



City Research Online

City St George's, University of London

Citation: Wang, J., Yan, S., Ma, Q., Wang, J., Xie, Z. & Marran, S. (2020). Modelling of focused wave interaction with wave energy converter models using qaleFOAM. Proceedings of the Institution of Civil Engineers - Engineering and Computational Mechanics, 173(3), pp. 100-118. doi: 10.1680/jencm.19.00035

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: <https://openaccess.city.ac.uk/id/eprint/25040/>

Link to published version: <https://doi.org/10.1680/jencm.19.00035>

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to [City Research Online policy](#).

Numerical Simulation of Focused Wave Interaction with WEC Models using galeFOAM

Author 1

- Junxian Wang, Msc
- School of Mathematics, Computer Science and Engineering, City, University of London, UK

Author 2

- Shiqiang Yan, Ph.D
- School of Mathematics, Computer Science and Engineering, City, University of London, UK
- ORCID number: 0000-0001-8968-6616

Author 3

- Qingwei Ma, Ph.D
- School of Mathematics, Computer Science and Engineering, City, University of London, UK

Author 4

- Jinghua Wang, Ph.D
- School of Mathematics, Computer Science and Engineering, City, University of London, UK

Author 5

- Zihua Xie, Ph.D
- School of Engineering, Cardiff University, Cardiff, UK

Author 6

- Sarah Marran
- School of Mathematics, Computer Science and Engineering, City, University of London, UK

Full contact details of corresponding author.

Shiqiang Yan, shiqiang.yan@city.ac.uk, 0044 20 7040 3330

School of Mathematics, Computer Science and Engineering, City, University of London

Northampton Square, London, EC1V 0HB, UK

Editor's note: your article's title and abstract are the main ways that readers will find your work. For each, aim to make them:

- o clear and interesting*
- o include keywords that your peers might type into a search engine*
- o place such keywords at the beginning of the first sentence. Google will then find them more easily*

Each keyword only needs to be mentioned once, after that use plenty of other similar words.

Abstract (150 – 200 words)

The paper presents a numerical investigation of the interaction between focused waves and wave energy converter (WEC) models using a hybrid solver, qaleFOAM, which couples a two-phase incompressible Navier-Stokes (NS) solver OpenFOAM/InterDyMFoam with the Quasi Lagrangian-Eulerian Finite Element Method (QALE-FEM) based on the fully nonlinear potential theory (FNPT) using the domain-decomposition approach. In the qaleFOAM, the NS solver deals with a small region near the structures (NS domain), where the viscous effect may be significant; the QALE-FEM covers the remaining computational domain (FNPT domain); an overlap (transitional) zone is applied between two domains. The WEC models, mooring system and the wave conditions are specified by the CCP-WSI (Collaborative Computational Project in Wave-Structure Interaction) Blind Test Series 2. In the numerical simulation, the incident wave is generated in the FNPT domain using a self-correction wavemaker and propagates into the NS domain through the coupling boundaries and attached transitional zones. An improved passive wave absorber is imposed at the outlet of the NS domain for wave absorption. The practical performance of the qaleFOAM is demonstrated by comparing its prediction with the experimental data, including the wave elevation, motion responses (surge, heave and pitch) and mooring load.

Keywords chosen from ICE Publishing list

Fluid Mechanics; Mathematical Modelling; Renewable Energy

List of notations (examples below)

| | |
|------------------|---|
| ρ_w | is the density of the water |
| ϕ | is the velocity potential |
| η | is the free surface elevation |
| \vec{u} | is the fluid velocity |
| p | is the pressure |
| w | is the weighting function ranging from 0 to 1 |
| d | is the water depth |
| \vec{U}_h | is the horizontal velocity component |
| U_z | is the vertical velocity component |
| $\tilde{\omega}$ | is the instantaneous wave frequency |
| \tilde{k} | is the instantaneous wave number |
| $\tilde{\eta}$ | is the recorded wave elevation at the wave absorber |
| \vec{n}_h | is the normal direction of the absorber surface |

1 Introduction

2

3 Reliable prediction on the structural responses in waves plays an essential role on the design, deployment
4 and operation of the offshore and marine structures, such as the wave energy converters (WECs). For
5 survivability of the structure, its behaviour in realistic extreme wave conditions need to be paid extra
6 attention. Such extreme wave conditions are often generated in physical and numerical wave tanks using
7 a focused wave group, e.g. the NewWave theory (Tromans et al. 1991). Consequently, modelling the
8 wave-structure interaction (WSI) in focused waves attracts the interests from both the academia and
9 industrial.

10

11 To model WSIs, numerous numerical models and software have been developed based on a wide range of
12 theoretical models, including the fully nonlinear potential theory (FNPT), where the fluid is assumed to
13 be incompressible, irrotational and inviscid, and the single- or multi-phase Navier-Stokes (NS) models
14 with or without turbulence modelling. The performances of these models rely on the effectiveness of
15 generating incident waves in the far field, modelling the wave propagation, simulating structural
16 responses and resolving small-scale turbulence/viscous effects in the near field. For the non-breaking
17 extreme waves, it is widely accepted that the FNPT model can satisfactorily reproduce the wave
18 conditions and model their propagation in a large computational domain (e.g. Grilli et al., 2001; Ma et
19 al., 2001, 2006, 2015; Ning et al., 2008, 2009; Stansby, 2013; Engsig-Karup et al., 2016; Wang et al.,
20 2018). For simulating structural responses, the FNPT model can also deliver a promising accuracy if the
21 structure is relatively big compared with the wave length (Celebi et al, 1998; Kashiwagi, 2000; Tanizawa
22 and Minami,2001; Wu and Hu, 2004; Bai and Eatock Taylor, 2006; Yan and Ma, 2007; Ma and Yan,
23 2009; Hu et al. 2020), due to insignificant viscous effects involved in such problems. This was further
24 confirmed by the final report of the first CCP-WSI (Collaborative Computational Project in Wave-
25 Structure Interaction) blind test held in ISOPE 2018 (Ransley et al. 2019), in which cases with a fixed
26 FPSO subjected to extreme wave conditions were numerically simulated using various numerical models
27 and compared with the experimental data. The blind test minimised the possibility of numerical
28 calibrations or tuning for the participated numerical models, due to the fact that the experimental data was
29 released after the numerical predictions were submitted, and, therefore, largely reflects the reliabilities of
30 participated numerical models for daily practices without available experimental data. One conclusion

31 given by Ransley et al (2019) is that FNPT methods have performed equally as well as the high fidelity
32 methods; the FEM-based FNPT method, i.e. the Quasi Lagrangian Eulerian Finite Element Method
33 (QALE-FEM, Ma & Yan, 2006,2009; Yan & Ma, 2007; Ma et al. 2015), is at least 1.5 orders of
34 magnitude faster than the quickest NS code and has comparable predictive capability in these cases
35 (Ransley et al. 2019), where the viscous and the turbulent effects are insignificant (Yan and Xie et al.
36 2019).

37

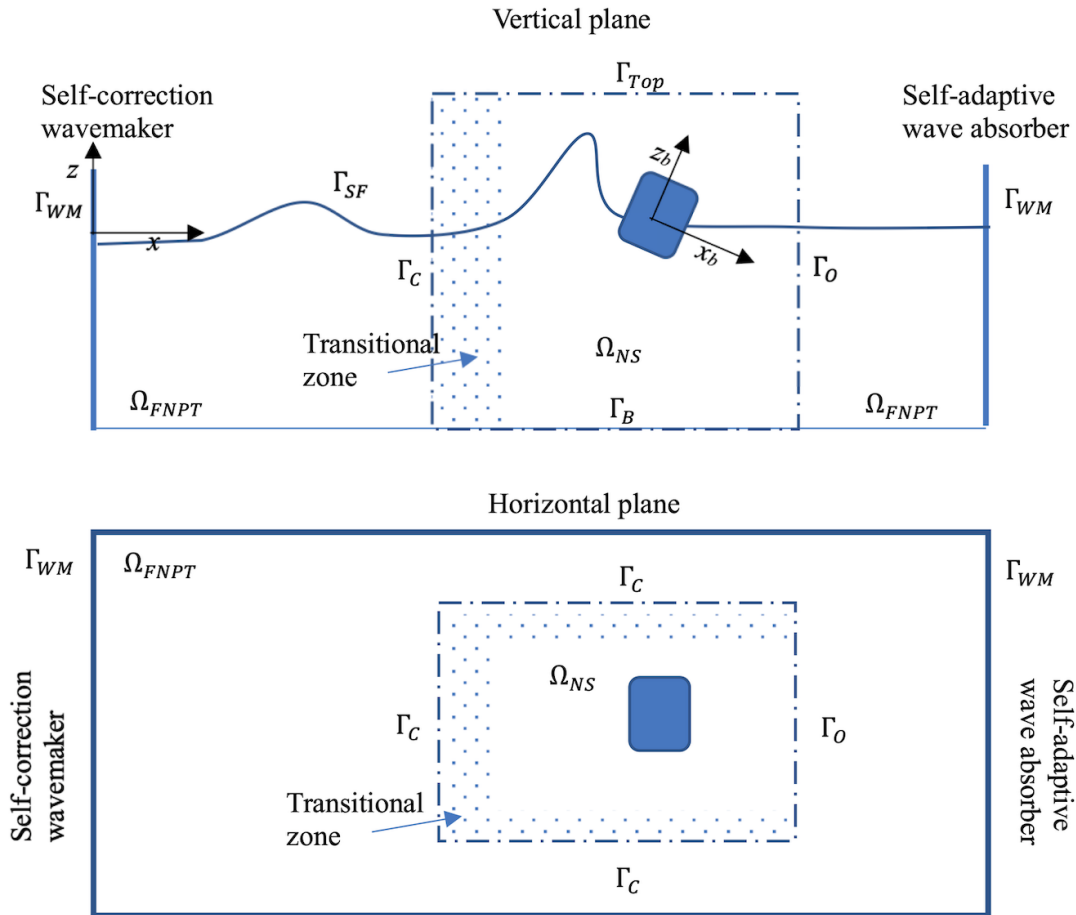
38 However, if the relative size of the structure is small compared with the characteristic wave length, e.g.
39 within the range of the application of the Morison's equation (usually < 0.2 characteristic wavelength),
40 the viscous effects become important. The viscous effects may also be significant when the motion of the
41 structure is significant (e.g. Yan & Ma, 2007; Hu et al, 2020) and/or the fluid is sloshing in a confined
42 zone (e.g. Yan and Ma et al. 2019). For such problems, the NS models may be necessary and the potential
43 theory is not suitable, unless an appropriate artificial viscosity is applied (e.g. Yan & Ma, 2007). The
44 artificial viscosity is often numerically calibrated using available experimental results or reliable high-
45 fidelity predictions. This obviously brings inconvenience and uncertainty into the numerical practices.
46 However, the NS model is more time-consuming compared with the FNPT models, as evidenced by
47 Ransley et al. (2019), not only because of its higher degree of complexity of the governing equations, but
48 also due to the fact that a much finer temporal-spatial resolutions are required by the former to achieve
49 convergent results. For these reasons, the NS models are rarely applied to modelling WSIs in large
50 spatial-temporal domain. In many applications (e.g. Hildebrandt and Sriram, 2014; Hu et al, 2014, 2017),
51 the computational domain of the NS model is limited to a finite space near the structure (near field). This
52 implies that one needs to accurately specify the wave field on the wave generation boundaries of the
53 computational domain. A few tools (e.g. Jacobsen et al. 2011; Hu et al. 2014) are available for specifying
54 the wave conditions using different wave theories, e.g. the linear wave theory, second-order wave theory,
55 Stokes wave theory, stream functions and high-order potential theories (e.g. OceanWave3D, Engsig-
56 Karup et al. 2008). Recently, developments on hybrid models, combining the NS solver with simplified
57 theory, for modelling WSIs have attracted interest of world-wide researchers. They take the advantages of
58 the simplified theories for robust modelling of large-scale wave propagations within their range of
59 application and the advantages of the NS models on resolving small-scale viscous/turbulent effects,
60 vortex shedding and flow separation, fluid compressibility and aeration. By limiting the computational

61 domain for the NS model to a small temporal/spatial zone, e.g. near the structure or where/when breaking
62 wave occurs, they are expected to achieve robust solutions without comprising the overall computational
63 accuracy. Broadly speaking, applying these tools with the NS models leads to a hybrid model combining
64 these wave theories with the NS model using one-way zonal approach (space-splitting or domain
65 decomposition). Both the function-splitting, e.g. the velocity-decomposition (Edmond et al, 2013), space-
66 splitting /domain-decomposition (e.g. Colicchio et al, 2006; Yan and Ma, 2010a; Hildebrandt et al., 2013;
67 Sriram et al. 2014; Fourtakas et al. 2017; Li et al. 2018; Zhang et al. 2020) and time-splitting approaches
68 (e.g. Wang et al, 2018) have been attempted. Systematic reviews on the development of the hybrid
69 models can be found in Sriram et al. (2014), Li et al. (2018), Wang et al. (2018) and Zhang et al (2020).
70 The effectiveness of the hybrid model on improving the computational efficiency has been reported by
71 recent CCP-WSI blind test for modelling the interaction between the focused wave and the floating
72 bodies (Ransley, Yan and Brown et al, 2020). It was concluded that the hybrid methods combining the
73 FNPT with NS solvers, including the qaleFOAM combining the QALE-FEM with openFOAM (Li et al.,
74 2018; Yan et al 2019; Yan et al. 2020) and a one-way hybrid model combining the FNPT with SPH
75 (Zhang et al 2020), demonstrate a potential improvement in the required CPU effort when compared to
76 the most robust NS solvers participating to the test, including one adopting the linear and second-order
77 wave condition in the OpenFOAM (wave2Foam, Jacobsen et al. 2011) . It is admitted that the
78 implementations of different numerical models, e.g. the computational domain and mesh sizes, are
79 considerably influenced by users' experiences, since no specific domain/mesh are provided for
80 standardisation. Nevertheless, the comparison by Ransley, Yan and Brown et al. (2020) may demonstrate
81 a better practical performance of the hybrid model for WSI problems than both the potential theory and
82 NS solvers.

83

84 This paper contributes to the CCP-WSI Blind Test Series 2, in which the cases with two simplified WEC
85 models subjected to focusing waves with different wave conditions are set. The details of the case
86 configurations can be found in Ransley, Brown and Hann, et al. (2020). The sizes of the WEC models in
87 this test are considerably smaller than the characteristic wavelength, implying that the associated viscous
88 effect may be significant. Furthermore, one of the WEC model is a cylinder with a moonpool at its centre,
89 in which the liquid sloshing is expected to bring additional viscous damping for suppressing the wave-
90 induced motions of the WEC model. Following Yan et al. (2020), the qaleFOAM with an improved

91 passive wave absorber is applied to model the cases considered in the blind test. The numerical results on
 92 the motions of the WECs have been obtained before the experimental data were released. This paper
 93 mainly focuses on the comparison with the experimental data to demonstrate the practical performance of
 94 the qaleFOAM. For this purpose, all results presented in this paper are the originally submitted ones but
 95 additional quantitative analysis is added.



96
 97 Figure 1. Schematic sketch of the domain decomposition and the coupling approach of the qaleFOAM
 98 (Ω_{FNPT} does not include the floating structure)
 99

100 2. Mathematical formula

101 The hybrid model, qaleFOAM, combines the QALE-FEM and OpenFOAM/InterDyMFoam (Jasak, 2009)
 102 using the domain-decomposition strategy. The details of the qaleFOAM have been given by Li et al.
 103 (2018) but a summary is given herein for completeness. Figure 1 illustrates the coupling of the FNPT
 104 and NS solvers, which are combined via a coupling boundary, Γ_c . The FNPT domain (Ω_{FNPT}) starts from a
 105 location far away from the structures, where a wavemaker is used to generate the incoming wave. The

106 length of the FNPT domain shall be sufficient to cover the inlet of the NS domain (Ω_{NS}). In this paper,
107 one-way coupling is adopted and, therefore, the solution in Ω_{FNPT} is only used to provide an accurate wave
108 condition at Γ_c . This means that the diffraction and radiation caused by the structures do not need to be
109 reproduced in Ω_{FNPT} and thus the structure is omitted from Ω_{FNPT} . The right end of Ω_{FNPT} is an absorption
110 boundary and the self-adaptive wave absorber (Yan et al. 2016) is employed. The absorption efficiency
111 of the absorber is approximately 95% in terms of wave energy for the case considered in this paper and is
112 at a similar level for a wide range of nonlinear regular and irregular waves, as demonstrated by Yan et al.
113 (2016). As all other techniques, perfect absorption is impossible and the reflection from the right end of
114 Ω_{FNPT} exists no matter how small it is. Such reflection can influence the structural responses when it
115 approaches the structure site. To minimise the effect, the length of Ω_{FNPT} is specified to be sufficiently
116 long such that required duration of the results is obtained before the reflection wave reaches the structure
117 site. In Ω_{FNPT} , the QALE-FEM is used to solve the governing equations and its high robustness on
118 modelling nonlinear waves up to wave breaking (Yan and Ma, 2010b) assures a good overall robustness
119 of the qaleFOAM, even though a long Ω_{FNPT} may be implemented to ensure a tolerable error caused by
120 the reflection from the end of Ω_{FNPT} during the simulation. Ω_{NS} is bounded by the coupling boundaries Γ_c
121 at its left end and two sides in longitude direction (dashed line in Figure 1), seabed Γ_B , a pressure
122 inlet/outlet boundary on the top Γ_{TOP} , where the total pressure is specified as the atmospheric pressure,
123 and the right end boundary Γ_O . In Ω_{NS} , the multiphase solver interDyMFoam, based on the finite volume
124 method (FVM) with volume of fluid (VOF) technique for identifying the fluid phases, is used. On the
125 coupling boundary Γ_c , the velocity and pressure for the NS solver are fed by the QALE-FEM using,

126

$$127 \quad \vec{u}(x, y, z) = \begin{cases} \nabla\phi(x, y, z) & z \leq \eta \\ (1 - R_z)\nabla\phi(x, y, \eta) + R_z\vec{u}_w(x, y, z) & z > \eta \end{cases}$$

128 1.

$$129 \quad p(x, y, z) = \begin{cases} -\rho_w \frac{\partial\phi}{\partial t} - \rho_w \frac{|\vec{\nabla}\phi|^2}{2} - \rho_w g z & z \leq \eta \\ 0 & z > \eta \end{cases}$$

130 2.

131

132 in which ρ_w is the density of the water; ϕ is the velocity potential; η is the free surface elevation; \vec{u} is the
133 velocity vector and p the pressure. It is noted that the FNPT is a single-phase model only describing the

134 water flow. In Eq. (1), the velocity of the flow above the free surface (i.e. $z > \eta$ the air phase) is specified
135 by a weighted summation of the corresponding water velocity on the free surface ($\nabla\phi(x, y, \eta)$) and the
136 wind velocity, $\vec{u}_w(x, y, z)$, where R_z is a ramp function ranging from 0 to 1, to ensure a smooth transition
137 of the fluid velocity from the water phase to the air phase. $R_z = 1 - e^{-\beta(z-z_t)/l_z}$ when the volume
138 fraction α at a surface cell on Γ_c is smaller than 0.01, otherwise, $R_z = 0$, where β is an exponential
139 coefficient, l_z is the size of the transition zone and z_t is the vertical coordinate corresponding to the upper
140 boundary of the surface cell in which $\alpha > 0.01$. In this paper, $\vec{u}_w(x, y, z) = 0$, $\beta = 5$ and l_z equal to the
141 vertical cell size near the free surface at Γ_c are appropriate according to the preliminary test. The volume
142 fraction at a surface cell on Γ_c is specified by the ratio of the wetted surface area against the total area of
143 the cell after the free surface at Γ_c is determined by η . Detailed numerical formulation may be found in
144 Yan and Ma (2010a) and Jacobsen et al.(2011).

145

146 It is noted that Eq. (2) can be used to specify the pressure at Γ_c of Ω_{NS} , acting as a pressure boundary
147 condition. However, applying both Eq. (1) and (2) for velocity and pressure boundary conditions at Γ_c
148 results in a scenario that the velocity-pressure relation at such boundary follows the Bernoulli's equation
149 and thus the NS equation is not satisfied, possibly yielding a unsmoothed NS solutions near Γ_c . In the
150 qaleFOAM, two techniques have been employed to overcome the problem. The first one is to use Eq. (1)
151 to specify the velocity boundary condition and to impose the fixed Flux Pressure condition, available in
152 OpenFOAM, as the pressure boundary condition. The 2nd approach is to implement a transitional zone
153 near Γ_c . (Fig. 1), similar to the relaxation zone suggested by Jacobsen et al. (2011). In the transitional
154 zone, the NS-solution f (velocity and pressure) is corrected by $f_{QALE}w + f_{NS}(1 - w)$, where subscripts
155 QALE and NS stand for QALE-FEM solution and NS solution respectively; w is the weighting function,
156 which is 1 on Γ_c , and 0 on the other boundary of the transitional zone, and the exponential function
157 following Jacobsen et al. (2011) is employed. This does not only ensure a smooth transition of the
158 solutions within the transitional zone, but also absorb the reflection/radiation waves from the structures.
159 The length of the transitional zone is determined based on a preliminary test, which suggests that a length
160 of 1 to 2 characteristic wave length is sufficient (Li et al, 2018).

161

162 The wave in the qaleFOAM is generated by the QALE-FEM in Ω_{FNPT} using a second order wavemaker
163 theory (Schaffer, 1996) and propagates towards Ω_{NS} through the coupling boundary Γ_c . Due to the fact

164 that neither the shape nor the motion of the wavemaker are specified in the blind test, to reproduce the
165 wave conditions identical to that in the laboratory, a self-correction technique (Ma et al. 2015) is
166 employed in this study. A summary of this technique is given here for completeness. The initial
167 amplitudes and phases of the wave components driving the motion of the wavemaker are given by $a_i^0 =$
168 $\sqrt{2S(\omega_i)\Delta\omega}$ and $\varphi_i^0 = k_i x_f - \omega_i t_f$, $i = 1, 2, \dots, N$, where x_f and t_f are the specified focusing location and
169 time, respectively. The target spectrum $S^*(\omega)$ and phase φ^* are obtained by applying FFT to the measured
170 surface elevation $\eta^*(t, x_r)$ at a specific gauge location x_r in the experiment. Then iterations are carried out
171 in the following procedures: (i) At the n th iteration, the wavemaker motion is specified by using a_i^n and
172 φ_i^n , based on the second order wavemaker theory (Schäffer, 1996), and the surface elevation $\eta^n(t, x_r)$ is
173 recorded; (ii) The amplitude and the phase of each component are corrected by $a_i^{n+1} =$
174 $a_i^n \sqrt{S^*(\omega_i)/S^n(\omega_i)}$, $\varphi_i^{n+1} = \varphi_i^n + \varphi_m^*(\omega_i) - \varphi_m^n(\omega_i)$, where the subscription m denotes the average
175 phase within the range $[\omega_i - \Delta\omega/2, \omega_i + \Delta\omega/2]$; (iii) The error between $\eta^*(t, x_r)$ and $\eta^n(t, x_r)$ is calculated by
176 using the formula, $Err = \max\{(\eta^* - \eta^n)^2 / \eta^{*2}\}$. If Err is sufficiently small, the iteration stops; Otherwise, n
177 $= n + 1$, go to step (i). Although this approach seems to calibrate the wave in the observation point,
178 numerical investigations have indicated that the wavemaker motion specified in such a way result in a
179 satisfactory agreement between the numerical wave elevation with the experimental data at other
180 locations (Ma et al, 2015; Yan et al, 2020).

181

182 On the right end of the NS domain, Γ_O , a fully absorption of the reflected wave from this boundary or a
183 free passage of the incoming wave is expected. In our previous paper (Li et al. 2018), this boundary was
184 treated in the same way as the left end. The numerical investigation by Li et al. (2018) has demonstrated
185 the effectiveness of this approach for a satisfactory absorption of the reflected waves. However, in this
186 paper, the improved passive wave absorber (Wang et al. 2019; Yan et al. 2020) is employed. On the
187 boundary applying such absorber, a fixed Flux Pressure condition is imposed, the fluid velocity above the
188 free surface (air phase) is specified by a zero-gradient condition, whereas the fluid velocity below the free
189 surface (water phase) are given by

190

$$191 \quad \vec{u}_h(t) = \tilde{\omega}(t) \frac{\cosh(\tilde{k}(t)(z+d))}{\sinh(\tilde{k}(t)d)} \tilde{\eta}(t) \cdot \vec{n}_h$$

192 3.

193 $\frac{\partial U_z}{\partial z} = 0$

194 4.

195

196 where \vec{U}_h and U_z are the horizontal and vertical velocity components, respectively; $\tilde{\omega}$, \tilde{k} , $\tilde{\eta}$ are
 197 instantaneous wave frequency, wave number and the wave elevation recorded at the location of the
 198 absorber; \vec{n}_h is the normal direction of the absorber surface. Once $\tilde{\eta}$ is recorded, $\tilde{\omega}$ can be obtained using
 199 the EKF filter and \tilde{k} can be determined using the linear wave dispersion. The effectiveness of the
 200 improved passive wave absorber has been demonstrated in Wang et al. (2019) and readers are referred to
 201 these references for further details. For the boundary on the floating body surface, the moving-wall
 202 velocity boundary condition and a zero-gradient pressure condition are imposed.

203

204 In the qaleFOAM, the NS equation, continuity equation and the transport equation for the volume fraction
 205 are solved in the arbitrary Lagrangian Eulerian (ALE) forms in order to use the dynamic mesh technique.
 206 After the governing equations are solved, the force and moment on the floating body can be evaluated.
 207 The following six-degree-of-freedom (6DoF) motion equation is solved in a body-fixed coordinate
 208 system (O_b - x_b - y_b - z_b , as sketched in Fig. 1), where the origin O_b locates at the centre of the gravity of the
 209 floating body, following Yan and Ma (2007) and Ma and Yan (2009),

210

211 $[M]\dot{\mathbf{U}}_c = \mathbf{F}$

212 5.

213 $[I]\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times [I]\boldsymbol{\Omega} = \mathbf{N}$

214 6.

215 $\frac{d\mathbf{S}}{dt} = \mathbf{U}_c$

216 7.

217 $[B]\frac{d\boldsymbol{\theta}}{dt} = \boldsymbol{\Omega}$

218 8.

219 where \mathbf{F} and \mathbf{N} are the external forces and moments acting on the floating body in the body-fixed coordinate
 220 system; \mathbf{U}_c and $\dot{\mathbf{U}}_c$ are translational velocity and acceleration at its gravitational centre (rotational centre);

221 Ω and $\dot{\Omega}$ are its angular velocity and acceleration; $\theta(\alpha, \beta, \gamma)$ are the Euler angles and S is the translational
 222 displacement. In Eq. (5) and (6), $[M]$ and $[I]$ are the mass and inertia-moment matrices, respectively. $[B]$
 223 in Eq. (8) is the transformation matrix formed by Euler angles and defined as

$$224 \quad [B] = \begin{bmatrix} \cos\beta\cos\gamma & \sin\gamma & 0 \\ -\cos\beta\sin\gamma & \cos\gamma & 0 \\ \sin\beta & 0 & 1 \end{bmatrix}$$

225 It is easy to deduce that $\Omega \times [I]\Omega = \mathbf{0}$ and $[B]$ is a unit matrix for the cases with 3 DoF, i.e. surge, heave
 226 and pitch. After the translational and rotational motions of the floating body are obtained by Eqs. (5-8), the
 227 OpenFOAM mesh will be updated using the dynamic mesh technique.

228
 229

Table 1 Wave Condition

| Case ID | An(m) | fp(Hz) | h(m) | Hs(m) | kA |
|---------|-------|--------|------|-------|----------|
| 1BT2 | 0.25 | 0.3578 | 3.0 | 0.274 | 0.128778 |
| 2BT2 | 0.25 | 0.4 | 3.0 | 0.274 | 0.160972 |
| 3BT2 | 0.25 | 0.4382 | 3.0 | 0.274 | 0.193167 |

230
 231

Table 2 Mass and Moment of Inertia

| Model | m(kg) | Z _{COM} (m) | I _{xx} (kgm ²) | I _{yy} (kgm ²) | I _{zz} (kgm ²) |
|-------|--------|----------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1 | 43.674 | 0.191 | 1.620 | 1.620 | 1.143 |
| 2 | 61.459 | 0.152 | 3.560 | 3.560 | 3.298 |

232
 233

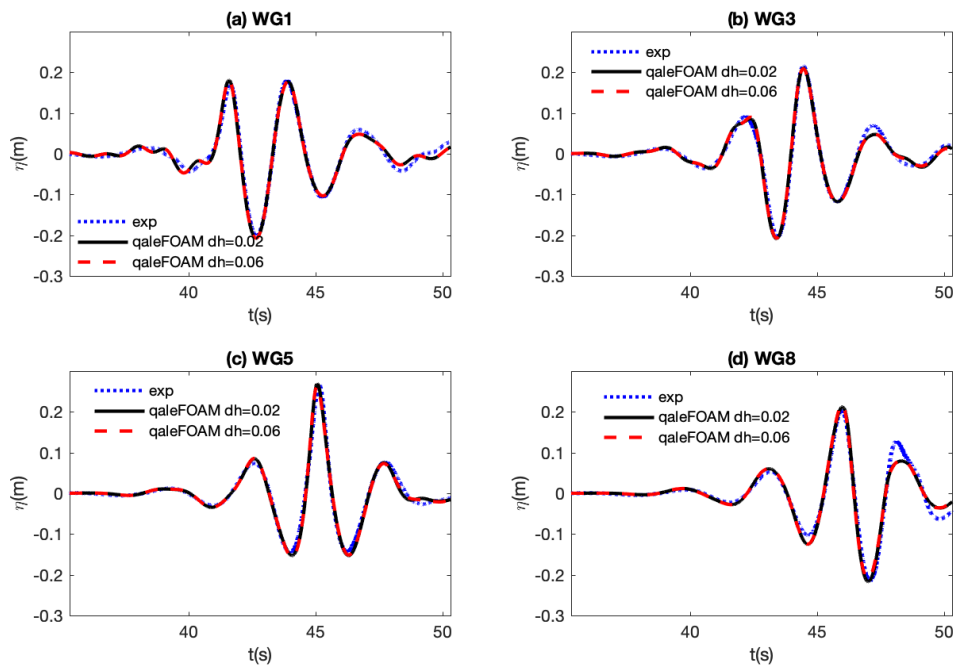
234 3. CCP-WSI Blind Test

235 For all cases considered by the CCP-WSI blind test, the experiment was performed in the wave basin at
 236 the University of Plymouth, which features 35 m in length, 15.5m in width and 3m in depth. Flap wave
 237 paddles are installed to generate three-dimensional waves. The temporal variation of surface elevations at
 238 various locations is recorded by 13 wave gauges (WG) with sampling frequency of 128Hz. The sketches
 239 of the geometry of the wave basin and the distribution of the gauges can be found in Ransley, Brown and
 240 Hann et al (2020) . Three wave conditions are used and summarized in Table 1. Two models of point-
 241 absorber WECs with a specific mooring system are initially placed at where WG5 is located. The
 242 geometries of these models are illustrated by Ransley, Brown and Hann et al (2020). The mass (m),
 243 moments of inertias (I_{xx}, I_{yy} and I_{zz}) at the centre of the mass (CoM) are summarised in Table 2, in which
 244 Z_{COM} stands for the vertical distance from the CoM to the bottom of the models. For both models, the
 245 mooring line is a linear spring with a stiffness of 67 N/m and a rest length of 2.224 m.

246 **3.1 Wave generation and absorption**

247 For all wave conditions, the corresponding empty-tank simulation are carried out to examine whether the
 248 target waves are generated properly. The wave is generated using the self-correction wavemaker in the left
 249 end of Ω_{FNPT} aiming to reproduce the same time history of the wave elevations recorded at WG5. In the
 250 empty tank test, Ω_{FNPT} starts from the wavemaker and the length of Ω_{FNPT} is 50 m, which is longer than the
 251 physical wave tank. As indicated above, this is to minimise the error caused by the reflection from the right
 252 end of Ω_{FNPT} , where a self-adaptive wave absorber is imposed and produces approximately 95% absorption
 253 efficiency. Ω_{NS} starts at $x = 11.55$ m, between WG1 and WG2. Generally speaking, the length of Ω_{NS} shall
 254 be sufficient to accommodate the transitional zone, whose thickness is 1.5 m in the front side and 0.5 m
 255 near the size boundaries of Ω_{NS} , according to the preliminary investigations. To investigate the absorption
 256 efficiency of the improved passive wave absorber applied at the right end of Ω_{NS} , Ω_{NS} ends at $x = 17.55$ m,
 257 where WG8 is placed. Using such a configuration, the gauge data at WG8 can be used as a reference to
 258 qualify the absorption efficiency. The height and width of Ω_{NS} are 6m and 3m respectively. For all cases, a
 259 laminar model is specified as the turbulence properties.

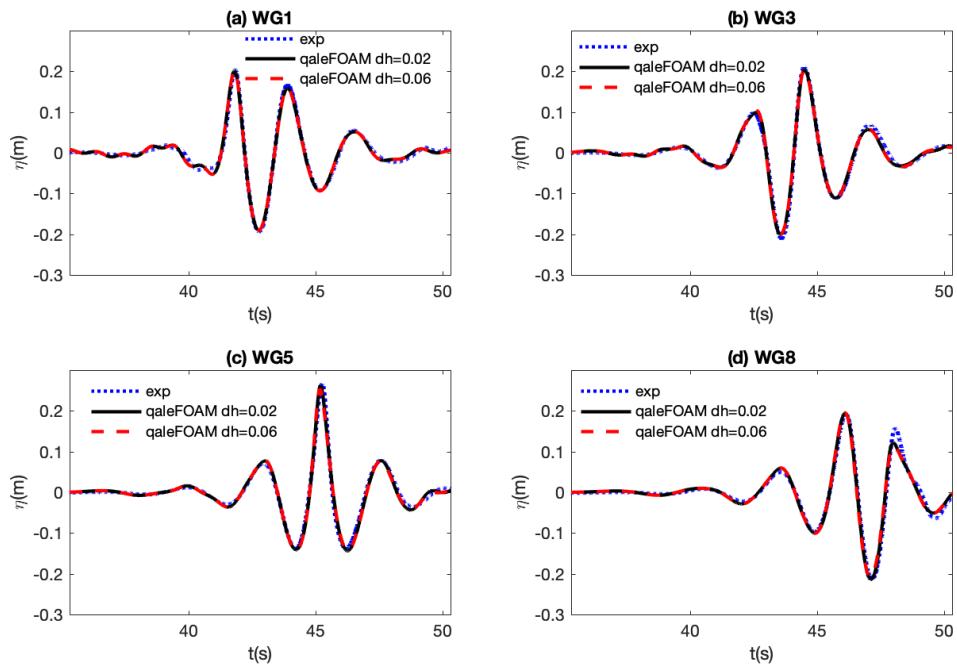
260



261

262 Figure 2. Comparison of the wave elevation recorded at different locations (case 1BT2, empty tank test,
 263 $d_{sv} = 0.0175\text{m}$)

264



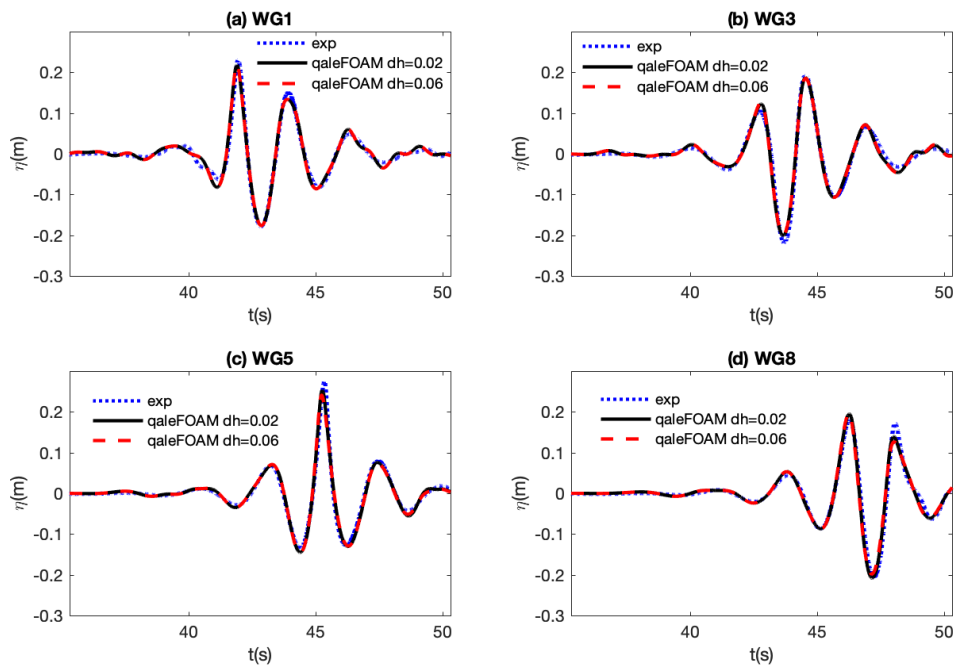
266

267

Figure 3. Comparison of the wave elevation recorded at different locations (case 2BT2, empty tank test, $d_{sv} = 0.0175\text{m}$)

268

269



270

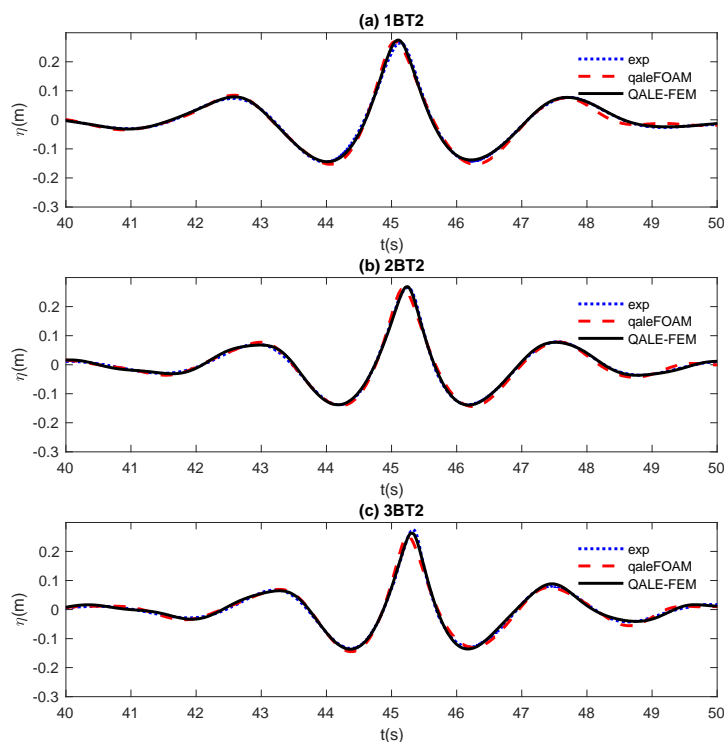
271

Figure 4 Comparison of the wave elevation recorded at different locations (case 3BT2, empty tank test, $d_{sv} = 0.0175\text{m}$)

272

273

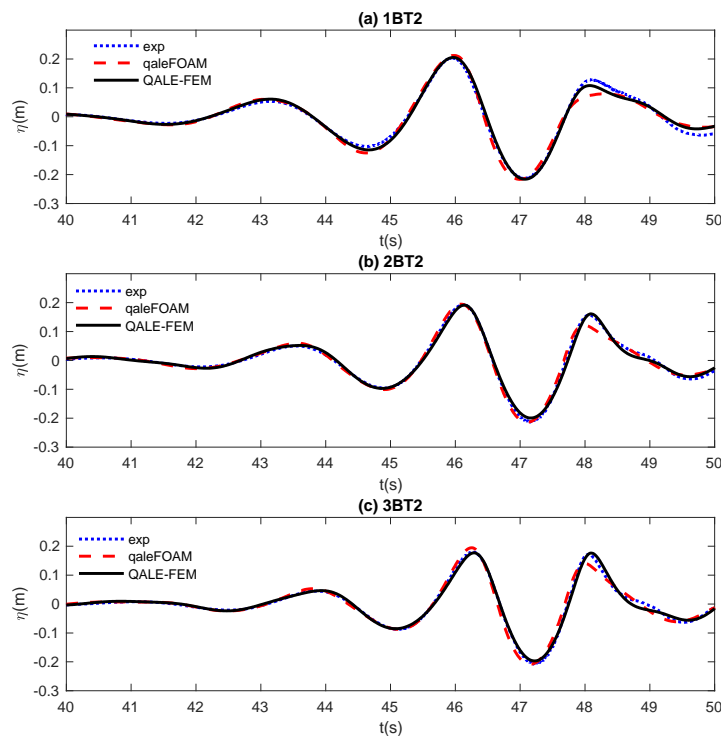
274 The comparisons of the wave elevations at different wave gauges between the qaleFOAM results and the
 275 experimental data are shown in Figures 2-4, where the qaleFOAM results with two different mesh
 276 resolutions are plotted. As observed, two sets of the qaleFOAM results are almost identical to each other,
 277 demonstrating a satisfactory convergence of the qaleFOAM in the empty-tank test. More importantly, the
 278 qaleFOAM results agree well with the corresponding experimental data. This conforms a satisfactory
 279 reproduction of the target waves at WG5 by the self-correction wavemaker technique, even though the tank
 280 geometry and the wavemaker used in the qaleFOAM are different from the experiment.
 281



282
 283 Figure 5 Comparison of the wave elevation recorded at WG5 (empty tank test, qaleFOAM: $d_{sh} = 0.05m$,
 284 $d_{sv} = 0.0175m$; QALE-FEM: $d_s = 0.075m$)
 285

286 Although the agreements between the qaleFOAM results and the experimental data at WG5 has proven
 287 that the present passive wave absorber applied at Γ_o can effectively prevent the wave reflected at Γ_o from
 288 influencing the wave condition at WG5 during the required duration of the simulation (the blind test
 289 requires the submission of the time history ranges from 35.3 s to 50.3 s), a further analysis has been
 290 carried out to quantitatively evaluate the absorption efficiency. As stated by Yan et al (2016), the
 291 theoretical approach based on the linear regular wave theory may not be applicable to highly nonlinear
 292 focusing waves considered in this paper, the absorption efficiency is estimated through the relative
 293 difference between the numerical results adopting the absorber and a reference data which does not

294 include reflection wave, e.g. the corresponding results obtained using a longer tank. One may agree that
 295 the wave elevation in Ω_{FNPT} by the QALE-FEM can be regarded as the reference data, since Ω_{FNPT} is
 296 sufficiently long and the reflection wave from the end of Ω_{FNPT} does not reach WG8 at $t = 50.3$ s. Figures
 297 5 and 6 compare the wave elevations record at WG5 and WG8, respectively. As observed from Figure 5,
 298 the qaleFOAM results are very close to the corresponding QALE-FEM results. The relative differences
 299 between them during $t = 35.3$ s to 50.3 s are all within 2% for three cases (yielding an absorption
 300 efficiency of 98%). Nevertheless, at WG8 (Figures 6), the QALE-FEM results agree with the
 301 experimental data, whereas the qaleFOAM with the wave absorber results in a slightly different results
 302 from others due to the reflection from Γ_O . The relative difference between the QALE-FEM results and
 303 the qaleFOAM results are 2%, 4% and 6% (yielding absorption efficiencies of 98%, 96% and 94%) for
 304 cases 1BT2, 2BT2 and 3BT2, respectively. This is consistent with what Yan et al (2020) concluded.



305
 306 Figure 6 Comparison of the wave elevation recorded at WG8 (empty tank test, qaleFOAM: $d_{\text{sh}} = 0.05\text{m}$,
 307 $d_{\text{sv}} = 0.0175\text{m}$; QALE-FEM: $d_{\text{s}} = 0.075\text{m}$)
 308

309 3.2 Mesh Convergent Test

310 The results shown in Figures 2-6 are obtained in a wave tank without WEC models. For the cases with
 311 WECs, mesh convergent tests are also carried out. For each WEC model, four sets of computational mesh
 312 are generated using the snappyHexMesh tool and adopted in the convergent test. The horizontal (d_{sh}) and
 313 vertical grid sizes (d_{sv}), the total number of grid, N_t , and the number of grid on the structure surface, N_s , are

314 summarised in Table 3. In order to capture the nonlinear wave-structure interaction, as well as small-scale
 315 viscous effects, e.g. boundary layer separation, near the structure, the mesh near a confined zone
 316 surrounding the WEC model with a radius of 0.5m is refined. One example of the mesh near the WEC is
 317 illustrated in Figure 7.

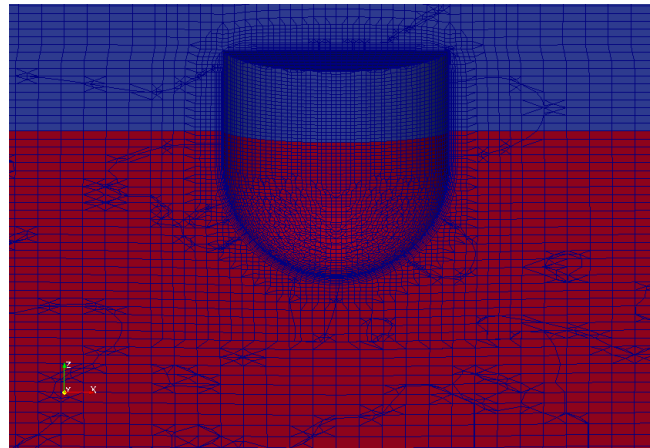
318

319

Table 3 Summary of computational grids used in the convergent test

| Model | Mesh | $d_{sh}(m)$ | $d_{sv}(m)$ | $N_t(M)$ | N_s |
|-------|--------|-------------|-------------|----------|-------|
| 1 | Finest | 0.04 | 0.015 | 1.550 | 10348 |
| 1 | Fine | 0.05 | 0.0175 | 0.956 | 7512 |
| 1 | Medium | 0.06 | 0.02 | 0.613 | 5346 |
| 1 | Coarse | 0.08 | 0.02 | 0.358 | 3882 |
| 2 | Finest | 0.04 | 0.015 | 1.549 | 20128 |
| 2 | Fine | 0.05 | 0.0175 | 0.937 | 13920 |
| 2 | Medium | 0.06 | 0.02 | 0.612 | 9840 |
| 2 | Coarse | 0.08 | 0.02 | 0.376 | 7244 |

320



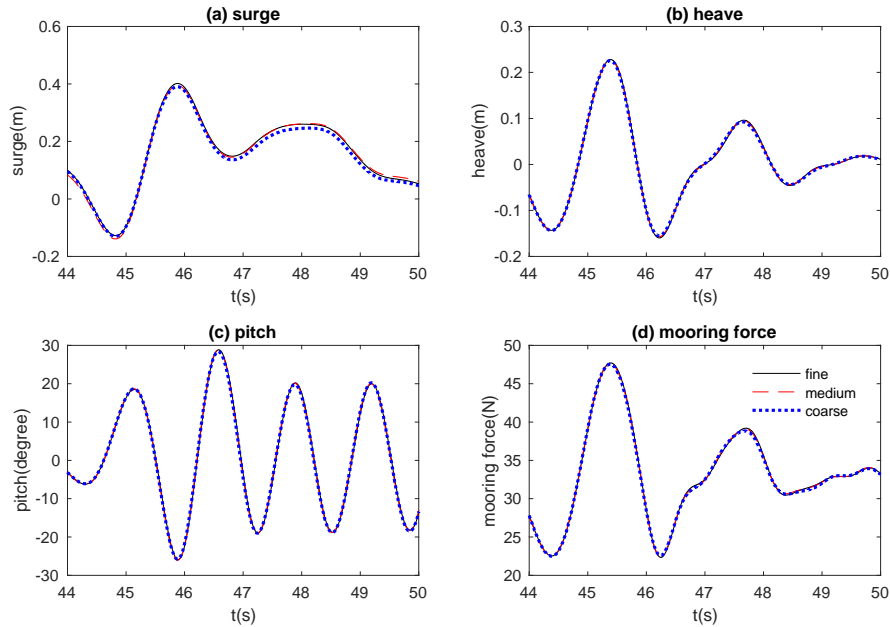
321

322 Figure 7 Illustration of the computational mesh near the WEC (Model 1, $d_{sh} = 0.05m$, $d_{sv} = 0.0175m$, red:
 323 water; blue: air)

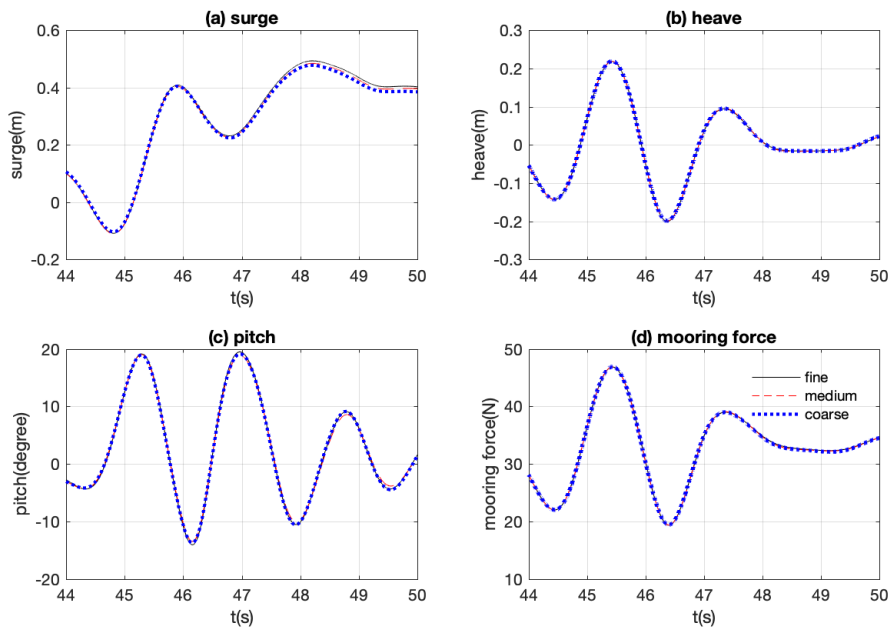
324

325 Figure 8 and Figure 9 compare the motions of and the mooring force on the WEC model 1 and model 2,
 326 respectively, subjected to the wave condition 3BT2, which has the highest wave steepness ($kA =$
 327 0.193127) within all wave conditions specified by the blind test. It is observed that the present results are
 328 insensitive to the mesh resolutions for all participated mesh; especially the results with medium mesh
 329 satisfactorily agree with the corresponding results with finer mesh. Relative errors of the qaleFOAM
 330 results with different mesh sizes are quantitatively analysed. Some results are summarised in Table 4, in
 331 which the relative errors of the numerical results with medium mesh in terms of both the peak value (E_p)
 332 and the RMS error using the time histories during $t = 35.3$ s to $t = 50.3$ s. Similar to Brown et al. (2020),
 333 the results with finest mesh are regarded as the reference values for the analysis. Considering the fact that

334 the maximum relative errors shown in Table 4 is RMS error of 7.5% for Model 1 subjected to Wave
 335 2BT2, one may agree that the medium mesh is sufficient to achieve convergent predictions on the WEC
 336 motions and the mooring force, although similar numerical uncertainty analysis by Brown et al. (2020) is
 337 not presented.



338
 339 Figure 8 Comparison of the WEC motions and mooring force in the cases with different mesh sizes (case
 340 3BT2, Model 1)

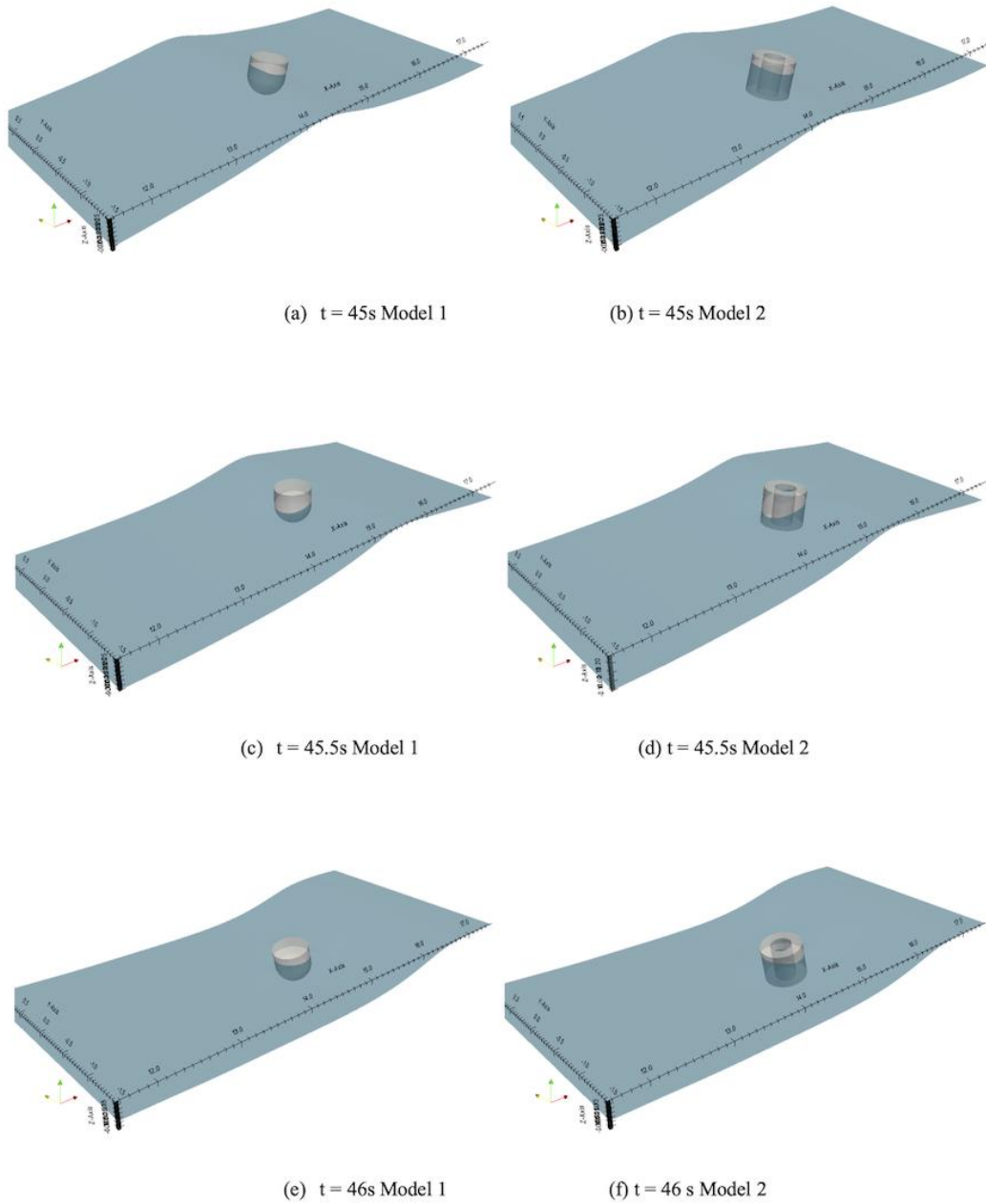


341
 342 Figure 9 Comparison of the WEC motions and mooring force in the cases with different mesh sizes (case
 343 3BT2, Model 2)

344

Table 4 Relative error of qaleFOAM results with the medium mesh

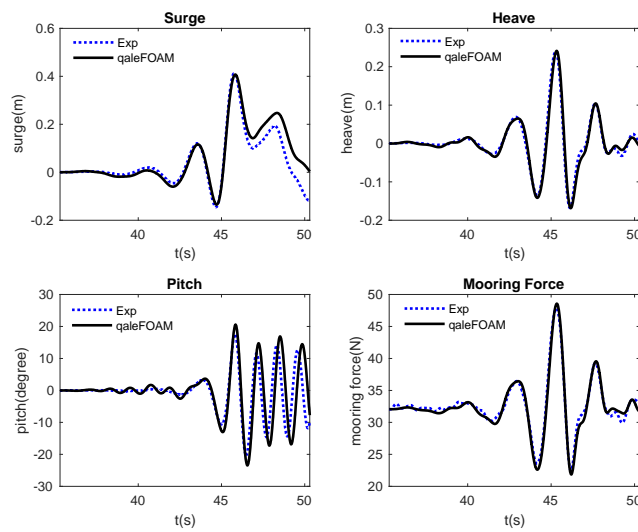
| Error (%) | Model 1 1BT2 | Model 1 2BT2 | Model 1 3BT2 | Model 2 1BT2 | Model 2 2BT2 | Model 3 3BT2 |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| E_p (Surge) | 0.17 | 2.53 | 1.69 | 0.49 | 0.84 | 1.83 |
| E_p (Heave) | 0.81 | 1.05 | 0.69 | 0.30 | 0.22 | 0.18 |
| E_p (Pitch) | 0.27 | 0.39 | 0.71 | 0.44 | 1.12 | 2.48 |
| E_p (Force) | 0.32 | 0.44 | 0.27 | 0.15 | 0.08 | 0.10 |
| RMS(Surge) | 5.22 | 7.47 | 5.36 | 1.60 | 1.12 | 1.75 |
| RMS(Heave) | 1.06 | 1.90 | 1.91 | 0.79 | 0.97 | 0.49 |
| RMS(Pitch) | 2.08 | 4.97 | 4.11 | 3.53 | 3.38 | 3.60 |
| RMS(Force) | 0.18 | 0.28 | 0.26 | 0.14 | 0.15 | 0.16 |



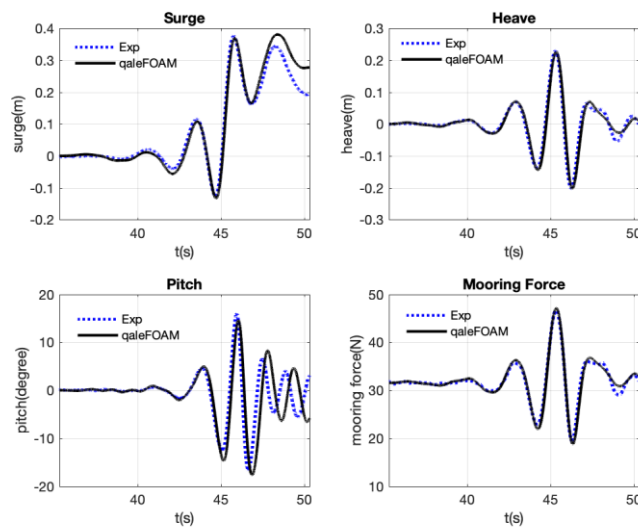
348 Figure 10 Wave elevations near the WECs at $t = 45s$ (case 2BT2)

349 **3.3 Responses of WECs in extreme waves**

350
 351 By using the medium mesh, the motions of the WECs subjected to three wave conditions are numerically
 352 simulated and analysed in this section. For demonstration, Figure10 illustrates the free surface profiles near
 353 the WEC models at three instants around the focusing time, i.e. $t = 45s$, $t = 45.5s$ and $t = 46s$, in the cases
 354 with wave condition 2BT2. As expected, the presences of the WECs do not seem to disturb the surrounding
 355 wave field, confirming to the typical feature of slender bodies (the sizes of the WECs considerably smaller
 356 than the characteristic wavelength).



(a) Model 1



(b) Model 2

Figure 11 Comparison of the time histories of the WEC motions and the mooring loads (case 2BT2)

357
 358

359
 360
 361
 362

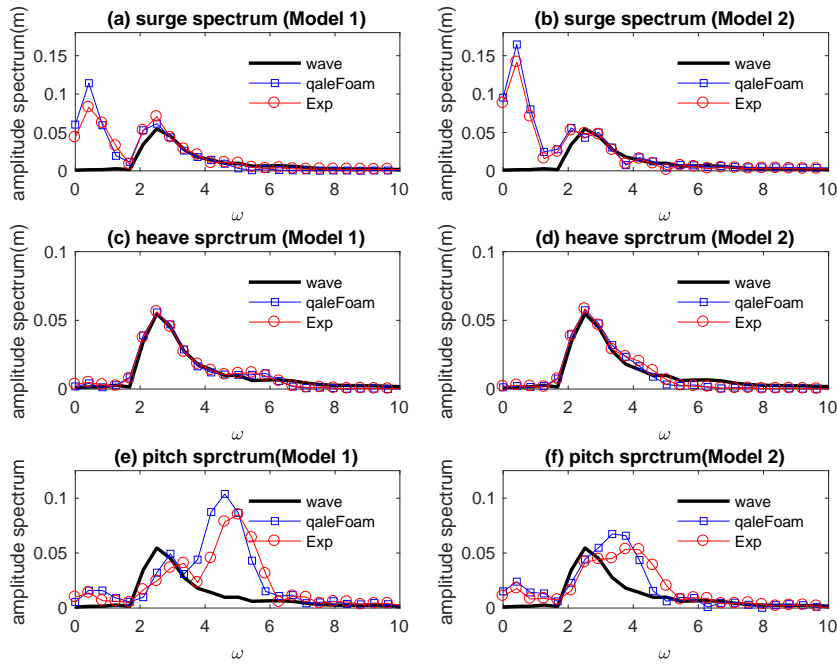


Figure 12 Comparison of the amplitude spectra of the WEC motions (case 2BT2)

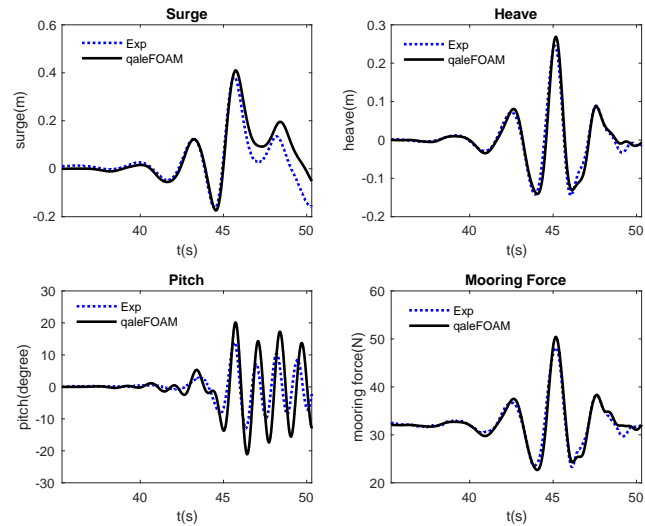
Table 5 Relative error of qaleFOAM results with reference to the experimental data

| Error (%) | Model 1 1BT2 | Model 1 2BT2 | Model 1 3BT2 | Model 2 1BT2 | Model 2 2BT2 | Model 3 3BT2 |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| E_p (Surge) | 6.94 | 1.36 | 7.52 | 6.20 | 1.14 | 7.39 |
| E_p (Heave) | 9.77 | 0.54 | 3.53 | 3.41 | 1.38 | 1.31 |
| E_p (Pitch) | 44.0 | 16.4 | 19.9 | 6.38 | 8.51 | 6.75 |
| E_p (Force) | 4.72 | 1.59 | 0.86 | 3.45 | 0.87 | 2.00 |

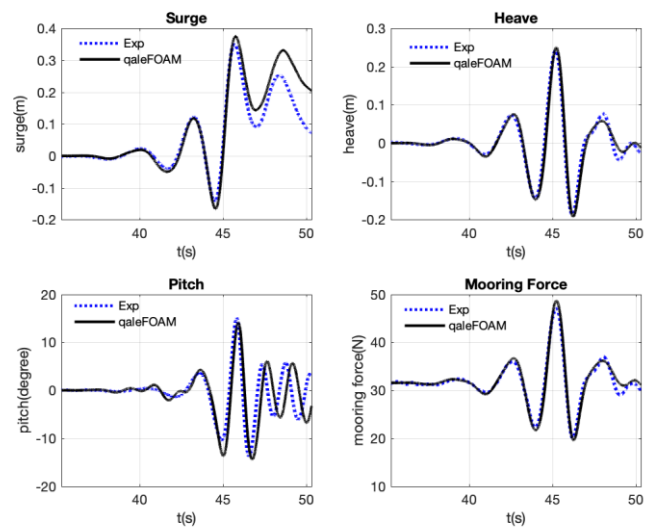
The motions of the WECs and the mooring force acting on the WECs in the case shown in Figures 10 are illustrated in Figure 11. It is found that the profiles of the heave motions largely follow the wave motion (Figure 5(b)). This can be confirmed by Figure 12, which displays the amplitude spectra of the WEC motions and the corresponding wave spectrum at WG5 where the WECs are initially located. The spectra shown in Figure 12 are obtained using the time histories at the duration of 35.3 – 50.3s with a sampling frequency of 128Hz. As observed from Figure 12(c and d), the amplitude spectra of the wave and the heave motion are very close, suggesting a linear heave response to the incident wave. However, the surge motion and the pitch motion exhibit different features from the expected wave at the WEC sites. Specifically, the surge motions suffer from a long-period oscillation after the focused wave crest passes the WECs at $t \approx 45s$ (Figure 11 (a)), whereas the pitch motion exhibits a high-frequency response, which

379 is gradually suppressed in the case with Model 2. These are confirmed by the corresponding spectrum
 380 analysis shown in Figure 12 (a and b) and (e and f), respectively.

381



(a) Model 1



(b) Model 2

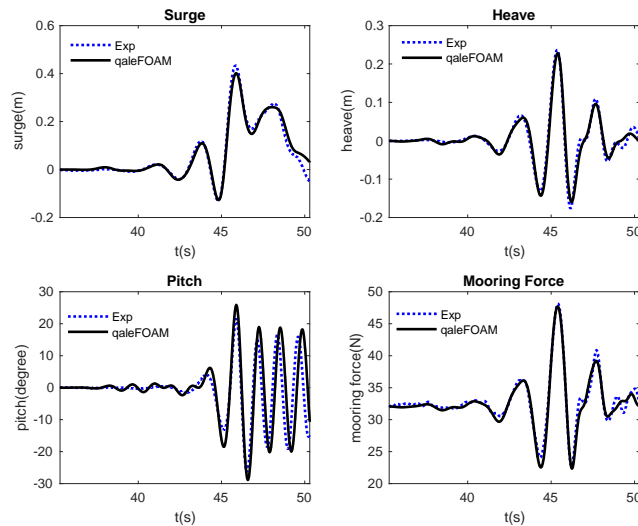
Figure 13 Comparison of the time histories of the WEC motions and the mooring loads (case 1BT2)

382
383

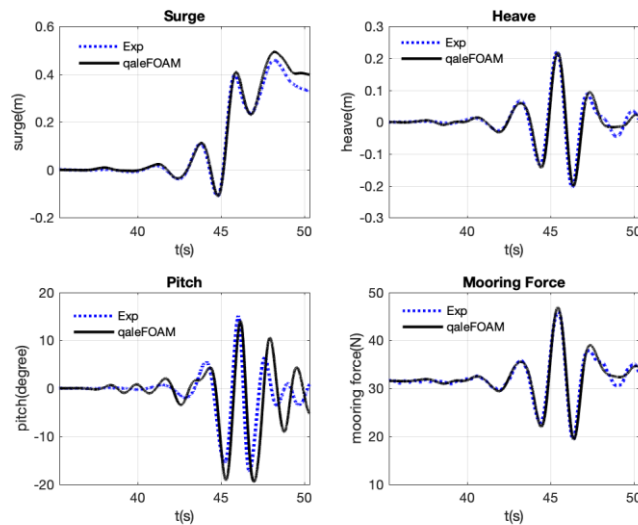
384
385
386
387
388

389 More importantly, the comparisons between the qaleFOAM results and the corresponding experimental
 390 data shown in Figure 11 and Figure 12 largely reflect the practical performance of the qaleFOAM on
 391 modelling the motions of the WECs in extreme waves. For three motion modes and the mooring loads,
 392 the qaleFOAM seems to satisfactorily capture the peak values. The corresponding errors are summarised
 393 in Table 5. Except the pitch motion, the relative errors on surge, heave and mooring load are all below
 394 2%. However, the relative error on peak pitch angle is 16.4% and 8.51% for Model 1 and 2 subjected to

395 Wave 2BT2. Not only the peak pitch angle, the spectra shown in Figure 12 (e) and (f) and the
 396 corresponding time histories shown in Fig. 11 have revealed an unsatisfactory prediction by the
 397 qaleFOAM. Similar phenomena are observed in other cases with different wave conditions. The
 398 corresponding motion responses and the mooring loads are shown in Figures 13-14 and the quantitative
 399 errors on the peak values are summarised in Table 5. In fact, numerical results by other numerical
 400 methods in Ransley et al (2020) behave similarly in terms of predicting pitch motion. A recent
 401 sensitivity analysis by Windt et al (2020) has shown that the pitch motion is sensitive to the centre of
 402 rotation and the moment of inertia. Ransley et al (2020) did not provide the free-decay test for pitch
 403 motion and, therefore, it is difficult to quantify whether the error in pitch motion is due to incorrect
 404 measure of the centre of rotation and the moment of inertia.



(a) Model 1



(b) Model 2

Figure 14 Comparison of the time histories of the WEC motions and the mooring loads (case 3BT2)

405
406

407
408
409

410 **4. Conclusions**

411 In this paper, the qaleFOAM is used to numerically simulate the cases specified by the CCP-WSI Blind
412 Test 2 (Ransley, Brown et al, 2020). All wave conditions summarised in Table 1 have been considered.
413 The effectiveness of the qaleFOAM on modelling focused wave group is assessed by comparing the wave
414 elevations in the empty tank tests, in which the WEC models are not placed. The results confirm a
415 promising accuracy of the qaleFOAM on modelling highly nonlinear water waves. In addition, the
416 convergence test has demonstrated a good convergence property in terms of predicting the motions of the
417 WECs and the associated mooring forces. The comparisons on the motion responses of the WECs
418 between the present numerical results and the experimental data demonstrate a satisfactory accuracy of
419 the qaleFOAM for modelling the highly nonlinear WSI problems addressed in this paper.

420

421 It is further noted that the CPU time spent on cases 1BT3, 2BT3 and 3BT3 to achieve convergent results
422 during $t = 35.3s$ and $t = 50.3s$ are, respectively 12 hours using an 8-processor MPI parallel computing in a
423 workstation with Intel Xeon E5-2680, 2.4GHz, 32G RAM. This demonstrates a satisfactory robustness of
424 the present qaleFOAM.

425

426 **Acknowledgements**

427 The authors gratefully acknowledge the financial support of EPSRC projects (EP/M022382, EP/N006569
428 and EP/N008863) and UKIERI-DST project (DST-UKIERI-2016-17-0029).

429

430 **References**

- 431 Bai W, Eatock Taylor R (2006) Higher-order boundary element simulation of fully nonlinear wave
432 radiation by oscillating vertical cylinders. *Applied Ocean Research*, 28:247–265.
- 433 Brown SA, Ransley EJ, Greaves DM (2020) Assessing focused wave impacts on floating WECs using
434 OpenFOAM, *Proceedings of the Institution of Civil Engineers - Engineering and Computational
435 Mechanics* (in review).
- 436 Celebi MS, Kim MH, Beck RF (1998) Fully nonlinear 3D numerical wave tank simulation. *Journal of
437 Ship Research*, 42:33–45.

438 Colicchio G, Greco M, Faltinsen OM (2006) A BEM-level set domain-decomposition strategy for non-
439 linear and fragmented interfacial flows. *International Journal for Numerical Methods in engineering*,
440 67: 1385-1419.

441 Edmund DO, Maki KJ and Beck RF (2013) A velocity-decomposition formulation for the incompressible
442 Navier–Stokes equations. *Computational Mechanics*, 52: 669–680.

443 Engsig-Karup AP, Bingham HB and Lindberg O (2008) An efficient flexible-order model for 3D
444 nonlinear water wave, *Journal of computational physics*, 228: 2100-2118.

445 Engsig-Karup AP, Eskilsson C and Bigoni D (2016) A Stabilised Nodal Spectral Element Method for
446 Fully Nonlinear Water Waves, *Journal of Computational Physics*, 318: 1-21.

447 Fourtakas G, Stansby PK, Rogers BD et al. (2017) On the coupling of Incompressible SPH with a Finite
448 Element potential flow solver for nonlinear free surface flows, *Proceedings of the 27th International
449 Offshore and Polar Engineering Conference, San Francisco, USA.*

450 Grilli ST, Guyenne P and Dias F (2001) A fully non-linear model for three-dimensional overturning
451 waves over an arbitrary bottom, *International Journal for Numerical Methods in Fluids*, 35(7): 829-
452 867.

453 Hildebrandt A and Sriram V (2014) Pressure distribution and vortex shedding around a cylinder due to a
454 steep wave at the onset of breaking from physical and numerical modeling, *Proceedings of the 24th
455 International Offshore and Polar Engineering Conference, Vol.3, 405-410, Busan, Korea.*

456 Hu ZZ, Greaves D and Raby A (2014) Simulation of extreme free surface waves using OpenFoam, 5th
457 Conference on the application of physical modelling to port and coastal protection, Varna, Bulgaria.
458 Vol. 2: 243-252.

459 Hu ZZ, Mai T, Greaves D et al. (2017) Investigations of Offshore breaking Wave Impacts on a large
460 offshore Structure, *Journal of Fluids and Structure*, 75: 99-116.

461 Hu ZZ, Yan S, Greaves D et al. (2020) Investigation of Interaction between extreme waves and a moored
462 FPSO using FNPT and CFD solvers, *Ocean Engineering*, in review.

463 Jacobsen NG, Fuhrman DR and Fredsøe J (2011) A wave generation toolbox for the opensource CFD
464 library: OpenFoam. *International Journal for Numerical Methods in Fluid* 70:1073-1088.

465 Jasak H (2009) OpenFOAM: Open source CFD in research and industry. *International Journal of Naval
466 Architecture & Ocean Engineering*, 1(2):89-94.

467 Kashiwagi M (2000) Nonlinear simulations of wave-induced motions of a floating body by means of the
468 mixed Eulerian–Lagrangian method. Proceedings of the Institution of Mechanical Engineers. Part C,
469 Journal of Mechanical Engineering Science, 214:841–855.

470 Li Q, Wang JH, Yan S et al. (2018) A Zonal Hybrid Approach Coupling FNPT with OpenFOAM for
471 Modelling Wave-Structure Interactions with Action of Current. Ocean System Engineering 8: 381-
472 407, 2018.

473 Ma QW, Wu GX and Eatock Taylor R (2001) Finite element simulation of fully nonlinear interaction
474 between vertical cylinders and steep waves. Part 1: Methodology and numerical procedure. Journal for
475 Numerical Methods in Fluid 36:265-285.

476 Ma QW and Yan S (2006) Quasi ALE finite element method for nonlinear water waves. Journal of
477 Computational Physics 212: 52-72.

478 Ma QW and Yan S (2009) QALE-FEM for numerical modelling of non-linear interaction between 3D
479 moored floating bodies and steep waves. International Journal for Numerical Methods in Engineering
480 78:713-756.

481 Ma QW, Yan S, Greaves D, Mai T et al. (2015) Numerical and experimental studies of Interaction
482 between FPSO and focusing waves. The Twenty-fifth International Ocean and Polar Engineering
483 Conference, Kona, Hawaii, USA.

484 Ning DZ, Teng B, Eatock Taylor R, et al. (2008) Numerical simulation of nonlinear regular and focused
485 waves in an infinite water-depth, Ocean Engineering, 35(8-9): 887-899.

486 Ning DZ, Zang J, Liu SX et al. (2009) Free surface and wave kinematics for nonlinear focused wave
487 groups, Ocean Engineering, 36(15-16): 1226-1243.

488 Ransley EJ, Brown SA and Hann M et al. (2020) Focused wave interactions with floating structures: A
489 blind comparative study, Proceedings of the Institution of Civil Engineers - Engineering and
490 Computational Mechanics (in review).

491 Ransley EJ, Yan S, Brown SA et al. (2019) A blind comparative study of focused wave interactions with
492 a fixed FPSO-like structure (CCP-WSI Blind Test Series 1). International Journal of Offshore and
493 Polar Engineering 29:113-128.

494 Ransley EJ, Yan S, Brown SA et al. (2020) A blind comparative study of focused wave interactions with
495 floating structures (CCP-WSI Blind Test Series 3), International Journal of Offshore and Polar
496 Engineering, 30(1): 1-10.

497 Schaffer HA (1996) Second-order wavemaker theory for irregular waves. *Ocean Engineering* 23: 47-88.

498 Stansby PK (2013) Coastal Hydrodynamics – present and future, *Journal of Hydraulic Research*, 51(4):
499 341-350.

500 Sriram V, Ma QW and Schlurmann T (2014) A hybrid method for modelling two dimensional non-
501 breaking and breaking waves, *Journal of Computational Physics*, 272: 429-454.

502 Tanizawa K, Minami M (2001) Development of a 3D-NWT for simulation of running ship motions in
503 waves. *International Workshop on Water Waves and Floating Bodies*, Hiroshima, Japan.

504 Tromans PS, Anaturk AR and Hagemeyer P (1991) A new model for the kinematics of large ocean
505 waves – application as a design wave. *The First International Offshore and Polar Engineering*
506 *Conference*. Edinburgh, UK, 1991.

507 Wang, JH, Ma, QW, Yan, S (2018) A hybrid model for simulating rogue waves in random seas on a large
508 temporal and spatial scale, *Journal of Computational Physics*, 313: 279-309.

509 Wang JX, Wang JH, Yan S et al. (2019) An improved passive wave absorber for FNPT-NS solver.
510 Twenty-ninth International Ocean and Polar Engineering Conference, Honolulu, Hawaii, USA,

511 Windt C, Schmitt P, Davidson J et al (2020) Wave-structure interaction of wave energy converters: a
512 sensitivity analysis, *Proceedings of the Institution of Civil Engineers - Engineering and Computational*
513 *Mechanics* (in review).

514 Wu GX, Hu ZZ (2004). Simulation of nonlinear interactions between waves and floating bodies through a
515 finite-element based numerical tank. *Proceedings of the Royal Society of London, Series A*,
516 460:3037–3058.

517 Yan S and Ma QW (2007) Numerical simulation of fully non-linear interaction between steep waves and
518 2D floating bodies using the QALE-FEM method. *Journal of Computational Physics* 221:666–692.

519 Yan S, Ma QW (2010a) Numerical simulation of interaction between wind and 2D freak waves. *European*
520 *Journal of Mechanics, B/Fluids*, 29(1): 18-31.

521 Yan S, Ma QW (2010b) QALE-FEM for modelling 3D overturning waves, *International Journal for*
522 *Numerical Methods in Fluids*, 63: 743-768.

523 Yan S, Ma QW, Wang JH et al. (2016) Self-adaptive wave absorbing technique for nonlinear shallow
524 water waves. *ASME 35th International Conference on Ocean, Offshore and Arctic Engineering*,
525 Busan, South Korea.

526 Yan S, Ma QW, Wang JH et al. (2019) Numerical modelling of wave resonance in a narrow gap between
527 two floating bodies in close proximity using a hybrid model. 38th International Conference on Ocean,
528 Offshore and Arctic Engineering, Glasgow, Scotland, OMAE2019-95247.

529 Yan S, Wang JH, Wang JX et al. (2020) CCP-WSI blind test using qaleFOAM with an improved passive
530 wave absorber, International Journal of Offshore and Polar Engineering, 30(1): 43-52.

531 Yan S, Xie ZH, Li Q et al. (2019) Comparative numerical study on focusing wave interaction with FPSO-
532 like structure. International Journal of Offshore and Polar Engineering 29: 149-157.

533 Zhang NB, Yan S, Zheng X et al. (2020) A 3D hybrid model coupling SPH and QALE-FEM for
534 simulating nonlinear wave-structure interaction, International Journal of Offshore and Polar
535 Engineering, 30(1): 11-19.

536

537

538