A DESIGN TOOL FOR FLEXIBLE WAVE ENERGY CONVERTERS BASED ON SPH

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I. INTRODUCTION

Commercialization of wave energy faces persisting bottlenecks due to the limited performance of Wave Energy Converters (WECs), leading to high manufacturing and investment costs. A promising approach to overcome these challenges involves the integration of flexible materials into WEC designs. In contrast to traditional rigid structures, flexible WECs (flexWECs) offer several key advantages. Firstly, such devices better adapt to dynamic wave loads, potentially improving energy capture and reducing fatigue. Besides, the potentially unlimited numbers of modes of vibration offer a wide spectrum of optimal operational frequencies [1]. FlexWECs, moreover, can accommodate innovative energy conversion technologies like Dielectric Elastomer Generators (DEGs), enabling more efficient and potentially lower-cost energy harvesting [2].

However, flexWECs need to still endure a refinement process that can be greatly sped up by numerical tools. Given that flexWECs consist of compliant structures interacting with fluid masses, often under resonant conditions or extreme sea states, a robustly coupled solution for the hydroelastic problem is critical for accurately predicting the loads and behavior of these devices. As such, the Smoothed Particle Hydrodynamics (SPH) method holds great potential, as its most valuable features for engineering applications are precisely related to extreme deformations, violent flows, and inherent treatment of fluid–solid boundaries in dynamic conditions.

This work presents a novel, high-fidelity numerical model for simulating flexWECs, leveraging the strengths of the open-source DualSPHysics [3] and Chrono [4] solvers. In such a framework, a lumped parameter discretization is implemented to cope with mono- and bi-dimensional compliant elements (beams and plates, respectively). The flexible structure modeling relies on co-rotational dynamics to solve high-strain/deformed states, achievable leveraging the multi-body Chrono solver and properly linear elastic constitutive models. The application of the developed framework to simulate flexWECs, particularly a modified FOSWEC concept [5], demonstrates its practical relevance for advancing wave energy technology.

II. NUMERICAL MODEL

The numerical environment is provided by the DualSPHysics framework, which features a two-way coupling with Project Chrono [6], functional to enable the simulation of flexible structures.

A. The DualSPHysics solver

DualSPHysics implements a weakly compressible SPH formulation for discretizing the Navier–Stokes equations, relying on the Tait's state equation to update particle pressure according to density oscillations. As such, it can be massively parallelized on Graphic Processing Units (GPUs) and provide competitive performance and scalability. Notably, the dissipative terms in the momentum equations are approximated by an artificial viscosity term [7], whereas the continuity equation features a density diffusion term defined upon the work of [8] to stabilize the SPH scheme. In this work, as general purpose fluid–solid boundary conditions, the modified Dynamic Boundary Conditions (mDBC) is used [9], which efficiently updates boundary particles pressure within the same loop as fluid particles.

B. Structural model

A lumped parameter method (LPM), firstly presented in [10] and here improved and extended to three dimensional plate elements, is adopted to model compliant structures. It leverages a set of rigid bodies, represented by SPH particles in a uniform Lagrangian framework, which can discretize beam or plate elements alike. These bodies are subject to force contribution from the fluid phase, computed via SPH integration, and localized reactive forces responding to the principles of linear elasticity. This cooperative framework is handled by the communicating interface presented in [6]. The principles of the LPM are briefly introduced here. Let us consider a regular quadrangular mesh discretizing a plate of dimensions L_1, L_2, h_b, (length, width and thickness aligned with the frame of reference $\{x, y, z\}$) in $N_1 \times N_2 = N$ sub-elements. The plate is made of isotropic and homogeneous material and its thickness is significantly smaller than the other two dimensions. Within the local stencil, two consecutive elements are connected by an elastic link that reacts to axial and flexural deformations, here relative displacements, according to:

$$\boldsymbol{f}_\varepsilon = K_\varepsilon \Delta \boldsymbol{w} + C_\varepsilon \Delta \dot{\boldsymbol{w}}, \tag{1}$$

$$\boldsymbol{f}_\vartheta = K_\vartheta \Delta \boldsymbol{\varphi} + C_\vartheta \Delta \dot{\boldsymbol{\varphi}}, \tag{2}$$

with $\boldsymbol{f}_\varepsilon$ and $\boldsymbol{f}_\vartheta$ being the spring–damper and mechanical joint reactive force and moment, respectively. The local discrete elongation and rotation of the elastic connections are identified as $\Delta \boldsymbol{w}$, which has non-zero components along x and y, and $\Delta \boldsymbol{\varphi}$, in which the torsional within-the-plane component is neglected. Since the plate element complies with Kirchhoff's theory, the extensional and rotational stiffness values can be deducted from linear considerations:

$$K_\varepsilon = \frac{EA_i}{\Delta x_i} \tag{3}$$

$$K_\vartheta = \frac{EI_i}{\Delta x_i (1 - \nu^2)} \tag{4}$$

with E being the Young's Modulus, ν the Poisson's Module, I_i and A_i the second moment of inertia and area of the cross section, respectively. $\Delta x_i = L_i / N_i$ represents the discrete dimension of each element, as the subscript $_i$ identifies x or y directions. C_ε and C_ϑ identify, finally, possible damping coefficients. A visual example of the structural kinematics, for a unitary stripe of the plate element, is given in Figure 1.

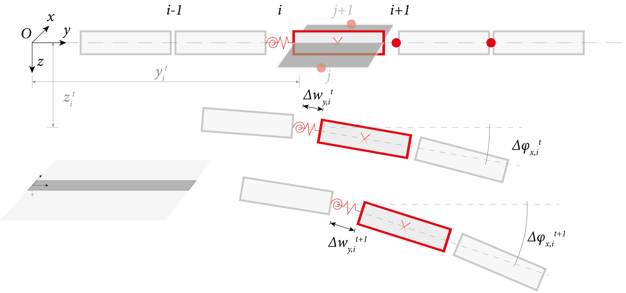

Fig. 1. Discrete kinematics of the structural model between two consecutive time intervals t and $t+1$.

III. APPLICATIONS

To demonstrate the capabilities of our framework, we firstly present a dam break impacting a flexible plate, replicating a well-established benchmark test [11]. Figure 2 displays the displacement time history of the beam free end, considering its lateral side in a two-dimensional fashion. The first phase of the impact is neatly reproduced, as the model also captures the initial negative displacement of the plate. However, after the first peak, the DualSPHysics result deviates from the experimental reference, as the plate shows excessive stiffness; proper behavior is recovered after 0.50 s, up to the moment when a second impact occurs. At this stage the single phase model can no longer capture the complex multi-phase flow which occurs after the impact of the fluid mass with the right-hand wall, and results in an excessive negative displacement. Differently from the majority of the literature references, the case is here performed in three dimensions, highlighting the 3-D behavior of the obstacle, with its out-of-plane deformations (Figure 3). The plate deformation is compatible with the solution proposed in [12], where a total Lagrangian framework is utilized. In spite of the restrictive assumptions posed by the Euler–Bernoulli beam and Kirchhoff plate theories, the presented model shows a broader application range: flexibility of rubber-like materials clearly out of the limitations imposed by the grounding linear theory, can anyway be properly reproduced and simulated.

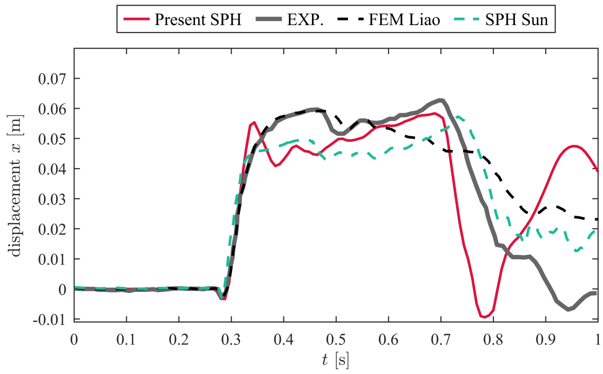

Fig. 2. Horizontal displacement of a reference marker close to the beam free-end, paired with experimental and numerical measurments.

We also apply the framework to a modified version of the Floating Oscillating Surge Wave Energy Converter (FOSWEC), firstly validated in DualSPHysics by [5], incorporating flexible plates as energy conversion elements. This simulation showcases the framework's potential for real-world applications, enabling the investigation of various design parameters and operating conditions to optimize energy capture and device performance. For this test case, the flaps of the original design are replaced by flexible plates, clamped along the transversal shafts. Their internal stress can be related to energy production by equivalent linear damping [13], which can be applied, in a discrete manner, to the elastic link equations (Equation 1 and 2). Moreover, the present approach can be easily adapted, using secondary constraints between the structural sub-elements, to reproduce nonlinear damping conditions suitable to describe the additional

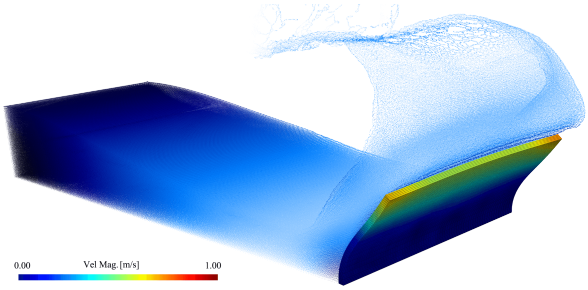

Fig. 3. Rendered visualization of the dam break impact and the out-of-plane deformation of the flexible obstacle.

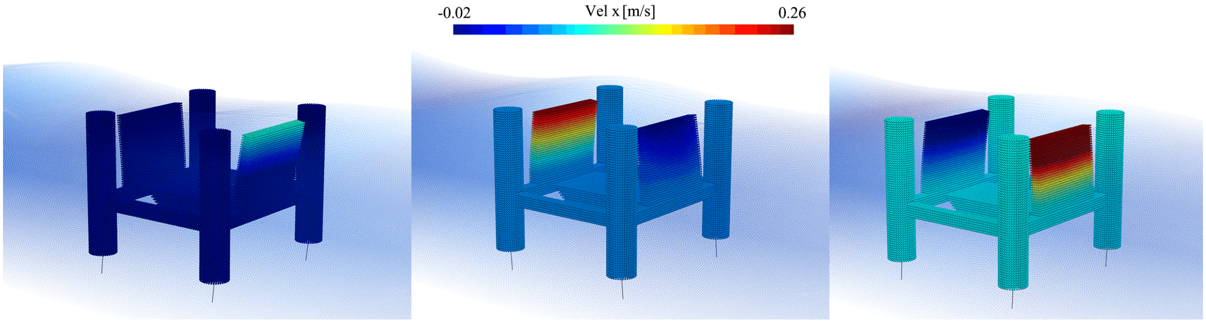

Fig. 4. The alternative FOSWEC concept under regular waves in three different instants; the velocity color map highlights the deformation of the clamped plates representing the FlexWECs.

mechanical stress due to DEG membranes. Figure 4 shows three instances of for a pilot simulation under regular waves, in which the structure responds with global surge motion and plate deformation. DualSPHysics, also thanks to the coupling with MoordynPlus [14], provides a complete simulation tool for transitioning towards efficient wave energy harvesting, making the most out of the high conversion efficiency of flexWECs [13].

IV. CONCLUSIONS

This work presents a novel and powerful numerical framework for simulating flexWECs. By combining the strengths of SPH, multi-body dynamics, and a LPM approach, the framework provides a high-fidelity and computationally efficient tool for wave energy research and development. The key advantages are:

- *Novelty*: The combination of the SPH features and the Chrono capabilities, unlocked through a LPM discretization, represents a significant advancement in wave energy simulation, pioneering the adoption of fully Lagrangian frameworks for flexWECs simulations.

- *Usability*: The open-source nature and GPU acceleration capabilities of DualSPHysics enhance the framework's accessibility and computational efficiency, making it a valuable tool for researchers and engineers. The LPM approach, moreover, can be directly implemented and customized by end-users within the standard DualSPHysics package, without the need for code modification or adaptation.

- *Competitiveness*: The framework offers a competitive advantage over existing tools by providing a comprehensive and accurate representation of complex hydroelastic interactions without sharpening the computational load. The LPM stands out for its adaptability to different structural configurations and nonlinear dynamics induced by the presence of DEGs, which would need, instead, low-level implementations in comparable FSI solvers.

The proposed framework is a suitable candidate to further unroll flexWECs technologies and help reach the long-awaited commercial leap for wave energy, coming with affordable numerical effort, in an open-source environment and with plenty of room for problem-dependent characterization.

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