scenario.

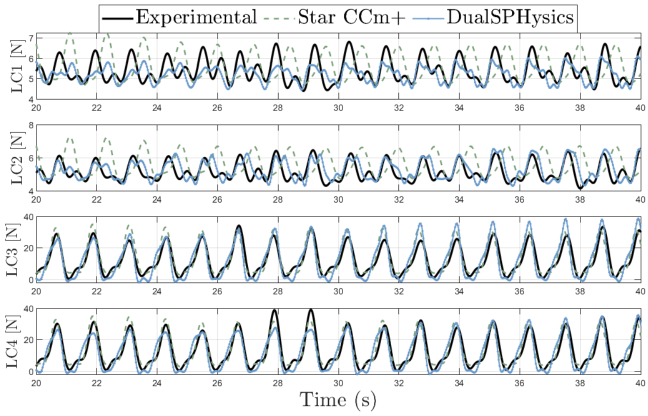

Figure 7: Comparison of the mooring tension of PeWEC. LC1 and LC2 are the stern mooring lines. LC3 and LC4 are the aft mooring lines

Table 2: Mean values of the kinematics and mooring tensions of PeWEC considering the signal after the transient phase.

Mean Values			
	Exp	STAR CCM+	DualSPHysics
Surge (mm)	611	510	608
Heave (mm)	2.86	2.03	5.22
Pitch (deg)	-1.02	-0.15	-0.44
LC1 (N)	5.37	5.57	5.23
LC2 (N)	5.12	5.57	5.30
LC3 (N)	12.4	13.3	12.7
LC4 (N)	12.9	13.3	12.1

Table 3: Standard deviation of the kinematics and mooring tensions of PeWEC considering the signal after the transient phase.

Standard Deviation			
	Exp	STAR CCM+	DualSPHysics
Surge (mm)	36.6	30.6	42.2
Heave (mm)	66.6	63.7	70.6
Pitch (deg)	17.6	16.7	17.5
LC1 (N)	0.71	0.64	0.48
LC2 (N)	0.60	0.64	0.71
LC3 (N)	8.50	9.59	11.7
LC4 (N)	9.09	9.59	11.1

4.2 *Numerical models cost comparison*

In addition to comparing the kinematic behavior and mooring tensions of PeWEC, we also evaluated the computational cost associated with employing STAR CCM+ and DualSPHysics. For STAR CCM+, the computational cost amounted to an elapsed time of approximately 52 hours. The hardware configuration utilized for this computation involved 12 nodes, housing a total of 580 cores. Each node was equipped with 2x Intel® Xeon® Platinum 8160 Processors (2017). In contrast, DualSPHysics exhibited a slightly lower computational cost, with an elapsed time of roughly 40 hours. The computational hardware for DualSPHysics comprised a RTX 4090 GPU. Although the computational cost between the two numerical models is comparable, the cost of the hardware used for these simulations differs significantly, both in terms of expense and power consumption, as shown in Figure 8.

If we solely consider the cost of the CPUs (which is not the only expense for an HPC setup as it requires other expensive materials), STAR CCM+ utilized hardware valued at approximately $60,000. While these processors are from 2017 and significant advancements have been made since then, even considering the cost of a CPU in 2023 capable of the same computational power, it still amounts to $20,000 in value (2xAMD Ryzen Threadripper PRO 7995WX). Conversely, the most expensive hardware component used for DualSPHysics is the RTX 4090 GPU (re-

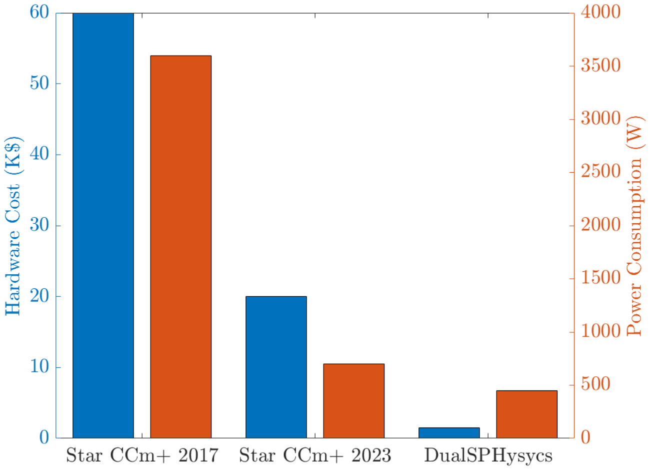

Figure 8: Comparison of hardware costs.

leased in 2022), which costs around $1,600, representing a difference in cost of more than an order of magnitude. Regarding power consumption, the hardware used to perform simulations in STAR CCM+ consumes approximately 3600W, while considering hardware from 2023, it should be equivalent to 700W. Conversely, the 4090 has a Thermal Design Power (TDP) of 450 W. It's important to note that this comparison only considers the TDP of the CPU for STAR CCM+ and the TDP of the GPU for DualSPHysics, which are not the total power consumption of the two systems but should provide a general idea. Additionally, the latest available version of DualSPHysics currently does not support multi-GPU usage, which could significantly speed up future simulations. Ongoing development efforts also aim to introduce adaptive particle sizing, potentially reducing the total number of particles required for simulations (Ricci et al., 2024). Incorporating regions with diverse particle sizes could significantly reduce the overall number of simulation elements. As the wave's velocity field decreases exponentially with vertical distance, there are substantial portions of the domain where smaller particle sizes offer no improvement to simulation accuracy. Lastly, there is the licensing cost to consider. While Siemens offers favorable prices for universities, STAR CCM+ remains paid software, whereas DualSPHysics is open-source and freely accessible.

5 CONCLUSION

In this study, we conducted an experimental validation of the DualSPHysics and STAR CCM+ numerical models for capturing the extreme response of WECs, focusing on the PeWEC as a case study.

The comparison between the numerical models and experimental data revealed promising results, indicating the efficacy of both DualSPHysics and STAR CCM+ in simulating the kinematic behavior and mooring tensions of PeWEC under extreme wave conditions.

The comparison of costs between the two software reveals a significant difference, heavily favoring DualSPHysics, which has still a huge potential to improve its computational efficiency with the introduction of different particle size in the domain and the multi-GPU computation, which is currently under development.

STAR CCM+ has also potential to improve its computational efficiency combining CPU and GPU computation for the simulation (which is currently available for a small portion of modules), but its benefits will be probably less impactful compared to DualSPHysics, increasing the gap between the two software on this particular matter.

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