Dynamic mesh motion in OpenFOAM for wave energy converter simulation

Josh Davidson, Mirlan Karimov and Adam Szelechman
Budapest University of Technology and Economics, Hungary
Christian Windt and John V Ringwood
Centre for Ocean Energy Research, Maynooth University, Ireland

Numerical wave tanks (NWTs) are an essential tool for wave energy converter (WEC) development. Due to it's opensource nature and wide user base, *OpenFOAM* is proving to be an effective software platform for implementing NWTs for WEC experiments. Indeed, in a recent review of Computational Fluid Dynamics based NWTs (CNWTs) for WECs [37], *OpenFOAM* was the most prominately used CFD software (39% of total). Dynamic mesh motion can prove a challenge during WEC simulation, due to factors such as: (a) large ampitude body motions when a WEC is driven into resonance, with the input waves, by an energy maximising control system (EMCS) [9], (b) multiple degree of freedom (DoF) motion by a floating WEC, and/or (c) multi-body WEC with different sections oscillating in close proximity to each other. Fortunately, the overset method has recently become available in *OpenFOAM* (v1706 onwards), which possesses the potential to eliminate many barriers for the challenging dynamic mesh motion (DMM) in WEC simulations. This paper presents ongoing investigations considering the application of the overset method to a number of difficult to handle DMM scenarios which can be encountered in WEC NWT experiments.

1 Introduction

WECs have the potential to provide a significant renewable energy resource to the energy supply mix, required to satisfy the increasing global demand [12]. As discussed in Weber *et al* [33], the successful development of an economically competitve wave energy technology relies heavily on early stage evaluation, optimisation and refinement of the device design using numerical tools. For the research and development of WECs, NWTs provide an excellent numerical tool, enabling a cost-effective testbed for WEC experimentation, analysis and optimisation.

1.1 CFD based NWTs

Different methods for simulating the hydrodynamics within the NWT have been developed over the years, with increasing levels of fidelity and associated computational expense [14]. In the past, the high computational requirements largely precluded CFD from being applied to WEC analysis. However, the continual improvement and availability of high performance computing has led to the steady increase of CFD-based NWTs for WEC experiments, as shown in Fig. 1, which plots the number of publications utilising CNWTs each year from 2004-2017 from the review in [37].

Compared to lower fidelity models, CNWTs capture a wider range of relevant hydrodynamic effects, such as: large free surface deformation and WEC displacements, vicous drag, turbulence, wave breaking and WEC overtopping. CNWTs are therefore a valuable tool and have been used for a range of applications, categorized in [37] as: evaluation of viscous (drag) effects, performance analysis, device optimisation, code assessment, (extreme) loads estimation, scale analysis, system identification, control evaluation and conceptual design.

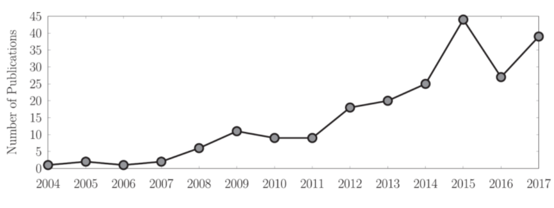

Figure 1: Use of CNWTs for WEC analysis [37]

1.2 OpenFOAM NWTs for WEC experiments

The implementation of an *OpenFOAM* NWT for WEC experiments is detailed in [3]. The review in [37], performed in 2017, shows that OpenFOAM is the most popular choice in CFD software for WEC experiments, with almost 40% of the collated publications using *OpenFOAM*. It is likely that this percentage would be even higher now, with the occurance of the commercial software usage being higher in the earlier years, and the prevalence of *OpenFOAM* increasing in recent years.

The growing popularity of *OpenFOAM* NWTs for WEC experiments can be attributed to: (1) No license fees, (2) The open sharing of toolboxes, such as numerical wave makers for wave generation and absorption in the NWT (using relaxation zones [19], dynamic boundary conditions [18] or impulse sources [29]), and (3) Full access to the source code, allowing modifications, such coupling to external models for WEC subsystems (generators/power-take offs [25], moorings [24] and control systems [4]).

A literature review, focussed specifically on the usage of OpenFOAM for WEC related simulations (up to 2015), is presented in [3] and then updated (for 2015-2017) in [9].

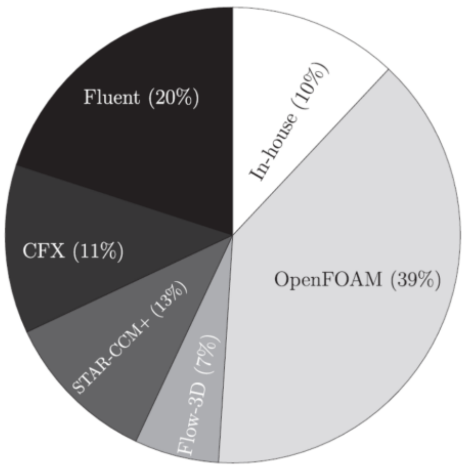

Figure 2: CFD software for WEC analysis [37]

1.3 Outline and scope of paper

This paper focusses on the challenge of DMM for WEC experiments simulated in *OpenFOAM* NWTs, and the solutions and limitations provided by the recently released overset method to the freely available versions of *OpenFOAM* (v1706 onwards). Section 2 introduces the DMM methods available in *OpenFOAM*, discussing their strengths and weaknesses. Section 3 then present a number of case studies where the DMM is particularly challenging for WEC experiments and discusses the application of the overset method to these cases. Finally, conclusions are drawn in Section 4.

2 Dynamic mesh motion

An overview of DMM for fluid structure interaction problems in *OpenFOAM* is detailed in [20]. Considering WECs, three DMM methods in *OpenFOAM* can be identified from the review in [37]: Mesh morphing, Sliding interfaces and Overset mesh.

2.1 Mesh morphing

Mesh morphing is by far the most common DMM method for WEC simulations. In a finite volume method algorithm, if grid connectivity should be retained (meaning no topological changes), mesh morphing is the classical method to accommodate body motion in the computational domain. The body displacement is diffused into the domain by solving the Laplacian equation:

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

where k describes the diffusivity and $\mathbf{u}$ the velocity of the moving boundary. The displacement of the body leads to a deformation of single control volumes, while the total volume of all control volumes in the domain remains constant throughout the simulation. Depending on the implementation, the diffusivity factor, k, gives control over the grid quality during mesh deformation. In the *OpenFOAM* environment, distance-based diffusivity is employed, with user specified *inner* and *outer* distance, between which mesh deformation is allowed and prohibited elsewhere, as depicted in Fig. 3.

The deformation of the original, high quality, mesh, can lead to poor grid quality, such as large aspect ratios and/or highly skewed cells, resulting in numerical stability issues. A mesh which has been optimised for a generated wave signal at a target location in a NWT [38], can then be influenced by the resulting deformation when a WEC is inculded at the target location and begins to move in response to the input wave. For large translational WEC displacements, moderate rotational WEC displacements, or mutiple-bodies moving in close proximity, the ensuing mesh deformation causes the simulation to crash.

This weakness of the mesh morphing method, in handling large displacements, limits the range of allowable motion in WEC experiments. This is especially true for the rotational DoFs, which commonly forces studies to constrain these modes of motion and consider WECs moving only in heave, for example. Certain sea states, or control settings, which result in large resonant WEC motions, can not be simulated, due to the numerical instability caused by the degradation in mesh quality. However, it is these sea states and conditions where the CNWT is required most, since the large resonant motions lead to nonlinearities not captured by lower fidelity simulation models.

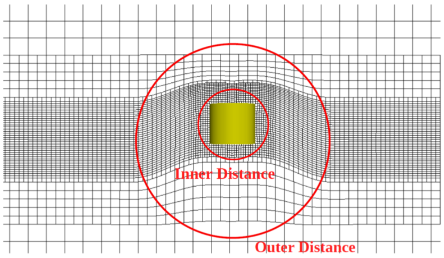

Figure 3: Mesh deformation between inner and outer radii in the mesh morphing method.

2.2 Sliding interfacecs

This DMM method allows one or more internal sub-domains to translate or rotate relative to a static background mesh domain, with the interface/borders between the domains sliding relative to each other. This is depicted in Fig. 4 for the case of a rotating flap-type WEC [28].

The solution is calculated separately in each domain. On the borders, the value of neighbouring field variables are transferred between the domains using an Arbitrary Mesh Interface (AMI). When a sub-domain slides relative to its neighbouring domain, the mesh cells will become misaligned across the borders, which the AMI handles by weighting the input from each of the intersecting cell faces based on the fraction of their overlapping areas.

The advantages of the sliding interfaces method is its ability to handle rotational motion and multiple-bodies oscillating in close proximity. Schmitt et al [27, 28] apply the AMI to cater for the large rotational angles of the flap type WEC, *Oyster* (Fig. 4). Devolder et al [10, 11] use the AMI to simulate an array of heaving WECs, where vertical cylindrical mesh blocks surrounding the WECs sliding vertically relative to each other. Mishra et al [22] use the AMI to model a two-body self-reacting WEC, like the *Wavebob*, where the spar-buoy is inside a sub-domain that slides inside the outer torus.

However, the main disadvantage of sliding interfaces is that they only appropriate for single DoF motions. However, it could be possible to have multiple sub-domains nested inside each other, where, for example, one dommain could slide vertically to account for heave motion and inside that domain is another domain which rotates to account for pitch.

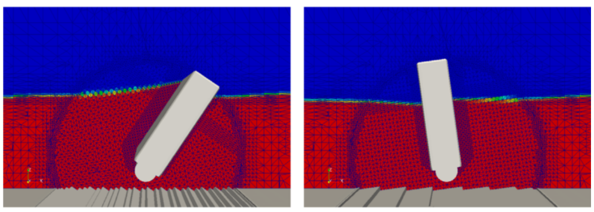

Figure 4: Rotating domain containing a flap-type WEC, inside the background mesh [28].

2.3 Overset mesh

In the overset grid method, (at least) two grids (background and body-fitted) are defined, which may arbitrarily overlay each other (see Fig. 5). The different grids are internally static, thereby retaining their original structure and quality, but are allowed to move relative to each other. In order to pass information between the different grids, interpolation has to be performed. The overset grid method can be split into the four sequential steps, performed at every time step:

(1) Identification of 'hole cells' in the background grid, lying inside the moving body, which are blanked out during the solution process. This procedure is the main cause for the extensive computational cost of the overset grid method [32].

(2) Identification of 'fringe cells', adjacent to hole cells and at the outer boundary of the body-fitted grid, which are used as boundary cells in the solution procedure. Boundary values for fringe cells are determined through solution interpolation.

(3) Identification of 'donor cells', which are the interpolation partners on both grids.

(4) Interpolation between fringe and donor cells.

The major advantage of the overset method, is that large amplitude motion in multiple DoFs is possible, with the mesh structure and quality remaining constant throughout the simulation. This has been used, for example, to simulate ships moving in seas with a moving rudder and a spinning propeller, using seperate overset grids for the hull, rudder and propeller [30].

The disadvantage of the overset method is the increase in computational time, due steps (1)-(4) described above. Additionally, the interpolation between grids can lead to conservation and convergence issues, and represents the biggest challenge of this method [13].

Due to their relatively recent release into the freely available versions on OpenFOAM, from v1706 onwards, overset grids in OpenFOAM have only been applied for WEC experiments by Windt et al [34, 35, 36] and Chen et al. [1, 2].

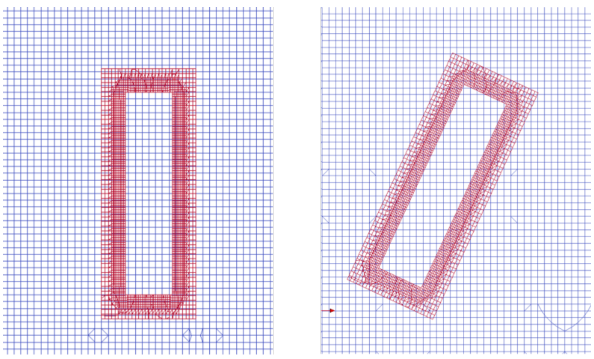

Figure 5: Illustration of the overset method. Background mesh in blue; overset mesh in red

3 Case studies

Here, three cases are presented, based on studies involving WEC experiments which were limited by previous DMM, and are currently under investigation by the authors using the overset method.

3.1 Case study 1 : Energy maximising control

By increasing the energy capture of a WEC, across changing sea states, EMCSs can improve the economic viability of the WEC. An EMCS effectively tunes the WEC dynamics to resonate with the incident waves, resulting in increased amounts of absorbed energy due to larger WEC motions.

Evaluating the performance of an EMCS classically relied on linear model simulations. However, the increased amplitude of the WEC's dynamics under controlled conditions challenge the validity of the linearising assumptions such models are built upon. The results in [5, 9, 15] show that increasing the amplitude of the WEC's operation away from its zero amplitude equilibrium state, leads to a divergence between linear hydrodynamic model and CFD simulations. Specifically, the levels of hydrodynamic damping experienced by a WEC are seen to increase as the amplitude of operation increases. Therefore, evaluating an EMCS with a linear model will likely result in predictions of unrealistically large WEC motions and energy capture, due to an underestimation of the hydrodynamic damping on the WEC. CFD, on the other hand, has a greater range of validity when simulating large amplitude WEC motions due to the treatment of nonlinear effects, such as viscosity and time-varying wetted surface area.

This is displayed in Fig. 6, from the case study in [9], which provides a comparison between the simulated motions and energy output of a WEC, in both controlled and uncontrolled conditions, calculated by a linear hydrodynamic model and OpenFOAM. An EMCS is used to drive a WEC into resonance with an incident wave field, resulting in larger WEC motions, and a divergence between the calculated linear model response and the OpenFOAM simulation. In this study, the WEC motion is constrained to heave only and mesh morphing could suffice.

However, for multi-DoF, the increase in WEC amplitude presents a problem for mesh morphing methods in OpenFOAM, as discussed in [35, 36] and displayed in Fig. 7. The mesh distortion, using the mesh morphing method, for a WEC without control is shown in Fig. 7-(a), and then for the same case with an EMCS applied shown in Fig. 7-(b), where the simulation crashed at 22.5s due to the highly distorted mesh (simulation results in Fig. 7-(c)). To overcome this problem, the overset method is being employed in these simulations to allow the performance of the EMCS to be evaluated.

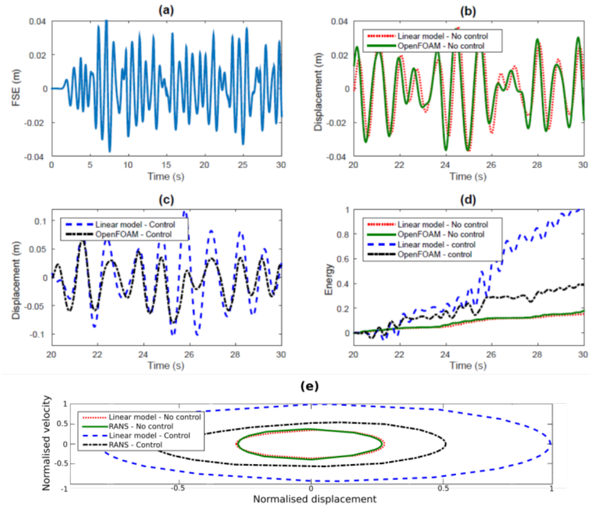

Figure 6: (a) The input wave series. (b) The WEC displacement calculated by a linear model and OpenFOAM without control and (c) with control. (d) The resulting energy capture (e) Comparison of the operational space for the WEC motion [9].

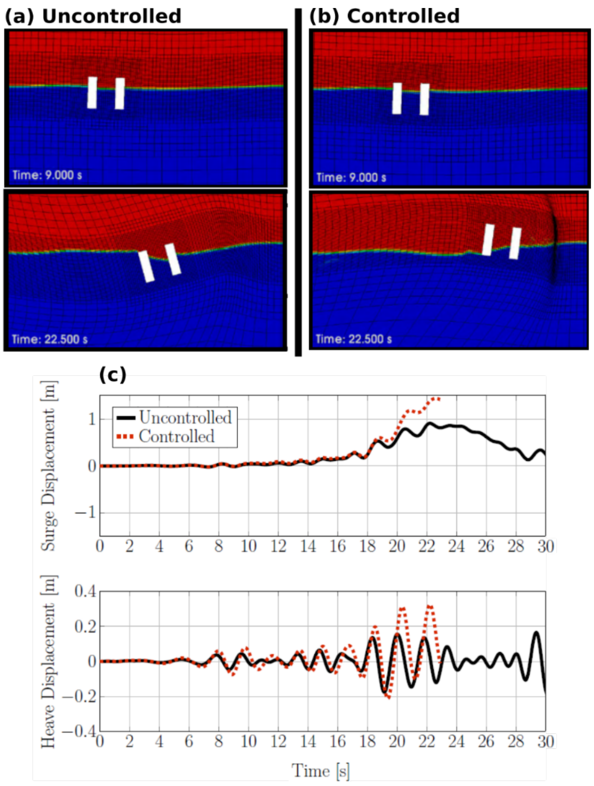

Figure 7: (a) The mesh distortion during a simulation for a tubular WEC when control is not applied and (b) is applied. (c) The corresponding surge and heave displacement of the WEC, where the control enhances the WEC motion to the point where the simulation crashes at 22.5s [35].

3.2 Case study 2 : Parametric pitch/roll motion

Parametric resonance is caused by the time varying changes in the parameters of the system. While resonance causes the oscillations of a system to grow linearly with time (until damping limits further growth), parametric resonance causes an exponential increase in oscillation amplitude, and can often be unexpected since it is a nonlinear phenomenom not predicted by linear analyses. Parametric resonance has been observed and studied in floating bodies, dating back to the work of Froude (1861) who described that large roll motions occur when a ship's roll natural period is twice the heave/pitch natural period. Similar to ships, large amplitude pitch/roll motions can occur to floating WECs, due to parametric resonance, and is often undesirbale with energy being parametrically transferred from the primary mode of motion used for energy conversion (heave), to the rotational DoFs (pitch and roll) [17].

For WECs, and other floating structures, one of the main drivers of paramertic pitch/roll is a time-varying hydrostatic restoring torque, which gives rise to a Mathieu type instability, whose activation threshold depends on the total damping in the system. Therefore, analysing parametric resonance requires the wide range of hydrodynamic nonlinearities offered by a CNWT. Simulating parametric resonance in a CNWT necessitates a multi-DoF simulation, capable of handing large rotational motions, which can be effectively handled by the overset method. However, Palm *et al* [23] successfuly simulated parametric pitch of a WEC, using mesh morphing in *OpenFOAM*, where the pitch motions were below 30 degrees (possibly constrained by the mooring system).

One particularly useful application of CNWTs, for the modelling, analysis and control of parametric resonance in WECs [7], is to provide high fidelity training and validation data for system identification of computationally efficient nonlinear parametric models [26]. An example of this is shown in Figs. 8-10 from a current study [8], comparing different dynamic vibration absorbers to mitigate parametric resonance in a floating cylinder. The current study identifies a time-varying restoring torque coefficient which is dependent on the instantaneous pitch and heave displacements, by extending to multi-DoFs, the methods presented in [6, 16], for the identification of single DoF nonlinear restoring and excitation force models using hydrostatic experiments in an *OpenFOAM* NWT. Fig. 8 shows snapshots of the CNWT experiment to measure the position dependent hydrostatic torque on the cylinder, where the body is very slowly moved, between -1m and 1m in heave and -50° and 50° in pitch, and the force from the fluid recorded (plotted in Fig. 9). A finite set of basis functions can then be fitted to the data in Fig. 9 (see [6, 16]), as a function of the heave and the pitch displacement, and then used to extend a conventional linear hydrodynamic model to include a time-varying restoring torque. Fig. 10 shows an example output from the identified model, where parametric pitch motion occurs and energy is transferred from the heave mode of motion to pitch.

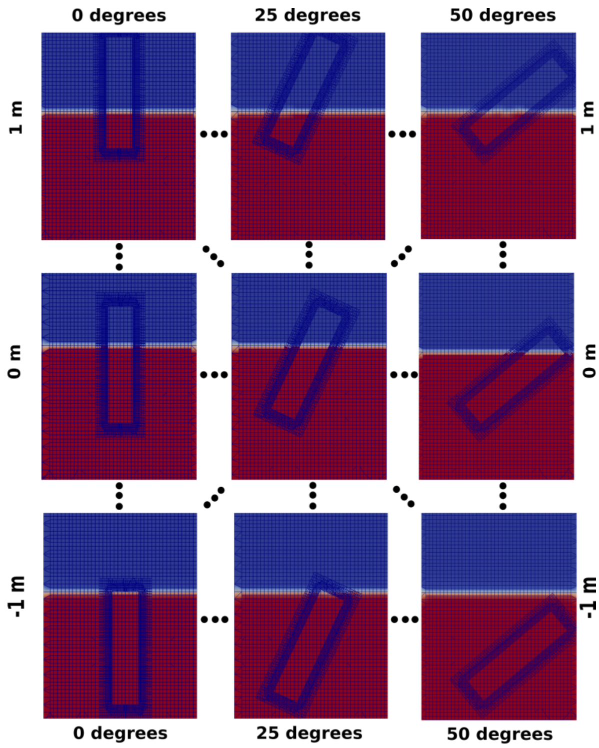

Figure 8: Array of NWT experiments to measure the hydrostatic force on the WEC for varying heave and pitch displacement [8]

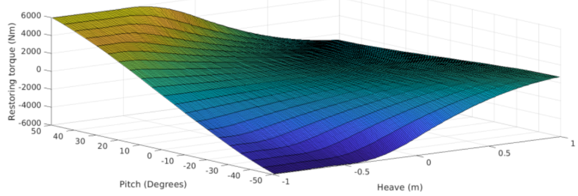

Figure 9: Measured pitch restoring force as a function of heave and pitch displacement [8]

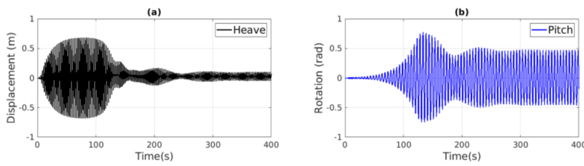

Figure 10: Example simulation result from the identified parametric model, displaying parametric pitch motion [8]

3.3 Case study 3 : Multi-body WEC

A range of WEC designs rely on multiple, interconnected bodies, moving relative to each other, in order to extract energy. Li *et al* [21] successfully model two connected bodies using mesh morphing in *OpenFOAM*, with one body submerged at a significant depth from the other floating at the surface. However, multi-body WECs in closer prximity pose a challenge for DMM in *OpenFOAM*. For example, considering the multi-body examples using sliding interfaces in Section 2.2, Mishra *et al* [22] held the outer torus body fixed and only allowed motion of the inner spar body, whereas the array of buoys in Devolder et al [10, 11], were constrained to move only in heave.

While the overset mesh is certainly very good at handling multiple bodies, with multiple DoFs, there appears to be a limit to their application. The simulation becomes numerically unstable and crashes when the bodies are in very close proximity. This is possbily due to the fringe cells of the overset region from one body overlaying the hole region from another body, or due to the mesh resolution becoming insufficient to handle the high gradients between the closely spaced moving walls. Current studies are investigating this further, with an example experiment, depicted in Fig. 11 [31], involving two closely spaced rectangular floating bodies connected by a spring.

The problem of applying the overset mesh to closely spaced bodies was encountered in the case study shown in Figs. 12 and 13. The goal of the study was to replicate wave tank experiments of the *Mocean* WEC, to extract the pressure over the device surface in extreme wave conditions. Fig. 12-(a) shows the extremely close proximity of the two bodies, that both rotate about a common hinge axis located near the end of the forward body, and one of the multiple unsuccesful attempts to mesh the geometry with the overset method. Achieving a stable simulation required a modification of the WEC geometry in order to accommodate the mesh motion, shown in Fig. 12-(b). Obviously, removing part of the geometry will influence the resulting behaviour of the WEC. While the hinge section of the WEC is certainly not as "hydrodynamically important" as the wave channels at the ends of the WEC, by deleting this part of the geometry, the mass/moments of intertia and CoM are altered. Additionally, other effects can occur, which are perhaps visible in the snap-shots shown in Fig. 13 at time instant 16s, showing the entrapment of air under the aft body which would likely alter the hydrodynamics. If the hinge was not removed from the geometry then it is likely that the air could not be so easily trapped under the Aft Body.

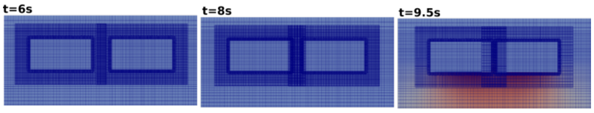

Figure 11: The overset mesh motion, and the resulting dynamic pressure in the fluid, for two colliding floating bodies.

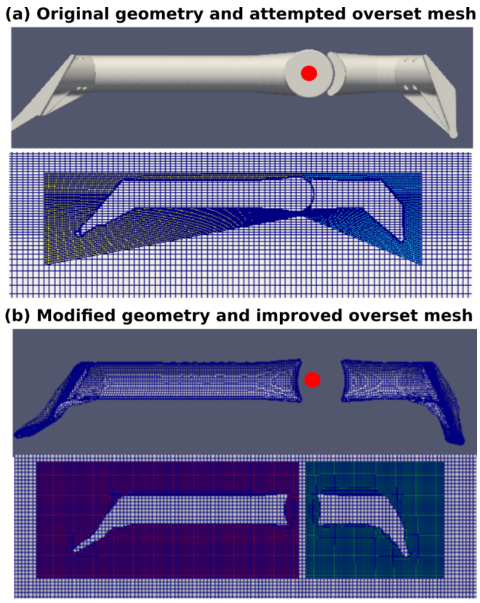

Figure 12: Modifications made to geometry to prevent simulation crashes. (Rotation axis marked by red dot)

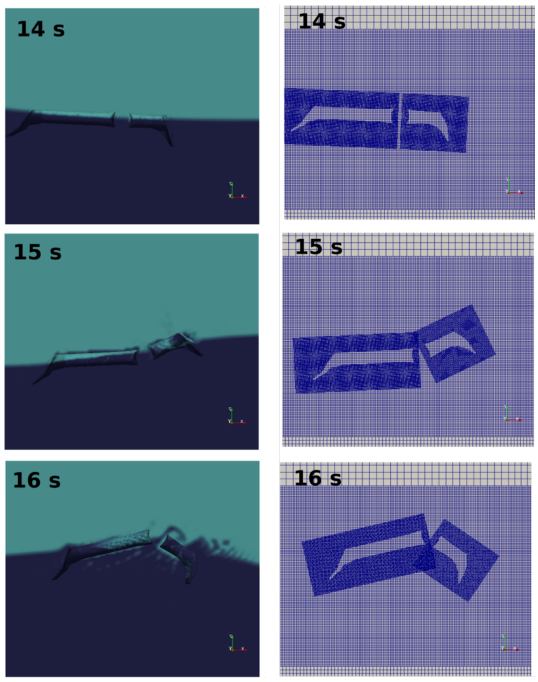

Figure 13: Post process view of the device in the water and correspoding mesh motion.

4 Conclusion

CNWTs developed in OpenFOAM are an effective tool for WEC analysis. However, the DMM required in WEC experiments has proven a challenge in the past and restricted the range of analysis applications, for example, devices restrained to single DoFs. The recent introduction of the overset mesh method to *OpenFOAM* (v1706 onwards) has the potential to remove many of these restrictions. However, cases involving mutliple-bodies moving in multiple DoFs in close proximity to each other is still too complicated, and simplfying modifications and approximations to the case must be made.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 867453. This paper is based upon work supported by Science Foundation Ireland under Grant No. 13/IA/1886.

References

[1] H. Chen, L. Qian, Z. Ma, W. Bai, Y. Li, D. Causon, and C. Mingham. Application of an overset mesh based numerical wave tank for modelling realistic free-surface hydrodynamic problems. *Ocean Engineering*, 2019.

[2] H. Chen, L. Qian, Z. Ma, W. Bai, and Z Lin. Ccp-wsi blind test series 3: Openfoam simulation of focused wave interaction with a simplified wave energy converter. In *Proceedings of the Twenty-ninth International Ocean and Polar Engineering Conference*, 2019.

[3] J Davidson, M Cathelain, L Guillemet, T Le Huec, and J.V. Ringwood. Implementation of an openfoam numerical wave tank for wave energy experiments. In *11th European Wave and Tidal Energy Conference*, 2015.

[4] J Davidson, R Genest, and J.V. Ringwood. Adaptive control of a wave energy converter simulated in a numerical wave tank. In *12th European Wave and Tidal Energy Conference*, 2017.

[5] J. Davidson, S. Giorgi, and J.V. Ringwood. Linear parametric hydrodynamic models for ocean wave energy converters identified from numerical wave tank experiments. *Ocean Engineering*, 103:31–39, 2015.

[6] J. Davidson, S. Giorgi, and J.V. Ringwood. Numerical wave tank identification of nonlinear discrete time hydrodynamic models. *Renewable Energies Offshore*, page 279, 2015.

[7] J. Davidson, T. Kalmar-Nagy, G. Giorgi, and J.V. Ringwood. Nonlinear rock and roll–modelling and control of parametric rresonances in wave energy devices. In *Proc. 9th Vienna Int. Conf. Math. Modelling*, 2018.

[8] J. Davidson, M. Karimov, G. Habib, , and T. Kalmar-Nagy. Parametric excitation suppression in a floating cylinder via dynamic vibration absorbers : A comparative analysis. *Nonlinear Dynamics*, (In preparation).

[9] J Davidson, C Windt, G Giorgi, R Genest, and J.V. Ringwood. Evaluation of energy maximising control systems for wave energy converters using OpenFOAM. In *OpenFOAM-Selected papers of the 11th Workshop, Nbrega, JM, Jasak, H.(Editors), Springer*, 2018.

[10] B. Devolder, P. Rauwoens, and P. Troch. Towards the numerical simulation of 5 floating point absorber wave energy converters installed in a line array using openfoam. In *12th European Wave and Tidal Energy Conference*, pages 739–749, 2017.

[11] B. Devolder, V. Stratigaki, P. Troch, and P. Rauwoens. Cfd simulations of floating point absorber wave energy converter arrays subjected to regular waves. *Energies*, 2018.

[12] AFO Falcao. Wave energy utilization: A review of the technologies. *Renewable and sustainable energy reviews*, 14(3):899–918, 2010.

[13] J.H. Ferziger and M. Peric. *Computational methods for fluid dynamics*. Springer Science & Business Media, 2012.

[14] M. Folley. *Numerical modelling of wave energy converters: state-of-the-art techniques for single devices and arrays*. Academic Press, 2016.

[15] R. Genest, J. Davidson, and J.V. Ringwood. Adaptive control of a wave energy converter. *IEEE Transactions on Sustainable Energy*, 9(4):1588–1595, 2018.

[16] S. Giorgi, J. Davidson, and J. Ringwood. Identification of nonlinear excitation force kernels using numerical wave tank experiments. In *Proceedings of the 11th European Wave and Tidal Energy Conference*, 2015.

[17] R Gomes, J Malvar Ferreira, S Ribeiro de Silva, J Henriques, and L Gato. An experimental study on the reduction of the dynamic instability in the oscillating water column spar buoy. In *Proceedings of the 12th European Wave and Tidal Energy Conference*, 2017.

[18] P. Higuera, J.L. Lara, and I.J. Losada. Realistic wave generation and active wave absorption for navier–stokes models: Application to openfoam®. *Coastal Engineering*, 71:102–118, 2013.

[19] N.G. Jacobsen, D.R. Fuhrman, and J. Fredsøe. A wave generation toolbox for the open-source cfd library: Openfoam®. *International Journal for numerical methods in fluids*, 70(9):1073–1088, 2012.

[20] H. Jasak and Ž. Tuković. Dynamic mesh handling in openfoam applied to fluid-structure interaction simulations. In *Proceedings of the 5th European Conference on Computational Fluid Dynamics*, 2010.

[21] L. Li, M. Tan, and J. Blake. Numerical simulation of multi-body wave energy converter. In *The Twenty-fifth International Ocean and Polar Engineering Conference*, 2015.

[22] Virag Mishra, Scott Beatty, Bradley Buckham, Peter Oshkai, and Curran Crawford. Application of an arbitrary mesh interface for cfd simulation of an oscillating wave energy converter. In *Proc. 11th Eur. Wave Tidal Energy Conf*, pages 07B141–07B1410, 2015.

[23] J Palm, C Eskilsson, and L Bergdahl. Parametric excitation of moored wave energy converters using viscous and non-viscous cfd simulations. In *Advances in Renewable Energies Offshore, Taylor & Francis Group*, 2018.

[24] J. Palm, C. Eskilsson, G. Paredes, and L. Bergdahl. Coupled mooring analysis for floating wave energy converters using cfd: Formulation and validation. *International Journal of Marine Energy*, 16:83–99, 2016.

[25] M Penalba, J Davidson, C Windt, and J.V Ringwood. A high-fidelity wave-to-wire simulation platform for wave energy converters: Coupled numerical wave tank and power take-off models. *Applied energy*, 226:655–669, 2018.

[26] J. V. Ringwood, J. Davidson, and S. Giorgi. Identifying models using recorded data. *Numerical Modelling of Wave Energy Converters: State-of-the-Art Techniques for Single Devices and Arrays*, pages 123–147, 2016.

[27] P Schmitt, S Bourdier, T Whittaker, D Sarkar, E Renzi, F Dias, K Doherty, J van't Hoff, et al. Hydrodynamic loading on a bottom hinged oscillating wave surge converter. In *The Twenty-second International Offshore and Polar Engineering Conference*, 2012.

[28] P. Schmitt and B. Elsaesser. On the use of openfoam to model oscillating wave surge converters. *Ocean Engineering*, 108:98–104, 2015.

[29] P. Schmitt, C. Windt, J. Davidson, J.V. Ringwood, and T. Whittaker. The efficient application of an impulse source wavemaker to cfd simulations. *Journal of Marine Science and Engineering*, 7(3):71, 2019.

[30] Z. Shen, D. Wan, and P.M. Carrica. Dynamic overset grids in openfoam with application to kcs self-propulsion and maneuvering. *Ocean Engineering*, 2015.

[31] A. Szelechman. Modelling and investigation of mulitple floating bodies in an openfoam numerical wave tank. Master's thesis, Budapest University of Technology and Economics, 2019.

[32] J.F. Thompson, B.K. Soni, and N.P. Weatherill. *Handbook of grid generation*. CRC press, 1998.

[33] J Weber, R Costello, and J.V. Ringwood. Wec technology performance levels (tpls)-metric for successful development of economic wec technology. *Proceedings EWTEC 2013*, 2013.

[34] C Windt, J Davidson, B Akram, and J.V. Ringwood. Performance assessment of the overset grid method for numerical wave tank experiments in the openfoam environment. In *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*, 2018.

[35] C Windt, J Davidson, D Chandar, and J.V. Ringwood. On the importance of advanced mesh motion methods for wec experiments in cfd-based numerical wave tanks. In *VIII International Conference on Computational Methods in Marine Engineering*, 2019.

[36] C Windt, J Davidson, D Chandar, and J.V. Ringwood. Numerical simulation of a point-absorber wave energy converter for control studies using the overset grid method in openfoam. *Journal of Ocean Engineering and Marine Energy*, (Submitted).

[37] C Windt, J Davidson, and J.V. Ringwood. High-fidelity numerical modelling of ocean wave energy systems: A review of computational fluid dynamics-based numerical wave tanks. *Renewable and Sustainable Energy Reviews*, 93:610–630, 2018.

[38] C. Windt, J. Davidson, P. Schmitt, and J.V. Ringwood. On the assessment of numerical wave makers in cfd simulations. *Journal of Marine Science and Engineering*, 7(2):47, 2019.