SPH CHAMBER MODEL TOWARDS PNEUMATIC PTO REPRESENTATION FOR FLOATING OWC DEVICES

Beatrice Mina,[1,4] Bonaventura Tagliafierro,[2] Iván Martínez-Estévez,[3]
Giovanni Malara,[4] Felice Arena,[4] Moncho Gómez-Gesteira[3]

[1]University School for
Advanced Studies (IUSS)
Pavia, Italy
beatrice.mina@iusspavia.it

[2]Dept. of Electrical
Engineering
Uppsala University
Sweden

[3]EPhysLab,
CIM-UVIGO
Universidade de Vigo
Ourense, Spain

[4]NOEL, "Mediterranea"
University of Reggio
Calabria, Italy

I. INTRODUCTION

Among the most challenging topics concerning oscillating water column (OWC) numerical modeling, surely, proper representations of the pneumatic power take-off (PTO) – often consisting of a turbine linked to a power generator – remains highly desirable. A turbine is activated by an air flow produced by the compression and decompression of the air pocket formed by the water column oscillation in the OWC chamber. For practical reasons, the head loss effect due to the turbine is usually simulated, both in experimental and numerical tanks, through either porous layer or an orifice plate, depending on the turbine technology at hand [1]–[5]. Frequently, the air inside the OWC chamber is assumed to be incompressible; this conjecture does not have relevant consequences at small scales, as supported by [6]'s conclusions, nonetheless may have significant impact at large scales. Usually, problems that involve both air and water phases are numerically dealt with employing mesh-based two-phase CFD simulations. In [7] a fixed OWC device is simulated by means of a two-phase mesh-based software, while [8] presents the investigation of a floating OWC through a two-phase SPH approach. Furthermore, in [9] a single-phase SPH method is considered to analyze the PTO of a fixed OWC device, exploiting the compression effect of a plate on top of the water free surface inside the OWC.

This work instead, focuses on single-phase SPH modeling of the interaction between waves and a floating OWC, imposing directly the air pressure on the water particles inside the OWC chamber, following the procedure proposed in [10]. It aims at fully exploiting the strengths of SPH modeling, since free surface tracking and floating bodies are involved, and, at the same time, can reduce the computational costs that intrinsically feature multi-phase SPH techniques. Moreover, the air volume variations computation is independent on the water free surface shape, as opposed to methodology presented in [10]. Such a decoupled computation fully motivates the novel implementation that will be illustrated in the following, and can work with very minor changes for 2-D and 3-D numerical models. In section II the methodology to implement the single-phase PTO modeling in SPH framework is described and some challenges, especially regarding the tracking of particles inside the OWC, are presented. section III shows the validation of the proposed method for two OWC devices leading to concluding remarks in section IV.

II. METHODOLOGY

The method to simulate the effect of the varying air pressure inside an OWC air chamber is based on the single-phase SPH technique proposed in [10] and relies on the addition of a pressure term P_{air} in the SPH momentum equation of certain water particles. P_{air} depends on the air flux in and out of the chamber q and on a damping coefficient K according to:

$$P_{air} = \begin{cases} (K\,q(t))^2 & q(t) > 0 \\ -(K\,q(t))^2 & q(t) \leq 0\,. \end{cases} \tag{1}$$

This formula relies on the assumption that the PTO is replicated by the presence of an orifice on the chamber top wall [2], [5], whose diameter is the only necessary parameter to determine the damping coefficient K. Assuming incompressible air then, $q(t)$ is determined by means of:

$$q(t) = \frac{\Delta V}{w \Delta \tau}, \tag{2}$$

where w is the chamber width (set to 1 in 2-D) and $\Delta\tau$ indicates the time interval over which the volume change is determined, which is bigger than the SPH simulation time step. Moreover, since a single-phase framework is being dealt with, the air volume changes are estimated by tracking the number of water particles, n, in a predefined area, which is representative of the potential OWC chamber. At each time τ, $n\Delta p^{dim}$, with $dim \in \{2, 3\}$ proxies the total fluid volume occupied by all particles inside the chamber, while $V_{chamber}$ is the total chamber volume comprising both air and water. Therefore, the air volume variation between time τ and $\tau+1$ corresponds to:

$$\Delta V = V_{chamber} - \Delta V_{water} = V_{chamber} - \Delta n \, \Delta p^2 \,. \quad (3)$$

The estimated air pressure P_{air} is then added in the SPH momentum equation of those water particles that belong to the OWC chamber and to the water free surface, hence for such particles, the pressure term is rewritten as:

$$\sum_b \left(\frac{P_a + P_b}{\rho_a \rho_b} \right) \nabla_a W_{ab} \rightarrow \sum_b \left[\frac{(P_a + P_{air})}{\rho_a \rho_b} + \frac{(P_b + P_{air})}{\rho_a \rho_b} \right] \nabla_a W_{ab}. \quad (4)$$

The particles belonging to the water free surface are identified through a constraint over the divergence of their position [10]–[12], and are searched among those belonging to the chamber. The volume tracking represents one of the novelties of this study and it works thusly. The fluid mass within a predetermined region, which overlaps the area that defines the OWC chamber, is monitored at a given time step. Such algorithm guarantees computational costs that scale as $\mathcal{O}(n)$, being n the number of particles, for 2-D and 3-D frameworks, regardless.

When the device is fixed, it is sufficient to look for those water particles whose position lies between a certain coordinate range, defined once at the beginning. Instead, when the OWC device is floating, tracking the particles inside the chamber is not a straightforward task. The approach implemented herein consists in identifying a fictitious chamber inside the physical one through the definition of some vertices – assuming a simple parallelepiped geometry in this case – and update their position according to the roto-translations of the floating body. Then, at every time step, a check is performed to verify if a certain particle is contained within the limits marked by such moving vertices. The analytical approach just described is referred to as chamber model; its schematic representation and its coupling with the SPH software of choice – DualSPHysics [13] in our case – are depicted in Fig. 1.

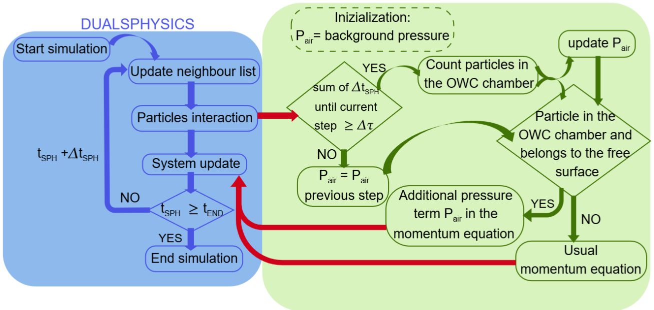

Fig. 1: Schematic representation of the chamber model and its coupling to SPH Software workflow.

III. NUMERICAL SET-UP AND VALIDATION

The proposed implementation has been validated against experiments both in 2D and 3D and some preliminary results are shown in the following. The first experimental configuration [8] features a floating OWC (Fig. 2) characterized by a 300-mm wide chamber with a 10-mm wide slot. The height of the device is 400 mm and the draft is 200 mm. The mooring chains, modeled through MoorDynPlus [14], are 1.60 m long and their anchor point is 1.65-m away from the device initial centerline. The water depth is 0.60 m, while wave height and wave period are respectively 4.00 cm and 1.50 s.

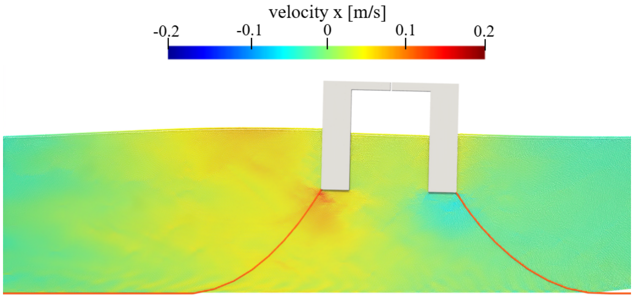

Fig. 2: 2-D simulation of floating OWC

Air pressure (P_{air}) inside the chamber is obtained from the 2-D SPH simulation coupled with the model illustrated in the previous section and it is plotted against the experimental one in Fig. 3. The numerical pressure despite being quite representative of the experimental one, still underestimates it by about 15%, in fact, further model parameters tuning and algorithm refinement including the feedback effect of air pressure on the device walls is required. This excessive noise is likely related to the relatively small number of particles that compose the control volume.

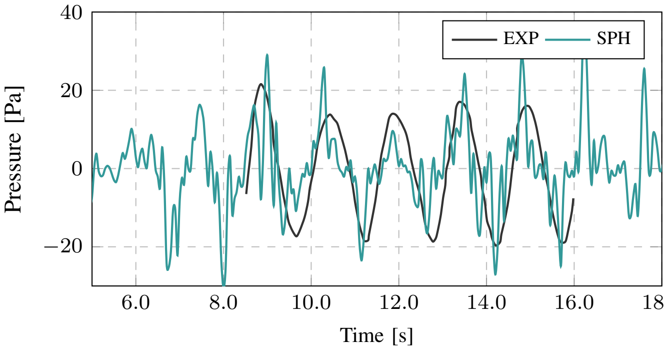

Fig. 3: Comparison between experimental and SPH air pressure inside the OWC in 2-D

The second experimental configuration [15], instead, concerns a 324-mm long, 400-mm wide and 500-mm high floating OWC moored to the tank bottom through four tension legs as depicted in Fig. 4. This figure illustrates the device with an opening on its top for representative purposes, whereas the 3-D numerical simulations are performed considering an orifice plate (with a 23.9-mm radius) on the air chamber top wall. Fig. 5 portrays a comparison between the numerical and experimental air pressure in the device chamber, showing the viability of the chamber model–SPH-scheme coupling.

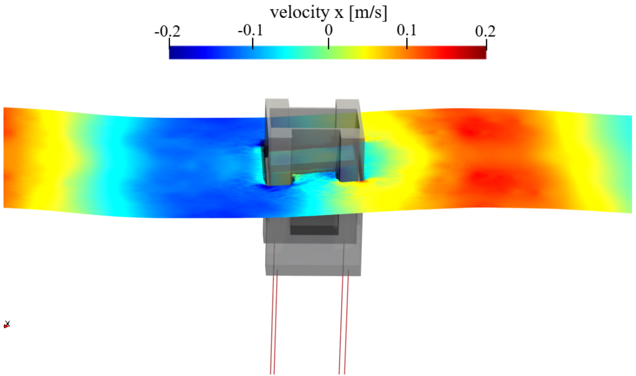

Fig. 4: Comparison between experimental and SPH air pressure inside the OWC in 3D.

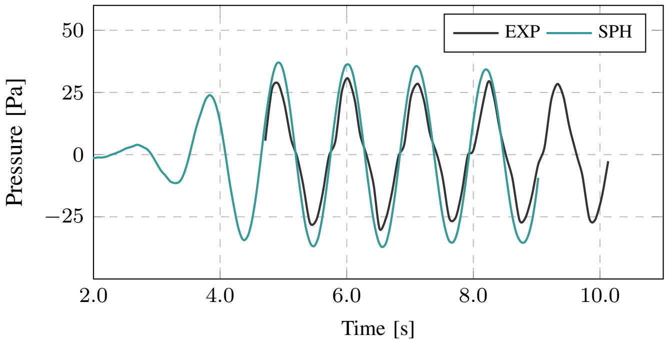

Fig. 5: Comparison between experimental and SPH air pressure inside the OWC in 3D

IV. CONCLUSIONS

In this work, we have presented a **novel** chamber model implementation for oscillating water column devices that has several new features when compared to SPH state-of-the-art distributions, among them: a direct fluid volume computation and a six DOF volume tracking algorithm.

This implementation, that consists in coupling a chamber model to the main SPH solver, has demonstrated to be quite effective. Its algorithm comprises the identification and tracking of water particles inside the chamber of a flaoting OWC and the addition of a fictitious air pressure term in the momentum equation of the identified particles. Some preliminary simulations – both in 2D and 3D – have provided quite promising results and shown its potential **applicability** to a variety of marine device structures: in principle, indeed, the fictitious chamber reference points (vertices in this study) can be defined for any arbitrary geometry. Furthermore, to the authors' knowledge, this work represents the first attempt at simulating, both in 2D and 3D, a free floating OWC in a single-phase framework exploiting the coupling with an analytical model, hence **improving** the computational time with respect to the analogous SPH two-phase simulations.

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