UMERC+OREC
2025 Conference

12-14 August | Corvallis, OR USA

Open Datasets For High-Fidelity Wave Energy Converter Simulations

Elyce Bayat[a,1], Nhu Nguyen[a], Chris Chartrand[a]

[a]*Sandia National Laboratories, Albuquerque, New Mexico, 87123, United States*

Abstract

High-fidelity Computational Fluid Dynamics (CFD) provides a cost-effective alternative to expensive, labor-intensive experimental studies of Wave Energy Converters (WECs) by enabling the creation of digital twins. However, adoption within the Marine Hydrokinetic (MHK) community has been limited by steep learning curves, high costs of commercial software licenses, and a lack of relevant example cases. To address these challenges, we have developed and publicly released detailed documentation, pre-configured real-world WEC simulation setups, pre-run examples (using the WEC Reference Model 6 as a case study), and their solutions, based on the open-source CFD suite OpenFOAM. The simulation setups are specifically optimized for MHK applications, minimizing the need for user inputs. Each stage of the typical WEC numerical simulation workflow is thoroughly documented, covering high-fidelity mesh generation, rigid-body motion solvers, mooring system modeling, Power Take-Off (PTO) modeling, wave condition setup, data acquisition, and power output calculations. Pre-run solutions for various scenarios, including wave-only flumes, floating or moored systems under regular and irregular waves, and systems with or without PTO, have been made publicly available to help developers follow the setup process, benchmark results, and debug their numerical models effectively. The work presented here includes the comprehensive documentation of configuration files, model geometries, and solution results required for modelers to confidently simulate novel marine energy devices using freely available open-source software.

Keywords: Computational Fluid Dynamics, OpenFOAM, Wave Energy Converter, Open Datasets, Graphical User Interface

---

[1] * Elyce Bayat
E-mail address: ebayat@sandia.gov

1 Introduction

The presented work aims to reduce barriers to simulation by developing and documenting detailed, real-world WEC simulation templates, tutorials, auxiliary scripts, and data sets for OpenFOAM to demonstrate how freely available open-source simulation software can be utilized by MHK developers to configure predictive simulations of their WEC prototypes. These configuration files and model data sets will streamline setup, simulation performance, and numerical analysis tasks, allowing early stage performance analysis prior to costly physical prototyping and experimental testing. Figure 1(a) outlines the steps to the typical WEC numerical simulation and analysis workflow, along with the various modeling and analysis sub-tasks typically involved with each step. The presented work aims to provide the necessary support for each stage of this process in a thoroughly documented way. In order to be accessible to users at varying skill levels and to provide a constructive learning experience, these data sets are provided in a manner that gradually increases in complexity, with the end goal of illustrating a real-world example. As a result, the final case presented in the data sets is a demonstration of an "RM6" digital twin (Reference Model 6 of the Department of Energy Water Power Technology Office's reference model project) [1] [2]. This is chosen for its relevance to WEC developers, whose specific devices often have similar operating principles to the reference models.

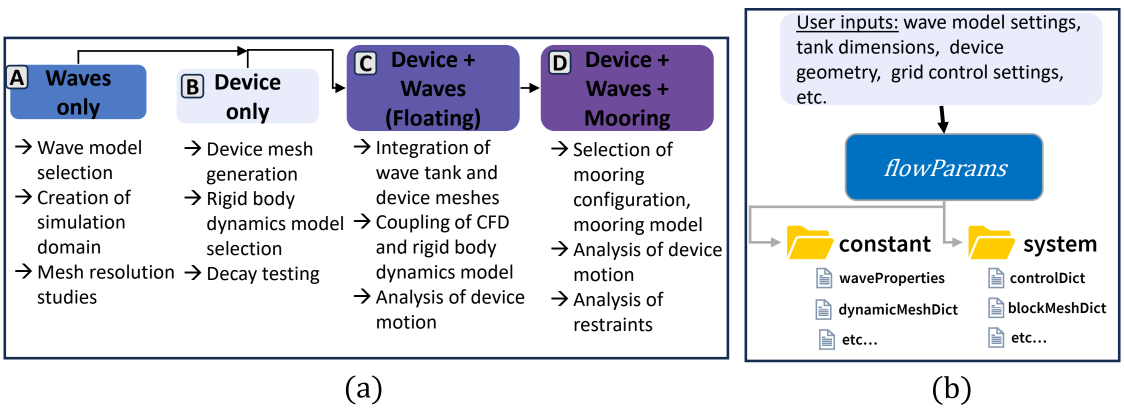


Figure 1: (a) Diagram illustrating the typical WEC design analysis workflow. The data sets presented in this work provide example simulation set-ups, results, and analysis scripts that encompass each stage of this process. (b) Illustration of the typical OpenFOAM case file structure for dictionary files. The user can interact with a text-based interface, *flowParams* , to make changes to the most relevant variables for a WEC analysis case. This interface simplifies and centralizes user interaction with configuration files, minimizing the start-up cost to simulation setup.

2 Case Descriptions

The cases provided are intended to guide the user through the typical WEC analysis workflow (as shown in Figure 1(a)) with gradually increasing layers of complexity: first starting with wave-only flumes, next integrating device model geometries with specialized mesh generation, performing device decay testing, and lastly modeling the device under wave conditions in first floating and then moored configurations.

2.1 Waves-only flume cases

For the wave-only cases, three conditions from the PacWave South test sites are selected (see Table 1). These represent: (1) the most commonly occurring sea states, (2) the highest annualized wave energy sea state, and (3) one of the extreme sea states on the 50-year contour [3]. While these correspond to the irregular sea states at the site, for the current work, they are simulated as regular wave conditions. The significant wave height (H_s) and energy period (T_e) are treated as regular wave height and period, respectively. For completeness, a fourth case is added in which case 2 of Table 1 is simulated as an irregular sea state. It is noted that all simulation demonstration cases developed in this work are scaled at a 1:15 ratio, which provides an appropriate size for typical wave flume experimental tests, where H_s and λ (wavelength) are scaled by $1/15$, while T_e is scaled by $\sqrt{1/15}$. The ratio can be adjusted based on users' needs. The values shown in the parenthesis of Table 1 reflect these scaled values.

Test Name	Case 1	Case 2	Case 3	Case 4
Wave Type	Regular	Regular	Regular	Irregular
H_s (m)	1.75 (0.12)	2.75 (0.18)	7.45 (0.50)	1.75 (0.12)
T_e (s)	8.50 (2.20)	10.5 (2.71)	10.0 (2.58)	8.50 (2.20)
λ (m)	112.80 (7.52)	172.13 (11.48)	156.13 (10.41)	112.80 (7.52)

Table 1: Wave characteristics employed for waves-only flume cases. Values in parentheses reflect the scaled values at a 1:15 ratio.

2.2 Device cases: Mesh generation and decay testing

The mesh generation examples developed here guide the user through a typical process to create a mesh for a given device geometry. This is a multi-step process that includes: (1)generating an overset mesh (using OpenFOAM's *blockMesh* utility), which will serve as the interface between the device mesh and background simulation domain mesh, (2) creating a body-fitted mesh from the block mesh for the provided device STL file using the *snappyHexMesh* functionality native to OpenFOAM, and then (3) merging the overset mesh into the background wave simulation domain mesh. These examples are provided in both 2D and 3D. For the 2D cases, the process of appropriately slicing the 3D .stl file and extruding the slice for 2D simulation is included. Additionally, there is an optional procedure for the creation of a circular baffle, which is used for the RM6 Power Take-Off (PTO) model (see the git repository listed in Section 3 for more information). For the free decay tests, the OpenFOAM dictionary files provided in the cases are updated to include the additional files and settings needed to solve the rigid body dynamics of the device, and couple it with the CFD. This includes the integration of the dictionary file *dynamicMeshDict*, which specifies properties of the rigid body, as well as any constraints on the motion, possible restraints attached to the body, etc. For the purposes of this work, the OpenFOAM library *sixDoFRigidBodyMotion* is chosen for the rigid body motion. These cases provide a valuable intermediate step between the waves-only flume and simulations of devices under full wave conditions.

2.3 Device cases: device + waves, floating and moored

Building upon the work described in the previous two sections, these cases combine the waves conditions from Section 2.1 with the overset meshes and rigid body motion models described in Section 2.2 to produce simulations of a device under PacWave conditions in both 2D and 3D. These are presented for both free floating (unmoored) and moored conditions. In the moored cases, a simplified mooring configuration is developed using linear spring model restraints in the rigid body dynamics library utilized. This is selected for simplicity – it eliminates the need for a user to download and/or build any other (more sophisticated) libraries, as this restraint model is available in the default OpenFOAM environment. Figure 2(a) displays a comparison of the simulated Reference Model 6 motion under wave conditions in both floating and moored configurations using simulation data from the herein described open data sets.

3 Available Data

The available datasets include three key components: OpenFOAM configuration files, pre-packaged simulation results, and analysis scripts. Details on each of these components is provided in the following subsections. All datasets can be accessed in the project's git repository, found at `https://github.com/sandialabs/WEC-OpenFOAM-Open-Datasets/tree/main`.

3.1 OpenFOAM Case Configuration Files

For each of the cases detailed in Section 2, a directory of all the OpenFOAM dictionary (or configuration) files needed to run the simulation case is provided. Two different formats for most cases are provided: *template*s , and *example*s . A *template* provides a set of OpenFOAM configuration files (to be discussed further in Section 3.1) which can be easily modified by the user to suit their own application. Then, a set of *example*s for each *template* are available, and represent specific instantiations of each *template* . For example, there is a *template* provided for a general 2D wave flume, along with a set of *example*s which are modifications to the *template* to create a variety of different wave conditions. The *example*s serve to illustrate how the *template*s can be modified by the user to produce a variety of different simulation configurations. A key component to these files is the development of a file titled *flowParams* , which is designed to simplify the setup of each numerical simulation by consolidating the most frequently modified parameters in one place. In a typical OpenFOAM dictionary file setup, it is common for there to be numerous dictionary files that all require user input in multiple locations, and this can be daunting to manage for new users. In the presented simulation cases, the developed *flowParams* file serves as a centralized location for a user to make changes to each case that are most relevant, and the rest of the dictionary files are set up to check the *flowParams* file for user-defined inputs. This concept is illustrated in Figure 1(b). This lowers the barrier-to-entry for new users – users are able to immediately make a number of changes to the provided configuration files by interfacing only with *flowParams* . Conversely, interested users can observe which dictionary files reference *flowParams* to gain a guided understanding of which dictionary files house the most relevant variables and inputs for WEC simulation setup. The general structure for each set of configuration files is as follows:

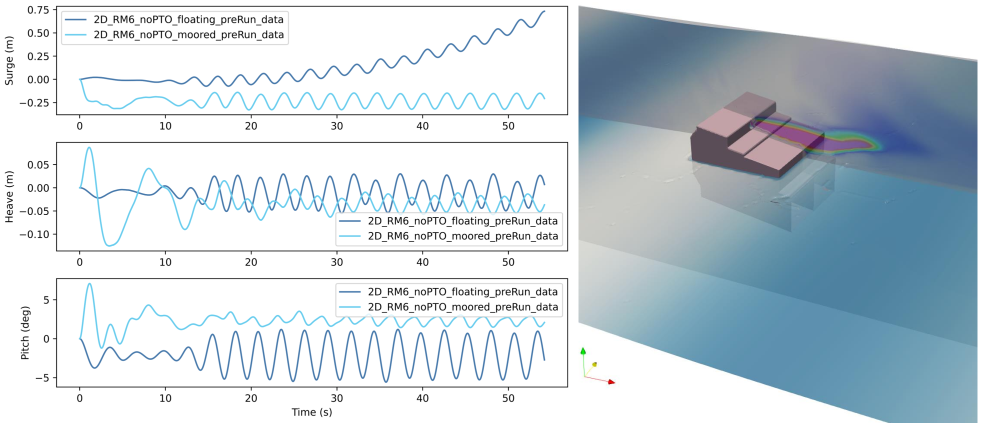
- *flowParams* : A dictionary file that contains user-defined input parameters, serves as an interface between the user and the rest of the dictionary files in the case
- Allrun.ser, Allrun, Allclean: Bash scripts to facilitate ease of running and cleaning the simulation. The first two scripts start the simulation using either a single processor (the former) or multiple processors (the latter). The last script resets the case to its initial state and removes all remnants of the previous simulation.
- 0.orig: A directory of dictionary files that contain the initial boundary condition information
- constant: A directory of dictionary files containing time-constant information such as wave conditions, and any rigid body constraints, etc. User-adjusted settings in *flowParams* will link to updates in the files housed in this directory.
- system: A directory of dictionary files related to solution methods, numerical schemes, and runtime calculations. Many of the settings here are pre-selected to be best suited to the WEC simulations considered. User-adjusted settings in *flowParams* will link to updates in the files housed in this directory.
- postProcessing: An output directory that will be created at runtime to store the simulation output data, such as wave height, WEC device motion, and recorded forces. This data can then be plotted and analyzed using python scripts described in Section 3.2.

3.2 Auxiliary Scripts

Also provided in the data sets is a collection of auxiliary analysis scripts provided in both bash and python. These scripts provide functionalities to the user for assistance in setting up configuration files, producing necessary simulation input data, extracting simulation output data into useful formats, computing relevant quantities from simulation output data, and plotting results. For example, the scripts provide some of the following services: (1) Generation of mesh dictionary files "under the hood" based on user inputs in *flowParams* . For example, one script might read the user specifications in *flowParams* and automatically generate an appropriate meshing dictionary file for the OpenFOAM configuration file directory. (2) Core functionalities for both generating wave spectra (i.e. as simulation input data for irregular wave models) and computing relevant quantities from simulated wave signals (i.e. wave height, period). (3) Extracting relevant output data from simulation log files. For example, an included bash script `extractLog.sh` extracts relevant device motion and force data from the OpenFOAM logfile and exports it into a file format that can be easily read into a scripting language for analysis and plotting (i.e. python). (4) Plotting results (both wave data and device motion data) from either one case or multi-case comparison, including plotting mesh resolution convergence study plots. This improves the ease of entry for new users to engage with the WEC numerical simulation process in OpenFOAM by providing a foundation of tools needed to set up simulations and engage with simulation results in meaningful ways immediately, without needing to invest time and effort into the development of these tools.

3.3 Pre-packaged Simulation Results

The final component to the presented data sets is the availability of "pre-packaged" simulation results. This allows users to quickly visualize what the results of a current *example* they are working with *should* look like; this enables



(a) (b)

Figure 2: (a) Comparison of Reference Model 6 device motion under wave conditions in floating versus moored configuration. The plot is generated using the included auxiliary script `plotMotion2D.py`, using simulation data generated from the RM6 2D example configuration files for each configuration. (b) Example visualization in ParaView of simulation output from the 3D RM6 unmoored example case provided in the datasets, with fluid velocity and pressure depicted in blue hues and jet colormap, respectively.

troubleshooting if cases are not performing as expected. For the cases detailed in Section 2, the following data is provided:

- Waves-only flume: wave probe data, wave surface elevation plots of expected output
- Decay testing: device motion data, hydrodynamic forces experienced by device, plots of expected device motion and forces, animation of simulation
- Waves + Device: device motion data, hydrodynamic forces experienced by device, restraint forces (in case of tethering), plots of expected device motion + forces and restraint forces, animation of simulation

This works in conjunction with the scripts described in Section 3.2, which allow a user to plot comparisons of results between multiple cases. A user can also plot key outputs from an *example* they have run, i.e. wave signal from a waves-only flume case, and compare it against the pre-packaged simulation data to "check their work", so to speak.

4 Conclusion

We have developed a repository of open datasets for the simulation of Wave Energy Converters using OpenFOAM. The datasets encompass templates and examples with accompanying documentation tailored to all the components of typical WEC numerical simulation and analysis workflow, including wave condition setup, mesh generation, rigid body motion solvers, mooring system modeling, and Power Take-Off modeling. The WEC Reference Model 6 is chosen as one of the example device geometries for its relevance to WEC developers. The OpenFOAM dictionary files used to run the simulations are pre-set with options for numerical solvers and settings that are suited to the WEC simulation use-case. A text file named *flowParams* is supplied, which interfaces with other dictionary files to provide a centralized location where users can adjust settings most commonly useful for WEC simulation to their needs. Helpful analysis tools for interacting with simulation data, such as python and bash scripts, are included to facilitate prompt ease-of-use. Pre-packaged simulation results are included for users to compare their own solutions against as they work through the examples. This body of work provides the configuration files, documentation, model geometries, analysis tools, and solution results modelers need to simulate their marine energy devices with ease, confidence, and a reduced barrier-to-entry using open-source and freely available CFD software.

Acknowledgments

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC (NTESS), a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA) under contract DE-NA0003525. This written work is authored by an employee of NTESS. The employee, not NTESS, owns the right, title and interest in and to the written work and is responsible for its contents. Any subjective views or opinions that might be expressed in the written work do not necessarily represent the views of the U.S. Government. The publisher acknowledges that the U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this written work or allow others to do so, for U.S. Government purposes. The DOE will provide public access to results of federally sponsored research in accordance with the DOE Public Access Plan.

References

[1] Diana L Bull et al. Reference Model 6 (RM6): Oscillating Wave Energy Converter. Tech. rep. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2014.

[2] PRIMRE/Signature Projects/Reference Model | Open Energy Information — openei.org. https://openei.org/wiki/PRIMRE/Signature_Projects/Reference_Model. [Accessed 07-03-2025].

[3] Gabrielle Dunkle et al. "Pacwave wave resource assessment". In: (2020).