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Vyzikas, T

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Numerical study of fixed Oscillating Water Column with RANS-type two-phase CFD model

Thomas Vyzikas^{a,1}, Samy Deshoulières^b, Olivier Giroux^c, Matthew Barton^a,
Deborah Greaves^a

^a *University of Plymouth, School of Marine Science and Engineering, Drake Circus,
PL48AA Plymouth, UK*

^b *Ecole Centrale de Marseille, 38 Rue Frédéric Joliot Curie, 13013 Marseille, France*

^c *Ecole nationale supérieure des mines de Nantes, 4 Rue Alfred Kastler, 44300 Nantes,
France*

Abstract

Various studies investigated the behaviour and the performance of Oscillating Water Columns (OWCs) suggesting many alternative design concepts to improve the efficiency of the device. The OWCs examined here are fixed on the seabed and have a slit opening at the seaward side. The present study investigates the applicability of a multiphase Reynolds Averaged Navier-Stokes (RANS) numerical model for simulating the interaction between an OWC and regular and irregular waves. An initial validation of the open-source computational fluid dynamics (CFD) software package OpenFOAM with the wave generation and absorption toolbox waves2Foam is performed against experimental results obtained at the COAST laboratory of the University of Plymouth. The main aim of the study is to complement to the validation of RANS CFD models and later employ the broadly used numerical tool for further studies for better understanding the behaviour of the OWCs. A method based on mechanical damped oscillations for calculating the eigenfrequency of the device from a decay test is presented and compared with the performance curve. The strength of CFD modelling for obtaining better insight to the hydrodynamics of OWCs is also demonstrated.

Keywords: CFD, OWC, validation, OpenFOAM, waves2Foam,

¹Corresponding author, Email address: thomas.vyzikas@plymouth.ac.uk

1. Introduction

Marine renewable energy (MRE) appears to be a viable alternative solution as a carbon-free energy generation method [1], covering a wide range of applications and being able to respond to power demands of remote island communities [2]. Thousands of prototypes have been developed for many decades now for exploiting the energy of the ocean waves, but a consensus to a single economically competitive prototype and reliable is yet to be reached [3].

The best-studied and most successful WEC concept seems to be the OWC technology, which has reached the stage of deploying full scale prototypes in open sea conditions [4] [5]. Floating OWC devices were commercialised in Japan in 1965 and more recently a 1:4th-scale buoy converter was deployed in Ireland [6]. Fixed OWC devices are commonly deployed near the shore in shallow water, where lower wave energy than offshore is available, due to the energy dissipation caused by the bottom friction and wave breaking [7]. This, however, can be mitigated if areas where wave energy is locally focused due to topography are chosen [8]. Nevertheless, near-shore OWCs are not exposed to harsh open-ocean wave conditions and they can be better monitored and maintained, which increases their survivability. Moreover, OWCs embedded in breakwaters or piers can have a dual functionality of energy generation and coastal protection [9], which increases the chances for investing in these projects.

In the present study, a conventional fixed OWC is used as a fundamental model for validating a numerical code. The classic design for OWCs embedded in breakwaters consists of a partially submerged hollow structure which incorporates a water column and an overlying air chamber. The front wall has an opening that allows interaction of the water column with the incident waves. The oscillation of the water inside the chamber of the OWC causes motion of the air, which is forced to pass through a bi-directional air turbine usually placed in a duct on the top of the structure. The turbine is the power take-off (PTO)

29 mechanism used to transform the pneumatic energy into mechanical energy and
30 afterwards to electricity with the use of a generator.

31 The numerical modelling of OWCs ranges from frequency-domain models
32 [10] [11] to time-domain 1D models [12] or more complicated potential flow
33 models employing Boundary Element Methods (BEM) [13] and high order BEM
34 combined with Eulerian-Lagrangian techniques [14]. A review of the different
35 numerical modelling techniques for OWC is available in [15].

36 The most advanced category of numerical models refers to CFD Navier-
37 Stokes codes, which have high computational cost, but can achieve high ac-
38 curacy when examining fully nonlinear problems [16]. Nowadays, increasing
39 processing power make these codes applicable for practical engineering prob-
40 lems. Regarding the CFD modelling of OWCs, Teixeira et al. [17] used the
41 RANS model Fluinco with an aerodynamic model and compared the results
42 with the commercial code Fluent. López et al. [18] examined different damp-
43 ing coefficients of the PTO with the RANS numerical model STAR-CCM+. A
44 similar study was performed in REFF3D [19]. ANSYS-ICEMCFD & CFX was
45 employed to examine the effect that geometric changes have on the performance
46 of the OWC [20]. A recent study validated OpenFOAM and IHFOAM [21] for
47 a fixed detached OWC device [22]. A similar detached OWC was simulated in
48 OpenFOAM testing different turbulence models and using boundary conditions
49 from waves2Foam and a piston-type wave maker [23].

50 Realising the insight into the behaviour and hydrodynamic characteristics
51 of a WEC that CFD modelling can provide, the present study aims to vali-
52 date the open-source robust CFD code OpenFOAM with the wave generation
53 toolbox waves2Foam [24] for the wave-OWC interaction problem against exper-
54 imental results produced for this scope [25]. The OWC is examined in regular
55 and irregular wave conditions with and without PTO, herein also mentioned
56 as “lid-on” and “lid-off” OWCs, essentially testing an absorbing sea wall. The
57 validation process of the present study is complementary to previous studies
58 [18] [19] [22] that used similar solvers and examined a wider range of wave con-
59 ditions. Here, the most challenging part was the high damping of the PTO.

60 The well-validated numerical wave tank (NWT) was used in the second part
61 of the work for additional investigations, such as the sloshing in the chamber
62 of the OWC and the reflection coefficients of the OWCs. Moreover, numerical
63 results are used to draw the performance curve of the OWC and to shed light
64 in the hydrodynamic and aerodynamic behaviour of the device. A time domain
65 method for calculating the natural frequency of the OWC via a decay test is
66 also demonstrated.

67 **2. Materials and methods**

68 *2.1. Description of the solvers*

69 OpenFOAM (Open source Field Operation and Manipulation) is an open-
70 source and freely available CFD package comprising a large set of C++ libraries.
71 The programming in OpenFOAM is efficient thanks to the mimicking of the form
72 of the partial differential equations (PDEs) in the code and to the modularity
73 of the object oriented language [26].

74 Regarding fluid flows, OpenFOAM can handle 3D domains solving multi-
75 phase flows with several approaches of solving the Navier-Stokes equations with
76 several turbulence models [27]. The free-surface flows are resolved with an ad-
77 vanced two-phase flow technique based on the Volume of Fluid (VoF) method
78 [28]. This technique for simulating free surface problems has great capacity
79 in simulating over-turning flows, wave breaking [29] and green water effects.
80 However, it might suffer from diffusion if the mesh resolution is too low.

81 In this study, the RANS set of equations was used with a $k - \epsilon$ turbulence
82 model. The standard values of the parameters of the $k - \epsilon$ turbulence model
83 were used: $C_\mu = 0.09$, $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.92$ and $\sigma_\epsilon = 1.30$ [30]. The standard
84 $k - \epsilon$ turbulence model was also used by López et al. [18] in a similar study,
85 while [19] and [22] employed a $k - \omega$ and a $k - \omega - SST$, respectively.
86 The two-equation turbulence closure models have similar range of applicability,
87 with $k - \omega$ being more appropriate for adverse pressure gradient problems.
88 A wide variety of turbulence models is readily available in OpenFOAM for more

89 specific studies [30]. The two fluids are considered incompressible and immisci-
 90 ble. The assumption of compressibility holds since the flow is below the subsonic
 91 limit, where compressibility effects become important [31]. This is confirmed
 92 by the results where the maximum air velocity encountered locally is about 35
 93 m/s, which gives a maximum ratio of flow velocity over Mach number equal to
 94 0.1. The governing equations are solved simultaneously for the two fluids and
 95 they can be written as a set of mass conservation equation (Equation 1) and
 96 momentum conservation equations (Equation 2) [21],.

$$\nabla \mathbf{U} = 0, \quad (1)$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) - \nabla \cdot (\mu_{eff} \nabla \mathbf{U}) = -\nabla p^* - g \cdot \mathbf{X} \nabla \rho + \nabla \mathbf{U} \cdot \nabla \mu_{eff} + \sigma \kappa_c \nabla \alpha_i \quad (2)$$

97 Here, \mathbf{U} is the velocity vector, ρ is the density, p^* the pseudo-dynamic pressure,
 98 \mathbf{X} the position vector, σ the surface tension coefficient, which is taken equal to
 99 zero, κ_c the curvature of the interface, α_i the fluid phase fraction and μ_{eff} the
 100 efficient dynamic viscosity. $\mu_{eff} = \mu + \mu_t$, with μ being the molecular dynamic
 101 viscosity ($10^{-3} m^2/s$ and $1.4810^{-5} m^2/s$ for water and air, respectively) and μ_t
 102 is the turbulent viscosity given by the turbulence model; here, $\mu_t = \rho C_\mu \frac{\kappa^2}{\epsilon}$ [31].

103 The most commonly used solver for multiphase incompressible flows supplied
 104 in OpenFOAM is “interFoam”. The pressure-velocity coupling is achieved with
 105 the use of the PIMPLE algorithm, which is a combination of SIMPLE and PISO
 106 algorithms [31] [30]. In the simulations presented in this paper, PIMPLE was
 107 operating in PISO mode.

108 The time step in the simulations is adjustable and controlled by the Courant
 109 number (C_o) ensuring numerical stability [32]. For the case of multiphase flows,
 110 OpenFOAM has an additional time-step controller, called “alphaCo”, which
 111 refers to the Courant number around the interface of the two fluids. The time-
 112 step is the minimum calculated by C_o and “alphaCo”. This feature can improve
 113 the computational efficiency of the simulation without reducing the accuracy of
 114 resolving the free water surface.

115 Regarding the numerical schemes for the discretization of the PDEs, the
116 “Euler” first order, bounded, implicit time scheme was used for the time in-
117 tegration and “Gauss linear corrected” second-order, unbounded, conservative
118 scheme for the Laplacian terms scheme. The gradient terms were discretized
119 with second order Gaussian integration.

120 *2.2. Wave generation and absorption in OpenFOAM*

121 The simulation of waves requires special boundary conditions for wave gen-
122 eration and absorption. The most commonly used libraries in OpenFOAM
123 for coastal and ocean engineering studies are waves2Foam [24] and IHFOAM
124 [21]. Both the libraries are based on the “interFoam” solver and they offer a
125 wide variety of pre- and post-processing tools for the simulation of waves. The
126 main difference between the two is that waves2Foam employs a passive wave
127 absorption method, while IHFOAM has an active correction method to absorb
128 reflections on the boundaries.

129 In this study, a second order Stokes wave definition [33] is used in waves2Foam
130 for the regular wave generation, allowing the calculation of the position of the
131 free water surface and the velocity components at the inlet boundary at every
132 time step. For irregular wave generation, waves2Foam offers the option of se-
133 lecting an energy spectrum, based on a theoretical distribution. However, it was
134 preferred to use the so called “combinedWaves” method, which allows greater
135 flexibility. Accordingly, multiple wave components are linearly superimposed
136 on the inlet boundary to form the examined JONSWAP spectrum. A ramp-up
137 time of approximately one wave period was used in order to account for the
138 smooth transition of the waves in still water. This follows the same practice as
139 in the experiments [25].

140 Regarding the absorption of the waves, waves2Foam uses dissipation layers,
141 called relaxation zones. The solution in the relaxation zone is a weighted com-
142 bination of the RANS solution in the domain and the linear solution based on
143 the boundary definition (target). Equation 3 [24] refers to the calculation of a
144 value of any flow variable ϕ in the relaxation zone. The air-phase velocities in

145 the relaxation zone are set to zero.

$$\phi = \alpha_R \phi_{computed} + (1 - \alpha_R) \phi_{target} \quad (3)$$

146 with α_R a weighting factor dependent on location in the relaxation zone.

147 The length of the relaxation zone determines its efficiency. Usually, long
148 relaxation zones provide better absorption, but they also increase the computa-
149 tional cost, while decreasing the effective length of the fully nonlinear domain.
150 Additionally, the relaxation zone has to be sufficiently far from the device in
151 order to allow it to interact freely with the waves.

152 *2.3. Characteristics of the NWT*

153 As the computational cost of CFD simulations is significant, it was decided
154 to use a shorter numerical flume compared to the physical one, which was 28m
155 [25]. The physical flume of the COAST laboratory is equipped with an absorbing
156 piston-type wave paddle and the acquisition of the water level and pressure had
157 a sampling frequency of 128 Hz. The geometric characteristics of the OWC
158 presented here are based on the U-OWC suggested by Boccotti [34]. The NWT
159 was at exactly the same scale as the physical flume, but the OWC was located
160 at 9 m away from the inlet boundary. A schematic of the physical and the
161 numerical wave flume is shown in Figure 1. The OWC occupies the entire
162 width of the flume and it comprises three identical independent chambers, each
163 with an orifice centrally located at the top wall.

164 Since the OWC was located at one end of the NWT, the outlet relaxation
165 zone was omitted. The total length of the domain is related to the minimum
166 required length of the inlet relaxation zone for absorbing the reflected waves
167 adequately. In preliminary tests, it was found that a relaxation zone of 3m
168 can absorb most of the reflected wave energy and it allows enough space in the
169 nonlinear domain for the wave-OWC interaction. It should be noted that the
170 former selection depends on the wavelength of the input wave. According to
171 sensitivity tests on relaxation zones [24], the reflection coefficient of the 3 m

172 relaxation zone and the regular wave used for the validation (see Section 3.1)
 173 is 0.5%. The wavelength of this regular wave was 5.20 m and essentially one
 174 wavelength of fully nonlinear domain was left for the wave-OWC problem. The
 175 computational cost of a longer high-resolution 3D domain was not manageable
 176 and taking into account the good performance of the relaxation zone, that was
 177 considered a good compromise between computational cost and accuracy.

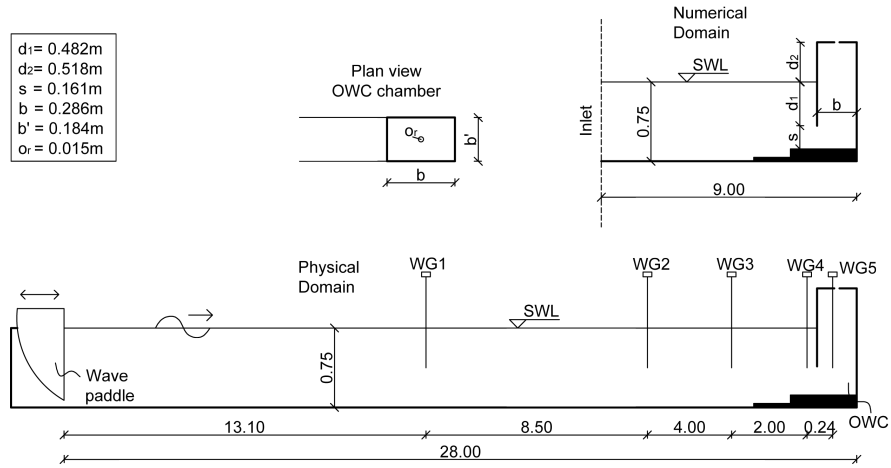


Figure 1: Schematic of the physical and the numerical wave flume, dimensions in (m).

178 The initial computational domain was three-dimensional and it included all
 179 the three chambers of the device. After the preliminary tests, it was decided
 180 to use only the central chamber for the sake of saving computational resources,
 181 since the behaviour of the chambers was similar. This was also justified by the
 182 analysis of the experimental results [25]. The left and right boundaries of the
 183 truncated NWT are treated as frictionless walls.

184 The implementation of the OWC model in the computational domain was
 185 achieved with the utility of OpenFOAM “snappyHexMesh”, which is an al-
 186 gorithm that refines the background computational cells around a predefined
 187 geometry using quadratic refinement. Moreover, “snappyHexMesh” was used
 188 to refine the region around the free surface, so that the interface of the two fluids
 189 is better resolved, and an area at the vicinity of the OWC, where the flow is

190 complex. After examining different parameters of the refinement, it was decided
 191 to use two levels of refinement and six buffer layers, in order to achieve smooth
 192 transition between the layers. Figure 2 shows the resulting computational mesh
 193 in the vicinity of the OWC and the refined region around the free surface. An
 194 extra refinement was applied near the orifice in order to resolve better the fast
 195 air flow through this small opening, which occupies 0.35% of the plan area of
 196 the chamber (Figure 3). This local refinement allowed the 15 mm diameter
 197 circular orifice to be discretized with 6 computational cells in diameter. For
 198 comparison, the orifice opening in other numerical studies was much greater
 199 varying from 2.7% - 14.7% [22], 0.78% - 7.8% [19] and 0.78% - 3.91% [18]. The
 200 induced high damping results in high pressure, which makes the present study
 201 more challenging. For the cases that no PTO was considered, the top-wall of the
 202 OWC was removed and atmospheric pressure was allowed in the OWC. No-slip
 203 and “zeroGradient” boundary conditions are defined on the walls of the OWC
 204 for the velocity and the phase fluid fraction, respectively.

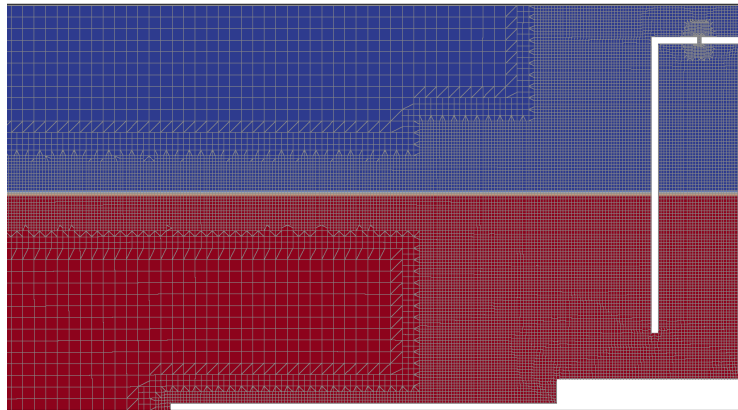


Figure 2: Vertical cross-section of the computational mesh at the vicinity of the OWC, depicting the different regions of refinement. Red and blue colours represent the water and air phase, respectively.

205 On achieving accurate and grid independent numerical simulations, system-

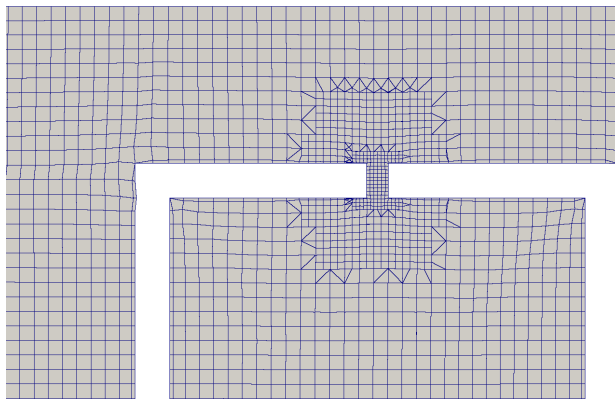


Figure 3: Local refinement of the computational mesh near the orifice of the OWC.

206 atic convergence tests were conducted. Cubic cells were used, since they are rec-
 207 ommended when applying “snappyHexMesh” [27] and because they give more
 208 accurate results for highly distorted interface [24]. Two values for the Courant
 209 number were used: a high value of $C_o = 1$ and a lower value of “alphaCo”.
 210 This allows the water phase to be always very well resolved and it does not
 211 cause a significant decrease of the timestep when high velocities occur at the
 212 orifice. For the cases without the PTO, $\text{alphaCo} = C_o = 0.2$. For the sake of
 213 brevity only three tests close to convergence are presented in Figure 4 for the
 214 time series of the surface elevation inside the chamber that refer to the OWC
 215 without the PTO and are conducted at a preliminary level to select the resolu-
 216 tion of the background mesh. Having selected the background mesh, thorough
 217 convergence was performed separately for the OWC with the PTO, testing the
 218 range of the refined areas, the levels of refinements and the sensitivity to $C_o = 1$
 219 and “alphaCo”. The characteristics of the mesh are presented in Table 1 in the
 220 form of $M \times C$, with M being the cell size of the background mesh in cm and
 221 C the value of “alphaCo”. It can be seen that the highest resolution ($R3$) and
 222 the low resolution cases ($R1$ and $R2$) are very similar with an average error of
 223 2% relative to the wave height, with discrepancies appearing only locally. The
 224 computational cost of $R3$ is almost double than that of $R1$ and $R2$ and Fig-

225 ure 4 does not justify its selection for the scope of the present study. Since the
 226 computational cost of $R1$ and $R2$ was similar, it was decided to use the resolution
 227 with the lower “alphaCo” ($R1$) for preventing any potential discrepancies when
 228 simulating irregular waves. This selection resulted in an 1 million-cell mesh.

	$R1$	$R2$	$R3$
Resolution	4x0.2	4x0.25	3x0.2

Table 1: Characteristics of the background mesh for the convergence tests. Cell size in cm x alphaCo.

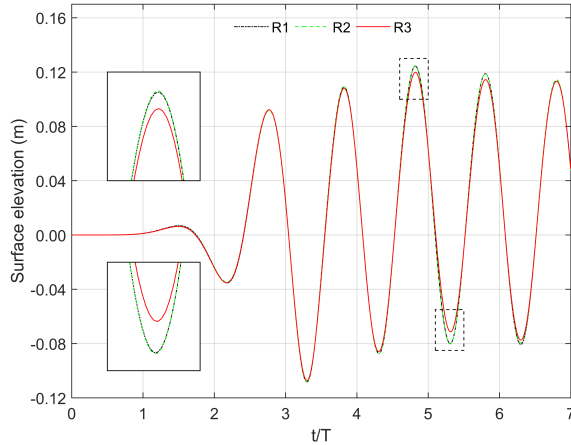


Figure 4: Mesh convergence test for the OWC “lid-off” tested. The time series of the surface elevation are recorded in the central chamber of the OWC.

229 All the numerical tests were simulated in parallel with Intel Xeon E5-2650
 230 processors at 2.6GHz with OpenFOAM 2.1.1. The presence of PTO increases
 231 the computational cost by at least one order of magnitude compared with the
 232 “lid-off” cases that require approximately 100 core-hours for 30 s of simulation.

233 3. Validation

234 For the regular wave, the validation was performed for the timeseries of the
 235 surface elevation inside the OWC and the pressure in the OWC for the cases

236 with the PTO. For the irregular wave, integrated parameters were compared
 237 with the experiment, such as the capture width, the energy density spectra of
 238 the response of the OWC to the incident sea state and reflection coefficient.

239 3.1. Regular wave

240 The wave characteristics used as input to the numerical model were deter-
 241 mined from the experimental results by analysing the recorded surface elevation
 242 in a time window after the ramp-up time of the wave paddle and before the oc-
 243 currence of reflections from the OWC, as seen Figure 5a. In this figure, part of
 244 the experimental surface elevation at WG1 is presented in comparison with the
 245 numerical signal at the inlet boundary. A wave height of $H = 0.088$ m and a
 246 wave period of $T = 2.15$ s was used. This wave was found in experiments to be
 247 close to the resonant frequency of the device and to have similar behaviour in
 248 each of the three chambers [25].

249 The comparison between the experimental and the numerical results inside
 250 the chamber when the PTO is absent is presented in Figure 5b. The frequency
 251 of the oscillation is very well resolved, apart from some minor discrepancies
 252 at the beginning that might be caused from the ramp-up time of the wave
 253 maker. The amplitude of the oscillation is also very well captured, leading to an
 254 almost excellent overall comparison. For quantifying and better evaluating the
 255 comparison between the physical and the numerical results, the mean average
 256 error (MAE) is used, which is calculated according to Equation 4.

$$MAE = \frac{mean(|\eta_{extr}^{exp} - \eta_{extr}^{num}|)}{\alpha^{exp}} \quad (4)$$

257 where η_{extr} refers to the local extrema and α to the wave amplitude, taken
 258 as half of the wave height for simplicity.

259 It was found that for the “lid-off” case the error is 5.7% of the height of the
 260 oscillation, corresponding to 2 mm. This is relatively close to the accuracy of
 261 the repeatability of the physical flume (1 mm) [25]. Considering that, it can
 262 be safely concluded that the numerical model can replicate an OWC without a
 263 PTO with great accuracy.

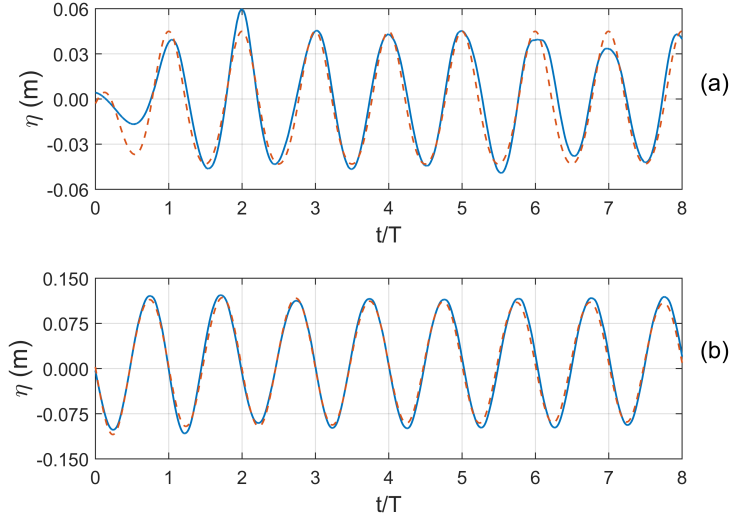


Figure 5: Surface elevation time series upstream of the device (a) and inside the chamber (b) of the model without PTO (- laboratory measurements, - - numerical results).

264 The comparison between the experimental and the numerical results in the
 265 presence of the PTO are shown in Figure 6a for the surface elevation and in
 266 Figure 6b for the air pressure inside the chamber of the OWC. The frequency of
 267 the oscillation is again very well resolved. The surface elevation in the numerical
 268 is also in very good agreement with the physical results, with a MAE of only
 269 6.9%. On the other hand, the pressure shows higher discrepancies than the
 270 surface elevation, which eventually causes a different result in the capture width,
 271 which is increased compared to the physical model from 0.43 to 0.44.

272 The study of the device with a PTO includes additional complications re-
 273 lated to the air phase, which cause the discrepancies in the pressure. Preliminary
 274 studies showed that small fluctuations in the surface elevation can result in sig-
 275 nificant differences in the air pressure. The accurate calculation of the pressure
 276 is challenging for numerical studies and there are commonly discrepancies when
 277 comparing with experiments, as observed in previous works [22] [18] [19]. One
 278 of the possible reasons that causes discrepancies in the surface elevation can be

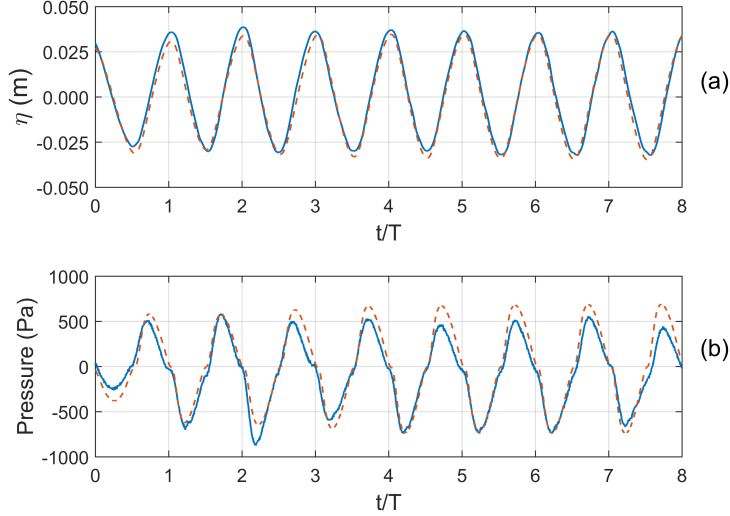


Figure 6: Surface elevation (a) and pressure (b) time series inside the chamber of the model with PTO (- laboratory measurements, - - numerical results).

279 the re-reflected wave from the inlet relaxation zone that effectively increased
 280 the energy of the incident wave as time passes. Evidence for the influence of
 281 the re-reflections can be seen from Figure 6b where the pressure gradually in-
 282 creases with time. Before the appearance re-reflected wave ($t/T < 3$) the MAE
 283 of the pressure is 7.1% of the maximum pressure difference in one period, while
 284 it reaches 14.7% when the re-reflected wave appears. It was observed that when
 285 the length of the inlet relaxation was increased, the reflected wave was better
 286 absorbed, but the computational cost was greatly increased, due to the added
 287 computational cells and the additional equations solved for the target solution
 288 of the flow variables at each cell (see Equation 3).

289 Other reasons that might cause the experimental pressure to be lower than
 290 the numerical predictions might be associated with imperfections in the manu-
 291 facturing of the physical model or with the inherited limitations of the numerical
 292 model. As mentioned in Section 2.1 the model solves the incompressible Navier-
 293 Stokes equations, which is an accurate approximation for the water phase, but

294 it might not be the case for the air phase. The compressibility of the air phase
295 might influence the results especially when rapid pressure fluctuations are en-
296 countered.

297 In recent work with OpenFOAM and IHFOAM, it was also observed that
298 the pressure in the numerical model was slightly over-predicted [22] when RANS
299 equations were solved. On the other hand, when a LES model was used, the nu-
300 merically predicted pressure was closer to the experimentally measured pressure
301 [35]. In other studies, the correlation between the experimental and the numer-
302 ical results is similar to the present study, however the pressure fluctuations
303 were 80 Pa [22], 180 Pa [18], 200 Pa [35] and 900 Pa [19], which are significantly
304 smaller in comparison to 1400 Pa which is observed here. The reason for the
305 high pressure is the high damping induced from the small orifice in combination
306 with the high waves.

307 All in all, the results of Figure 6 demonstrate that the model performs suffi-
308 ciently well when a PTO of high damping is present. This is further supported
309 by the fact that the capture width differs only by 2.3% between the physical and
310 the numerical model (0.43 and 0.44 respectively). However, further validation
311 can be useful to identify the source of the discrepancies in the pressure observed
312 here. Taking into account previous works [18] [19] [22], it can be concluded that
313 a RANS-VOF model performs sufficiently well for OWC simulations.

314 *3.2. Irregular wave*

315 The irregular wave tested in the numerical model is based on a JONSWAP
316 spectrum with $H_s = 0.045$ m and $f_p = 0.465$ Hz. The phases were selected by
317 a random number generator that created random phases uniformly distributed
318 between 0 rad and 2π rad. The spectrum is discretized by 200 wave compo-
319 nents with equidistant frequencies and a low and high cut-off frequency of $0.3f_p$
320 and $3f_p$, respectively. The time of the simulation was selected such that all
321 the components were present in the NWT and the shape of the spectrum was
322 properly retrieved at any location in the tank, finding that 157 s is sufficient for
323 that. The computational cost of simulating a 3D OWC with a PTO in irregular

324 waves is about 25K core hours, posing a serious limitation to the cases that can
325 be examined.

326 In order to evaluate the numerical results, the same techniques for smoothing
327 the spectrum [36] and reflection analysis [37] were used, as for the experimental
328 results [25]. The original signal was separated into 8 segments and a method sim-
329 ilar to Welch method without overlapping was used. This method is described
330 in [36] and results in a smoother spectrum in the expense of lower frequency
331 resolution. If p_n segments are selected, the frequency resolution of the spectrum
332 is reduced by p_n times, yielding an error of this process of $\frac{1}{p_n}100\%$. The optimal
333 number of segments is selected by trials. The reproduction of the irregular wave
334 in the NWT is examined in Figure 7. It is shown that in the numerical model
335 the incident energy density spectrum retrieved after the reflection analysis in
336 the middle of the NWT is in very good agreement with the input JONSWAP
337 spectrum. In the experiment, the only WGs available for the reflection analysis
338 were $\Delta x = 4.0$ m apart, which is not an indicated distance for separating the
339 phases of the incident and reflected waves. However, as shown here, reflection
340 analysis can be used to retrieve the incident energy spectrum. The applicability
341 of the reflection analysis was tested in the numerical model between WGs that
342 were close to each other ($\Delta x = 0.2$ m), as the common practice suggests, and
343 farther apart at a distance of $\Delta x = 3.0$ m, after the end of the relaxation zone
344 and sufficiently away from the device. It is demonstrated that the shape and en-
345 ergy of the spectrum are very similar regardless the distance between the WGs,
346 giving confidence that reflection analysis can be applied to obtain the incident
347 spectrum even when the WGs are far apart. Similar results were obtained for
348 different distances between the WGs varying from 0.1 m to 5.0 m with the nu-
349 merical model at preliminary tests. The recommended distances between the
350 WGs for the reflection analysis are discussed by Goda & Suzuki [38], as well as
351 the possibility of divergence and the distance of the closest WG to the reflective
352 structure. In our case, divergence is expected at 0.3 Hz, where there is not high
353 energy content and WG3 is far enough from the OWC, in order to prevent any
354 discrepancies in the recordings caused by the reflective structure. The measured

355 spectra after the reflection analysis in Figure 7 are not exactly the same with
 356 the input spectrum, because in a random process of irregular wave generation
 357 and propagation the behaviour of the numerical and the experimental tank is
 358 expected to be different. For the conditions tested, the experimental spectrum
 359 had a lower peak and greater spread of energy to high frequencies.

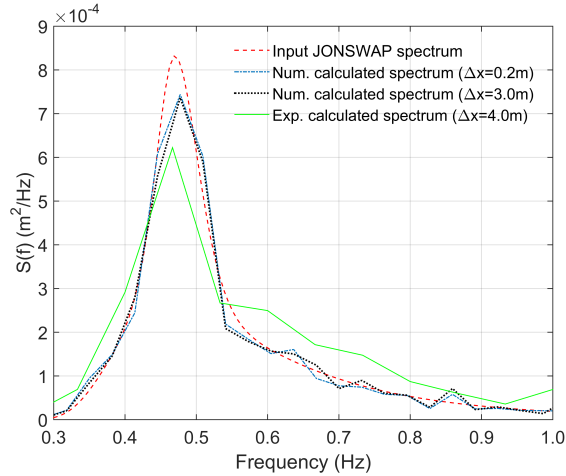


Figure 7: Comparison between the experimental and the incident spectra calculated with the reflection analysis for different distances between the WGs in the NWT.

360 Since the time series of the surface elevation is random, only the capture
 361 width and the spectrum inside the chamber of the OWC can be considered for
 362 the validation. The capture width in the numerical model has a value of 0.42,
 363 which is close to that measured in the experiment (0.41). The difference between
 364 the two is only 2.4%, which is considered good agreement. The comparison of
 365 the energy density spectra inside the OWC in Figure 8 shows that the response
 366 of the OWC to the incident irregular sea is similar between the numerical model
 367 and the experiment, both for the cases when the PTO is present (Figure 8a)
 368 and when the PTO is absent (Figure 8b). Figure 8c shows the spectrum of the
 369 measured pressure inside the central chamber of the OWC in the experiment and
 370 compares it against the numerical model results for the model with the PTO.
 371 Good agreement is observed, but the differences are greater compared with the

372 spectra of the surface elevation. As demonstrated for the regular waves, small
373 differences in surface elevation in the OWC result in augmented differences in
374 the pressure, especially in the case for PTO with high damping. Nevertheless,
375 any discrepancies can be readily attributed to the differences between measured
376 incident spectra in the physical and numerical flumes and to a lesser extent to
377 the decreased frequency resolution. Using the exact measured spectrum from
378 the physical flume is expected to minimize these discrepancies, however in many
379 cases, such as field and hindcast data the phases are not known.

380 In conclusion, together with previous validations using two-phase RANS
381 numerical models [18] [19] [22], it was demonstrated that the NWT designed
382 in OpenFOAM and waves2Foam can adequately replicate the complex phe-
383 nomenon of wave-OWC interaction and it can be used for further studies. De-
384 spite the good performance of the NWT for the OWC with and without PTO
385 in regular and irregular waves, the validation section indicates that there are
386 still issues that require further efforts in order to be addressed. The imperfect
387 absorption of the reflected waves from the inlet can cause considerable pressure
388 discrepancies in the OWC and the study of irregular waves should be performed
389 in a more computationally efficient way in order to be able to examine the effect
390 of random phases on the response of the OWC.

391 **4. Further numerical studies**

392 The first part of the paper dealt with the validation of the NWT for the wave-
393 OWC interaction problem. The present study contributes to further validate the
394 RANS-VOF NWT that was used in similar previous studies [18] [19] [22]. The
395 validated numerical model is used in the following part of the paper to examine
396 the sloshing in the OWC chamber, the reflected waves from the OWC and to
397 determine the resonant frequency of the OWC with a performance curve and a
398 decay test. Insight into the hydrodynamics and aerodynamics of the OWC is
399 provided at the end of this section.

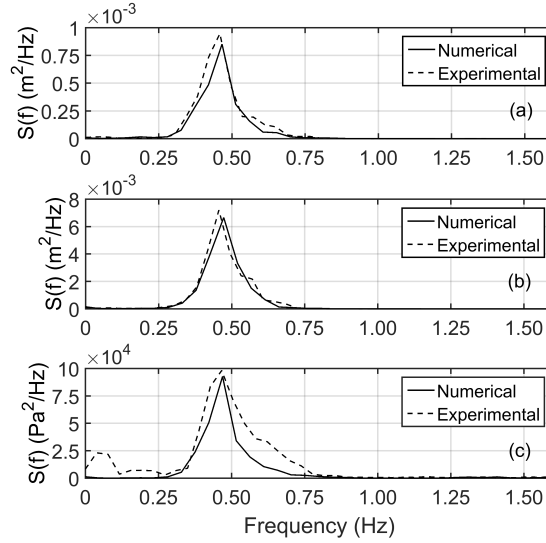


Figure 8: Comparison between the measured energy density spectra inside the OWC with the PTO (a) and without the PTO (b) in the experiment and numerical model. Comparison of the pressure spectrum inside the central chamber (c).

400 4.1. Sloshing and other disturbances in the chamber

401 For all the results presented until now, the free surface elevation inside the
402 chamber was measured by a single wave gauge located in the centre of the
403 OWC. However, under certain conditions, an internal lateral wave can appear
404 in the chamber, which is commonly referred to as sloshing. Sloshing occurs
405 under certain conditions that depend on the wavenumber K and the width of
406 the OWC b . According to [39], the first mode of the standing wave (sloshing)
407 occurs when $Kb = \pi$. For the OWC examined here, this corresponds to wave
408 frequency of 1.65 Hz. Therefore, sloshing is not expected for the wave conditions
409 tested throughout the paper. Despite that, there might be other disturbances
410 of the flow, for example vortices caused from the lip of the front wall or reflected
411 waves from the back wall that are partially trapped in the chamber. Such an
412 effect is visible in Figure 6d and Figure 11 in [40], where it is argued that the
413 internal disturbances are caused by sloshing, but this is not justified based on
414 the geometry of the OWC and the waves tested. However, it is clear that these

415 effects can alter the performance of the OWC and give a false picture of the
416 water motion in the chambers, if this is measured at one location only [40].

417 To ensure that there is no sloshing or other disturbances of the free water
418 surface in the OWC, four wave gauges were added close to each corner of the
419 chamber. The comparison of the results revealed a maximum difference of 0.2%
420 relative to the wave height among the WGs. Practically, the effect of any spuri-
421 ous oscillations in the OWC is negligible and the use of a single wave gauge was
422 sufficient for the present study. It can be argued that the high draught of the
423 front wall of the OWC facilitates a piston-type movement of the water column
424 inside the device, which limits any disturbances at the free water surface.

425 *4.2. Reflection analysis*

426 The evaluation of the behaviour of OWCs should include additional param-
427 eters apart from the performance, since the devices might be located in opera-
428 tional breakwaters and piers. The results of the reflection analysis [37] of the
429 OWCs are compared with a fully reflective vertical wall, tested at the exactly
430 the same conditions in the NWT and located at the same place of the front wall
431 of the OWC. The numerical reflection coefficient is also compared with that
432 obtained from the physical model tests.

433 The reflection coefficient is calculated as the ratio of the difference between
434 the total and incident energy with the incident energy. The energy of the spectra
435 is calculated as the integral of the variance energy density. All measurements are
436 taken in the middle of the NWT, where additional WGs are placed, sufficiently
437 away from the device and the inlet relaxation zone, so that the results remain
438 intact from the local distortions.

439 The results presented in Figure 9 show the theoretical input spectrum, the
440 incident calculated wave spectrum from the reflection analysis and the total
441 measured spectrum for a vertical wall (a), OWC “lid-off” (b) and OWC “lid-
442 on” (c). As seen that the theoretical and calculated incident spectra are similar.
443 The reflection coefficient of the vertical wall was calculated at 97%, while it was
444 only 39% and 46% for the OWC without and with PTO, respectively. The

445 experimental reflection coefficient were calculated at 30% and 34% for the “lid-
 446 off” and “lid-on” case, respectively, which are similar to the numerical values.
 447 The agreement is satisfactory, especially taking into account the randomness of
 448 the wave field.

449 It can be seen that the employment of an OWC in a breakwater can po-
 450 tentially limit the reflected waves in comparison with a vertical breakwater and
 451 can create a calmer wave field for navigation.

452 4.3. Performance curve

453 One of the most crucial aspects in the examination of an OWC is to de-
 454 termine its resonant frequency in order to be able to tune it to the incident
 455 waves and increase its hydrodynamic efficiency. In this section, the OWC with
 456 the same PTO of 15 mm diameter is tested under various regular waves with
 457 frequencies varying from 0.36 Hz to 1 Hz and constant wave height of 0.03 m, in
 458 order to derive its performance curve. This is done with the calculation of the
 459 capture width C_w for every test, as a ratio of the absorbed power of the OWC

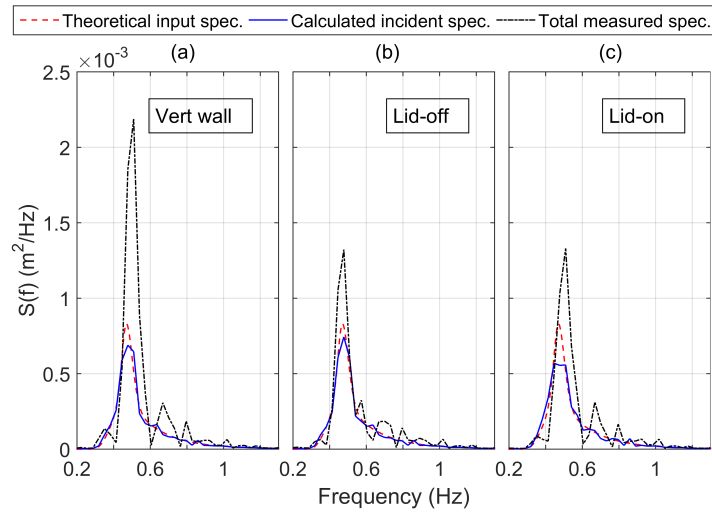


Figure 9: Frequency spectrum of the free surface elevation at 4.5 meters in front of the front wall of the OWC and the vertical wall breakwater.

460 over the incident wave power per meter length of the OWC [41].

461 Figure 10 shows the performance curve for different dimensionless wave
 462 numbers (Kh), which is defined from the linear dispersion relation as $\omega^2/g =$
 463 $K \tanh(Kh)$, where $\omega = 2\pi f$, with f being the frequency of the wave in Hz, h is
 464 the water depth and K the wavenumber. The present results are compared with
 465 the experimental study of Morris-Thomas [42], the analytical study of Evans
 466 & Porter [39] and the numerical study of Zhang, et al. [40] (case C of high
 467 draught). To allow an easier evaluation of the results, the points of each study
 468 were fitted with a fifth order polynomial curve.

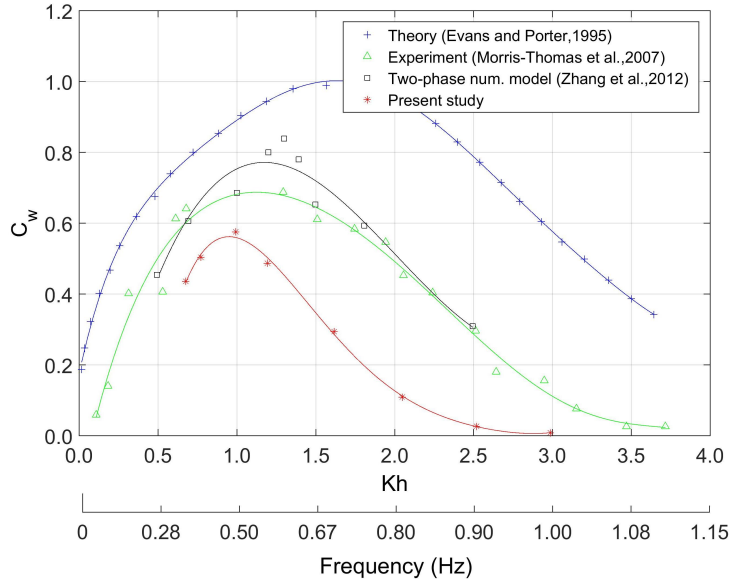


Figure 10: Performance curve presented as the hydrodynamic efficiency versus dimensionless wave number and the frequency of each regular wave tested.

469 It can be seen in Figure 10 that the present study has a peak of performance
 470 at around $Kh = 1$, corresponding to $f = 0.50$ Hz, and a maximum capture
 471 width of $C_w^{pres} = 0.57$. On the other hand, Zhang's numerical tests and Morris-
 472 Thomas' experimental tests have a peak performance at around $Kh = 1.2$ and
 473 a capture width of $C_w^{Zh} = 0.68$ and $C_w^{MT} = 0.76$, respectively. The low capture
 474 width of the present study can be explained by the high damping of the model

475 and different geometric parameters. Very low frequency waves ($Kh < 0.5$) could
476 not be tested in the present NWT, since they have a disproportional wavelength
477 to the length of the numerical flume, causing standing waves.

478 The biggest disadvantages of the performance test are the requirement for
479 many simulations with regular waves and the long NWT needed for testing low
480 frequency waves.

481 *4.4. Decay test*

482 The decay test is an alternative method for determining the resonance fre-
483 quency of a device by imposing initial conditions to the system and then to
484 let it respond freely. Contrary to the performance curve, this method needs
485 only one test which can save a lot of computational resources. This method
486 is commonly used for floating bodies [43], but rarely for fixed OWC. A similar
487 approach to the present one for performing a decay test with a fixed OWC was
488 presented recently [35], where the FFT of the time series was used to determine
489 the resonant frequency of the device. Here, the theory of mechanical vibrations
490 with viscous damping is employed.

491 To perform the decay test in the NWT, the free surface elevation inside the
492 device was set at 0.15 m higher than the still water level (SWL) and then, the
493 system was released to respond freely in the absence of any incident waves. The
494 time series of the surface elevation inside the OWC is shown in Figure 11 for
495 the “lid-off” and the “lid-on” case.

496 *Lid-off case*

497 Assuming that the OWC is a system with a linear viscous damping be-
498 haviour, the decay test can be used as a time response method to determine
499 the damping of the system and estimate the natural and resonant frequency.
500 The Logarithmic Decrement Method (LDM) is employed, which holds for single
501 degree of freedom oscillatory underdamped motions [44]. According to LDM,
502 when a system with viscous damping is excited, it decays based on Equation 5.

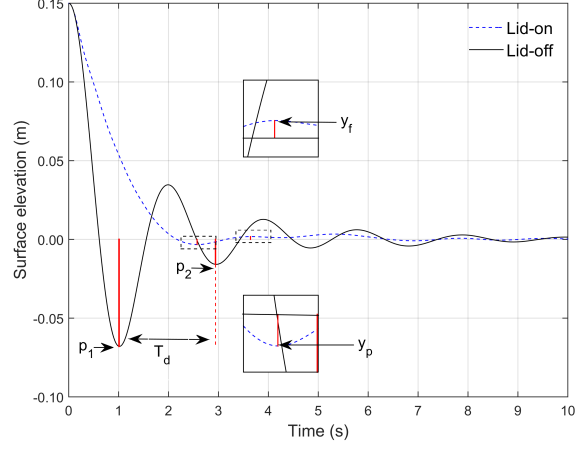


Figure 11: Time history of the surface elevation in the centre of the central chamber for the “lid-off” and “lid-on” cases used for the decay test.

503 The ratio between two amplitudes separated by r number of periods is defined
 504 as the logarithmic decrement δ (Equation 6).

$$y(t) = y_0 e^{-\zeta \omega_n t} \sin(\omega_d t) \quad (5)$$

505 where $y(t)$ is the response of the system, y_0 the initial excitation (here, 0.15
 506 m), ω_n the undamped natural frequency, ω_d the damped natural frequency and
 507 ζ the damping ratio.

$$\delta = \frac{1}{r} \ln \left(\frac{y(t)}{y(t + rT_d)} \right) \quad (6)$$

508 where T_d is the period of the damped response given as $T_d = 2\pi/\omega_d$ (see
 509 Figure 11).

510 The damped natural frequency (ω_d) is related to the undamped natural
 511 frequency (ω_n) and damping ratio (ζ) as:

$$\omega_d = \sqrt{1 - \zeta^2} \omega_n \quad (7)$$

512 Substituting Equation 5 and Equation 7 to Equation 6 for two successive

513 peaks p_1 and p_2 ($r = 1$), as seen in Figure 11, yields:

$$\delta = \ln(e^{\zeta \frac{\omega_n}{\omega_d} 2\pi}) = \frac{\zeta}{\sqrt{1 - \zeta^2}} 2\pi \quad (8)$$

514 For an underdamped oscillation ($\zeta < 1$) the damping ratio is expressed as:

$$\zeta = \frac{1}{\sqrt{1 + (\frac{2\pi}{\delta})^2}} = \frac{1}{\sqrt{1 + (\frac{2\pi}{\ln \frac{p_1}{p_2}})^2}} \quad (9)$$

515 The resonant frequency ω_r for a damped oscillation with sinusoidal excitation
516 force is given as:

$$\omega_r = \sqrt{1 - 2\zeta^2} \omega_n \quad (10)$$

517 It should be noted that $\omega_r < \omega_d < \omega_n$.

518 Applying the quantities measured from Figure 11 into Equation 7-10 and
519 taking into account that $f = \omega/2\pi$, the resonant frequency f_r is found. All the
520 parameters are summarized in Table 2.

	p_1 (m)	p_2 (m)	ζ	T_d (s)	ω_n (rad/s)	f_r (Hz)
Lid-off	0.067	0.016	0.226	1.950	3.308	0.499

Table 2: Parameters calculated for the decay test for the “lid-off” case.

521 *Lid-on case*

522 The time series of the decay test in Figure 11 for the “lid-on” case show that
523 the decay test for the OWC with the PTO is almost a non oscillatory response,
524 which corresponds to critical damping ($\zeta = 1$). However, according to the curves
525 for various damping ratios [44], ζ appears to be between $0.5 < \zeta < 1$. If LDM is
526 applied also here, it gives $\zeta = 0.577$, $\omega_d = 1.74$ rad/s and $f_r = 0.196$ Hz. This is
527 an unrealistic result, which is caused due to the fact that the accuracy of LDM
528 decreases as ζ increases past 0.5.

529 For damping ratios $0.5 < \zeta < 0.8$ the Method of Fractional Overshoot (MFO)
 530 is commonly applied [45]. The fractional overshoot OS is given as:

$$OS = \frac{y_p - y_f}{y_f} \quad (11)$$

531 where y_p is the amplitude of the first peak of the step response and y_f is the
 532 settling amplitude (see Figure 11).

533 The damping ratio is then related to OS as:

$$\zeta = \frac{-\ln(OS)}{\sqrt{\pi^2 + \ln^2(OS)}} = \frac{1}{\sqrt{1 + \left(\frac{\pi}{\ln(OS)}\right)^2}} \quad (12)$$

534 The time of the local maxima and minima is given by:

$$t = \frac{n\pi}{\omega_n \sqrt{1 - \zeta^2}} \quad (13)$$

535 For $n = 1$ the time of the first peak:

$$t_p = \frac{\pi}{\omega_n \sqrt{1 - \zeta^2}} \quad (14)$$

536 The settling time, which is the time required for the transient oscillation to
 537 reach the steady-state within $\pm 2\%$ of its value is approximated as:

$$t_s = \frac{4}{\omega_n \zeta} \quad (15)$$

538 Ideally, if the damping is not very high, y_p and y_f represent distinct values
 539 in the decay graph and OS can be evaluated in a straight forward manner.
 540 However, in the present case y_p is already almost within $\pm 2\%$ of the settling
 541 value, i.e. 0.003 m, which brings the MFO to its limits of applicability. The
 542 values of the settling time and the time of the first peak can be estimated from
 543 Figure 11, which are found as $t_s = 2.701$ s and $t_p = 2.585$ s, respectively.
 544 Substituting these values in Equations 14 and 15 results in a system with two
 545 unknowns: ζ and ω_n . The solution yields $\zeta = 0.773$ and $\omega_n = 1.916$ rad/s. The
 546 natural frequency is calculated as $f_n^d = 0.305$ Hz. Resonance frequency for this

547 case is not defined. It can be seen from the value of ζ that the PTO induces
 548 very high damping. All the parameters are summarized in Table 3.

	t_p (s)	t_s (s)	ζ	ω_n (rad/s)	f_n^d (Hz)
Lid-on OWC	2.585	2.701	0.773	1.916	0.305

Table 3: Parameters calculated for the decay test for the “lid-on” case.

549 The damped natural frequency found with the decay test for the “lid-on”
 550 OWC is $f_n^d = 0.305$ Hz, which compares well with the RAO of the surface
 551 elevation for the “lid-on” case (see Figure 5 [25]), where the surface elevation
 552 resonance appears to be below 0.400 Hz. The resonance frequency found from
 553 the decay test for the “lid-off” OWC is $f_r = 0.499$ Hz, which is very close to the
 554 peak of the RAO of the physical model (Figure 5 in [25]) estimated at 0.470 Hz
 555 and at the same time practically identical to the peak of the performance curve
 556 in Figure 10 estimated at approximately 0.500 Hz.

557 Applying a FFT analysis on the time series of the decay test presented in
 558 Figure 11, reveals the response of the OWC in the frequency domain. As it can
 559 be seen from Figure 12 the OWC with the PTO does not exhibit a resonant
 560 frequency, while the OWC without the PTO shows resonance close to 0.500 Hz.

561 Practically, the small difference between the resonant frequencies calculated
 562 from the decay test without the PTO, the response amplitude operator (RAO)
 563 and the performance curve gives great importance to the decay test, since it
 564 requires only one simulation of few seconds to find with relatively good accu-
 565 racy the resonance frequency of the OWC. On the contrary, the RAO and the
 566 performance curve method require many and relatively long simulations. Em-
 567 ployment of the decay test can reduce the range of the frequencies required for
 568 the performance curve and save significant computational effort.

569 The present results demonstrate that when the damping is not high allowing
 570 the system to oscillate (“lid-off” case), the resonant frequency of an OWC can
 571 be calculated from the commonly used LDM. When the damping induced by the
 572 PTO is very high and the system practically does not oscillate, the MFO can

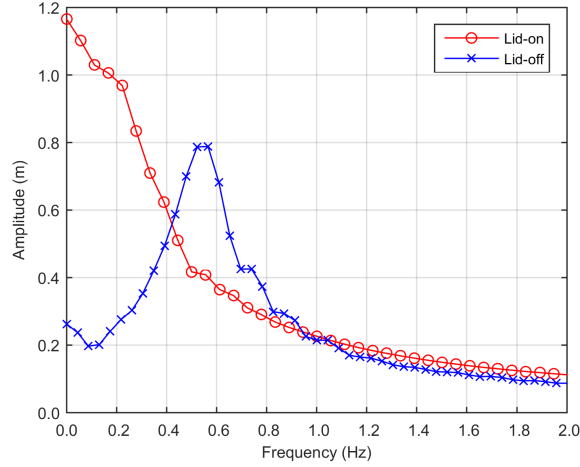


Figure 12: Frequency response of the decay test for the “lid-on” and “lid-off” OWC.

573 provide a first approximation of the resonant frequency, in order to decrease the
 574 range of the frequencies to test for the performance curve. The MFO can also
 575 be considered as a good alternative to LDM, when the damping of the system
 576 is high, but still the system oscillates and it has not settled before the first peak
 577 of the oscillation.

578 4.5. Hydrodynamic behaviour

579 The greatest advantage of a CFD model is that it can offer high density
 580 information about the flow properties at any time and location in the compu-
 581 tational domain. In this section, the numerical results for the regular wave are
 582 presented at eight characteristic time instances during a wave cycle, as shown
 583 in Figure 13, where the surface elevation in the chamber of the OWC is pre-
 584 sented, together with the relative pressure, defined as the difference between the
 585 recorded and the atmospheric pressure.

586 The numerical model outputs for these characteristic time instants are pre-
 587 sented in Figure 14. In this figure, the magnitude of the velocity of the two
 588 fluid phases is plotted together with the direction vectors for the water phase
 589 in a vertical plane that passes from the middle of the OWC and it is normal

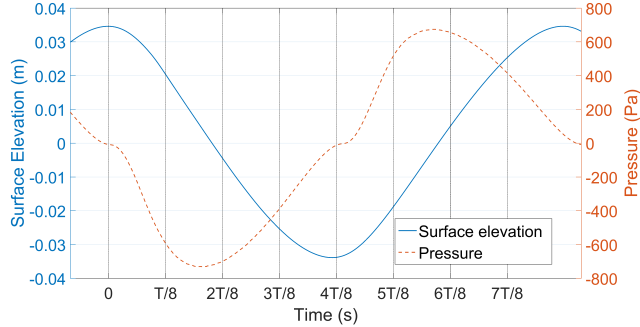


Figure 13: Timeseries of the surface elevation (- blue) and relative pressure (- - red) inside the OWC chamber at eight characteristic time instances during one wave period, marked with vertical lines.

590 to its front wall. The vertical profile of the horizontal velocity under the front
 591 wall of the OWC is presented as well. For convenience, the vertical and hori-
 592 zontal frame of the graphs represent the distance from the SWL and the wave
 593 paddle, respectively. The velocity in the air phase is two orders of magnitude
 594 higher than that of the water phase, which is expected as the air is accelerated
 595 through the orifice. Because of the significant difference between velocity mag-
 596 nitudes in air and water, the two fluid phases are plotted separately. This also
 597 explains why different values for C_o and “alphaCo” were chosen in the NWT
 598 (see Section 2.1).

599 It can be clearly seen that the water flow near and in the OWC is complex
 600 with stagnant regions or regions of violent jet-type flow ($2T/8$) and local vortices
 601 ($6T/8$). Perhaps, the most important location is that of the front wall opening
 602 that controls the inflow and outflow in the OWC. It can be seen from the
 603 horizontal velocity profiles plotted next to the velocity field graphs that the
 604 flow is far from a uniform distribution and only part of the opening is active.
 605 Moreover, for the first half of the wave cycle ($0-3T/8$), there is a net outflow
 606 from the OWC, until the next incident wave arrives ($4T/8$) and water flows
 607 again into the OWC chamber increasing the surface elevation.

608 The air motion is also very complex with circulations dominating inside the

609 chamber when the pressure is close to zero (0 and $7T/8$) or when the OWC is
 610 “exhaling” ($5T/8$ - $6T/8$). In the latter case, the air flow is stronger near the
 611 walls and directly under the orifice. On the other hand, when the pressure
 612 drops below zero in the OWC ($T/8$ to $3T/8$) a violent jet-type flow of air enters
 613 through the orifice and spreads until it meets the interface with the water. A
 614 significant amount of turbulence is expected in the air phase. The present results
 615 can be compared with those presented for a detached OWC where the maximum
 616 vertical component of the velocity at the orifice was computed at 3 m/s [22] and
 617 15 m/s [23], while here it reached around 30 m/s, indicating the high damping
 618 of the PTO.

619 Another aspect that can be commented here is the effect of the air compress-

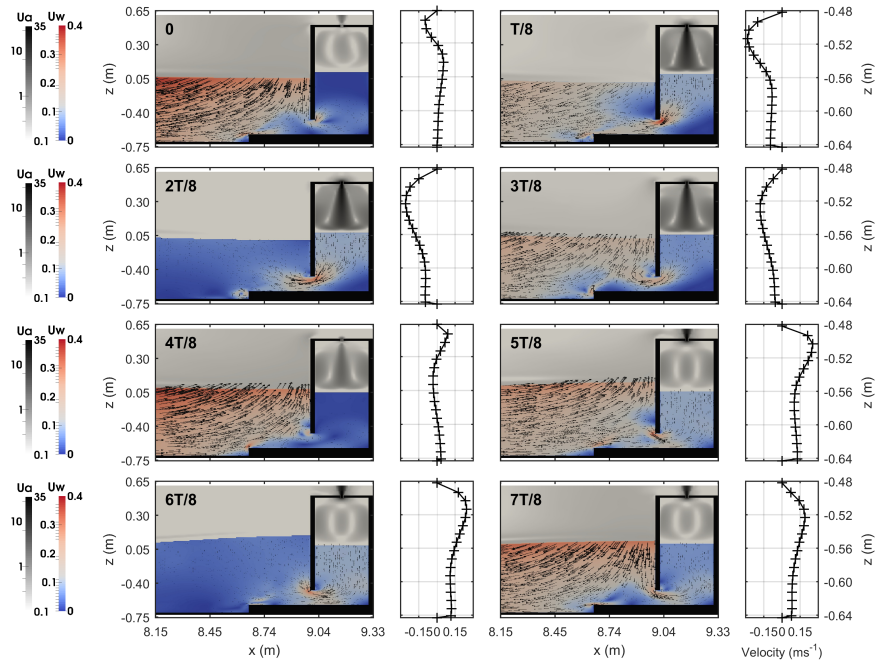


Figure 14: Velocity magnitude fields of the water and air phase inside the OWC and its vicinity every $1/8$ of the wave period. The grayscale results in logarithmic scale represent the air phase (U_a) and the colour plot the water phase (U_w). The velocity profiles next to the contour plots represent the horizontal component of the velocity at the opening of the front wall.

620 ability inside the chamber of the OWC for the case of very high damping. One
621 could argue that discrepancies observed in the pressure in Figure 6b might be
622 caused by the incompressibility assumption in the RANS model. Compressibil-
623 ity starts influencing the flow when entering the subsonic regime, which occurs
624 when the ratio of the flow velocity over the speed of sound (for present condi-
625 tions 340 m/s) is greater than 0.3 [31]. For the highest instantaneous velocities
626 observed in the present study, this ratio is approximately 0.1. Therefore, the
627 assumption of incompressibility still holds without any concerns.

628 In conclusion, the analysis shows that CFD models can offer valuable in-
629 formation for the kinematics of the two fluid phases, which can lead to better
630 optimization of the OWC devices. A key aspect for increasing the performance
631 [39] is the creation of a piston-type movement of the OWC, which causes the
632 least turbulence. The kinematics can also offer information for the loading on
633 the walls of the OWC, which is a crucial element in the structural design.

634 5. Conclusions

635 In this paper, a NWT designed in the open-source RANS-based CFD model
636 OpenFOAM was used to replicate experimental results regarding the interaction
637 between an OWC with regular and irregular waves. For the cases examined,
638 very good agreement with the experiment was found for the pressure and the
639 surface elevation inside the OWC for the regular waves and taking into account
640 previous works with similar NWTs the model can be considered sufficiently
641 validated. The minor discrepancies appearing in the air pressure are a common
642 issue in similar NWTs and they are likely to be caused by the re-reflected
643 waves from the inlet relaxation zone. For the irregular waves, the numerical
644 and the physical model appear to have similar bulk properties regarding the
645 hydrodynamic efficiency, response of the OWC and the reflection coefficients.

646 In the second part of the study, the numerical model was used for addi-
647 tional studies, namely the sloshing in the OWC chamber, the decay test, the
648 performance assessment and the reflection analysis. The result of the decay test

649 had very good agreement with the classical method for finding the performance
650 curve and it can be used in numerical models to save significant computational
651 effort. The OWCs appear to have less reflections than conventional vertical
652 breakwaters and the OWC model without the PTO can be a promising alter-
653 native design of absorbing sea walls. One of the greatest strengths of the CFD
654 model is that it can provide a valuable insight in the kinematics of the water
655 and air in the vicinity of the device, which can be used for detailed optimization
656 of the OWCs.

657 Future work should include further comparisons between the physical and
658 the numerical model, such as the air velocities near the orifice and the loads
659 on the walls of the OWC. An important issue that has to be tackled is the
660 computational efficiency of the numerical model. Despite its high accuracy, a 3D
661 CFD model is computationally expensive and difficult to apply. Future studies
662 should exploit the capabilities of OpenFOAM to create equivalent 2D cases that
663 will be more efficient for the preliminary studies and the long simulations with
664 irregular waves. Moreover, since the inlet relaxation zones occupy a big part of
665 the computational domain and the alternative of active wave absorption should
666 also be considered [21]. Another way to decrease the computational cost is to
667 explore different methods of simulating a PTO, so that high air velocities of
668 the orifice are limited and the simulation does not slow down or experience
669 instabilities. The domain decomposition and coupling of different numerical
670 models can also be used to improve the computational efficiency [46].

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