PAPER • OPEN ACCESS

Numerical simulation of fluid structure interaction in free-surface flows: the WEC case

View the article online for updates and enhancements.

Numerical simulation of fluid structure interaction in free-surface flows: the WEC case

Eugenio Schillaci[a,b],Federico Favre[c],Peter Troch[d], Assensi Oliva[a]

[a] Heat and Mass Transfer Technological Centre (CTTC), Universitat Politcnica de Catalunya (UPC), ESEIAAT, Carrer de Colom 11, 08222, Terrassa (Barcelona), Spain

[b] Termo Fluids S.L., Avda Jacquard 97 1-E, 08222 Terrassa (Barcelona), Spain

[c] Instituto de Ingeniería Mecánica y Producción Industrial (IIMPI), Universidad de la Repblica, Uruguay

[d] Dept. of Civil Engineering, Ghent University, Technologiepark 60, B-9052 Zwijnaarde (Gent), Belgium

E-mail: eugenio.schillaci@upc.edu

Abstract. In this work we present a numerical framework to carry-out numerical simulations of fluid-structure interaction phenomena in free-surface flows. The framework employs a single-phase method to solve momentum equations and interface advection without solving the gas phase, an immersed boundary method (IBM) to represent the moving solid within the fluid matrix and a fluid structure interaction (FSI) algorithm to couple liquid and solid phases. The method is employed to study the case of a single point wave energy converter (WEC) device, studying its free decay and its response to progressive linear waves.

1. Introduction

The necessity of analyzing the mutual interaction between a solid and the surrounding two-phase medium rises in several physical problems, many of them related to marine engineering. The most notable example consists in the study of the sea waves influence over floating objects, as buoys, ships or other kinds of platforms. The demand has increased further in recent years due to the popularity increase of floating devices for extracting energy from the waves, namely, wave-energy converters (WEC), which follow several different design characteristics. Between the others, a point absorber buoy consists of a small anchored device floating on the sea surface. Buoys exploit the rise and fall movement caused by waves to generate electricity in various ways as by means of linear generators or linear-to-rotary converters. According to the current trend, increasingly massive WECs will appear, including floating platform sustaining huge windmills. In this work we show how a point absorber device can be analyzed by means of numerical simulations. In particular, a FSI problem is solved within a multiphase flow scenario. The IBM method is employed to represent a solid with 6 possible Degrees of Freedom (DoF) [1, 2]. The free surface approximation proposed by Schillaci et al. [3] is adopted to simulate the water movement independently from the air effect, in order to obtain a more stable and efficient calculation. Fluids and Body motion are coupled by means of a semi-explicit coupling. In this short paper we propose a validation case, consisting in the free-decay analysis of the single point absorber studied by Devolder et al. [4]. Hence, the case of the WEC device subjected to progressive waves is briefly presented.

2. Numerical framework

The movement of the Newtonian incompressible fluids analyzed is described by the classic Navier-Stokes equations, expressing mass and momentum conservation equations in the

divergence form

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

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla \cdot (\rho\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot [\mu(\nabla\mathbf{u} + \nabla^{\mathsf{T}}\mathbf{u})] + \rho\mathbf{g}, \tag{2}$$

where $\mathbf{u}$ and p represent velocity and pressure, $\rho\mathbf{g}$ accounts for the gravitational acceleration. No surface tension effect is considered. The discrete solution is obtained by applying a fractional step projection method together with an explicit time integration. A single-phase scheme is employed, aimed at optimizing the solution of free-surface problems on 3-D unstructured meshes [3, 2]. The physical properties, namely, density ρ, and dynamic viscosity μ, are calculated as function of the phase-volume fraction $\phi(\mathbf{x}, t)$ as: $\rho = \sum_k \phi(\mathbf{x}, t)\rho_k$ and $\mu = \sum_k \phi(\mathbf{x}, t)\mu_k$. The scalar field $\phi(\mathbf{x}, t)$, indicating the presence of phase k, is a regularized distance function, represented by means of a Conservative Level-Set (CLS) method. In detail, this work uses the CLS scheme implemented and verified in [5]. The movement of $\phi(\mathbf{x}, t)$ is described by an advection equation, while, as characteristics of CLS methods, the CLS function is re-initialized at every time step, in order to maintain a constant interface width. The solid presence within the flow is represented by means of a second-order direct forcing Immersed Boundary Method (IBM), described in detail by [1] and already introduced in free-surface simulations in [2]. The IBM method introduces a specific treatment of the Navier-Stokes equations at the interface between solid and fluids. In particular, we consider the following NS equation in discrete form

$$\frac{\mathbf{u}^p - \mathbf{u}^n}{\Delta t} = \mathrm{RHS}^n + \vec{f} \qquad \vec{f} = \frac{U_s - \mathbf{u}^p}{\Delta t} - \mathrm{RHS}^n \tag{3}$$

where RHS includes convective, diffusive and source terms and $\vec{f}$ is an additional source term used to consider the effects of the solid motion on the fluid. The forcing term is evaluated as function of U_s, which is calculated iteratively during the fluid-structure coupling routine in the nodes interiors to the solid body or must follow a particular second-order interpolation [6] for the forcing points that coincide with the interface between solid and fluids.

2.1. Rigid-Body Motion

The rigid motion of the bodies considered in this work responds to the classic Newton's conservation equation in a general 6 DoF system. The conservation of forces and torque, whose resolution yields the vector position, $\mathbf{x}$, and the rotation angle, θ, scalar fields, is expressed in the following differential form

$$m\frac{\partial^2\mathbf{x}}{\partial t^2} + C_{\mathbf{x}}\frac{\partial\mathbf{x}}{\partial t} = \mathbf{F_b} + \mathbf{F_p}, \qquad I\frac{\partial^2\theta}{\partial t^2} + C_{\theta}\frac{\partial\theta}{\partial t} = \mathbf{M_b} + \mathbf{M_p}, \tag{4}$$

where m is the mass of the object, $C_{\mathbf{x}}$ is the displacement damping coefficient, $\mathbf{F_b}$ are the body forces and $\mathbf{F_f}$ are the pressure and viscous forces exerted on –or by the surrounding fluid. On a discrete basis, $\mathbf{F_f}$ is evaluated by integrating it over the control volumes and applying the divergence theorem. Hence, it can be expressed as the sum of faces contributions in the following form

$$\mathbf{F_f} = \mathbf{F_p} + \mathbf{F_v} = \sum_{f \in F(b)} S_f p_f \mathbf{n} + \sum_{f \in F(b)} S_f \mu_f (\nabla\mathbf{v} - (\nabla\mathbf{v} \cdot \mathbf{n}) \cdot \mathbf{n})_f, \tag{5}$$

where $F(b)$ is the complex of faces delimiting the body contour, the subscript f refer to the face quantities, S is the face surface and $\mathbf{n}$ is the normal vector to the body surface. In the torque equation, I expresses the rotational inertia of the object, C_{θ} is the rotational damping coefficient, $\mathbf{M_b}$ are momentum torques due to the body mass and $\mathbf{M_f}$ are the torques due to pressure and viscous forces of the surrounding fluid. Similar to the previous case, $\mathbf{M_f}$ is evaluated as follows

$$\mathbf{M_f} = \mathbf{M_p} + \mathbf{M_v} = \sum_{f \in F(b)} S_f p_f \mathbf{r} \cdot \mathbf{n} + \sum_{f \in F(b)} S_f \mu_f \mathbf{r} \cdot (\nabla\mathbf{v} - (\nabla\mathbf{v} \cdot \mathbf{n}) \cdot \mathbf{n})_f, \tag{6}$$
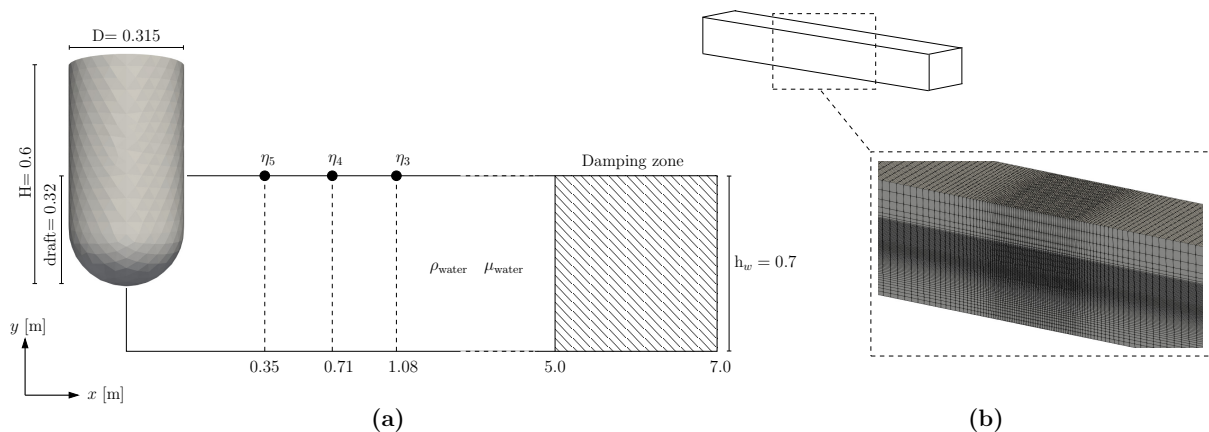
Figure 1. WEC Free-Decay: domain description and mesh.

where $\mathbf{r}$ is the vector connecting the body mass center to the contour point. A semi-explicit advancement of NS equations is employed to solve the solid-fluid interaction, together with a relaxation method which fastens the convergence of the algorithm. A particular treatment of the pressure at the solid-fluid interface is employed in order to exactly conserve the mass of the different phases.
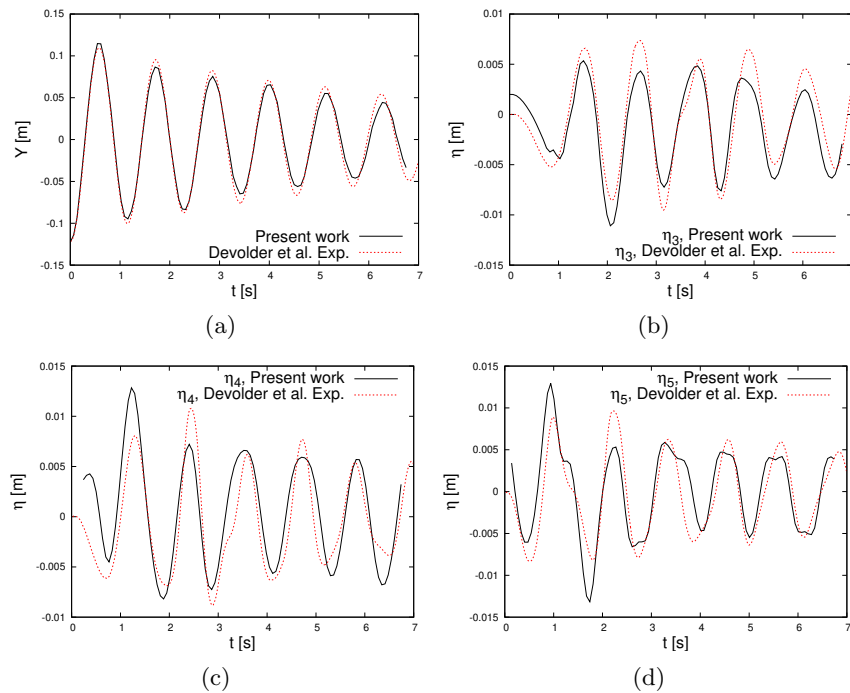
3. WEC free-decay

This case consists in evaluating the oscillatory movement of a WEC device dropped on a liquid surface, with a single degree of freedom in the vertical direction. The case is designed to reproduce the experimental test produced by Devolder et al. [4], in which the device was left to slide along a vertical bar with an initial displacement $h = -0.124$ m. The domain has a size of $14 \times 2 \times 2$ m while the device has the dimensions shown in Fig. 1(a). Viscous damping zones are imposed on the domain ends to dissipate superficial waves generated by the wave fluctuation. The mesh used has a hyperbolic distribution with higher nodes density in proximity of the WEC zone and accounts for 600k elements, departed on 64 CPUs for simulations. A sketch is reported in Fig. 1(b). The results presented consist in the vertical displacement of the buoy, which shows a good agreement with the experimental data (Fig. 2(a)), and in the height of the waves, measured in various points of the domain. In this case, the agreement is more qualitative than quantitative, still representing an acceptable result, Figs. 2(b)-(d).
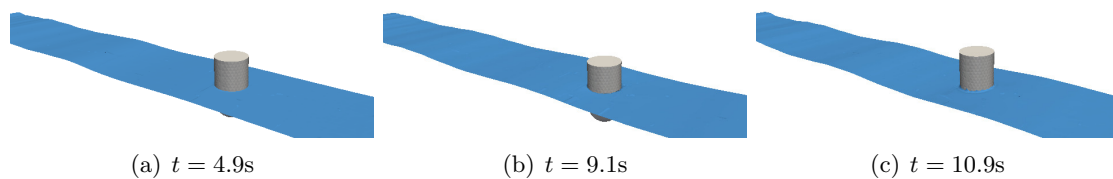
4. WEC subjected to progressive waves

In this case, the WEC device is subjected to the action of progressive waves coming from the left end of the domain. The waves are generated through a wave maker, which consists in imposing an analytical function within the numerical solver. The analytical forcing function that imposes the wave elevation is a sinusoidal function that produces progressive waves, identified by the wavelength λ and the amplitude a, where wave frequency and period are correlated according to the dispersion relation: $\tau = \sqrt{(2\pi\lambda(\rho_a D_a + \rho_w D_w))/((\rho_w - \rho_a)g)}$ with $D_w = 1/\tanh\left(\frac{2\pi h_w}{\lambda}\right)$ $D_a = 1/\tanh\left(\frac{2\pi h_a}{\lambda}\right)$. On the right end of the domain, a viscous damping zone is again set. Screenshots reported in Fig. 3 show the buoy evolution when subjected to progressive waves characterized by $\lambda = 1.982$ m, $\tau = 1.14$ s and $a = 0.02$ m, as an example of numerical output obtainable for this kind of cases.

5. Conclusions and future work

In this work we have presented briefly a numerical framework to carry out simulations of free-surface phenomena with mutual interactions between the liquid phase and a floating object. In order to show a possible industrial application of this method, we have presented the study of a wave energy converter, in particular, a single point absorber which extracts energy from the sea waves. The method is validated by analyzing the WEC free-decay and comparing the

Figure 2. WEC Free-Decay: WEC vertical position (Y) during free-decay and free-surface elevation at point probes (η_3, η_4, η_5). Comparison to experimental data by Devolder et al.[4].

(a) $t = 4.9$s   (b) $t = 9.1$s   (c) $t = 10.9$s

Figure 3. WEC subjected to regular waves: (b) waves reach WEC, (c) WEC device lowest point, (d) WEC highest point.

results to experimental data obtained by Devolder et al. [4]. The possibility of studying the device response to progressive waves is also presented. In the extended version of this work, the coupling FSI algorithm will be presented in detail, together with more validation cases.

Acknowledgments

References

[1] Favre F, Antepara O, Oliet C, Lehmkuhl O and Perez-S C D 2019 *Applied Thermal Engineering* **148** 907–928
[2] Schillaci E, Favre F, Antepara O and Balcázar N 2018 *Int. J. Comp. Meth. and Exp. Meas.,* **6** 98–109
[3] Schillaci E, Jofre L, Balcázar N, Lehmkuhl O and Oliva A 2016 *Computers & Fluids* **140** 97–110
[4] Devolder B, Rauwoens P and Troch P *Progress in Renewable Energies Offshore Guedes Soares (Ed.)* 197–205
[5] Balcázar N, Jofre L, Lehmkuhl O, Castro J and Rigola J 2014 *Int. J. Multiphas. Flow* **64** 55–72
[6] Fadlun E, Verzicco R, Orlandi P and Mohd-Yusof J 2000 *Journal of computational physics* **161** 35–60