# Numerical simulation of the full non-linear behaviour of Wave Energy Converters

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*Abstract*—**The present work aims to prove the benefits of using a mesh-less particle numerical model to design Wave Energy Converters (WEC). In particular, the capabilities of the SPH-based code named DualSPHysics is here presented. SPH models can simulate the non-linear wave-structure interaction where large deformation can be efficiently treated since there is no mesh distortion and no special treatment to detect the free surface. Herein, DualSPHysics has been coupled with other free and open source codes to simulate mooring forces of the floating moored structures using the library MoorDyn, and mechanical constraints of WECs using the multiphysics library Project Chrono. The coupling between DualSPHysics with MoorDyn and with Chrono are here described, validated with experiments and applied to simulate different types of WECs: i) Oscillating Water Column (OWC), and ii) Oscillating Wave Surge Converter (OWSC).**

*Keywords*—**CFD, Chrono, MoorDyn, Numerical modelling, SPH, DualSPHysics.**

## I. INTRODUCTION

WECANet (A pan-European Network for Marine Renewable Energy) is the first open European COST Action Network for Marine Renewable Energy. During the 1st WECANet Annual Assembly in February 2019, the current state of numerical modelling of WECs was discussed. Some of the main conclusions were that hybrid modelling is required, namely, coupling between models and multi-model approach. This manuscript follows this recommendation and a novel coupled numerical code is here presented and applied to simulate different WECs.

Numerical modelling plays a key role to accelerate the design phases of Wave Energy Converters (WEC) ([1]). However, the numerical tools need to be very flexible and powerful to foster the technological development of different WECs, to support the achievements of new results e.g. regarding structure survivability under high energetic sea states, and to obtain the optimum mooring layout (in the case of a moored floating WEC) to increase structure's lifetime.

The mechanical constraints are a fundamental subject in the numerical modelling of WECs due to their influence on the hydrodynamic response ([2]). Although research has been going on for a few years, currently, most of the Computational Fluid Dynamic (CFD) codes use simplified approach to model wave-WEC interaction, neglecting the description of its large and complex mechanical systems. Only few works about numerical modelling WECs with mechanical systems, including the constraint of the Power Take-Off (PTO) system, can be found in the literature ([3], [4], [5], [6]), however these mechanical constraints are usually simplified.

In recent years, a considerable effort has been made to establish accuracy in the numerical modelling of WECs. As a part of this effort, several numerical models have been proposed, using CFD codes based on mesh-based and more recently on mesh-free methods.

Mesh-based methods have been widely applied in the modelling of WECs. However, these methods suffer from some inherent difficulties in many aspects, which limit

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their applications to the modelling of WECs: i) in the case of large motion of floating bodies, mesh-based methods require commonly expensive and complicated mesh moving algorithms, ii) solving the mechanical systems usually requires additional complex mathematical transformation that can be even more expensive than solving the hydrodynamic interaction between wave and WECs and, iii) some mechanical constraints (e.g. impact, frictional contacts, slider joints) require mesh size and time steps in the mesh-based methods that can be impracticable ([7], [8]).

An alternative to mesh-based are the mesh-free methods, which are favoured for modelling flows with large motion since a mesh is not required when solving the Lagrangian formulation of the Navier-Stokes equations. The mesh-free Smoothed Particle Hydrodynamics (SPH) method has been widely adopted in the study of complex free-surface flows for its merits to easily calculate interactions between waves and fixed or floating bodies ([9], [10]). There is no special treatment to detect the free surface in the SPH method since it is captured implicitly. A detailed description of the SPH method and applications with free-surface flows are presented in [11]. Only few works can be found in the literature where SPH is used to simulate WECs. The references [12] and [13] simulated oscillating wave surge devices and [14] studied point absorber devices.

The DualSPHysics code ([15]) has been developed to use SPH for real engineering problems with software that can be run on either CPUs or GPUs (Graphics Processing Units with powerful parallel computing). One of the limitations of the numerical modelling is the low computational efficiency, especially for complex models. However, executing DualSPHysics on a GPU card installed on a personal computer alleviates this weakness. Moreover, DualSPHysics is open source and can be freely downloaded from the website: www.dual.sphysics.org. The DualSPHysics package includes dedicated pre- and post-processing tools. The pre-processing code that generates the initial state of the simulation can load different 3-D models for the complex geometries including CAD, STL, PLY files, etc. On the other hand, the advanced post-processing tools enable users to visualise data or to measure interesting physical magnitudes such as vorticity, velocity, force, torque, etc.

The version of DualSPHysics presented in this work includes, in the same meshless framework, the functionalities to study the wave-structure interaction, the mooring forces and the numerical behaviour of the PTO system. Mooring forces are solved by the external library MoorDyn (http://www.matt-hall.ca/moordyn.html) that has been also coupled with DualSPHysics. PTO can be now simulated using the coupling with the multiphysics library Chrono (https://projectchrono.org/). In fact, DualSPHysics has been used recently to simulate an Oscillating Water Column (OWC) in [16] and an Oscillating Wave Surge Converter in [17].

## II. NUMERICAL MODELLING

### A. *Smoothed Particle Hydrodynamics (SPH)*

DualSPHysics is a SPH based code, so it is fully Lagrangian and meshless. The fluid is discretised into a set of nodal points, called particles, where position, velocity, density and pressure are computed as an interpolation of the corresponding parameter values of the neighbouring particles. The contribution of those neighbouring particles depends on the distance between the particles and the corresponding parameter value is obtained using a weighted kernel function ($W$) with an area of influence that is defined using a characteristic length called "smoothing length" ($h$). Weight functions play a fundamental role in SPH methods. More information about the properties of kernel functions can be found in [18] and [19].

The Navier Stokes equations can be written in a discrete SPH formalism. In this way, the system of equations to be solved are:

$$\frac{d\boldsymbol{r}_a}{dt} = \boldsymbol{v}_a \tag{1}$$

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b \left(\frac{P_b + P_a}{\rho_b \cdot \rho_a} + \pi_{ab}\right) \nabla_a W_{ab} + \boldsymbol{g} \tag{2}$$

$$\frac{d\rho_a}{dt} = \sum_b m_b \boldsymbol{v}_{ab} \nabla_a W_{ab} \; + \; +2\delta h c \sum_b (\rho_b - \rho_a) \frac{\boldsymbol{v}_{ab} \nabla_a W_{ab}}{\boldsymbol{r}_{ab}^2} \frac{m_b}{\rho_b} \tag{3}$$

being $t$ time, **r** position, **v** velocity, $P$ pressure, $\rho$ density, $m$ mass, $c$ speed of sound, $g$ the gravitational acceleration and $\Pi_{ab}$ the viscous term.

The kernel function, $W_{ab}$, depends on the normalised distance between particles $a$ and $b$. The Quintic kernel ([20]), where the weighting function vanishes for inter-particle distances greater than $2h$, was adopted for the present study.

The artificial viscosity proposed in [18] is used here ($\Pi_{ab}$). In addition, the delta-SPH formulation proposed by [21] is applied. This approach introduces a diffusive term to reduce density fluctuations, being $\delta$=0.1 recommended for most of applications.

The fluid is treated as compressible in DualSPHysics, which means that an equation of state is used to calculate fluid pressure as a function of density rather than solving a Poisson-like equation. However, the compressibility is adjusted to slow the speed of sound so that the time step (based on the sound speed) is reasonable. Therefore, the system is closed by the addition of Tait's equation of state:

$$P = \frac{c^2 \rho_0}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \quad (4)$$

where $\gamma$=7 is the polytropic constant, with $\rho_0$ being the reference density of the fluid.

Finally, a Symplectic algorithm ([22]) was used to integrate variables in time. A variable time step was calculated, involving the CFL (Courant-Friedrich-Lewy) condition, the force terms and the viscous diffusion term.

### B. *Fluid driven objects*

One of the most interesting capabilities of DualSPHysics is the correct simulation of fluid-driven structures. In this way, it is possible to derive the motion of a floating structure by considering its interaction with fluid particles and using these forces to drive its motion. This can be achieved by summing the force contributions for the entire floating structure. By assuming that the structure is rigid, the net force on each boundary particle is computed according to the sum of the contributions of all surrounding fluid particles. Therefore, each boundary particle $k$ experiences a force per unit mass given by

$$\boldsymbol{f}_k = \sum_{a \in WPs} \boldsymbol{f}_{ka} \quad (5)$$

where $\boldsymbol{f}_{ka}$ is the force per unit mass exerted by the fluid particle $a$ on the boundary particle $k$, which is given by

$$m_k \boldsymbol{f}_{ka} = -m_a \boldsymbol{f}_{ak} \quad (6)$$

For the motion of the floating structure, the basic equations of rigid body dynamics can then be used:

$$\begin{aligned} M\frac{d\boldsymbol{V}}{dt} &= \sum_{k \in BPs} m_k \boldsymbol{f}_k \\ I\frac{d\boldsymbol{\Omega}}{dt} &= \sum_{k \in BPs} m_k\left(\boldsymbol{r}_k - \boldsymbol{R}_0\right) \times \boldsymbol{f}_k \end{aligned} \quad (7)$$

where $M$ is the mass of the object, $I$ the moment of inertia, $\boldsymbol{V}$ the velocity, $\boldsymbol{\Omega}$ the rotational velocity and $\boldsymbol{R_0}$ the centre of mass. Equations (7) are integrated in time in order to predict the values of $\boldsymbol{V}$ and $\boldsymbol{\Omega}$ at the beginning of the next time step. Each boundary particle within the structure has a velocity, $\boldsymbol{u}$, given by

$$\boldsymbol{u}_k = \boldsymbol{V} + \boldsymbol{\Omega} \times \left(\boldsymbol{r}_k - \boldsymbol{R}_0\right) \quad (8)$$

Finally, the boundary particles that constitute the rigid structure are moved by integrating (8) in time. The work of [9] showed that this technique conserves both linear and angular momentum. Validations about buoyancy-driven motion are performed in [10], where DualSPHysics was tested for solid objects larger than the smallest flow scales and with various densities. Simulations are compared with analytical solutions, other numerical methods and experimental measurements. Moreover, simulations of a floating box under the action of regular waves were also compared with experimental data in [23] where a good agreement was observed between numerical and experimental heave and surge motions and pitch rotation.

### C. *Coupling with mooring library (MoorDyn)*

MoorDyn is a lumped-mass mooring system dynamics model that is open source and designed to be used for coupling with other numerical models ([24]). It discretizes mooring lines as point masses connected by linear spring-damper elements to provide elasticity in the axial direction. Bending and torsional stiffness are neglected. Hydrodynamic drag and added mass are represented using Morison's equation. Vertical seabed-contact forces are handled by a spring-damper approach that is activated whenever nodes pass below the defined seabed elevation. Structural damping in the model can be used to critically damp non-physical resonances that can occur at the natural frequencies of individual segment due to the model discretization. With its simple formulation, MoorDyn has shown to be computationally efficient and reliable for common offshore renewable energy mooring scenarios, giving accurate results with discretizations in the order of 20 segments per mooring line ([25], [26]). Finer discretizations are typically only necessary for detailed modelling of seabed contact dynamics. Work is ongoing in the addition of lateral seabed friction models ([27]). MoorDyn supports moorings that have interconnections or that connect multiple floating structures ([28]).

In the coupling of MoorDyn with other codes the fairlead kinematics are passed to MoorDyn, the mooring system dynamics are calculated for one or more time steps, and then the resulting fairlead tension vectors are returned to the other simulation code. This is the approach used in the present work. DualSPHysics solves the resulting forces acting on the floating structure considering: weight of the floater, forces from the interaction with the surrounding fluid and external constraints (in this case solved by MoorDyn). The computational cost of MoorDyn at each time step is negligible compared to the execution time to solve one time step in the SPH model.

A more complete description and validation of the coupling between DualSPHysics and MoorDyn can be found in [23].

### D. *Coupling with multiphysics library (Chrono)*

The Project Chrono is implemented and coupled with DualSPHysics to take into account the mechanical restrictions applied on the rigid body. Project Chrono is an open-source multi-physics simulation platform implemented in C++. The library allows to simulate million-body models and for the straightforward definition of a large number of mechanical systems, such as joints and sliders, with arbitrary degrees of freedom ([7], [29]). Furthermore, Project Chrono allows the efficient treatment of kinematic restrictions with user defined dynamic properties such as friction and restitution coefficients, restitution forces from spring and damper systems ([8]). The solver is capable of integrating externally applied forces and torques (the resultants of the fluid-body interactions) and the effects of kinematic-type restrictions, dynamic-type restrictions and internal collisions, as shown in [30]. The problem is described using a Differential Variational Inequality (DVI), cast in Cone Complementary Problem (CCP) form and solved with a novel fixed point iterative method ([29]).

A more complete description and validation of the coupling between DualSPHysics and Chrono can be found in [30].

## III. RESULTS

This section includes the study of two different WECs. Each device can be simulated using the coupling model between DualSPHysics with MoorDyn and with Chrono, respectively. The simulations are validated by comparing numerical results with experimental data.

### *E. Oscillating Water Column*

Oscillating Water Column (OWC) consist of a partially submerged reservoir with a water column (open to the sea below the water line) and a column of trapped air. The incident waves change the water level inside the reservoir, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere through a turbine where its rotation is used to generate electricity.

An experimental campaign was carried out in the Ghent University (Belgium) where a floating moored OWC was tested under regular and irregular waves ([31]) with a model scale of 1:25. The geometry of the floating OWC follows the fixed device studied by [32]. The model has a rectangular shape with dimensions of 0.2 m x 0.2 m x 0.44 m with the front part partially open to the incoming waves as shown in Fig. 1. The OWC is composed of different materials (extra floaters, main structure and weights) with different densities. The total mass of the OWC model is 2.593 kg and the numerical device is generated with SPH particles of density 578 kg/m$^3$. At model scale, the OWC turbines are replaced by orifices at the top of the structure which aim to simulate different levels of PTO damping. In this test, the orifice has a diameter of 5 cm and, during the experiment the air was compressed and decompressed following the wave oscillations inside the OWC chamber.

Different wave conditions were tested during the experimental campaign. One of those conditions is used here to validate the coupling between DualSPHysics and MoorDyn; the one with regular waves of *H*=0.11 m, *T*=1.6 s. The water depth (*d*) is equal to 0.6 m, leading to a wavelength of *L*=3.27 m. Fig. 2 shows the numerical domain and setup. The OWC is moored to the wave flume bottom using four slack-chains, so the motion of the floating device in the experiments is totally free (6 degrees of freedom) and only hydrostatics and the relatively soft catenary mooring lines restrain the motions. Each mooring line is discretized in MoorDyn into 40 segments, and a per-unit-length stiffness value of 30 N was set to represent experimental tension measurements.

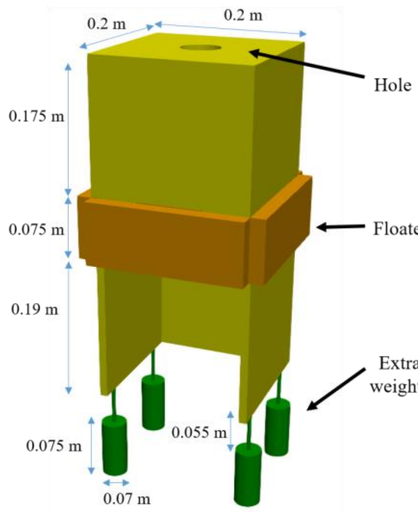


Fig. 1. Geometric characteristics and parts of the floating OWC.

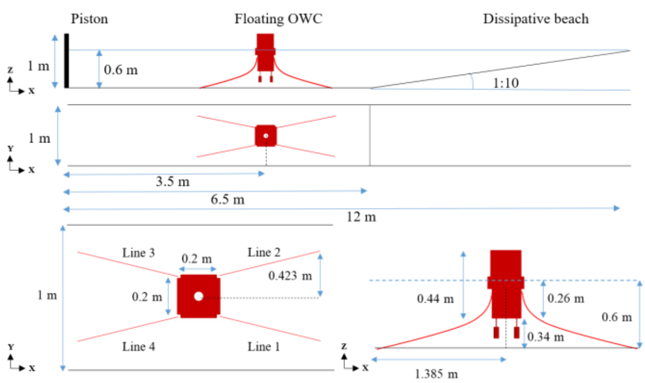


Fig. 2. Numerical setup for the simulation with the floating moored OWC.

The initial numerical domain is generated in DualSPHysics using an initial particle distance of *dp*=0.01 m, leading to 5,929,594 particles. The simulation of 40 s of physical time took 196 hours on the GPU card GTX 1080. Fig. 3 shows different time instants within a complete wave period, i.e. a complete heave and surge cycle.

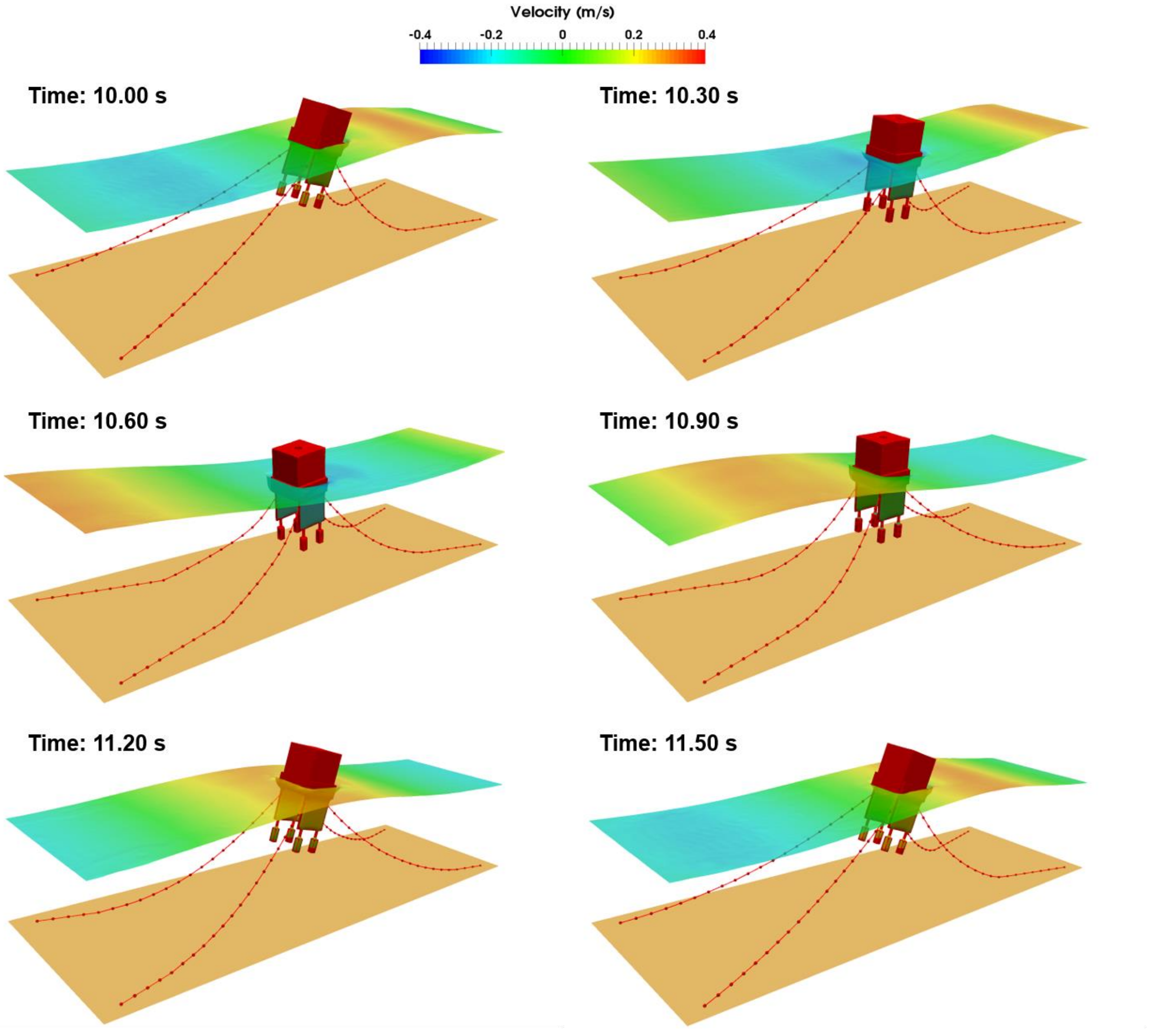


Fig. 3. Different time instants of the simulation of the floating moored OWC using DualSPHysics+MoorDyn.

The numerical heave and surge motions and pitch rotation are compared with the experimental ones in the Fig. 4. There are small differences but the overall comparison is satisfactory. The numerical mooring tensions are compared with the experimental data in Fig. 5. The tension experienced by the front lines (Line 3) in the simulation are in concordance with the experiment, but the numerical tensions of the back lines (Line 1) are higher than the experimental results. One reason for these discrepancies can be related to the fact that in this study, the air inside the chamber is not simulated and therefore the pressure changes of the air are not considered. However, the specific arrangement of the measuring sensors in the laboratory should be also considered as source of these discrepancies.

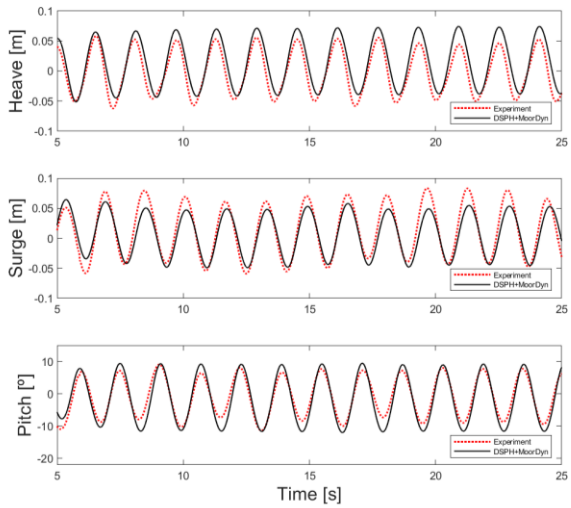


Fig. 4. Numerical and experimental heave and surge motions and pitch rotation of the floating moored OWC.

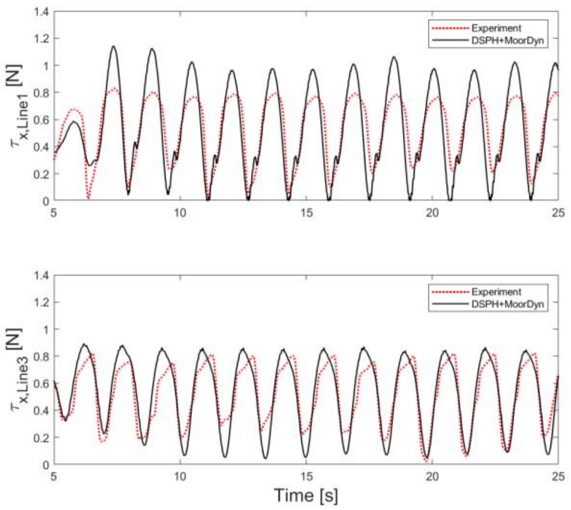


Fig. 5. Numerical and experimental mooring tension of the floating moored OWC.

Fig. 6 compares the surface elevation oscillations inside the chamber, which were measured during the experiment, against the ones computed with the one-phase model (only water phase). The compression and decompression of the air inside the chamber seems to be not very significant in this case with an orifice of 5 cm of diameter (5% of the area of the top of the chamber is open to atmosphere), so that the agreement is good even though the air phase is not considered at this stage.

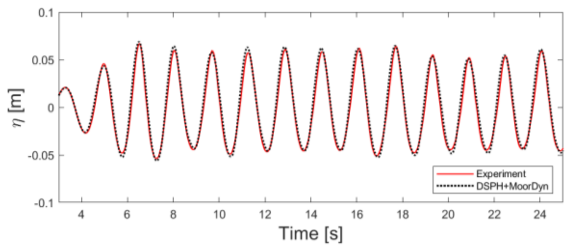


Fig. 6. Numerical and experimental surface elevation inside the floating OWC chamber.

The reader is referred to the works of [16] and [23] for more details about the implementation and the validation of DualSPHysics with MoorDyn.

*F. Oscillating Wave Surge Converter*

An Oscillating Wave Surge Converter (OWSC) is composed by a buoyant flap and by a hydraulic PTO system. The flap is attached to the foundation via bearings, hinged on a fixed horizontal axis at the flume bed, pitching under the action of incoming waves. The PTO system is composed by hydraulic cylinder that pumps fluid inside a closed hydraulic circuit. The energy conversion process of this device consists on the complex interactions between wave and flap and between flap and mechanical constraints, such as hydraulic PTO system, revolute joints, sliders and frictional contacts among components.

The coupling between DualSPHysics and Chrono has been applied to study this type of WECs in [17] and [33]. The work of [17] presented the application of this numerical tool to determine the influence of several PTO damping characteristics and flap configurations in order to emphasise its robustness and versatility as a design tool.

The experimental campaign carried out by [33] is used here for the validation of the coupling model. A 1:10 scale model of an OWSC, composed by a buoyant flap and by a hydraulic PTO system, was used. The flap is composed by PVC tubes, stainless steel frame and bearings and was attached to the foundation via bearing with internal diameter of 0.05 m, hinged on its horizontal axis (see Fig. 7). The flap is 0.84 m tall, 1.31 m wide, 0.17 m thick, and with a mass of 72.3 kg.

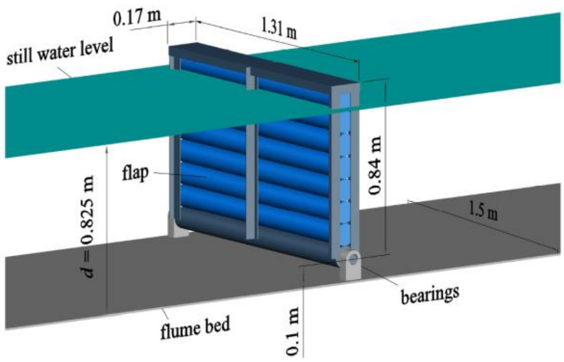


Fig. 7. Geometric characteristics and parts of the OWSC.

The wave flume was approximately 60 m long (wave direction), 1.5 m wide and 1.8 m deep, and was equipped with a piston-type wavemaker. At end of the wave flume, there was a passive beach with longitudinal slope of 0.3 m/m. The bed and the sidewalls of the wave flume were made of polished concrete. The details of OWSC model in the wave flume is presented in Fig. 7. The flap is hinged on y-axis at 0.10 m above the flume bed with a total gap of 9.5 cm between the lateral sides of the flap and the sidewalls of the flume. A schematic sketch (not to scale) of the wave flume is shown in Fig. 8.

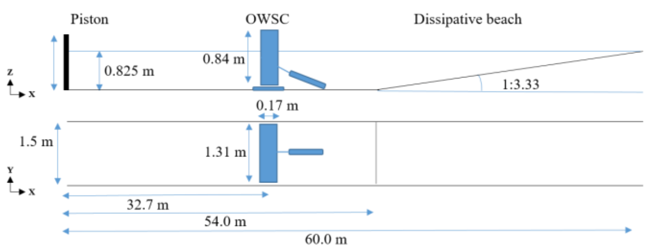


Fig. 8. Numerical setup for the simulation with the OWSC.

The dynamics of the OWSC model are validated in 3D with a computational domain of approximately 3 times the wavelength long, for the regular wave conditions of $T$=3.5 s, $H$=0.2 m and $d$=0.9 m. The initial numerical setup is generated using an initial particle distance of dp=0.01 m, leading to about 7.5 million of particles. The simulation of 120 s of physical time took 10 days using GPU card RTX 2070. Fig. 9 shows different time instants of the simulation.

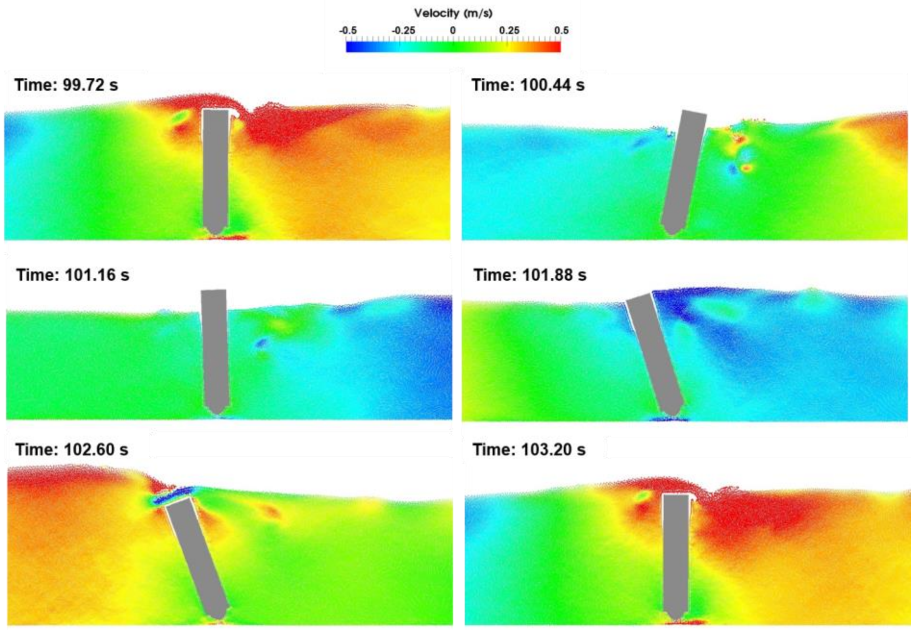


Fig. 9. Different time instants of the simulation of the OWSC using DualSPHysics+Chrono.

The PTO system is composed by a hydraulic cylinder, linked to the flap at z=0.47 m and x=0.09 m and to the flume bed at z=0 and x=1.04 m. The constraint force of the PTO system, $F_{PTO}$, on the slider joint between piston rod and cylinder body is given by $F_{PTO} = F_f + F_p$ where $F_f$ and $F_p$ are respectively the friction and pressure forces of the hydraulic cylinder. The friction torque on the revolute joint between flap and bearings was modelled using the Coulomb friction, with static friction coefficient of 0.16.

The comparison between the numerical and experimental angle ($\theta$), angular velocity of the flap ($\dot{\theta}$) and torque ($T$) are shown in Fig. 10. It can be observed how the numerical model can predict, with a satisfactory accuracy, the dynamic behaviour of the flap in regular excitation (after the quasi-steady condition).

The influence of PTO system on the hydrodynamics of OWSC is numerically analysed through the change of the PTO damping coefficients. From the several coefficients of $F_f$ and $F_p$, the pressure loss coefficient, $K_p$, that is used to determine $F_p$, has shown to be one of the most relevant on the power capture. The value of $K_p$ is directly related with hydraulic circuit that included hydraulic cylinder, check-valves, globe valves, pipes and reservoir. All parameters and constants introduced here are better described in [33].

Therefore, the analysis was performed for different values of $K_p$. Fig. 11 plots the time series of angle, angular velocity and torque without PTO system (i.e. $F_f$=0 and $F_p$=0) and for two different PTO damping coefficients ($K1$=1100 Nms², $K2$=2200 Nms²).

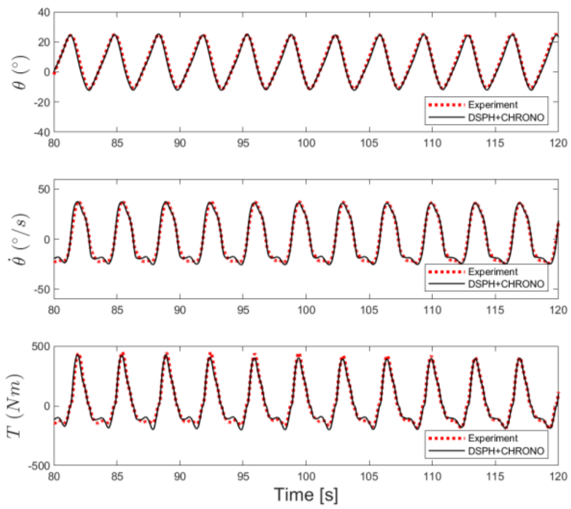


Fig. 10. Numerical and experimental angle, angular velocity and torque of the OWSC.

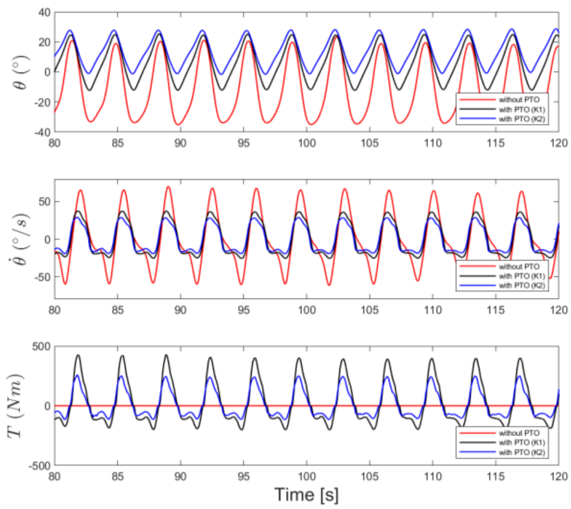


Fig. 11. Numerical angle, angular velocity and torque of the OWSC using different PTO damping coefficients.

## IV. Conclusion

Following the need of hybrid modelling, the SPH-based DualSPHysics code has been coupled with external libraries. In this way, DualSPHysics solves not only the violent wave-structure interaction, but also the mooring forces and non-linear PTO behaviour in the same meshless framework. Besides, real engineering applications can be simulated with high resolution at a reasonable computation time using only one execution device (GPUs).

The coupling with MoorDyn allows to simulate floating devices moored to the seabed. Physical tests with a floating moored OWC were reproduced with the numerical tool and good agreement was observed when comparing experimental and numerical results considering the motions of the OWC and the tensions in the chains. On the other hand, the augmentation of the DualSPHysics code by inclusion of Project Chrono library was validated by describing the motion of an OWSC with hydraulic PTO system. Nonlinear constraints were considered to simulate the effect of mechanical systems. The numerical model can predict, with a satisfactory accuracy, most of the dynamic behaviours of PTO in the OWSC.

It is important to mention that only regular waves have been presented in this work for validation purposes. Waves generated from specified spectra can be used for practical applications. Moreover, this model can be ideal to model WECs with mechanical constraints and/or different mooring layouts under the action of extreme waves, including wave breaking and overtopping, in order to study their survivability under high energy sea states and efficiency to absorb the available wave energy.

The DualSPHysics code, coupled with MoorDyn and with Chrono, can be proposed as complementary tool to physical modelling for a preliminary design of different types of WECs.

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