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1 Highlights

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6 • A new fully nonlinear potential flow wave model based on Finite Volume
7 Method

8 • A new Fourth-Order Damping Correction scheme is proposed and im-
9 plemented

10 • The model is validated against existing numerical and experimental
11 results

12 • It provides an alternative for coupling with multiphase flow solvers in
13 OpenFOAM

A Finite Volume Based Fully Nonlinear Potential Flow Model for Water Wave Problems

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Abstract

A new Fully Nonlinear Potential Flow (FNPF) numerical model has been developed for the simulation of nonlinear water wave problems. At each time step, the mixed boundary value problem for the flow field is spatially discretised by Finite Volume Method (FVM) and the kinematic and dynamic free surface boundary conditions are defined in a semi-Eulerian-Lagrangian form, which are used to update the wave elevation and velocity potential on the free surface. In the numerical model, waves are generated through a relaxation zone and absorbed by an artificial damping zone at the inlet and outlet of the numerical wave tank (NWT), respectively. Instead of a five-point smoothing technique, a more versatile fourth-order technique is developed to eliminate the possible saw-tooth instability at the free surfaces. Test cases of increasing complexities, such as wave generation and absorption, 2- and 3-Dimensional wave shoaling, and wave-cylinder interaction are simulated to assess its accuracy, convergence, and robustness. For all the cases considered, satisfactory agreements of free surface elevation and wave-induced forces against the experimental measurements and other existing numerical results are achieved. The developed numerical model fully utilises the existing functionalities in OpenFOAM and has the potential to provide an effective alternative to other FNPF based models for constructing a hybrid numerical wave tank model through its coupling with the multiphase flow models in OpenFOAM.

Keywords:

Fully nonlinear potential flow, Finite volume method, OpenFOAM, Wave

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47 **1. Introduction**

48 As a challenging and longstanding scientific problem in coastal, ocean,
49 and offshore engineering, the development of an accurate, efficient, and ro-
50 bust numerical model for wave-wave and wave-structure interactions has been
51 the ultimate goal of computational hydrodynamics. For non-breaking water
52 waves propagation and transformation in the areas from deep offshore water
53 to shallow water, Fully Nonlinear Potential Flow (FNPF) numerical models
54 can provide sufficiently accurate solutions to practical engineering problems.
55

56 In the past decades, substantial progress has been made in applying the
57 fully nonlinear potential flow theory for wave-wave and wave-structure inter-
58 actions. Various conventional discretisation methods, such as Boundary Ele-
59 ment Method (BEM), Finite Element Method (FEM), and Finite Difference
60 Method (FDM), have been adopted to provide accurate solutions to poten-
61 tial flow problems. Whilst FDM (Bingham and Zhang, 2007; Engsig-Karup
62 et al., 2009) as used in OceanWave3D and FEM (Wu and Eatock Taylor,
63 1994; Wu et al., 1998) solve a sparse linear equation system resulting from
64 the discretisation of full computational domain, BEM requires the represen-
65 tation of boundaries including free surfaces only, leading to the formulation
66 of the boundary integral equation in association with the Green’s function
67 and the formation of a full asymmetric matrix (Celebl et al., 1998; Bai and
68 Eatock Taylor, 2006; Eatock Taylor et al., 2008; Bai and Eatock Taylor, 2009;
69 Bai et al., 2014; Hannan and Bai, 2015; Ning et al., 2015). By extending a
70 2-Dimensional (2-D) FNPF model (Grilli et al., 1989), Grilli et al. (2001)
71 further developed a 3-Dimensional (3-D) FNPF model based on higher-order
72 BEM. It was demonstrated that the high-resolution regridding approach used
73 in the 3-D BEM FNPF model can be applied to simulate the highly non-
74 linear process of overturning breaking waves (Guyenne and Grilli, 2006).
75 In order to improve the efficiency of this 3-D FNPF model, Fochesato and
76 Dias (2006) incorporated the Fast Multipole Algorithm (FMA) to substitute
77 matrix-vector product operations and prevent the formation of influence ma-
78 trix. By reducing computational complexity from $O(N^2)$ to nearly $O(N)$,
79 this 3-D BEM based FNPF model with FMA considerably improved com-
80 putational efficiency of the higher-order 3-D BEM FNPF model and allows

for large-scale parallel computing. In the meantime, further improvements to the FEM based solvers have also been made. Ma et al. (2001a,b) implemented an extrapolation scheme for boundary cells to improve the FEM solution and applied the model to investigate the interactions between waves and a fixed cylinder. The FEM FNPF model was further extended using the Quasi Arbitrary Lagrangian-Eulerian approach (QALE-FEM) (Ma and Yan, 2006), which adopts unstructured mesh and avoids mesh regeneration at every time step. The developed code was applied to investigate 2-D (Yan and Ma, 2007) and 3-D (Ma and Yan, 2009) wave interaction with floating structures, demonstrating its capability in accurately capturing 6 Degree of Freedom of body motions.

In addition to the conventional discretisation methods, several alternative efficient or high-order discretisation methods have been proposed with less spatial representations, such as Harmonic Polynomial Cell (HPC) in Shao and Faltinsen (2014), Spectral Element Method (SEM) in Engsig-Karup et al. (2016) and Engsig-Karup and Eskilsson (2019), High-Order Spectral (HOS) model in Ducroz et al. (2006) and Ducroz et al. (2016), and spectral boundary integral method in Wang and Ma (2015) and Wang et al. (2016). The σ -coordinate transformation is another commonly applied technique to deal with the change of the computational domain due to the movement of free surfaces, which has been implemented in FEM, FDM, and SEM in Cai et al. (1998), Turnbull et al. (2003), (Bingham and Zhang, 2007), and Engsig-Karup et al. (2009, 2012, 2016). An extensive comparative study of high-order FDM and pseudo-spectral HOS method Ducroz et al. (2006) demonstrated that given the same level of solution accuracy the pseudo-spectral HOS method presents better computational efficiency for cases of long-distance wave propagation. Although high computational efficiency can be achieved using σ -coordinate transformation, one potential difficulty associated with the method lies in the handling of the potentially complex geometry when simulating wave interaction with floating structures. To overcome this, an overlapping body fitted mesh was introduced in Amini-Afshar et al. and the concept is rather similar to the overset meshing technique (Chen et al., 2019b). As the majority of work on the FNPF models was based on the Mixed-Eulerian-Lagrangian (MEL) method or semi-Eulerian-Lagrangian method, in which the mesh is updated at every time step, another feasible solution to deal with the interaction between waves and semi-submersible or fully submerged floating structures is to develop FNPF models based on

119 MEL with aforementioned high-order discretisation method (Engsig-Karup
120 et al., 2019; Engsig-Karup and Eskilsson, 2019).

121
122 It is well known that the FNPF models fail to correctly simulate post-wave
123 breaking flows and violent wave impact on structures where the effects of fluid
124 viscosity including flow turbulence may become important, although it is pos-
125 sible to apply them to model initial wave overturning process (Grilli et al.,
126 2001; Yan and Ma, 2010; Song and Zhang, 2018). On the other hand, the
127 open source package OpenFOAM, which is based on the NS-VoF models and
128 capable of modelling complex wave structure interaction problems, has be-
129 come increasingly popular. Wave generation and absorption techniques, such
130 as Jacobsen et al. (2012), Higuera et al. (2013, 2015), Martínez-Ferrer et al.
131 (2018), and Chen et al. (2019a), have been integrated into the *interFoam*
132 solver in OpenFOAM and the models have been applied to simulate vio-
133 lent wave impact on ocean and coastal structures under extreme conditions
134 (Paulsen et al., 2014b; Lin et al., 2016, 2017, 2020). However, compared to
135 FNPF models, the computational costs of these solvers are still very high
136 and inherent numerical damping in the solution may lead to energy loss in
137 waves travelling over a long distance. This has led to the development of
138 one-way or two-way coupled FNPF and NS-VoF models (Guignard et al.,
139 1999; Paulsen et al., 2014a; Yan et al., 2019), as well as coupled FNPF and
140 meshless/particle models (Sriram et al., 2014), with the premise that wave
141 generation/propagation and wave/wave interactions over a large portion of
142 the domain can be modelled by an efficient FNPF solver while the local
143 complex fluid-structure interactions can be resolved by NS-VoF or mesh-
144 less/particle models.

145
146 As FVM is the discretisation method adopted in OpenFOAM, the devel-
147 opment of a 3-D FNPF numerical model based on FVM which can be coupled
148 with NS-VoF solvers within the framework of OpenFOAM provides a number
149 of advantages. For examples, all the advanced features and functionalities of
150 OpenFOAM can be fully utilised when developing the new numerical model,
151 including mesh generation, advanced discretisation schemes and OpenMPI
152 for parallelisation. Furthermore, compared to other hybrid numerical wave
153 tank models based on different numerical discretisation methods, program-
154 ming languages and code development environments a FVM based FNPF
155 free surface model can provide a seamless linkage to the existing NS-VoF
156 models in OpenFOAM with the potential to achieve better code accuracy

and efficiency. Earlier work along this line e.g. Mehmood et al. (2015, 2016) has been focused on 2-D wave only problems and suffers from numerical instabilities for long time simulations. In the present work, a new 3-D FVM based FNPF free surface solver has been developed. This is achieved through implementing kinematic and dynamic boundary conditions at free surfaces and wave generation and absorption techniques based on linear and high order wave theories. To maintain the numerical stability of the solver a new smoothing technique applicable to both structured and unstructured meshes is proposed and implemented. A number of test cases have been used to validate the developed solver including wave generation and propagation in 3-D tanks, wave shoaling over 2-D and 3-D slopes, and wave interaction with a fixed cylinder, demonstrating its ability to accurately and efficiently capture highly nonlinear water waves and their interaction with structures. In the following sections, the mathematical formulation of the method is firstly outlined which is followed by the details of numerical implementation including both kinematic and dynamic boundary conditions using the semi-Eulerian-Lagrangian approach and Fourth-Order Damping Correction scheme to eliminate sawtooth instability. Then, the numerical solutions from the current solver for a number of test cases are presented and validated against existing numerical and experimental data. Finally, key conclusions from the present work are given along with a brief plan for the future work.

2. Mathematical formulation

Under the assumption that the fluid is incompressible, inviscid and flow irrotational, the potential flow theory is adopted here to simulate the fully nonlinear water waves. In a computational domain with a Cartesian coordinate system defined, still water surface is located in the xz -plane and the y -axis points vertically upwards, as shown in Figure 1. The governing equation is given as follow:

$$\nabla^2 \phi = 0 \quad (1)$$

where ϕ is the velocity potential. To formulate the boundary value problem for water wave problems, the kinematic and dynamic boundary conditions are satisfied on free surface:

$$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial y} - \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} - \frac{\partial \phi}{\partial z} \frac{\partial \eta}{\partial z} \quad (2)$$

Figure 1: Sketch of the numerical wave flume.

$$\frac{\partial \phi}{\partial t} = -\mathbf{g}\eta - \frac{1}{2}\nabla\phi \cdot \nabla\phi \quad (3)$$

where η is wave elevation, $\mathbf{g}$ is gravitational acceleration, and t is the time. It should be noted that the boundary conditions in Eqs. (2) and (3) are presented in the Eulerian description. However, in the simulation of fully nonlinear wave problems, the free surface boundary conditions need to be satisfied on instantaneous moving boundary surface, leading to the introduction of the well-known Lagrangian description of the free surface boundary conditions. In present study, a semi-Lagrangian method is adopted, in which the total derivative $\frac{\delta(\cdot)}{\delta t}$ in the Lagrangian description is constructed by following a point on the free surface moving with a prescribed velocity $\mathbf{U}_m$,

$$\frac{\delta(\cdot)}{\delta t} = \frac{\partial(\cdot)}{\partial t} + \mathbf{U}_m \cdot \nabla(\cdot) \quad (4)$$

When a point on the free surface is only allowed to move vertically, the prescribed velocity becomes $\mathbf{U}_m = (0, \frac{\partial\eta}{\partial t}, 0)$. In addition, Eq. (2) is rewritten into an equivalent form in terms of the fluid particle velocity at the free surface $\mathbf{U}_\eta$ and the unit normal vector of the free surface $\mathbf{n}$ (Mayer et al., 1998), as they are readily available as part of the output at each time step in OpenFOAM. So, the fully nonlinear free surface boundary conditions in the semi-Lagrangian form can be expressed as follows:

$$\frac{\delta\eta}{\delta t} = \frac{\mathbf{U}_\eta \cdot \mathbf{n}}{n_y} \quad (5)$$

$$\frac{\partial \phi}{\partial t} = -\mathbf{g}\eta - \frac{1}{2}\nabla\phi \cdot \nabla\phi + \frac{\partial\eta}{\partial t} \frac{\partial\phi}{\partial y} \quad (6)$$

205 where n_y is the vertical component of the unit normal vector $\mathbf{n}$.
 206

207 Furthermore, to avoid wave reflection a sponge layer is placed at the far
 208 end of a numerical wave flume. This is achieved by adding an additional
 209 term to the right-hand side of both the kinematic and dynamic boundary
 210 conditions to damp out the wave energy, and Eqs. (5) and (6) consequently
 211 become:

$$\frac{\delta\eta}{\delta t} = \frac{\mathbf{U}_\eta \cdot \mathbf{n}}{n_y} - v(x)(\eta - \eta_s) \quad (7)$$

$$\frac{\partial\phi}{\partial t} = -\mathbf{g}\eta - \frac{1}{2}\nabla\phi \cdot \nabla\phi + \frac{\partial\eta}{\partial t} \frac{\partial\phi}{\partial y} - v(x)\phi \quad (8)$$

$$v(x) = \begin{cases} \alpha\omega\left(\frac{x-x_0}{\beta\lambda}\right)^2, & x \geq x_0 \\ 0, & x < x_0 \end{cases} \quad (9)$$

212 where x_0 is the starting point of the sponge layer; α and β are the damping
 213 coefficients that control the strength and length of the sponge layer, respec-
 214 tively; η_s is the at-rest free surface elevation; λ is the wavelength; and ω is
 215 the wave frequency. The length of sponge layer is recommended to be of 1-2
 216 wavelengths (Ferrant, 1993; Bai and Eatock Taylor, 2006). At the other solid
 217 boundary surfaces of the computational domain, such as the side walls and
 218 the bottom, the impermeable condition is used. When the solid boundary is
 219 fixed, the boundary condition can be expressed as

$$\frac{\partial\phi}{\partial\mathbf{n}} = 0 \quad (10)$$

220 Once the velocity potential is determined by solving the boundary value
 221 problem, the pressure field of the entire domain can be predicted by the
 222 Bernoulli equation:

$$p = -\rho \left(\frac{\partial\phi}{\partial t} + \frac{1}{2}\nabla\phi \cdot \nabla\phi + \mathbf{g}y \right) \quad (11)$$

223 where ρ is water density. The corresponding hydrodynamic force on an
 224 object can then be obtained by the integration of pressure over its wetted

225 surfaces.

226

227 In present numerical wave flume, the waves are generated in the relaxation
228 zone near the inlet boundary of the computational domain by the following
229 equations:

$$\eta = \alpha_R \eta_{computed} + (1 - \alpha_R) \eta_{target} \quad (12)$$

$$\phi = \alpha_R \phi_{computed} + (1 - \alpha_R) \phi_{target} \quad (13)$$

230 where the subscripts *computed* and *target* represent the corresponding
231 values from the computational results and the target waves respectively.
232 This wave generation mechanism can also absorb the reflected wave from
233 the structure inside a NWT, so as to avoid the unwanted second reflection
234 from the inlet boundary. The relaxation function α_R is defined as (Bingham
235 and Zhang, 2007; Jacobsen et al., 2012)

$$\alpha_R(\chi_R) = 1 - \frac{\exp(\chi_R^{3.5}) - 1}{\exp(1) - 1} \quad (14)$$

236 where χ_R is the function that satisfies $\chi_R = 0$ at the inlet and $\chi_R =$
237 1 at the end of a relaxation zone. It is suggested in Bingham and Zhang
238 (2007) and Engsig-Karup (2007) that a relaxation zone of two wavelengths
239 is able to sufficiently absorb the reflected wave. In this study, due to the
240 use of a sponge layer at the far end of the wave tank, this relaxation zone
241 is only located at the wave generation zone to generate waves and absorb
242 possible reflected waves. From Eqs. (12) and (13), it can be seen that
243 the values of wave elevation and velocity potential at the inlet boundary are
244 determined by the corresponding values of the target waves and these will
245 in turn drive the generation of waves in the computational domain. Due to
246 this, the solid wall or zero-flux condition (Eq.(10)) is applied at both inlet
247 and outlet boundaries when solving the Laplace equation (Eq. (1))

248 3. Numerical implementation

249 As indicated above, the present numerical wave flume is developed on
250 the platform of the software package OpenFOAM and the existing func-
251 tions/modules, e.g. the Laplacian solver in OpenFOAM, are fully utilised to
252 avoid duplication of work. To solve the Laplace equation (Eq.1), it is first

Figure 2: Interpolation and mesh update process on a mesh cell on free surface.

integrated over a computational cell of volume V and then converted into surface integration based on Gauss theorem, which in turn is discretised into the sum of the dot product from all cell face values:

$$\int_V \nabla \cdot (\nabla \phi) dV = \oint_S \nabla \phi \cdot d\vec{S} = \sum_i^{\text{nFace}} (\nabla \phi)_{f,i} \cdot \vec{S}_{f,i} = 0 \quad (15)$$

where $\vec{S}_{f,i} = A_{f,i} \vec{n}_{f,i}$, $A_{f,i}$ and $\vec{n}_{f,i}$ are the area and outward unit normal of cell face i respectively.

In present numerical model, computational mesh needs to be updated every time step to account for the motion of free surfaces. This is done by stretching the mesh in the vertical direction using the semi-Lagrangian approach, as demonstrated in Figures 2 and 3. In OpenFOAM, the values of variables, such as velocity potential, pressure, and velocity field, are stored at cell centres, while the mesh update is based on cell vertices. This difference indicates the requirement of additional interpolations from cell centres to cell vertices in order to update the computational mesh according to the kinematic free surface boundary condition. The data interpolation and mesh update processes are shown in Figure 2. Firstly, the Laplace equation is solved numerically using the *fvm :: laplacian* solver in OpenFOAM, in which a non-orthogonal correction scheme is applied to minimise the dis-

Figure 3: Interpolation and mesh update process on a mesh cell on free surface.

271 cretisation errors caused by mesh distortion, and the corresponding results
 272 are stored at cell centres. Secondly, the data at face centres on free surface
 273 are extrapolated from adjacent cell centres, as indicated by the first step in
 274 Figure 2. Then the data at neighbouring face centres are adopted to obtain
 275 the data at cell vertices on free surface by the distance-weighted interpola-
 276 tion indicated as the second step in Figure 2. After obtaining point field data
 277 from neighbour face centres, the cell vertices on free surface move vertically
 278 on the basis of the kinematic free surface boundary condition (see the third
 279 step in Figure 2). Finally, a fourth step is needed to update the mesh of the
 280 fluid domain based on the updated positions of cell vertices on free surfaces
 281 from the third step.
 282

The overall flow chart for the solution of the fully nonlinear potential flow model for water wave problems is shown in Figure 3. In addition to the mesh update process in Figure 2, the first-order Euler explicit time scheme is used to discretise the unsteady term in the free surface boundary conditions and update the wave elevation (Eqs. 5 and 7) and velocity potential (Eqs. 6 and 8) on the free surface respectively. By introducing target wave parameters into the relaxation zone (Eqs. 12-14) in the kinematic and dynamic boundary conditions, the Laplace equation is numerically solved using the new mesh updated by kinematic boundary condition from previous time step, together with solid boundary condition. After solving Laplace equation, velocity field ($\mathbf{U}$) is obtained for updating the mesh in next time step, together with pressure calculation based on Bernoulli equation (Eq. 11). During the simulation in the time domain, the time interval Δt between each step is determined by the Courant–Friedrichs–Lewy (CFL) condition where the CFL number is defined as $u\Delta t/\Delta x$, where u is the local typical velocity and Δx is the local typical mesh size. In present study, the CFL number is chosen to be 0.3 for all the cases.

One issue with the fully nonlinear potential flow model is the numerical instability, which has been reported and treated extensively in literature. This is due to the fact that any numerical error in the fully nonlinear potential flow model can be accumulated until it may build up the saw-tooth instability in many situations, as there is no energy dissipation under the potential flow assumption. As a general solution to deal with this numerical instability, the 5-point low-pass filter is used to smooth the wave elevation and velocity potential at the free surface boundary (Bai and Eatock Taylor, 2006, 2007; Shao and Faltinsen, 2014; Lin et al., 2019). Alternatively, the mesh regeneration and interpolation are another means to mitigate the numerical instability. In the present study, a new Fourth-Order Damping Correction (FODC) scheme is developed to work with the unstructured meshes at the free surface, which are introduced to better represent complex geometry of structures. In the FODC scheme, the new value can be calculated based on the computed value according to

$$\varphi_{new} = \varphi_{computed} - \beta_{FODC}\varphi_{FODC} \quad (16)$$

where φ stands for either the free surface elevation η or the velocity potential ϕ at the free surface; β_{FODC} is a case dependent correction coefficient,

typically ranging from 0.1 to 0.3, which takes the value of 0.2 in present study. φ_{FODC} is the four-order damping correction variable estimated in the following manner:

$$\varphi_{FODC} = \sum_{i=1}^n \left(\varphi_{i,SODC}^D - \varphi_{SODC}^R \right) W_i \quad (17)$$

$$\varphi_{SODC}^R = \sum_{i=1}^n \left(\varphi_{i, \text{computed}}^D - \varphi_{\text{computed}}^R \right) W_i \quad (18)$$

$$W_i = \frac{Dist_i}{\sum_{i=1}^n Dist_i} \quad (19)$$

where the superscripts R and D indicate the values of the receptor and the donor (see Figure 4 for details), respectively; i is the neighbouring donor index; n is the number of the neighbouring donors; φ_{SODC} is the second-order damping correction variable; W_i is the weight function in terms of the distance; $Dist$ is the distance between the receptor and each donor. The second-order damping correction variable φ_{SODC} is calculated on the face vertices (Figure 4a) and face centres (Figure 4b) for η and ϕ , respectively, depending on different storage locations. The main concepts in Eq. 18 for η and ϕ are identical that φ_{SODC}^R is estimated from the difference of computed φ between the donor and the receptor, weighted by their distance in Eq. 19. After that, Eq. 17 is applied to obtain φ_{FODC} from the weighted difference of φ_{SODC} between the donor and the receptor. The last step of the FODC scheme is to correct the computed value in the kinematic and dynamic free surface boundary conditions at the receptor according to Eq. 16 to obtain the final new value.

4. Validations and applications

In order to validate the proposed fully nonlinear numerical model, several representative test cases are selected here. In the first test case, the relaxation zone and a sponge layer for wave generation and absorption, respectively, are introduced in a 3-D numerical wave flume and the results are compared with the analytical solutions (Le Méhauté, 1976; Fenton, 1985), along with a mesh sensitivity study. In addition to wave propagation over a flat seabed, two more test cases involving wave propagation and transformation over a submerged bar are simulated and compared with experimental data and other

Figure 4: Sketch of fourth-order damping correction. Red dot: Receptor; Green rectangular: Neighbouring donor.

existing numerical results. Furthermore, the validations of the code with 3-D shoaling cases are performed to evaluate its applicability of proposed FNPF model for modelling 3-D wave propagation and transformation. Finally, the proposed fully nonlinear potential flow model is validated against the experimental data and the numerical results from a NS-VoF model for the test cases of regular waves interaction with a bottom-mounted circular cylinder.

4.1. Wave generation and absorption

In this test case, wave generation and propagation in a 3-D wave tank is simulated, in which the relaxation zone near the inlet and a sponge layer near the outlet as shown in Figure 5 are introduced in the FNPF model to generate and absorb progressive waves. The case R2 and case R3 in Table 1, which are a second-order Stokes wave and a fifth-order Stokes wave, respectively, are selected to show the performance of the developed numerical model. In section 4.4, wave conditions cases R1 and R2 described in Table 1 will also be used for modelling wave-cylinder interactions. The lengths of the relaxation zone and sponge layer are set to one wavelength. The total length of the numerical wave tank is four times the wavelength in order to examine the capacity of wave absorption and reduce computational efforts. The mesh setup is also presented in Figure 5, where the mesh is refined in the vertical direction near free surface. To examine the mesh convergence of the solution, four different mesh setups are selected as listed in Table 2.

Figure 5: Snapshots of 3-D numerical wave flume. (a) Top view; (b) Side view.

Table 1: Wave parameters for wave generation in a 3-D wave flume

Case ID	Wave amplitude: A (m)	Wave height: H (m)	Wave period: T (s)	Water depth: d (m)	Wave length: λ (m)
R1	0.07	0.14	1.22	0.505	2.106
R2	0.06	0.12	1.63	0.505	3.164
R3	0.125	0.25	2	0.7	4.62

367 To measure the free surface elevation, two Wave Gauges (WGs) are lo-
 368 cated at $x = 0.05\text{m}$ (WG1) and $x = 6\text{m}$ (WG2), respectively. WG1 is used
 369 to measure the reproduction of analytical waves in the relaxation zone, while
 370 WG2 is adopted to measure the numerical waves in the working area. The
 371 simulation time is 40s, which is approximately 25 wave periods. In Figure 6,
 372 the numerical results at WG2 with four different mesh setups are shown and
 373 compared with analytical solution. It is evidently noticed that the wave am-
 374 plitude with Mesh setup M1 dissipates gradually along the wave tank due to
 375 its coarseness and the numerical error introduced by the second-order finite
 376 volume scheme. As the cell number Per Wave Length (PWL) increases from
 377 15 to 30, the simulated waves at WG2 become steady and closer to analytical
 378 solution. It can be seen that the difference in the numerical results between
 379 the mesh setups of M3 and M4 in the zoomed-in (Figure 6b-c) is negligible
 380 and they are all in good agreement with analytical solution. Therefore, based

Table 2: Meshes for sensitivity study

Mesh	Mesh setup (x, y, z)	Cells PWL	Total mesh number
M1	$60 \times 10 \times 10$	15	6,000
M2	$80 \times 10 \times 10$	20	8,000
M3	$100 \times 10 \times 10$	25	10,000
M4	$120 \times 10 \times 10$	30	12,000
M5	$1080 \times 30 \times 5$	50	162,000

Note: PWL is Per Wave Length.

on the mesh sensitivity study it is recommended to have over 25 cells PWL to maintain the stability and accuracy of progressive waves in the proposed FNPF numerical wave tank.

To show the capability of the current model to generate highly nonlinear waves, the fifth-order Stokes waves have been reproduced in the NWT using the proposed FNPF model. The size of a NWT for case R3 is $100\text{m} \times 0.7\text{m} \times 1\text{m}$ in x , y , and z directions, respectively, and the corresponding mesh setup M5 is listed in Table 2. Due to the high nonlinearity of the fifth-order Stokes waves, the number of cells PWL is slightly more than the recommended value above. The numerical results of case R3 are shown in Figure 7, where x is the distance away from inlet boundary. Excellent agreements have been achieved compared to analytical solution of fifth-order Stokes waves based on Fenton (1985), even at WG4 which is 30m away from wave generation zone. This indicates that the present FNPF model is capable of accurately predicting propagation of highly nonlinear waves in a NWT.

Table 3: Wave parameters for 2-D and 3-D shoaling

Case ID	Wave amplitude: A (m)	Wave height: H (m)	Wave period: T (s)	Water depth: d (m)	Wave length: λ (m)
2-D_S1	0.01	0.02	2.02	0.4	3.737
2-D_S2	0.018	0.036	1	0.4	1.4637
3-D_S1	0.0195	0.039	1	0.4572	1.4957
3-D_S2	0.0075	0.015	2	0.4572	3.9095
3-D_S3	0.0106	0.0212	2	0.4572	3.9095
3-D_S4	0.0068	0.0136	3	0.4572	6.1364

Figure 6: Time histories of free surface elevation at WG1 (analytical solution) and WG2 with various mesh densities. (a) Overall time history of free surface elevation; (b) Time history of free surface elevation within $t/T = 20$ - 22 ; (c) Time history of free surface elevation within $t/T = 20.8$ - 21.1 and $\eta/A = 0.7$ - 1.2 .

4.2. 2-D shoaling

In this section, two more complex validation cases, i.e., a 2-D shoaling over a submerged slope with two different wave steepness, are performed to demonstrate the model's ability to accurately predict the effects of bathymetry on wave propagation and transformation. The wave parameters for these two shoaling cases are listed in Table 3, where the case IDs start with 2-D. The experiments of these 2-D cases are described in Beji and Battjes (1993, 1994). The corresponding mesh setups are tabulated in Table 4 and the mesh is refined horizontally in the area around the slope where the wave shoaling phenomenon is significant.

For the 2-D shoaling case, the sketch for laboratory setup is presented in Figure 8, and the time histories of wave elevation at different wave gauges obtained with mesh setup 2-D.M1 are shown in Figure 9. The CPU time taken for the simulation is 1141s using 3 processors (CPU: Intel® Xeon® CPU-E5 2699 v4 @ 2.20 GHz). It can be seen from Figure 9(a) that the incoming waves agree well with the experimental data, even after 10 wave periods. This indicates the target waves are well reproduced, which are also well absorbed by the relaxation zone and the sponge layer at the two ends of

Figure 7: Time histories of free surface elevation at various WGs along the NWT. (a) WG1: $x = 0.5\text{m}$; (b) WG2: $x = 10\text{m}$; (c) WG3: $x = 20\text{m}$; (d) WG4: $x = 30\text{m}$.

the wave tank. According to the results at WG2 ($x = 12.5\text{m}$) to WG9 ($x = 21.0\text{m}$) Figure 9(b-h), decreasing water depth over the submerged slope leads to an increase of wave amplitude and stronger nonlinear effects, which can be observed from both the numerical and experimental results. The fairly good agreements between the numerical and experimental results clearly indicate the proposed FNPF model is able to accurately reproduce the 2-D wave shoaling process, including wave propagation and transformation, although a slight discrepancy between the numerical and experimental results can be observed at WGs 5-8 in Figure 9(e-h), presumably due to the coarse mesh used in the calculation.

To further examine the applicability of the proposed FNPF model in capturing higher nonlinear effects, a higher steepness wave (2-D_S2 in Table 3)

Table 4: Mesh for 2-D and 3-D shoaling

Case ID	Mesh setup (x, y, z)	Cells PWL	Total mesh number	Mesh size in x direction	Mesh size in y direction	Mesh size in z direction
2-D_M1	1213 $\times$ 25 $\times$ 1	Varied	30,325	7.7mm $< \Delta x$ < 210 mm	5mm $< \Delta y$ < 31 mm	N/A
2-D_M2	3000 $\times$ 20 $\times$ 1	Varied	60,000	4.4mm $< \Delta x$ < 210 mm	3mm $< \Delta y$ < 61 mm	N/A
3-D	1500 $\times$ 30 $\times$ 50	Varied	2,250,000	22.5mm $< \Delta x$ < 192 mm	0.67mm $< \Delta y$ < 67.7 mm	Δz $= 121.92$ mm

Note: PWL is Per Wave Length.

Figure 8: Sketch of numerical wave tank for the 2-D shoaling test case (not to scale).

is adopted to investigate the shoaling process over the same submerged bar in Figure 8. The total CPU time taken for the simulation is 4958s using 3 processors. This longer computational time may be attributed to the combined effects of larger velocities in the flow field and corresponding smaller time step under the same CFL number, and slightly increased cell numbers (2-D_M2 in Table 4). It should be noted that the original input wave height for the 2-D_S2 case was 0.041m as indicated in Beji and Battjes (1993), however, the experimental measurement of WG1, located at $x = 6.0$ m just before the submerged slope, showed the generated wave height is actually around 0.036m. Therefore, this measured wave parameter ($H = 0.036$ m) is adopted to reproduce the incident wave, instead of using the original wave height.

In Figure 10(a), the time history of free surface elevation at WG1($x = 6.0$ m) is compared with the experimental results, which demonstrates that the incident waves used in the wave tank test have been accurately repro-

Figure 9: Free surface elevation at various locations and comparison with experimental data of case 2-D_S1 with mesh setup 2-D_M1.

444 deduced by the numerical model. Furthermore, excellent agreements between
 445 numerical and experimental results are achieved at other positions as shown
 446 in Figure 10(b-d) when shoaling occurs and in Figure 10(e-f) when the wave is
 447 passing the rear slope. It can be concluded from the two validation cases that
 448 the proposed FNPF model is capable of accurately predicting wave propaga-
 449 tion and transformation, though computationally it is more expensive than
 450 the high-order discretisation methods (Engsig-Karup et al., 2009; Ducroz et
 451 al., 2014; Engsig-Karup et al., 2016), primarily due to the higher number
 452 of cells required for each wavelength and MEL method used in present FNPF
 453 model.

Figure 10: Free surface elevation at various locations and comparison with experimental data of case 2-D_S2 with mesh setup 2-D_M2

4.3. 3-D shoaling

In additional to the 2-D shoaling, the proposed FNPF model is applied to simulate the well-known benchmark test case of 3-D shoaling (Whalin, 1971) over a submerged semi-circular slope to demonstrate the capacity of the present fully nonlinear numerical model in predicting the nonlinear characteristics of 3-D wave propagation and transformation. In the 3-D shoaling experiment, the water depth is defined as follows: (1) the water depth at left flat bottom is 0.4572m with $0 \leq x \leq 10.67 - G(z)$, where $G(z) = \sqrt{z(6.096 - z)}$; (2) the water depth at semi-circular slope is described as $0.4572 + \frac{1}{25}(10.67 - G(z) - x)$ at $10.67 - G(z) < x < 18.29 - G(z)$; (3) the water depth at right flat bottom is 0.1524m with $18.29 - G(z) \leq x \leq 35.0$. Four different wave parameters are adopted, as listed in Table 3, while the

Figure 11: Harmonic components of numerical results and experimental measurements at the streamwise central line of numerical wave tank. (a) Case 3-D_S1; (b) Case 3-D_S2; (c) 3-D_S3; (d) 3-D_S4.

466 mesh setups are tabulated in Table 4 with various horizontal stretching ratios
 467 depending on the wavelength and wave focusing zone.

468

469 In Figure 11, the different harmonic components obtained by Fast Fourier
 470 Transform (FFT) along the streamwise central line of the domain are com-
 471 pared among the experimental measurements and the numerical results from
 472 the present FNPF model, Shao and Faltinsen (2014), and Engsig-Karup et al.
 473 (2009). Overall, the present numerical results agree well with the experimen-
 474 tal results and other numerical results up to the third harmonic component
 475 for all the four different cases. The snapshots of Case 3-D_S3 in the form

Figure 12: Snapshots of wave shoaling over a semi-circular slope for Case 3-D.S3 (Not in scale in the y direction and exaggerated 20 times)

of free surface elevation are presented in Figure 12, which shows that the 2-D waves generated in the relaxation zone first propagate towards the semi-circular slope (Figure 12a), then become locally steeper due to the presence of the semi-circular slope and eventually dissipated in the sponge layer zone (Figure 12b-d). From the above discussion, it is concluded that the 3-D and nonlinear wave effects of the flow problem can be accurately captured by the proposed FNPF model.

In addition to validating the FNPF model, the OpenMPI has been implemented for running the code in parallel with its efficiency evaluated using case 3-D.S4 shown in Table 3 and mesh setup 3-D in Table 4. The results showed that a speedup of 2.1 and 8.1 has been achieved from using 4 processors and 24 processors respectively, compared to the serial computation. As the focus of the current work was to develop and properly validate the 3D FNPF free surface code, there is still scope for further improving its parallel efficiency and this will be done in the near future.

4.4. Wave-cylinder interaction

To investigate the capability and accuracy of the present model in predicting wave loading on structures, a further test case involving wave interaction with a surface piercing cylinder is performed (Zang et al., 2010), together with an examination on the performance of the applied unstructured mesh for the relatively complex geometry of the computational domain. The setup of the unstructured mesh for the simulation is shown in Figure 13, where

Figure 13: Mesh setup for wave-cylinder interaction.

499 nearly equal sized mesh cells are predominantly adopted in the computa-
 500 tional domain, with local mesh refinement in the vicinity of the circular
 501 cylinder in order to capture the fine details of the wave-structure interaction.
 502 The ranges of mesh cell dimensions are $0.0075\text{m} < \Delta x < 0.05\text{m}$, 0.006m
 503 $< \Delta y < 0.0345\text{m}$, $0.0075\text{m} < \Delta z < 0.05\text{m}$, respectively, and the total num-
 504 ber of cells is around 1.4 million. The wave tank is 12.6m long, 4m wide, and
 505 0.505 deep, in which the cylinder diameter is 0.25m. The relaxation zone for
 506 wave generation is 1 wavelength long and the length of sponge layer is two
 507 wavelengths.

508
 509 Two sets of wave parameters in Chen et al. (2014) are adopted for vali-
 510 dation as listed in Table 1. The FFT analysis in Chen et al. (2014) indicated
 511 that these two waves are second-order stokes waves and higher harmonic
 512 components are introduced when the incident wave interacts with the circu-
 513 lar cylinder. These provide good validation test cases for the present FNPF
 514 model to examine its ability to model strongly nonlinear wave-wave and
 515 wave-structure interaction problems. In addition to the comparison with ex-
 516 perimental measurements, the numerical results from a NS-VoF model are

Figure 14: Free surface elevation at the front stagnation point of the cylinder. (a) Case R1; (b) Case R2.

also presented and compared with the results from the FNPF model in Figures 14 and 15 for the wave elevation and wave force, respectively. The fairly good agreements between the two numerical results and experimental data demonstrate that the present FNPF model has the capacity of capturing strongly nonlinear wave-cylinder interaction using the unstructured mesh setup, despite the small discrepancy of free surface elevation between the FNPF and NS-VoF models at wave troughs and wave crests as shown in Figure 14(a). This may be attributed to the existence of higher-order nonlinear components, which may appear in some local areas and be caused by the viscous effects. However, it can be observed from Figure 15 that the viscous effect plays an insignificant role in determining the inline force for these cases.

To clearly illustrate the interactions between the waves and a circular cylinder using the present FNPF model, the snapshots of free surface elevation of Case R1 within one wave period are shown in Figure 16, together with the mesh motions on cylinder surface. When the wave crest approaches the cylinder (Figure 16a-b), wave run-up takes place as indicated by the mesh movement on cylinder surface. After the passing of wave crest (Figure 16c), two wave fronts merge at the rear side of the cylinder, causing a large vertical motion of the surface mesh. Following this, the wave trough approaches the front stagnation point of the cylinder and a return flow from the rear side to the front side is evidently captured in Figure 16(d-e). Before the arrival of

Figure 15: Time series of inline forces on the cylinder. (a) Case R1; (b) Case R2.

539 next wave crest at the front stagnation point, the return flow merges into a
 540 small wave run-up in Figure 16(f). Based on the results, it can be concluded
 541 that the present FNPF model is able to accurately capture the detailed flow
 542 patterns of the wave-structure interaction problem where the viscous effect
 543 is shown to be insignificant.

544 5. Conclusion

545 In this paper, a new fully nonlinear potential flow based numerical wave
 546 model is developed using Finite Volume Method on the platform of Open-
 547 FOAM, which provides an effective alternative for modelling wave-wave and
 548 wave-structure interaction problems and for coupling with the finite volume
 549 based Navier-Stokes models in OpenFOAM in a consistent and efficient man-
 550 ner. The development of the numerical model conforms to the coding stan-
 551 dard of OpenFOAM and makes full use of the its existing functionalities. The
 552 numerical implementation of the present FNPF model is described in detail,
 553 which includes the variable interpolations between the cell centres and the
 554 cell faces/vertices for implementing the free surface boundary conditions, as
 555 well as the high-order smoothing technique for mitigating the issue of numer-
 556 ical instability. A variety of test cases have been simulated to validate the
 557 developed code and to demonstrate its robustness. Fairly good agreements
 558 between the present numerical results and the experimental measurements
 559 and other numerical results are obtained for all the test cases, which indicate

Figure 16: Snapshots of wave-cylinder interaction and mesh motions on cylinder surface for Case R1 at various time instants.

560 that the developed FNPf numerical model is able to accurately simulate the
 561 problems of wave generation, propagation and its interaction with fixed struc-
 562 tures as long as no wave breaking occurs. One should be noted that, although
 563 the present FNPf model may be computationally more expensive than the
 564 existing high-order discretisation methods due to the requirements of finer
 565 mesh for spatial representation and MEL used to represent free surface, it
 566 is more flexible as far as the modelling of interaction between waves and
 567 floating structures with complex geometry is concerned. In the future, the
 568 model will be further optimised for better computational/parallel efficiency,
 569 extended to model the interactions between waves and floating structures,
 570 and coupled with the existing NS-VoF models in OpenFOAM to construct
 571 an efficient and robust numerical wave tank model.

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References

- Amini-Afshar M, Bingham HB, Henshaw WD, Read R. A nonlinear potential-flow model for wave-structure interaction using high-order finite differences on overlapping grids. In: Preceeding of the 34th International Workshop on Water Waves and Floating Bodies (IWWWFB). .
- Bai W, Eatock Taylor R. Higher-order boundary element simulation of fully nonlinear wave radiation by oscillating vertical cylinders. *Applied Ocean Research* 2006;28(4):247–65.
- Bai W, Eatock Taylor R. Numerical simulation of fully nonlinear regular and focused wave diffraction around a vertical cylinder using domain decomposition. *Applied Ocean Research* 2007;29(1):55–71.
- Bai W, Eatock Taylor R. Fully nonlinear simulation of wave interaction with fixed and floating flared structures. *Ocean engineering* 2009;36(3):223–36.
- Bai W, Feng X, Eatock Taylor R, Ang K. Fully nonlinear analysis of near-trapping phenomenon around an array of cylinders. *Applied Ocean Research* 2014;44:71–81.
- Beji S, Battjes J. Experimental investigation of wave propagation over a bar. *Coastal Engineering* 1993;19(1-2):151–62.
- Beji S, Battjes J. Numerical simulation of nonlinear wave propagation over a bar. *Coastal Engineering* 1994;23(1-2):1–16.
- Bingham HB, Zhang H. On the accuracy of finite-difference solutions for nonlinear water waves. *Journal of Engineering Mathematics* 2007;58(1-4):211–28.
- Cai X, Langtangen HP, Nielsen BF, Tveito A. A finite element method for fully nonlinear water waves. *Journal of Computational Physics* 1998;143(2):544–68.

606 Celebl M, Kim M, Beck RF. Fully nonlinear 3-D numerical wave tank sim-
607 ulation. *Journal of Ship Research* 1998;42(1):33–45.

608 Chen H, Qian L, Bai W, Ma Z, Lin Z, Xue MA. Oblique focused wave
609 group generation and interaction with a fixed FPSO-shaped body: 3D
610 CFD simulations and comparison with experiments. *Ocean Engineering*
611 2019a;192:106524.

612 Chen H, Qian L, Ma Z, Bai W, Li Y, Causon D, Mingham C. Application
613 of an overset mesh based numerical wave tank for modelling realistic free-
614 surface hydrodynamic problems. *Ocean Engineering* 2019b;176:97–117.

615 Chen L, Zang J, Hillis A, Morgan G, Plummer A. Numerical investiga-
616 tion of wave–structure interaction using OpenFOAM. *Ocean Engineering*
617 2014;88:91–109.

618 Ducrozet G, Bonnefoy F, Le Touzé D, Ferrant P. Implementation and val-
619 idation of nonlinear wavemaker models in a HOS numerical wave tank.
620 *International Journal of Offshore and Polar Engineering* 2006;16(03).

621 Ducrozet G, Bonnefoy F, Le Touzé D, Ferrant P. HOS-ocean: Open-source
622 solver for nonlinear waves in open ocean based on high-order spectral
623 method. *Computer Physics Communications* 2016;203:245–54.

624 Ducrozet G, Engsig-Karup AP, Bingham HB, Ferrant P. A non-linear wave
625 decomposition model for efficient wave–structure interaction. Part A: For-
626 mulation, validations and analysis. *Journal of Computational Physics*
627 2014;257:863–83.

628 Eatock Taylor R, Wu G, Bai W, Hu Z. Numerical wave tanks based on finite
629 element and boundary element modeling. *Journal of Offshore Mechanics*
630 *and Arctic Engineering* 2008;130(3):031001.

631 Engsig-Karup AP. Unstructured nodal DG-FEM solution of high-order
632 Boussinesq-type equations. Ph.d.; 2007.

633 Engsig-Karup AP, Bingham HB, Lindberg O. An efficient flexible-order
634 model for 3D nonlinear water waves. *Journal of computational physics*
635 2009;228(6):2100–18.

- 636 Engsig-Karup AP, Eskilsson C. Spectral element FNPF simulation of focused
637 wave groups impacting a fixed FPSO-type body. *International Journal of*
638 *Offshore and Polar Engineering* 2019;29(02):141–8.
- 639 Engsig-Karup AP, Eskilsson C, Bigoni D. A stabilised nodal spectral element
640 method for fully nonlinear water waves. *Journal of Computational Physics*
641 2016;318:1–21.
- 642 Engsig-Karup AP, Madsen MG, Glimberg SL. A massively parallel GPU-
643 accelerated model for analysis of fully nonlinear free surface waves. *Inter-*
644 *national Journal for Numerical Methods in Fluids* 2012;70(1):20–36.
- 645 Engsig-Karup AP, Monteserin C, Eskilsson C. A mixed eulerian–lagrangian
646 spectral element method for nonlinear wave interaction with fixed struc-
647 tures. *Water Waves* 2019;1(2):315–42.
- 648 Fenton JD. A fifth-order stokes theory for steady waves. *Journal of waterway,*
649 *port, coastal, and ocean engineering* 1985;111(2):216–34.
- 650 Ferrant P. Three-dimensional unsteady wave-body interactions by a Rankine
651 boundary element method. *Ship Technology Research* 1993;40:165–75.
- 652 Fochesato C, Dias F. A fast method for nonlinear three-dimensional free-
653 surface waves. *Proceedings of the Royal Society A: Mathematical, Physical*
654 *and Engineering Sciences* 2006;462(2073):2715–35.
- 655 Grilli ST, Guyenne P, Dias F. A fully non-linear model for three-dimensional
656 overturning waves over an arbitrary bottom. *International Journal for*
657 *Numerical Methods in Fluids* 2001;35(7):829–67.
- 658 Grilli ST, Skourup J, Svendsen IA. An efficient boundary element method
659 for nonlinear water waves. *Engineering Analysis with Boundary Elements*
660 1989;6(2):97–107.
- 661 Guignard S, Grilli ST, Marcer R, Rey V. Computation of shoaling and break-
662 ing waves in nearshore areas by the coupling of BEM and VOF methods.
663 In: *The Ninth International Offshore and Polar Engineering Conference.*
664 *International Society of Offshore and Polar Engineers; 1999. .*
- 665 Guyenne P, Grilli S. Numerical study of three-dimensional overturning waves
666 in shallow water. *Journal of Fluid Mechanics* 2006;547:361–88.

- 667 Hannan M, Bai W. Nonlinear hydrodynamic responses of submerged mov-
 668 ing payload in vicinity of a crane barge in waves. *Marine Structures*
 669 2015;41:154–79.
- 670 Higuera P, Lara JL, Losada IJ. Realistic wave generation and active wave ab-
 671 sorption for Navier–Stokes models: Application to OpenFOAM®. *Coastal*
 672 *Engineering* 2013;71:102–18.
- 673 Higuera P, Losada IJ, Lara JL. Three-dimensional numerical wave generation
 674 with moving boundaries. *Coastal Engineering* 2015;101:35–47.
- 675 Jacobsen NG, Fuhrman DR, Fredsøe J. A wave generation toolbox for the
 676 open-source CFD library: OpenFoam®. *International Journal for numer-*
 677 *ical methods in fluids* 2012;70(9):1073–88.
- 678 Le Méhauté B. *An Introduction to Hydrodynamics and Water Waves*. Springer
 679 Study Ed. Springer, Berlin Heidelberg, Germany., 1976.
- 680 Lin Z, Guo Y, Jeng Ds, Liao C, Rey N. An integrated numerical model for
 681 wave–soil–pipeline interactions. *Coastal Engineering* 2016;108:25–35.
- 682 Lin Z, Pokrajac D, Guo Y, Jeng DS, Tang T, Rey N, Zheng J, Zhang J.
 683 Investigation of nonlinear wave-induced seabed response around mono-pile
 684 foundation. *Coastal Engineering* 2017;121:197–211.
- 685 Lin Z, Pokrajac D, Guo Y, Liao C, Tang T. Near-trapping effect of wave-
 686 cylinders interaction on pore water pressure and liquefaction around a
 687 cylinder array. *Ocean Engineering* 2020;218:108047.
- 688 Lin Z, Qian L, Bai W, Ma Z, Chen H, Zhou J. Development of a 3D fully
 689 nonlinear potential flow wave tank in framework of OpenFOAM. In: Pro-
 690 ceedings of the ASME 38th International Conference on Ocean, Offshore
 691 and Artic Engineering (OMAE). 2019. .
- 692 Ma Q, Wu G, Eatock Taylor R. Finite element simulation of fully non-linear
 693 interaction between vertical cylinders and steep waves. Part 1: methodol-
 694 ogy and numerical procedure. *International Journal for Numerical Meth-*
 695 *ods in Fluids* 2001a;36(3):265–85.
- 696 Ma Q, Wu G, Eatock Taylor R. Finite element simulations of fully non-linear
 697 interaction between vertical cylinders and steep waves. Part 2: numerical

- 698 results and validation. *International Journal for Numerical Methods in*
699 *Fluids* 2001b;36(3):287–308.
- 700 Ma Q, Yan S. QALE-FEM for numerical modelling of non-linear interaction
701 between 3d moored floating bodies and steep waves. *International Journal*
702 *for Numerical Methods in Engineering* 2009;78(6):713–56.
- 703 Ma QW, Yan S. Quasi ALE finite element method for nonlinear water waves.
704 *Journal of computational physics* 2006;212(1):52–72.
- 705 Martínez-Ferrer PJ, Qian L, Ma Z, Causon DM, Mingham CG. Improved
706 numerical wave generation for modelling ocean and coastal engineering
707 problems. *Ocean Engineering* 2018;152:257–72.
- 708 Mayer S, Garapon A, Sørensen LS. A fractional step method for unsteady free
709 surface flow with applications to nonlinear wave dynamics. *International*
710 *Journal for Numerical Methods in Fluids* 1998;28(2):293–315.
- 711 Mehmood A, Graham DI, Langfeld K, Greaves DM. OpenFOAM finite vol-
712 ume method implementation of a fully nonlinear potential flow model for
713 simulating wave-structure interactions. In: *The 25th International Ocean*
714 *and Polar Engineering Conference*. International Society of Offshore and
715 *Polar Engineers*; 2015. .
- 716 Mehmood A, Graham DI, Langfeld K, Greaves DM. Numerical simulation
717 of nonlinear water waves based on fully nonlinear potential flow theory in
718 OpenFOAM®-Extend. In: *The 26th International Ocean and Polar Engi-*
719 *neering Conference*. International Society of Offshore and Polar Engineers;
720 2016. .
- 721 Ning DZ, Shi J, Zou QP, Teng B. Investigation of hydrodynamic perfor-
722 mance of an OWC (oscillating water column) wave energy device using a
723 fully nonlinear HOBEM (higher-order boundary element method). *Energy*
724 2015;83:177–88.
- 725 Paulsen BT, Bredmose H, Bingham HB. An efficient domain decomposition
726 strategy for wave loads on surface piercing circular cylinders. *Coastal*
727 *Engineering* 2014a;86:57–76.

- 728 Paulsen BT, Bredmose H, Bingham HB, Jacobsen NG. Forcing of a bottom-
729 mounted circular cylinder by steep regular water waves at finite depth.
730 Journal of Fluid Mechanics 2014b;755:1–34.
- 731 Shao YL, Faltinsen OM. A harmonic polynomial cell (hpc) method for 3d
732 laplace equation with application in marine hydrodynamics. Journal of
733 Computational Physics 2014;274:312–32.
- 734 Song B, Zhang C. Boundary element study of wave impact on a vertical
735 wall with air entrapment. Engineering Analysis with Boundary Elements
736 2018;90:26–38.
- 737 Sriram V, Ma Q, Schlurmann T. A hybrid method for modelling two dimen-
738 sional non-breaking and breaking waves. Journal of computational physics
739 2014;272:429–54.
- 740 Turnbull MS, Borthwick AGL, Eatock Taylor R. Numerical wave tank based
741 on a σ -transformed finite element inviscid flow solver. International Journal
742 for Numerical Methods in Fluids 2003;42(6):641–63.
- 743 Wang J, Ma Q. Numerical techniques on improving computational efficiency
744 of spectral boundary integral method. International Journal for Numerical
745 Methods in Engineering 2015;102(10):1638–69.
- 746 Wang J, Ma Q, Yan S. A hybrid model for simulating rogue waves in random
747 seas on a large temporal and spatial scale. Journal of Computational
748 Physics 2016;313:279–309.
- 749 Whalin RW. The limit of applicability of linear wave refraction theory in a
750 convergence zone. Report; Research Report H-71-3, U.S. Army Corps of
751 Engineers, Waterways Experiment Station, Vicksburg, Mississippi; 1971.
- 752 Wu G, Eatock Taylor R. Finite element analysis of two-dimensional non-
753 linear transient water waves. Applied Ocean Research 1994;16(6):363–72.
- 754 Wu G, Ma Q, Eatock Taylor R. Numerical simulation of sloshing waves
755 in a 3D tank based on a finite element method. Applied ocean research
756 1998;20(6):337–55.
- 757 Yan S, Li Q, Wang J, Ma Q, Xie Z, Stoesser T. Comparative numerical
758 study on focusing wave interaction with fpso-like structure. International
759 Journal of Offshore and Polar Engineering 2019;29(02):149–57.

- 760** Yan S, Ma Q. Numerical simulation of fully nonlinear interaction between
761 steep waves and 2d floating bodies using the QALE-FEM method. Journal
762 of Computational physics 2007;221(2):666–92.
- 763** Yan S, Ma Q. Qale-fem for modelling 3d overturning waves. International
764 Journal for Numerical Methods in Fluids 2010;63(6):743–68.
- 765** Zang J, Taylor PH, Morgan G, Orszaghova J, Grice J, Stringer R, Tello M.
766 Steep wave and breaking wave impact on offshore wind turbine founda-
767 tions–ringing re-visited. In: Proc. 25th International Workshop on Water
768 Waves and Floating Bodies (IWWWFB). 2010. p. 1–4.