NUMERICAL WAVE TANKS FOR WAVE ENERGY CONVERTERS USING HIGH-PERFORMANCE COMPUTING

Milad Abdollahpour, Federico Domenichini, Lorenzo Cappietti

Abstract: Numerical Wave Tanks (NWTs) powered by Computational Fluid Dynamics (CFD) and High-Performance Computing (HPC) offer a cost-effective and flexible alternative to physical wave tanks. They are essential for simulating complex wave phenomena and wave-structure interaction. This research explores the assessment of NWT reliability, particularly in HPC environments, using OpenFOAM, an open-source CFD toolbox. OpenFOAM's parallel processing capabilities leverage HPC to achieve accurate and efficient simulations of wave dynamics, crucial for optimizing wave energy converter designs and advancing renewable energy generation. HPC reduces execution time, enabling more comprehensive simulations and faster design optimization, ultimately accelerating progress in wave energy technologies. The study demonstrates OpenFOAM's suitability for NWT simulations while acknowledging the need for validation and optimization of grid and discretization methods.

Keywords: Numerical Wave Tanks (NWTs), CFD, OpenFOAM, Parallelization, High-Performance Computing (HPC)

Milad Abdollahpour, University of Florence, Italy, milad.abdollahpour@unifi.it
Federico Domenichini, University of Florence, Italy, federico.domenichini@unifi.it
Lorenzo Cappietti, University of Florence, Italy, lorenzo.cappietti@unifi.it, 0000-0002-3957-5763

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Milad Abdollahpour, Federico Domenichini, Lorenzo Cappietti, *Numerical Wave Tanks for Wave Energy Converters Using High-Performance Computing*, pp. 835-845, © 2024 Author(s), CC BY-NC-SA 4.0, DOI: 10.36253/979-12-215-0556-6.72

1. Introduction

Marine structures play a crucial role in our understanding of how they respond to environmental conditions, particularly ocean waves. These waves impose loads and movements that require precise analysis. Coastal areas are significantly impacted by water waves, affecting shoreline stability and offshore installations. Researchers employ specialized facilities like wave tanks and flumes to study these effects (Sierra and Casas-Prat, 2014). While physical modeling and field data collection remain valuable (Hughes, 1993), Numerical Wave Tanks (NWTs) have revolutionized coastal engineering research by providing a virtual platform for simulating complex wave-structure interactions (Simonetti et al., 2015). Researchers have explored NWTs and their applications since the 19th century, making them a powerful tool for studying various coastal engineering scenarios (Boo et al., 1994; Boo and Kim, 1997, 1997; Cointe and Geyer, 1991; Dommermuth and Yue, 1987; Grilli and Horrillo, 1998; Longuet-Higgins and Cokelet, 1976; Nojiri, 1980; Tanizawa and Naito, 1997; Vinje and Brevig, 1980). In recent years, several systematic studies have been found with NWTs and their application in different analyses. They excel in simulating wave interaction with various structures, including floating platforms used in offshore operations and wave energy converters (e.g. Didier and Teixeira, 2024; Olbert and Abdel-Maksoud, 2023; Qian et al., 2005; Simonetti and Cappietti, 2017; Zullah et al., 2010); coastal erosion and evaluating the effectiveness of protection strategies (e.g. (Dao et al., 2018; Jin et al., 2022; Qian et al., 2023); ship motion and stability in wave conditions (e.g. Contento, 2000; Sen, 2016; Zhuang and Wan, 2019).

Due to their increased complexity, these models require greater computational resources and longer computation times. Recent advancements in computational techniques have led to the development of Computational Fluid Dynamics (CFD) models. CFD models have allowed accurate simulation of wave behavior by providing detailed flow information across different scales, device shapes, and wave conditions (Liu et al., 2014; Robaux and Benoit, 2021; Silva et al., 2015; Simonetti et al., 2018, 2014; Simonetti and Cappietti, 2017; Windt et al., 2019). The availability and development of High-Performance Computing (HPC) have resulted in a consistent increase in CFD-based NWTs (CNWTs) in recent years. The integration of Computational Fluid Dynamics (CFD) and High-Performance Computing (HPC) within NWTs plays an important role in simulating and optimizing complex interactions between waves and applications, offering cost-effective experimentation and a deeper understanding of fluid dynamics. High-fidelity simulations require precise consideration of parameters, and HPC's parallelization capabilities efficiently handle vast datasets, enabling simulations with finer spatial and temporal resolutions and critical for resolving small-scale features.

HPC has become a critical tool in advancing various fields including hydraulics (Sotiropoulos, 2015), offshore renewable energy (Ouro et al., 2021; Stoesser, 2014); tidal flow (Stansby and Ouro, 2022) water resources hydrodynamics (Morales-Hernández et al., 2020) have leveraged HPC to model complex fluid dynamics, demonstrating the transformative impact of computational power which is crucial for engineering applications. Despite HPC's transformative impact across related fields, there remains a significant gap in research specifically targeting offshore applications, highlighting the need for more focused efforts in Numerical Wave Tanks (NWTs) to fully exploit HPC's capabilities and achieve significant breakthroughs in these areas. This research investigates a methodology for assessing the reliability and accuracy of CFD-based NWTs, specifically within the context of HPC simulations. OpenFOAM, a versatile open-source CFD toolbox, is employed for these simulations. Grid convergence tests are conducted to ensure numerical solutions achieve the desired level of accuracy. By delving into this area, the aim is to establish a robust framework for utilizing HPC-powered NWTs with confidence, focusing on the way for more efficient and optimized designs offshore structures.

2. Materials and Methods

2.1. Set-Up of the Numerical Simulations

Numerical simulations were performed using OpenFOAM V-2306, considering the two-dimensional geometry of the physical wave flume available at the Laboratory of Maritime Engineering (LABIMA) at the University of Florence. The flume has dimensions of 37 meters in length, 0.8 meters in width, and 0.8 meters in height. Figure 1 illustrates the geometry of the wave tank.

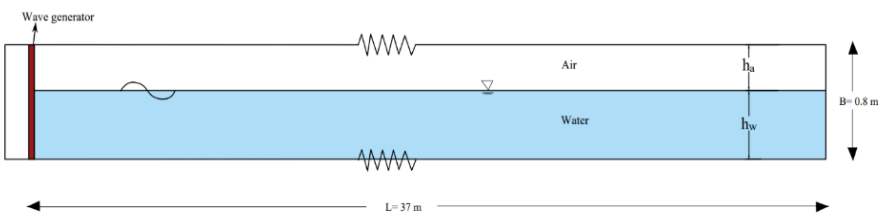

Figure 1 – Sketch of wave flume (not to scale). Overview of the simulation setup following the physical experiments, where h_w and h_a, represent the water depth and height of the air region, respectively. L and B are the length and height of the flume, respectively.

In multiphase flows, topologically orthogonal meshes with their axis aligned with the fluid interface tend to show fewer numerical problems. In OpenFOAM, geometries for internal flows are typically created using a meshing tool, known as blockMesh, which creates fully structured hexahedral meshes. A fine mesh near the free surface is needed to capture the details of wave crests, troughs, and their interactions. As shown in Figure 2, the mesh was gradually refined free surface.

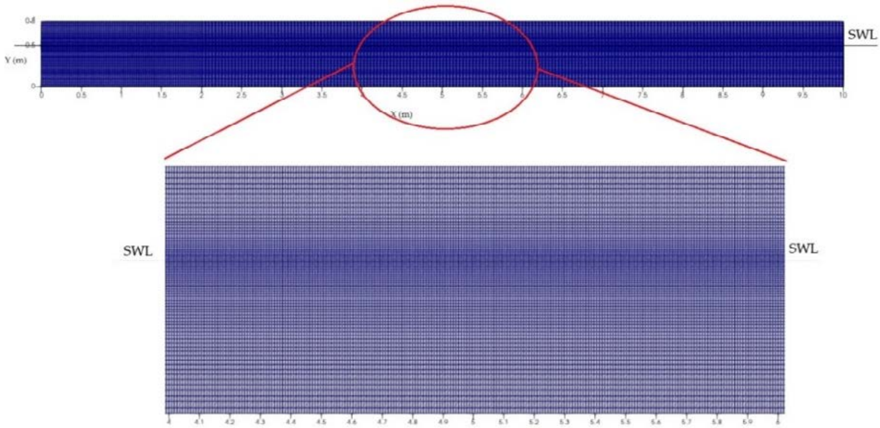

Figure 2 – The general view of the grid and zoom of the grid in the vicinity of the water surface.

The Volume of Fluid method (VOF) is used to resolve the two-phase (air and water) flow. Both phases are assumed to be incompressible, at a constant temperature, and incapable of mixing. Table 1 shows a summary of the physical properties of models.

Table 1 – Summary of physical properties of models.

Parameter		**Value**
Gravity (m/s2)		$g = 9.81$
Density (kg/m³)	Water	$\rho_w = 1000$
	Air	$\rho_a = 1$
kinematic viscosity (pa/s)	Water	$\upsilon = 10^{-5}$
	Air	$\upsilon = 1.48 \times 10^{-4}$

The boundary conditions are crucial elements determined by the specific requirements of each numerical solution. In this study, the Inlet and Outlet boundaries are especially significant for implementing the CFD-based NWT. The inlet boundary generates the wave, while the outlet boundary ensures the fluid exits without backflow. A summary of these boundary conditions which were used is given in Table 2.

Table 2 – Summary of boundary condition implemented in OpenFOAM.

Boundary	Pressure (p_rgh)	Velocity (u)	alpha.water
Inlet (left wall – piston type wave maker)	fixedFluxPressure	movingWallVelocity	zeroGradient
Bottom	fixedFluxPressure	fixedValue	zeroGradient
Outlet (right wall)	fixedFluxPressure	waveVelocity	zeroGradient
Top (Atmosphere)	totalPressure	pressureInletOutletVelocity	inletOutlet

2.2. Computational resource

In this research, we used a diverse range of computational resources optimized for specific computational tasks. These resources include a workstation and the CINCA HPC system in Italy, one of the world's leading supercomputer clusters.

The workstation, equipped with a Core i9-9900K CPU running at 3.6 GHz, features 8 cores and 16 GB of RAM. It is utilized for moderately demanding simulations and preliminary data analysis. For more intensive computational tasks, we leverage the CINCA HPC system. This system comprises Intel Xeon Platinum 8260 processors running at 2.4 GHz, with each processor featuring 24 cores. The HPC system consists of 48 nodes, each with 384 GB of RAM, a total of 554 nodes. This architecture exploits parallel processing, allowing numerous processors to work concurrently on different segments of a task. As illustrated in Figure 3, workload distribution across these processors enhances efficiency and speed, employing advanced techniques such as distributed computing and optimized algorithms to deliver rapid and precise results for complex simulations.

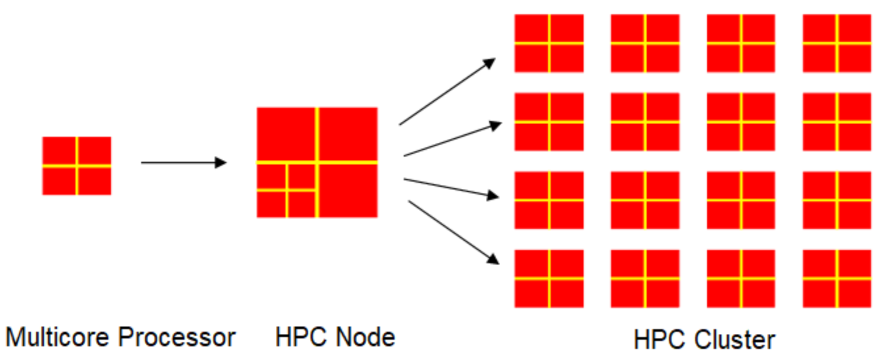

Figure 3 – Overview of High-Performance Computing (HPC) Architecture.

3. Results and discussion

3.1. Grid convergence tests

It is crucial to perform a dedicated validation focused on wave accuracy in the numerical simulation before comparing experimental data. This validation, as suggested by Coe and Neary (Coe and Neary, 2014), helps to minimize potential errors and ensures a reliable foundation for the main investigation. Mitigation strategies exist for each category to improve simulation accuracy (Oliveira et al., 2022). A precise Numerical Wave Tank (NWT) involves initial tests to determine how the size of the grid and the time steps influence the simulated waves. To find the optimal spatial and temporal discretization size—specifically the time step and cell size—researchers conduct convergence studies based on regular wave data (Windt et al., 2020). Regular waves, defined by their consistent wave height, period, and wavelength, are fundamental benchmarks in coastal engineering for analyzing wave behavior. In this study, the regular waves are characterized by a period of 1 second, a wavelength of 1.56 meters, a height of 0.1 meters, and a water depth of 0.5 meters. Spatial discretization is categorized by the number of cells per wave height (CPH), the number of cells per wavelength (CPL), and the maximum cell horizontal-to-vertical aspect ratio (AR). The temporal discretization is categorized using fixed or variable time steps, where the latter is controlled through the Courant Friedrichs Lewy (CFL) condition. A convergence analysis was conducted to determine the optimal balance between spatial and temporal discretization for accurate wave simulations within the long Numerical Wave Tank. This analysis focused on six cases, exploring the impact of CPH and CPL on accuracy. Table 3 summarizes the discretization schemes investigated for the cases, including variations in CPL and CFL.

Table 3 – Summary of discretization schemes investigated for grid convergence study.

Test Case	Number of cells	CPL	CPH	ΔT	AR
Case 1	62 900	80 - 215	11-30	T/1000	<2.2
Case 2	99 330				
Case 3	150 000				
Case 4	296 000				
Case 5	421 800				
Case 6	579 700				

CPH: number of cells per wave height; CPL: number of cells per wavelength; AR: aspect ratio; T: wave period.

Convergence analysis of various discretization schemes (CPH and CPL) identified a minimum cell requirement for accurate and efficient wave simulations in an NWT. By analyzing the convergence trends across different CPH and CPL combinations, we aimed to identify the minimum number of cells required to achieve a desired level of accuracy while maintaining computational efficiency.

The results indicate convergence in free surface elevation for cases with Cells per Wavelength (CPL) greater than 160 and Cells per Wave Height (CPH) greater than 21. This convergence balances accuracy and computational efficiency in the High-Performance Computing (HPC) cluster. Three cases (Cases 4, 5, and 6) were selected for parallel processing on a multiprocessor system to explore this efficiency further. The analysis will assess the scalability and effectiveness of utilizing HPC for NWT simulations.

3.2. Development of Model Parallelization on HPC

The high computational cost associated with long-wave tank simulations necessitates parallel computing for efficient analysis. OpenFOAM, a popular CFD software, facilitates model parallelization on HPC systems. In this study, we explored the capabilities of an HPC system with 24 cores. We investigated the impact of using 1, 4, 8, 16, and 24 processors on the simulation runtime within the long wave tank for three cases, resulting in a total of 15 tests. Table 4 presents the computational resources available for this study. It details the configurations used, including the workstation and the High-Performance Computing (HPC) system with various processor allocations.

Table 4 – Computational Resources and Processor Allocations.

Computational resources	Number of Processor used
Workstation (Desktop) (Core i9-9900K, CPU@ 3.6 GHz, With 8 cores and 16 GB RAM)	1
HPC (Intel Xeon Platinum 8260 @2.4 GHz 24 cores each, total Nodes 48*554 / 554 with 384 GB RAM)	1
	4
	8
	16
	24

Figure 4 shows the impact of utilizing varying processor cores on the computational time within the HPC environment for 2D NWT simulations. The results reveal promising trends in terms of parallel speedup but also highlight potential limitations as the number of cores increases.

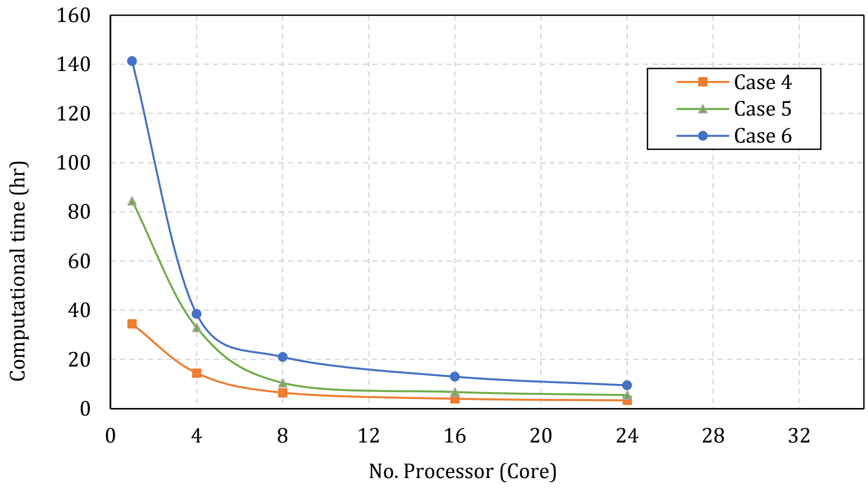

Figure 4 – Parallel Scaling Performance for 2D Numerical Wave Tank within HPC.

The observed speedup closely follows the linear scaling up to 4 processors, demonstrating efficient utilization of HPC resources. Further scaling to 16 cores maintains a nearly linear relationship, indicating continued strong performance. However, a slight degradation in speedup is observed when increasing from 16 to 24 cores. This deviation from ideal scaling suggests potential limitations due to factors such as increased communication overhead within the HPC system. These findings align with typical parallel computing trends, where initial strong scaling is often followed by diminishing returns as the number of cores increases. Addressing these limitations could involve optimizing communication patterns or exploring alternative parallelization strategies to maximize HPC efficiency.

Conclusion

This study investigated the suitability of Numerical Wave Tanks (NWTs) for simulating wave-structure interactions, focusing on the importance of grid convergence and the potential benefits of High-Performance Computing (HPC). A grid convergence analysis identified optimal cell sizes for accurate wave representation, ensuring reliable simulation results. HPC capabilities demonstrated strong parallel scaling, indicating efficient resource utilization. However, declining returns were observed as the number of cores increased, indicating potential limitations due to communication overhead. Overall, the study highlights the critical role of HPC in advancing coastal engineering simulations.

These findings underscore the importance of careful grid selection and the potential of HPC to accelerate 3D NWT simulations. Further research could explore advanced parallelization techniques and hardware optimizations to maximize HPC efficiency.

Acknowledgments

The University of Florence acknowledges the contribution of the National Recovery and Resilience Plan, Mission 4 Component 2 - Investment 1.4 - NATIONAL CENTER FOR HPC, BIG DATA AND QUANTUM COMPUTING, funded by the EU - NextGenerationEU - (CUP B83C22002830001).

References

[1] Boo, S.Y., Kim, C.H., (1997) - *Nonlinear irregular waves and forces on truncated vertical cylinder in a numerical wave tank*. Presented at the ISOPE International Ocean and Polar Engineering Conference, ISOPE, p. ISOPE-I-97-268.

[2] Boo, S.Y., Kim, C.H., Kim, M.H., (1994) - *A numerical wave tank for nonlinear irregular waves by 3-D higher order boundary element method*. International Journal of Offshore and Polar Engineering 4.

[3] Coe, R.G., Neary, V.S., (2014) - *Review of methods for modeling wave energy converter survival in extreme sea states.*

[4] Cointe, R., Geyer, P., (1991) - *Nonlinear and linear motions of a rectangular barge in a perfect fluid.*

[5] Contento, G., (2000) - *Numerical wave tank computations of nonlinear motions of two-dimensional arbitrarily shaped free-floating bodies*. Ocean Engineering 27, 531–556.

[6] Dao, M.H., Chew, L.W., Zhang, Y., (2018) - *Modelling physical wave tank with flap paddle and porous beach in OpenFOAM*. Ocean Engineering 154, 204–215.

[7] Didier, E., Teixeira, P.R., (2024) - *Numerical analysis of 3D hydrodynamics and performance of an array of oscillating water column wave energy converters integrated into a vertical breakwater*. Renewable Energy 120297.

[8] Dommermuth, D.G., Yue, D.K., (1987) - *Numerical simulations of nonlinear axisymmetric flows with a free surface*. Journal of Fluid Mechanics 178, 195–219.

[9] Grilli, S.T., Horrillo, J., (1998) - *Periodic wave shoaling over barred beaches in a fully nonlinear numerical wave tank*. Presented at the ISOPE International Ocean and Polar Engineering Conference, ISOPE, p. ISOPE-I-98-239.

[10] Hughes, S.A., (1993) - *Physical models and laboratory techniques in coastal engineering. World Scientific*.

[11] Jin, Y., Wang, W., Kamath, A., Bihs, H., (2022) - *Numerical Investigation on Wave-Overtopping at a Double-Dike Defence Structure in Response to Climate Change-Induced Sea Level Rise*. Fluids 7, 295.

[12] Liu, Q., Xie, W., Duan, W.Y., Hu, C.H., (2014) - *Numerical Simulation of Flow around a Cylinder under Different Reynolds Number*. Presented at the Applied Mechanics and Materials, Trans Tech Publ, pp. 434–440.

[13] Longuet-Higgins, M.S., Cokelet, E.D., (1976) - *The deformation of steep surface waves on water-I. A numerical method of computation*. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences 350, 1–26.

[14] Morales-Hernández, M., Sharif, M.B., Gangrade, S., Dullo, T.T., Kao, S.-C., Kalyanapu, A., Ghafoor, S.K., Evans, K.J., Madadi-Kandjani, E., Hodges, B.R., (2020) - *High-performance computing in water resources hydrodynamics*. Journal of Hydroinformatics 22, 1217–1235.

[15] Nojiri, N., (1980) - *Study on the Drifting Force on Two-Dimensional Floating Body in Regular Waves.* Transactions of the West-Japan Society of Naval Architects 131–152.

[16] Olbert, G., Abdel-Maksoud, M., (2023) - *High-fidelity modelling of lift-based wave energy converters in a numerical wave tank*. Applied Energy 347, 121460.

[17] Oliveira, D., de Almeida, J.L., Santiago, A., Rigueiro, C., (2022) - *Development of a CFD-based numerical wave tank of a novel multipurpose wave energy converter*. Renewable Energy 199, 226–245.

[18] Ouro, P., Lopez-Novoa, U., Guest, M.F., (2021) - *On the performance of a highly-scalable Computational Fluid Dynamics code on AMD, ARM and Intel processor-based HPC systems*. Computer Physics Communications 269, 108105.

[19] Qian, L., Mingham, C., Causon, D., Ingram, D., Folley, M., Whittaker, T., (2005) - *Numerical simulation of wave power devices using a two-fluid free surface solver*. Modern Physics Letters B 19, 1479–1482.

[20] Qian, Z., Wang, L., Zhang, C., Liu, Q., Chen, Q., Lü, X., (2023) - *Numerical modeling of water waves with the highly efficient and accurate Lagrangian-Eulerian stabilized collocation method (LESCM).* Applied Ocean Research 138, 103672.

[21] Robaux, F., Benoit, M., (2021) - *Development and validation of a numerical wave tank based on the Harmonic Polynomial Cell and Immersed Boundary methods to model nonlinear wave-structure interaction*. Journal of Computational Physics 446, 110560.

[22] Sen, D., (2016) - *Time domain simulation of side-by-side floating bodies using a 3D numerical wave tank approach.* Applied Ocean Research 58, 189–217.

[23] Sierra, J.P., Casas-Prat, M., (2014) - *Analysis of potential impacts on coastal areas due to changes in wave conditions*. Climatic change 124, 861–876.

[24] Silva, M.C., Vitola, M.A., Esperança, P.T.T., Sphaier, S.H., Levi, C.A., (2015) - *Numerical simulations of regular waves in an ocean basin.* Marine Systems & Ocean Technology 10, 131–144.

[25] Simonetti, I., Cappietti, L., (2017) - *A CFD Study on the Balance of Energy in a Fixed Bottom-detached Oscillating Water Column Wave Energy Converter*. Presented at the Proceedings of the 12th European Wave and Tidal Energy Conference, European Wave and Tidal Energy Conference 2017, pp. 0–0.

[26] Simonetti, I., Cappietti, L., El Safti, H., Manfrida, G., Matthies, H., Oumeraci, H., (2015) - *The use of OpenFOAM as a virtual laboratory to simulate oscillating water column wave energy converters.* Presented at the MARINE VI: proceedings of the VI International Conference on Computational Methods in Marine Engineering, CIMNE, pp. 153–164.

[27] Simonetti, I., Cappietti, L., El Safti, H., Oumeraci, H., (2014) - *3D numerical modelling of oscillating water column wave energy conversion devices: current knowledge and OpenFOAM® implementation.* Presented at the Proceedings of the 1st International Conference on Renewable Energies Offshore, Lisbon, Portugal, pp. 24–26.

[28] Simonetti, I., Cappietti, L., Elsafti, H., Oumeraci, H., (2018) - *Evaluation of air compressibility effects on the performance of fixed OWC wave energy converters using CFD modelling.* Renewable Energy 119, 741–753.

[29] Sotiropoulos, F., (2015) - *Hydraulics in the era of exponentially growing computing power.* Journal of Hydraulic Research 53, 547–560.

[30] Stansby, P.K., Ouro, P., (2022) -*Modelling marine turbine arrays in tidal flows.* Journal of Hydraulic Research 60, 187–204.

[31] Stoesser, T., (2014) - *Large-eddy simulation in hydraulics: Quo Vadis?*. Journal of Hydraulic Research 52, 441–452.

[32] Tanizawa, K., Naito, S., (1997) - *A study on parametric roll motions by fully nonlinear numerical wave tank.* Presented at the ISOPE International Ocean and Polar Engineering Conference, ISOPE, p. ISOPE-I-97-267.

[33] Vinje, T., Brevig, P., (1980) - *Numerical simulation of breaking waves.* Presented at the Proc. 3rd Int. Conf.

[34] Windt, C., Davidson, J., Ransley, E.J., Greaves, D., Jakobsen, M., Kramer, M., Ringwood, J.V., (2020) - *Validation of a CFD-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter*. Renewable Energy 146, 2499–2516.

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

[36] Zhuang, Y., Wan, D., (2019) - *Numerical simulation of ship motion fully coupled with sloshing tanks by naoe-FOAM-SJTU solver.* Engineering Computations 36, 2787–2810.

[37] Zullah, M.A., Prasad, D., Ahmed, M.R., Lee, Y.-H., (2010) - *Performance analysis of a wave energy converter using numerical simulation technique.* Science in China Series E: Technological Sciences 53, 13–18.