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Numerical study of a Wave Energy Converter located in front of a vertical breakwater.

Tournant[a] P, Perret[a] G., Neuvéglise[a] S., Marin[a] F., Smaoui[b] H. and Sergent[b] P.

***Abstract*—We consider the numerical modelling of a quayside WEC (*Wave Energy Converter*) using OpenFOAM. The numerical model uses sliding interfaces with moving mesh and waveFoam's method to generate and absorb wave reflection. Water overtoppings over the wall and RAO (Ratio Amplitude Response) results are investigated. The influence of clearence distance and the buoy draft is studied. The numerical model is validated by comparing the results with experimental data and analytical results using a linear potential model. We observed a good correlation between experimental and numerical results. Overtoppings decrease and RAO values increase when the clearance distance is decreased.**

***Index Terms*—CFD, OpenFOAM, vertical wall, Wave Energy Converter,**

I. Introduction

DUE to global warming, renewable energy technologies present a very active research sector. Unlike wind turbine, wave energy converters are dependent on the desired location. A system at deep water, will be very different from a nearshore system.

Nearshore systems present the advantages to reduce OPEX (Operational Expenditure) by reducing maintenance and grid connection costs. In addition, quayside systems benefit from waves reflection on the vertical breakwater.

The influence of a vertical wall on floating systems was first studied analytically in different configurations using a linear potential model. Such model was first developed by Mc Iver and Evans [1] to study the impact of additional vertical walls on energy devices performance. Hsu and Wu [2] showed that hydrodynamics coefficients of a heaving buoy were strongly modified by the presence of the wall. His model was completed by Zheng *et. al.* [3]. Still using linear potential model, Elchahal *et. al.* [4] studied the clearance distance influence on the RAO (*Response Amplitude Ratio*) of a rectangular floating breakwater in front of a harbour. Bhattacharjee and Guedes Soares [5] added a bottom topography. WEC efficiency and the CWR (*Capture Width Ratio*) increase were studied for circular floating buoy [6]. A detailed study of a rectangular floater in front of a vertical wall has been recently performed analytically by Zhang *et. al.* [7].

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Those results were compared with experimental and numerical studies. The ability to study WEC performance using OpenFOAM is investigated in many research [8]. There are some dynamic mesh methods to move the buoy [9]. Numerically modeling of a rectangular buoy in front of a vertical wall with sloping bottom topography has been performed using OpenFoam by Gao *et. al.* [10]. They have shown that for all frequencies tested, maximal vertical wave force in the gap decreases when the topography slope increases. Neuvéglise *et. al.* showed that analytical model were not valid for large draft or short clearance distances [11]. Moreover, quayside heaving buoy were experimentally showed to reduce overtopping for regular waves [12]. The ability of OpenFOAM to characterize overtoppings has been studied and validated by Chen et al. [13].

In the present study, we consider the behaviour of a rectangular heaving buoy in front of a rectangular wall. RAO results are compared with the analytical potential model developed by [3]. The impact of the floater on overtopping is highlighted for regular and irregular waves. Experimental and numerical modelling are performed. Numerical results are carried out by OpenFOAM.

II. Experimental set-up

The numerical model has been validated by comparing the results with experimental data for one configuration described below. Experimental measurements have been performed in LOMC wave flume (*Laboratory of waves and complex media*) of Le Havre Normandie University. The wave flume dimensions are 35m long, 1.2m high and 0.9 wide (Fig. 1).

The floater oscillates along two vertical spikes to en-

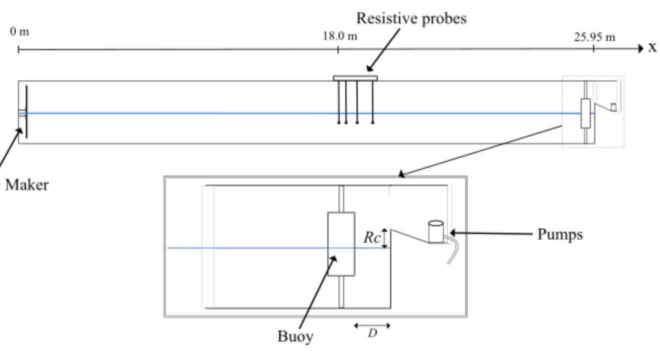

Fig. 1. Scheme of the wave flume used in this study.

sure only a heave motion. Draft, total height and width of the buoy are respectively $\Gamma = 0.25m$, $H_f = 0.4m$, $L = 0.1m$ and the clearance distance, *i.e.* the distance between the floater and the vertical breakwater, is $D = 0.01m$. The water depth is fixed at $h = 0.63m$. The distance between the free surface and the top of the vertical breakwater is $Rc = 0.07m$. Overtoppings are collected in a tank behind the vertical wall. They are measured by two pumps with volume counters. The measured water volume are rejected in the flume, to ensure a constant mean water level. Irregular and regular waves have been tested. A JONSWAP spectrum is considered with a peak enhancement factor $\gamma = 3.3$ for irregular waves. The wave height is fixed to $H_i = 0.1m$ for regular wave and the significant wave height to $H_s = 0.1m$ for irregular waves. The periods are varied between $1.15s$ and $3.5s$ for regular waves, like peak periods for irregular waves. Reflected waves are absorbed by the paddle. ore details on the experimental set-up can be found in Neuvéglise *et. al.* [11].

III. Numerical model

A. Governing equations

Numerical modelling is performed using OpenFoam software. InterFoam solver is used to solve two-phase fluid, incompressible and inviscid. Mass and momentum equations are formulated as:

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_i} - g_i x_i \frac{\partial \rho}{\partial x_j} + \mu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (2)$$

Where p, u_i and g_i represent the dynamic pressure, the velocity, and the gravity acceleration, in air and water phases. These equations are solved in both phases. To solve them in the whole domain, we use VoF method (*Volume of fluid*) which consists in introducing a scalar quantity α characterizing the mass fraction, $\alpha = 1$ corresponding to water and $\alpha = 0$ to air phase. Density ρ and dynamic viscosity μ are defined by 3 and 4.

$$\rho = \alpha \rho_{water} + (1-\alpha)\rho_{air} \quad (3)$$

$$\mu = \alpha \mu_{water} + (1-\alpha)\mu_{air} \quad (4)$$

An other equation is added to characterize scalar α advection in 5.

$$\frac{\partial \alpha}{\partial t} + \frac{\partial \alpha u_i}{\partial x_i} + \frac{\partial \alpha(1-\alpha)u_{ir}}{\partial x_i} = 0 \quad (5)$$

The $\frac{\partial \alpha(1-\alpha)u_{ir}}{\partial x_i}$ term allows to artificially compress the interface. The interface is defined as $\alpha = 0.5$. Turbulence model $k - \epsilon$ SST is used [14].

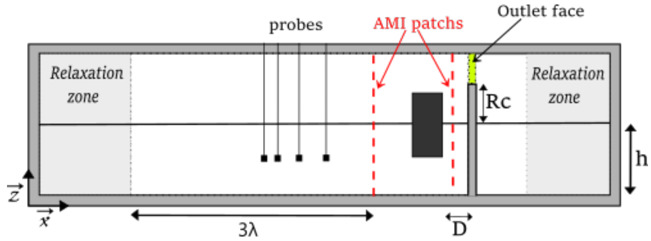

Fig. 2. Domain dimensions and configuration.

B. Numerical configuration

Waves are generated in waveFoam relaxation zone which is added to the domain. This zone enables to properly absorb wave reflection and avoid re-reflection [15]. The numerical domain is bi-dimensional (Fig. 2).

The buoy is rectangular, moving only in heave motion. The relaxation zone lengths are set to 2λ and the flume length to 3λ, where λ is the wave length.

Regular and irregular waves are modeled. Stokes model at first order is used for regular waves. A JONSWAP spectrum with $\gamma = 3.3$ is chosen for irregular waves. The incident and reflected wave amplitude is measured according to Mansard & Funke method [16]. Sampling is defined so as to respect the Shannon condition. Overtoppings are determined with the temporal evolution of the mass flux through the outlet face.

C. Mesh

The mesh is realized with *blockMesh* and *snappyHexMesh*, implemented in OpenFOAM to generate and refine mesh.

The sliding interfaces method was chosen to model buoy motion. This method has the advantage of being less expensive in time than mesh morphing or overset mesh. Moreover, when the gap is small ($D \leq 0.01m$), the mesh morphing strongly deforms the cells in the gap and does not allow to model important buoy displacements. Use of overset mesh is also difficult for small gaps. Sliding interfaces is thus a good option for one degree of freedom systems in front of structure.

However there are currently parallelisation problems with this method in OpenFOAM. Cells addition and suppression do not work well in several cases. The mesh definition is one of the biggest challenge.

D. Convergence

The size of the optimal cells is studied according to the GCI (Grid Convergence Method) method presented by Celik [17]. This method permits to estimate discretization error by comparing results of three different meshes, if the ratio between the characteristic cell size is more than 1.3. According to Fig. 3, the optimal mesh obtained with this convergence method is mesh $\#4$ corresponding to 100k cells. Region around buoy contains the smallest cells with a size of 1.6 mm.

Meshes	1	2	3	4	5	6
Minimal cell size [mm]	0.5	0.7	1.1	1.6	2.2	3.1

TABLE I
MESH SIZES TESTED

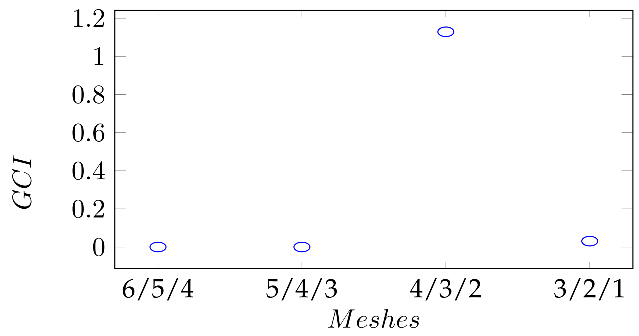

Fig. 3. GCI values for different meshes applied to the buoy amplitude.

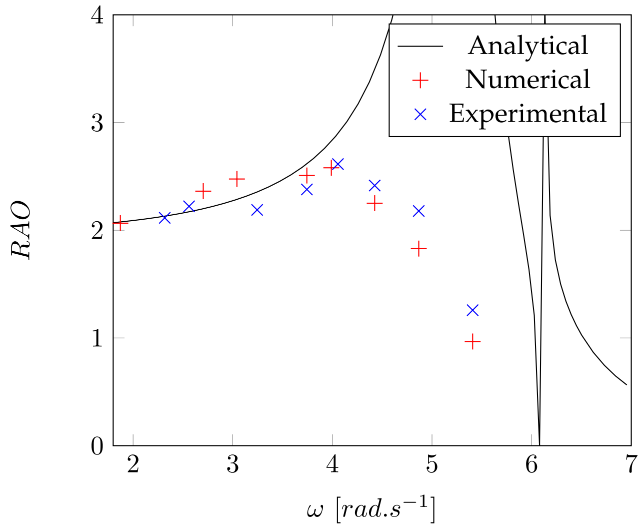

Fig. 4. Ratio Amplitude Operator : comparison between experimental, analytical, and numerical results

IV. NUMERICAL VALIDATION

In order to validate the numerical model, the RAO is compared with experimental results. The buoy amplitude is normalized by the incident wave amplitude in Fig. 4. Both numerical and experimental results are in good agreement. Relative maximum deviation is 23%. Results are also compared with linear potential model based on Haskind decomposition [3]. However, as previously observed by Neuvéglise [11], physical and numerical results are far from the linear potential model. Indeed, damping and nonlinear phenomena are not taken into account in such model.

V. OVERTOPPINGS

Numerical overtopping $\mathcal{V}_N$ are obtained using Eq. 6. We calculated the mass flow Q_m that crosses outlet face with Eq. 7. Mass flux is directly determined by waveFoam solver. The time step is $\Delta t = 10ms$. S_{outlet} is the outlet face surface.

$$\mathcal{V}_N = \frac{1}{\rho}\sum_{t=0}^{t_f} Q_m \Delta t \qquad (6)$$

$$Q_m = \int_{S_{outlet}} \rho\phi \, \mathrm{d}S \qquad (7)$$

For each tested condition, numerical simulations are performed with and without the floater in order to calculate the overtopping ratio $\Delta\mathcal{V}_N = \mathcal{V}_{N_{withbuoy}}/\mathcal{V}_{N_{withoutbuoy}}$.

In addition to numerical overtopping, overtopping is estimated using the EuroTop manual [18] equation for a vertical sea wall without buoy (Eq. 9). The same equation is used with the buoy where the incident wave height H_i is replaced by the wave height in the gap $H^{(1)}/2$. The correction performed by S. Neuvéglise et al. [12] to take into account the dissipation in the gap between the floater and the vertical breakwater, is used.

$$\mathcal{V}_{A_{with\ buoy}} = 0.054 \cdot exp\left[-\left(2.12\frac{R_C}{\frac{H^{(1)}}{2}}\right)^{1.3}\right]\cdot\sqrt{g\left(\frac{H^{(1)}}{2}\right)^3} \qquad (8)$$

$$\mathcal{V}_{A_{without\ buoy}} = 0.054 \cdot exp\left[-\left(2.12\frac{R_C}{H_i}\right)^{1.3}\right]\cdot\sqrt{gH_i^3} \qquad (9)$$

Where $\frac{H^{(1)}}{2}$ represents wave height in the gap and H_i the incident wave height. The overtopping ratio is then defined as:

$$\Delta\mathcal{V}_A = \frac{\mathcal{V}_{A_{withbuoy}}}{\mathcal{V}_{A_{withoutbuoy}}}\cdot F_{corr} \qquad (10)$$

Where F_{corr} is a correcting factor defined by the buoy parameters to take into consideration the pressure drop due to viscous effects in the gap, characterised by the friction coefficient Λ.

$$F_{corr} = 1 - \Lambda\frac{R_C + \Gamma}{D} \qquad (11)$$

Thus, overtopping ratio is equal to one without buoy.

Overtopping results are presented in Fig. 5 and 6 for regular and irregular waves. For regular waves, Neuveglise *et. al.* [12] showed that overtoppings strongly increase close to the resonance. This result is confirmed by numerical simulations for large clearance distance, *i.e.* $R_c/D = 0.7$ although overtopping increase is smaller than experimental ones. For a small one, $R_c/D = 7$, overtopping ratio measured numerically is decreased for all sea-states. The same result is observed for irregular waves: overtopping ratio is reduced for a small clearance distance, *i.e.* when the floater is close to the wall. Indeed, dissipation in the gap increases as the clearance distance decreases leading to a decrease of overtopping in these cases.

VI. EXTREME CONDITION

To study the clearance distance influence on the RAO, two different buoys are tested experimentally in regular and irregular waves for one extreme condition. Buoys have two different drafts, $\Gamma = 0.08m$

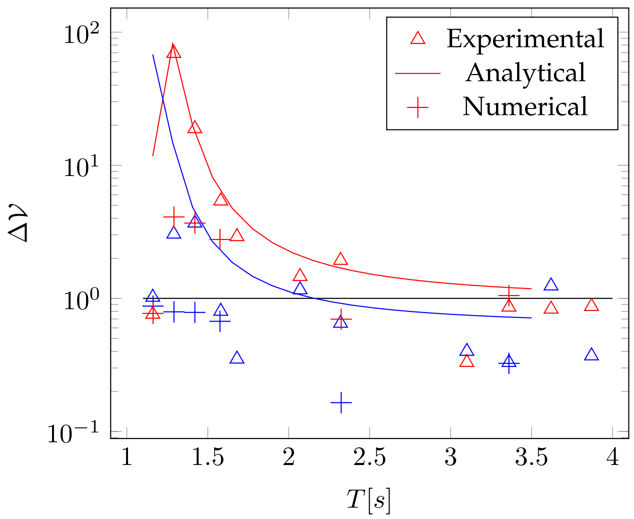

Fig. 5. Overtoppings for regular waves. Full line represents the analytical model. Red markers represent results for $Rc/D = 0.7$ and blue for $Rc/D = 7$. The horizontal black line indicates the value of the overtopping ratio without buoy

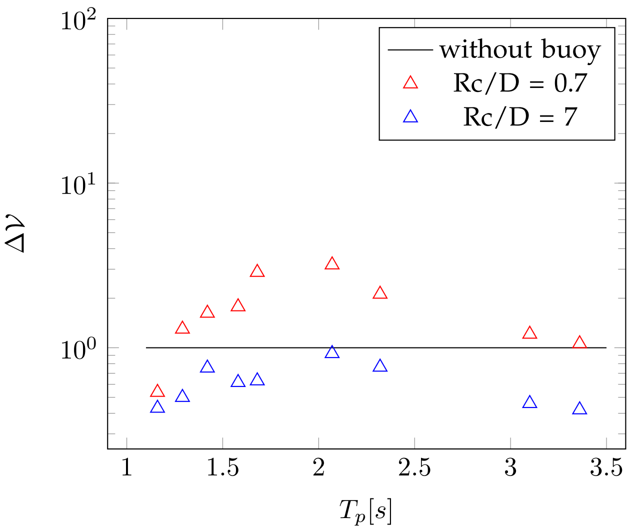

Fig. 6. Overtopping ratio measured experimentally in irregular waves.

and $\Gamma = 0.125m$. The buoys' width remains constant at $L = 0.1m$. The sea states parameters are $h = 0.65m$ and $H_s = 0.175m$. For regular waves, the wave period is $T = 1.79\,s$. A JONSWAP spectrum is used for irregular wave with $T_p = 1.79s$ and $\gamma = 3.3$.

The floater amplitude for irregular waves is determined similarly to the significant wave height using the 0th order moment m_0 defined in Eq. 12 where $S_f(\omega)$ represent the amplitude spectrum of the buoy and a_f the buoy amplitude.

$$m_0 = \int_0^\infty S_f(\omega)d\omega \qquad (12)$$

$$a_f = 2\sqrt{m_0} \qquad (13)$$

RAO results are presented in Fig. 7. The RAO values are more important in irregular waves than regular waves. However, when the clearance distance D decreases, RAO increases in regular and irregular waves for both tested buoys.

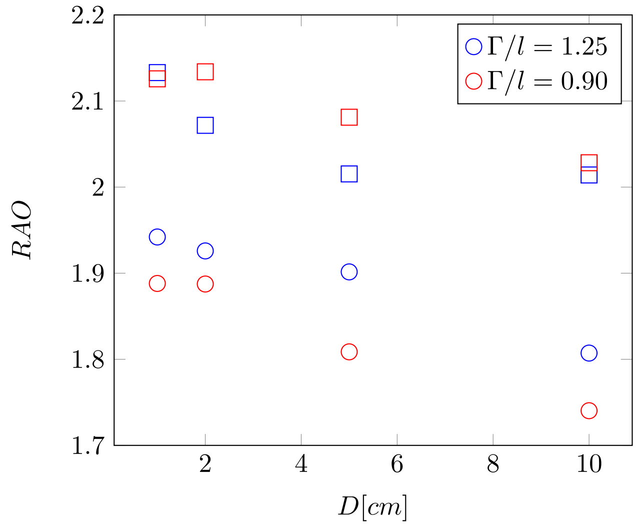

Fig. 7. Influence of the clearance distance on RAO for regular waves (○) and irregular waves (□).

VII. Conclusion

The present model carried out with OpenFOAM allows us to study the behavior of a buoy located in front of a vertical wall. Overtopping ratio and RAO obtained numerically have been compared with experimental results. Both approaches show a good agreement. It is shown that a small clearance distance increases RAO and minimizes overtopping in regular and irregular waves.

A quayside device may have two main functions, recovering energy and protecting the vertical breakwater by reducing overtopping. Reducing the clearance distance provides better results for both device functions. In a future study, we will study the effort applied on the structures and estimate the amount of water volume crossing for different buoy shapes. A modeled PTO will be added to the experimental set-up and numerical model. The objective is to optimize the shape of the float to increase the production of electrical energy with a PTO, minimize overtopping and reduce the manufacturing cost, mainly depending on the shape of the main body.

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