A NEW OPEN SOURCE SOLVER FOR MODELLING FLUID-STRUCTURE INTERACTION: CASE STUDY OF A POINT-ABSORBER WAVE ENERGY CONVERTER WITH POWER TAKE-OFF UNIT

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Abstract. *In this work, the capabilities of the open source code DualSPHysics coupled with the multiphysics library Project Chrono are shown. The framework is validated through an experimental campaign performed on a wave energy converter, which consists of a cylindrical heaving-buoy and a power take-off unit. The numerical model proves to correctly reproduce the hydrodynamic response of the wave energy converter under regular waves, and with three different damping coefficients of the power take-off. With this validated setup, the sensitivity of a wave energy converter to the lateral stiffness of the anchoring system is investigated. The outcomes of this numerical campaign show that the correct design of the anchoring structure should develop along with the design of the system. Enough lateral stiffness is able to avoid excessive displacements to limit the loss of efficiency. DualSPHysics is a toolbox ready to manage complex simulations, including mechanical constraints, high energetic sea states. Various scenarios along the lifespan of a floating structure can be investigated. More importantly, the model supports the preliminary studies that are of vital importance to design a test campaign.*

1 INTRODUCTION

The process of shifting our primary energy source from fossil fuel to renewable energy seems to be driven by the increased worldwide awareness about climate change. However, many other driving forces are behind the events of the past decades, such as the economic benefit. Along with solar and wind energy, a more energy-dense source with comparable availability is represented by ocean wave energy [1]. Wave energy converters (WECs) are devices that can capture the wave energy and turn it into electricity using a power take-off (PTO) system. The movement of a floating body is often the input for any system that turns mechanical energy into electric one. Point-absorbers are representative of the most widely applied class of WECs. The floating bodies of such devices are smaller than others, and easier to produce and install [2]. On top of this, they can harvest energy irregardless of the wave directionality.

Along with physical tests, the design and optimisation of such devices can be approached via numerical modelling. A range of models is available to face this problem, such as potential flow based, boundary element method, and computational fluid dynamic (CFD) models. The first two methods—to name some implementations, WAMIT [3] and WEC-Sim [4]—are well suited to tackle the design of WECs, with a particular focus on energy efficiency. However, these approaches ground on over-relaxed conditions when it comes to model fluid, waves, and the buoy mechanics. On this account, such models cannot be used when the device is under operational sea states, where the ability of simulating nonlinearities is strictly advised to obtain reliable predictions. Very energetic sea states may represent more stressing scenarios for both buoys and structures used to restrain their movement [5]. On the other hand, CFD methods can guarantee a wider field of application.

Some meshless methods have appeared over the last decade and grown in popularity as they can be applied to highly nonlinear problems in arbitrarily complex geometries — difficult to be solved by mesh-based methods instead [6]. Among the others, Smoothed Particle Hydrodynamics (SPH) meshless technique is the most popular, having attained the required level of maturity to be used for engineering purposes [7]. Being Lagrangian, SPH can be conveniently adopted to simulate free-surface flows and for capturing highly nonlinear behaviour of wave-structure interactions, or fluid-driven objects. DualSPHysics has been already used, with outstanding outcomes, to simulate WECs [8], such as an oscillating water column [9, 10], an oscillating wave surge converter [11], and a point-absorber device [12], based on the device shown in [13].

In this work, the DualSPHysics code is used to simulate a WEC under regular sea states and with different PTO systems. The energy efficiency dependence on the anchoring-structure stiffness is investigated accounting for different configurations. A simplified model is used to mimic the effect of the structure on the buoy's dynamics.

2 DUALSPHYSICS CODE

2.1 SPH Method

This section introduces the SPH formulation implemented in DualSPHysics code, and important functionalities that are required to simulate the interaction between regular waves and a heaving cylinder.

Smoothed Particle Hydrodynamics (SPH) is a mesh-less method that discretises a volume of fluid into *particles*, whose motion is given by the governing dynamics. These *particles* represent the nodal points where physical quantities (e.g. position, velocity, density, pressure) are approximated with an interpolation of the values of the neighbouring particles on a short-ranged compact support [14, 15]. It is recognised that for free surface flows, the Lagrangian

nature of the SPH method allows multiple connections among the particles, without special treatments of any surface, for the definition itself of free surface loses all meanings. Hence, the technique is ideal for studying irregular and violent flows. SPH has been used to describe a variety of free-surface flows (wave propagation over a beach, plunging breakers, impact on structures and dam breaks [16, 17]).

The mathematical fundamental of SPH is based on the approximation of any quantities by convolution integrals. Any function F can be computed by:

$$F(\mathbf{r}) = \int F(\mathbf{r}')W(\mathbf{r} - \mathbf{r}')d\mathbf{r}' \quad (1)$$

where W is the kernel function [18], $\mathbf{r}'$ is the position of a generic computational point. This function F can be approximated by interpolating particle contributions; the summation is performed over all the particles within an influence region of the compact support of the kernel:

$$F(\mathbf{r}_a) \approx \sum_b F(\mathbf{r}_b)W(\mathbf{r}_a - \mathbf{r}_b, h)\frac{m_b}{\rho_b} \quad (2)$$

where a is the interpolated particle, b is a neighbouring particle, m and ρ being the mass and the density, respectively, m_b/ρ_b the volume associated to the neighbouring particle b . The kernel functions W fulfils several properties, such as positivity inside the area of interaction, compact support, normalisation and monotonically decreasing with distance [19]. One option is the piecewise polynomial Quintic Wendland kernel [20]:

$$W(q) = \alpha_D(1 - \frac{q}{2})^4(2q + 1) \quad 0 \leq q \leq 2 \quad (3)$$

where α_D is a real number that accounts for the nature of the formulation, r is the distance, and h is the smoothing length.

The code used in this work uses the weakly compressible SPH (WCSPH) for modelling fluid. The Navier-Stokes (NS) equations are solved on account of that assumption. Hence, the differential form of the NS equations are written in a discrete version using the kernel function.

$$\frac{d\mathbf{v}_a}{dt} = - \sum_b m_b \left(\frac{P_a + P_b}{\rho_a \rho_b} + \Pi_{ab} \right) \nabla_a W_{ab} + \mathbf{g} \quad (4)$$

$$\frac{d\rho_a}{dt} = \rho_a \sum_b \frac{m_b}{\rho_b} \mathbf{v}_{ab} \nabla_a W_{ab} + 2\delta hc \sum_b (\rho_b - \rho_a) \frac{\mathbf{v}_{ab} \nabla_a W_{ab}}{\mathbf{r}_{ab}^2} \frac{m_b}{\rho_b} \quad (5)$$

where t is the time, $\mathbf{v}$ is the velocity, P pressure, Π_{ab} is the artificial viscosity [19], $\mathbf{g}$ is the gravitational acceleration, and W_{ab} the kernel function, whose value depends on the distance $a - b$. The system of equations is bonded by a relationship between density and pressure. For the WCSPH formulation, Tait's equation of state is used to determine fluid pressure based on particle density.

$$P = \frac{c^2 \rho_0}{\gamma} \left(\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right) \quad (6)$$

where c is the speed of sound, ρ_0 is the reference fluid density, γ is the politropic constant. The fluid compressibility is adjusted so that the c can be artificially lowered to assure reasonable values for the timesteps. The Symplectic time integration algorithm [21] is used in the present work and a variable time step is calculated, involving the CFL (Courant-Friedrich-Lewy) condition, the force terms and the viscous diffusion term.

2.2 Rigid body dynamics and Coupling with Project Chrono

Fluid-driven body can be easily implemented into a SPH domain. The movement of objects interacting with fluid particles in DualSPHysics is handled with different techniques. A full SPH model can deal with a rigid body by summing the total force contributions of the surrounding fluid. By assuming that a body is rigid, the net force on each boundary particle is computed according to the designated kernel function and smoothing length. Each boundary particle k experiences a force per unit mass given by:

$$\mathbf{f}_k = \sum_{b \in \text{fluid}} \mathbf{f}_{kb} \quad (7)$$

where $\mathbf{f}_{kb}$ is the force per unit mass exerted by the fluid particle b on the boundary particle k . For the motion of a rigid body, the basic equations of rigid body dynamics can then be used:

$$\mathbf{M} \frac{d\mathbf{V}}{dt} = \sum_k m_k \mathbf{f}_k \quad (8)$$

$$\mathbf{I} \frac{d\boldsymbol{\Omega}}{dt} = \sum_k m_k (\mathbf{r}_k - \mathbf{r}_0) \wedge \mathbf{f}_k \quad (9)$$

where $\mathbf{M}$ is the mass of the object, $\mathbf{I}$ is the moment of inertia, $\mathbf{V}$ is the velocity, $\boldsymbol{\Omega}$ the angular velocity, and $\mathbf{r}_0$ the centre of mass. Equations 8 and 9 are integrated in time in order to predict the values of $\mathbf{V}$ and $\boldsymbol{\Omega}$ at the beginning of the next time step. Each boundary particle within the body has a velocity given by:

$$\mathbf{v}_k = \mathbf{V} + \boldsymbol{\Omega} \wedge (\mathbf{r}_k - \mathbf{r}_0) \quad (10)$$

Finally, the boundary particles within the rigid body are moved by integrating 10 in time. This approach has been checked out by Monaghan et al. (2003) [22], which shows that linear and angular momentum are conservative properties. Validations about buoyancy-driven motion are performed in Dominguez et al. (2019) [23], where DualSPHysics is tested for solid objects larger than the smallest flow scales and with various densities.

Mechanical restrictions among rigid bodies, within the DualSPHysics framework, can be handled by the solvers provided by Project Chrono [24]. The Chrono-Engine library has been implemented into the original framework, creating an integrated interface for simulating structure-structure interaction as well. In fact, the library is primarily developed to handle very large systems of 3D rigid bodies [25]. The coupling allows for arbitrarily shaped bodies to be considered, and the solver is capable of integrating externally applied forces and torques, and the effects of kinematic-type restrictions, dynamic-type restrictions and internal collisions [26]. 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 [27]. To mimic the PTO system under study, a spring-damper system is employed (see also [28]). Such element is able to apply a force according to:

$$F(t) = b\dot{z} + kz \quad (11)$$

where b is the viscous damping, k is the stiffness, and z is the displacement.

Figure 1: Snapshots of the simulations of the point-absorber for different values of the damping coefficient of the PTO.

3 VALIDATION

The specimen used for validation purposes is the wave energy converter studied by Zang et al.(2018) [29], which consists of a cylindrical heaving-buoy ($D = 0.50\text{m}$, $m = 21.6\text{kg}$, and $draft = 0.11\text{m}$) attached to a PTO system at its bottom. Rather than relying on a real device, a linear air-damper is put in its stead. This is advantageous since it allows to tune the damping coefficient and it guarantees a small variability of its value with velocity. The validation is performed by comparing the hydrodynamic response of the WEC under regular waves ($H = 0.16\text{m}$ and $T = 1.50\text{s}$), and with three different damping coefficients of the PTO (b_{PTO} [Nsm^{-1}]). Different instants of the simulations can be observed in Figure 1 for two different values of b_{PTO} .

The numerical domain is modelled in the same fashion of the experimental geometries involved in (Figure 3). The flume is replicated into its exact geometries but the length. This is necessary to reduce the computational effort needed to perform the numerical analyses. A length proportional to the wave length L is used, specifically $1.50L$, and the centre of the buoy is located at $1L$ from the piston. This distance guarantees an optimum location, for it is far enough to allow local effects from the wave paddle, and, at the same time, close enough to avoid disturbances in the wave profile. To avoid excessive drag due to the lateral walls, periodic boundary conditions are used in place of solid boundaries. The anti-reflective structure is replaced with a dissipative beach, whose effectiveness is boosted by an additional numerical damping. Figure 1 proposes several snapshots of the numerical model, with the buoy heaving under regular waves.

Figure 2 compares the times series of the experimental and numerical vertical velocities. Each test is repeated with two different inter-particle distances, namely $dp = 0.01\text{m}$ and $dp = 0.02\text{m}$, which represent the resolution of the model. As shown in past research with SPH method [30], a value of dp of around $H/10$, being H the wave height, provides accurate results. However, for a 3D environment, this may pose a limitation to the physical time to be simulated. The two investigated resolutions are respectively representative of $H/16$ and $H/8$.

Figure 2: Comparison of the numerical and experimental time series for the vertical velocity with three different values of the damping coefficient of the PTO.

The agreement shown in Figure 2 is rather satisfying for both resolutions. For validation purposes, the time required to perform 15.00s of physical time is of around 20h for $dp = 0.01\text{m}$, and 2h for $dp = 0.02\text{m}$. These short runtimes are achieved thanks to a GTX2080 GPU card. Even though the finer mesh adheres more closely to the reference solution, the improvement is not as noticeable as the increment of runtime. Overall, the results collected in this section prove the capability of the SPH method to reproduce accurately the fluid dynamics and as well as the wave-structure interaction, which result in a correct prediction of the buoy's motion.

4 EFFICIENCY SENSITIVITY TO STRUCTURAL STIFFNESS

Test models provide researchers with a tool to investigate the physics of a natural phenomena. More than often, the model is a *scaled* reproduction of the specimen to be studied, and the scaling procedure has to be skilfully set up, taking in mind the trade off between feasibility and unavoidable scale effects. Tests in the range 1:10 and 1:20, whose parameters are given by Froude similarity, are deemed to be reliable on account of hydrodynamics. The tests presented by [29] are performed at 1:10 scale. The structure that takes in place the buoy, as it can be observed in Figure 3, may be assumed stiff enough to assume that the dynamics of the buoy develops only along the z-axis (Figure 3a)). However, the same structure can hardly be put in place just by solely scaling the model up. It is necessary to design a proper structure, which should guarantee the same degree of constraint.

Figure 3: Structural models for the validation case a) and the modified one b)

Herein, along with the vertical spring-damper element, the submerged structure is modelled as a spring-damper element able to mimic its *lateral* damping and stiffness (Figure 3b)). It is assumed that the structure is clamped at the sea-bottom level and a hollow circular steel cross section makes up the beam. Its properties are given by:

$$k_{rod} = \frac{E \pi t_n d^3}{8L} \quad \& \quad b_{rod} = 2m_{rod}\xi \sqrt{\frac{k_{rod}}{m_{rod}}} \quad (12)$$

where E is the elastic modulus, t_n is the thickness, d is the diameter, L is the length (0.890m), ξ is the damping ratio that is associated to the beam ($\xi = 0.10$), and m_{rod} is the mass of the beam. Note that the mass of the beam is considered lumped at its top. Additionally, the mass could be neglected due to its low impact on the overall kinematic.

Table 1: Geometric and mechanical properties of the profiles used for the anchoring structure.

	d [mm]	t [mm]	m	k_{rod} [N/m]	b_{rod} [Ns/m]
<i>flexible</i>	30	2.5	1.1	6 185	14
<i>quasi flexible</i>	40	3.2	1.4	18 766	32
<i>quasi rigid</i>	40	4.0	1.7	23 457	40
<i>rigid</i>	60	5.0	3.2	98 960	112

The dependence on the structural stiffness of the PTO's efficiency is investigated comparing the results obtained for the stiff structure (*rigid* in Table 1) with the results for the remaining

cases presented in Table 1. The wave height is the same used before, $H = 0.16\text{m}$, with wave periods ranging in $0.97 - 3.30\text{s}$, for a grand total of fourteen cases. In accordance with the tests presented for validation scope, the setup of the numerical domain is consistent: the length of the flume is $1L$, the width is twice the width of the device, the depth is the same. The four different viscous damping coefficients are used $[60, 240, 480, 720]\text{Ns/m}$.

The average power absorbed P is the quantity used as a proxy of the performance of the system. It is given by:

$$P = \frac{1}{T} \int_{t_0}^{t_0+T} b_{PTO} \dot{v}^2 dt \quad (13)$$

In general, heaving-buoy dynamics is highly affected by the wave conditions. This can be easily understood from the following equation:

$$\omega_0 = \sqrt{\frac{\rho g S}{m_a(\omega) + m}} \quad (14)$$

where ω_0 is the natural frequency of vibration, ρ is the buoy density, g is the gravity acceleration, S is the cross section of the heaving buoy, m_a is the added mass. For a heaving cylinder the excitation force and thus the added mass are given in an analytic form in Ref. [31]. The complex amplitude of the excitation force acting on a generic device is made up of two contributions: the Froude-Krylov force and the diffraction force. Under the assumption that the dimensions of the buoy are small in comparison with the wave length, the following holds:

$$F_e^* \approx (1 - khA^*)e^{-kh} \quad (15)$$

where F_e^* is the dimensionless amplitude of the excitation force, $k = 2\pi/L$ is the wave number, and h is the height of the cylinder. A numerical solution for the added mass, which can be found in [31], is given by:

$$m_a(\omega) = \frac{\rho S}{k} \left(1 - \frac{1.089e^{-(0.669k\frac{d}{2})^{0.604}}e^{-kh}}{e^{-kh}} \right) \quad (16)$$

Figure 4 collects the results of the analyses as performed on the model as described in Figure 3b). Each chart depicts the results for a value of the damping in the range above mentioned, while the four values of stiffness are compared (Table 1). Please note the dynamics of the *rigid* structure perfectly match the dynamics of the structure as shown in Figure 3a). The trend displayed by the charts is quite apparent: the less the stiffness of the system, the less the efficiency. Comparing the optimum points, the point at which the maximum power is harvested, it can be seen that there are no substantial differences between stiff and flexible structures. Though there is no difference in frequencies where the maxima are achieved, the average harvested power is sensibly lower, up to 40% in the case of the flexible structure. This trend appears to be quite consistent moving from *rigid* to *flexible* structures. The overall loss of efficiency shown in the four charts can be explained considering that the floating buoy, when free to surge, is prone to exhibit lateral displacements, according to the development of the free surface. However, for the way this PTO system works, this movement is not converted into harvested power.

5 CONCLUSIONS

This piece of research has shown that an SPH framework can presently deal with multi-physics phenomena effectively. The coupling DualSPHysics - Project Chrono library has skyrocketed the engineering applications that can be studied with this code. Many relevant features

Figure 4: Absorbed power with the relative period of the buoy. Different values of the damping are presented. Each panel presents the results for a different lateral stiffness.

of a complex system can be modelled, allowing to account for the fully nonlinearities that are inherent in any natural phenomena. However, the importance of introducing flexible elements for simulating fluid-structure is not negligible. The structure can be indeed directly model into the simulation, hence considering its interaction with fluid without further assumptions on its behaviour. Indeed this feature would allow for more comprehensive survivability analyses of wave energy converters.

The validation of the numerical model has shown that, for this specific case, it is possible to achieve a high degree of reliability. The model indeed predicts the response of the fluid-driven buoy with accuracy and the runtime is reasonable for a fully 3D simulation. Therefore, the sensitivity to the structural stiffness shows that it is important to include the anchoring structure, even in a simplified way, from the preliminary phases of the design process.

Further implementations are needed to still widen the field of application of the code. It is already ongoing the implementation of Euler-Bernoulli elements, and isogeometric analyses (IGA), which a quite novel approach for finite elements analyses (FEAs).

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