CCP-WSI Blind Test Series 2: Modeling focused wave impact on a floating wave energy converter by the SWENSE method

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1 Introduction

Nowadays, Computational Fluid Dynamics (CFD) based Numerical Wave Tanks (NWT) are increasingly used for marine and offshore applications. CFD solvers offer possibilities to investigate complex flow phenomena, such as flow separation and wave breaking, which are not feasible with traditional potential theory (PT) based NWTs. However, the CFD solvers often requires more computational resources. In CCP-WSI Blind test Series 1, the efficiency comparison between CFD and PT based NWTs concludes that a PT-NWT is 1 or 2 orders of magnitude faster than a CFD-NWT [10].

As both CFD and PT have clear advantages and drawbacks, research in coupling CFD and PT emerges to combine the advantages from each side. The coupling strategy can be divided into two-main categories, as follows:

- Domain Decomposition (DD): DD splits the computational domain into an inner CFD part and an outer potential domain, e.g., to use the incident wave information as the boundary condition of the CFD zone [6, 9].
- Functional Decomposition (FD): FD splits the total flow problem into (i) a part to be solved with the PT solver, containing as much information as possible and (ii) the complementary part, solved by the CFD code, to obtain the total solution [2]. For instance, the wave-structure interaction problem can be decomposed into an incident wave part and a complementary part taking into account the effect of the structure in the Spectral Wave Explicit Navier-Stokes Equation (SWENSE) method [5, 7, 11].

With the PT-CFD coupling, the SWENSE method uses the PT to solve the incident wave propagation in the entire fluid domain with fully nonlinear spectral wave models, and uses the CFD solver to obtain a corrector on the incident wave (the complementary part), mostly due to the presence of the structure. As the interesting zone of the complementary part is often only near the structure, coarse mesh can be used in the far-field of the CFD domain, achieving a reduction of CPU time for similar accuracy [8]. In the literature, several versions of the SWENSE method exist, including: (i) the original single-phase version [5], (ii) the two-phase version using velocity decomposition [11], and (iii) the two-phase version using both velocity and pressure decomposition [7].

In this paper, the SWENSE method [7] is applied to the modeling of the focused wave impact on a floating wave energy converter. The objective is to validate this new SWENSE methodology to floating structure. The PT-CFD coupled NWT consists of (i) a fully non-linear single-phase spectral wave solver HOS-NWT to reproduce the incident waves [3], and (ii) a two-phase CFD solver, foamStar-SWENSE to solve the complementary field. Note that foamStar-SWENSE is developed by Ecole Centrale de Nantes (ECN) and Bureau Veritas, based on OpenFOAM[1].

2 Theory

The SWENSE method decomposes the wave-structure interaction problem into an incident part and a complementary part:

1. the incident part concerns the propagation of the incident waves in the computational domain without the structure. This solution is given directly by a dedicated non-linear wave model based on potential theory;

[1]www.openfoam.org

2. the complementary part serves as a correction to the incident part due to the disturbance caused by the viscosity and the presence of the structure.

This decomposition is shown by Eqn.(1) where a primitive field of the flow χ (pressure, velocity, and free surface elevation) is divided into the incident part χ_I and the complementary part χ_C. χ_I is explicitly evaluated by the wave model; χ_C is to be calculated by the CFD solver. The decomposition is also illustrated by Fig 1.

$$\chi = \chi_I + \chi_C \tag{1}$$

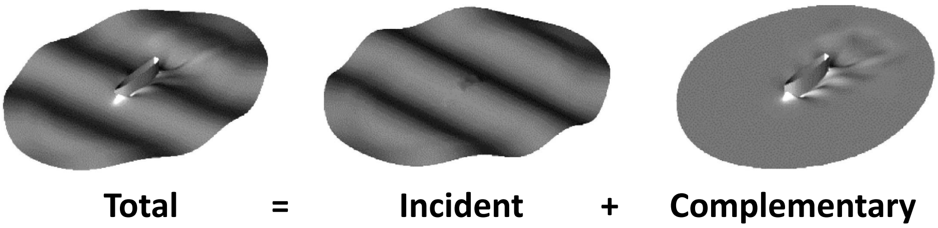


Figure 1: SWENSE Decomposition

The governing equations of the complementary variables are derived with the governing equations of the incident variables (incompressible Euler equations) and the ones of the total field (two-phase Navier-Stokes Equations). The final version of two-phase SWENSE equations using the Volume of Fluid (VOF) method as interface capture technique are as follows. The reader is referred to [7] for the derivation details.

$$\rho = \alpha\rho^w + (1-\alpha)\rho^a \tag{2}$$
$$\mu = \alpha\mu^w + (1-\alpha)\mu^a \tag{3}$$
$$\frac{\partial\alpha}{\partial t} + \mathbf{u}.\nabla\alpha = 0 \tag{4}$$
$$\nabla.\mathbf{u}_C = 0 \tag{5}$$
$$\frac{\partial\mathbf{u}_C}{\partial t} + \mathbf{u}_C.\nabla\mathbf{u}_C + \mathbf{u}_C.\nabla\mathbf{u}_I + \mathbf{u}_I.\nabla\mathbf{u}_C - \nu\nabla^2\mathbf{u}_C = -\frac{\nabla p_C}{\rho} - \frac{p_I}{\rho_I}\frac{\nabla\rho}{\rho} \tag{6}$$

where w and a stand for the properties in the water and in the air respectively. The α is the VOF field representing the volume rate of water in computational cells. It equals to 1 for a cell full of water and equals to 0 when a cell is full of air.

The advantages of the SWENSE method are:

1. The accuracy of the incident waves: it is explicitly obtained by a dedicated wave model so it is not influenced by the quality of the CFD solution (resolution, time integration, etc.);

2. The efficiency: for a given accuracy, the SWENSE method can use coarser meshes in the far field compared with the conventional CFD methods;

3. The far field boundary conditions are simple even in complex directional irregular sea states: the complementary fields are forced to vanish at the far field boundary.

3 Test case description

The simulation reproduces the blind test case in the Collaborative Computational Project for Wave/Structure Interaction (CCP-WSI)[2]. In this test case, the experiment is carried out at University of Plymouth. The participants are required to reproduce the experiments with the incident wave information only. The present test case is the Blind Test Series 2, considering a mooring floating buoy impacted by three different focused waves.

The experiments were performed in the COAST Laboratory Ocean Basin (35m long x 15.5m width) at Plymouth University, UK. The water depth at the wave makers is 4m and there is a linear slope to the working area where the water depth, h, was set to 3.0m. At the far end of the basin there is a parabolic absorbing

[2] http://www.ccp-wsi.ac.uk/

beach. The structure is a hemispherical-bottomed buoy with both the radius of the hemisphere and the cylinder equal to 0.25m. The height of the cylindrical section is also 0.25m. The reader is referred to the official site of CCP-WSI for more information[3].

4 Numerical Set-up

The present NWT combines a PT and a CFD solver. A fully-nonlinear PT wave solver, HOS-NWT [3] is used to reproduce the incident waves in the entire experimental wave tank, using the incident wave information provided by the Blind Test. The CFD zone is defined near the structure with a radius of 5 m ($r = 5$ m). In this zone, the two-phase CFD solver solves the SWENSE equation to obtain the complementary fields. This kind of domain decomposition reduce drastically the CFD computational domain compared to a full CFD-NWT, as shown in Fig. 2. Moreover, in the CFD computational domain, the mesh size is gradually increased in the away from the structure to reduce the total number of grids (see Fig. 3).

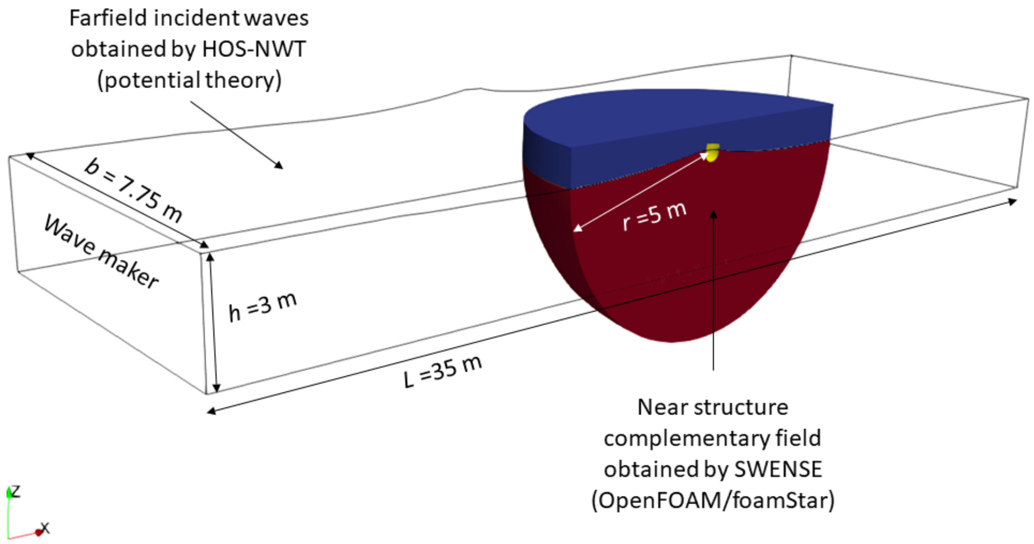


Figure 2: Layout of the PT and CFD computational domain.

For the far-field incident wave simulation, the HOS-NWT software is used. The computational domain two-dimensional. The domain length is equal to 35 m with a 10.4 m wave absorption zone close to the opposite wall, similar to the experimental set-up. The domain water depth is 3 m (the depth variation is neglected). The transverse direction is not simulated, while 512 Fourier modes are used in the longitudinal direction, 32 additional modes are used to simulate the wave maker at (x=0). The Time-Reversal (TR) methodology [1, 4] is used for an efficient control of the incident wave field at the structure location.

The center of the CFD domain locates at x = 14.8 m at the center of the buoy. The mesh consists a hemi-spherical part and a cylindrical part. This kind of mesh are often used by the SWENSE method to reduce mesh in the far-field and to capture flow details near the structure with fine mesh. The hemi-spherical mesh contains 64 grids in the tangential directions and 80 grids in the radial direction. The total number of cells is approximately 0.6M. No turbulence model is used and the mooring line is modeled as an ideal spring without mass and volume.

As required by the Blind Test, the simulation starts at $t = 35.3$ s and ends at $t = 50.3$ s. A fixed time step is set to be $\Delta t = 0.005$ s.

[3] http://www.ccp-wsi.ac.uk/data_repository/test_cases/test_case_004

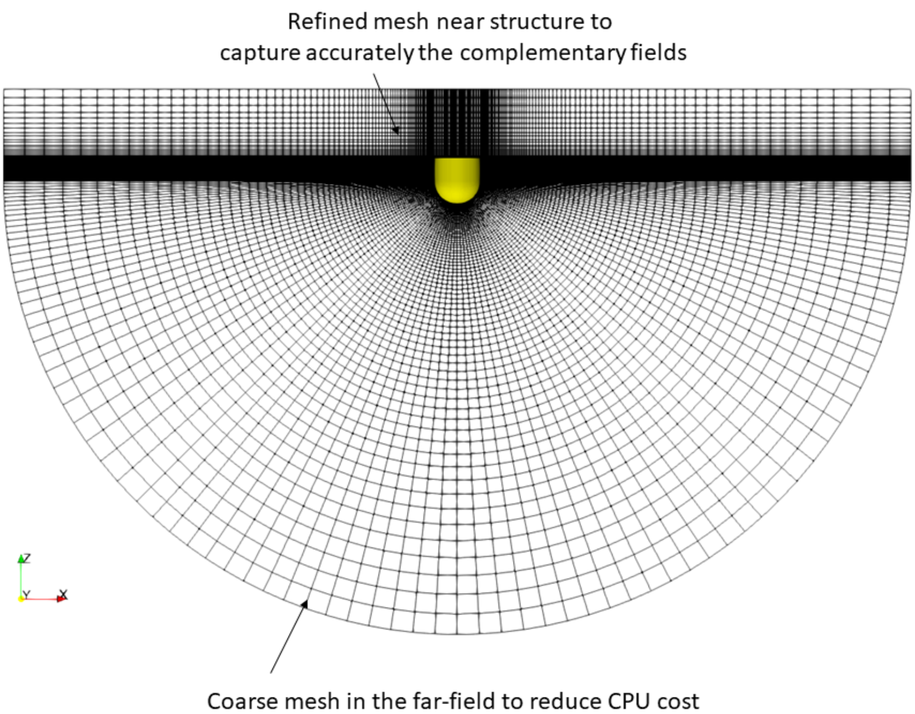


Figure 3: Layout CFD computational mesh.

5 Results

5.1 Empty tank incident waves

The time evolution of the free surface elevation at the wave probe 5 ($x = 14.8$ m) in the empty tank simulation is compared with the experimental data, see Fig. 4. This location corresponds to the position of the structure when it will be placed in the tank. In the time period of interest ($t = 35.3$ s to $t = 50.3$ s), the agreement between numerical simulations and experiments is very good. The quality of the reproduction of the incident wave field is ensured by the use of the TR methodology. The three different wave profiles, which exhibit different steepnesses at the focusing point, are accurately reproduced.

5.2 Buoy motion and mooring force

The heave, surge and pitch motion of the buoy, and the tension of the mooring line are recorded during the simulation and shown in Fig. 5.

The influence of the steepness of the wave packet is obvious on this test case. The heave motion as well as the mooring loads are slightly influenced by the form of the wave packet, while it is more sensitive for surge and pitch.

6 Conclusion

In this paper, the CCP-WSI Blind Test Series 2: focused wave interacting with floating structures are simulated with the two-phase SWENSE method in the OpenFOAM framework. The combined use of the potential theory for the incident waves and the CFD solver for the complementary field works successfully in the floating body scenario. The proposed functional decomposition allows for a significant reduction of the mesh size for the CFD computations, which results in a reduced computational effort for a given level of accuracy. This is considered as the key advantage of the SWENSE method, which is extended to the configuration of floating bodies in the present study.

References

[1] A. Chabchoub and M. Fink. Time-reversal generation of rogue waves. *Physical review letters*, 112(12): 124101, 2014.

[2] D. G. Dommermuth. The laminar interactions of a pair of vortex tubes with a free surface. *Journal of Fluid Mechanics*, 246:91–115, 1993.

[3] G. Ducrozet, F. Bonnefoy, D. Le Touzé, and P. Ferrant. A modified high-order spectral method for wavemaker modeling in a numerical wave tank. *European Journal of Mechanics-B/Fluids*, 34:19–34, 2012.

[4] G. Ducrozet, M. Fink, and A. Chabchoub. Time-reversal of nonlinear waves: Applicability and limitations. *Physical Review Fluids*, 1(5):054302, 2016.

[5] P. Ferrant, L. Gentaz, B. Alessandrini, and D. Le Touzé. A potential/RANSE approach for regular water wave diffraction about 2-D structures. *Ship Technology Research*, 50(4):165–171, 2003.

[6] 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.

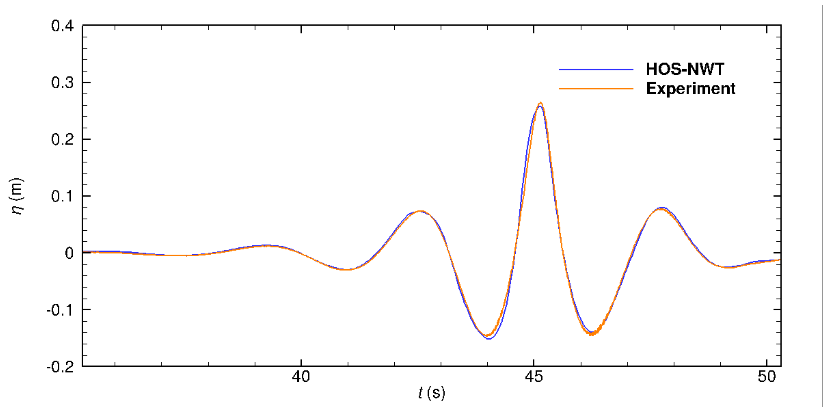
[7] Z. Li, B. Bouscasse, L. Gentaz, G. Ducrozet, and P. Ferrant. Progress in coupling potential wave models and two-phase solvers with the SWENSE methodology. In *37th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers, 2018.

[8] Z. Li, G. Deng, P. Queutey, B. Bouscasse, G. Ducrozet, L. Gentaz, D. Le Touzé, and P. Ferrant. Comparison of wave modeling methods in cfd solvers for ocean engineering applications. *Ocean Engineering*, 188:106237, 2019.

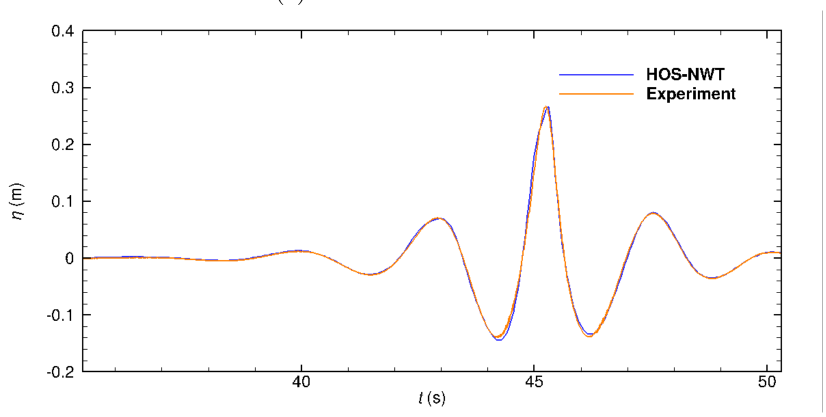
[9] X. Lu, D. D. J. Chandar, Y. Chen, and J. Lou. An overlapping domain decomposition based near-far field coupling method for wave structure interaction simulations. *Coastal Engineering*, 126:37–50, 2017.

[10] E. Ransley, S. Yan, S. A. Brown, T. Mai, D. Graham, Q. Ma, P.-H. Musiedlak, A. P. Engsig-Karup, C. Eskilsson, Q. Li, et al. A blind comparative study of focused wave interactions with a fixed fpso-like structure (ccp-wsi blind test series 1). *International Journal of Offshore and Polar Engineering*, 29(02): 113–127, 2019.

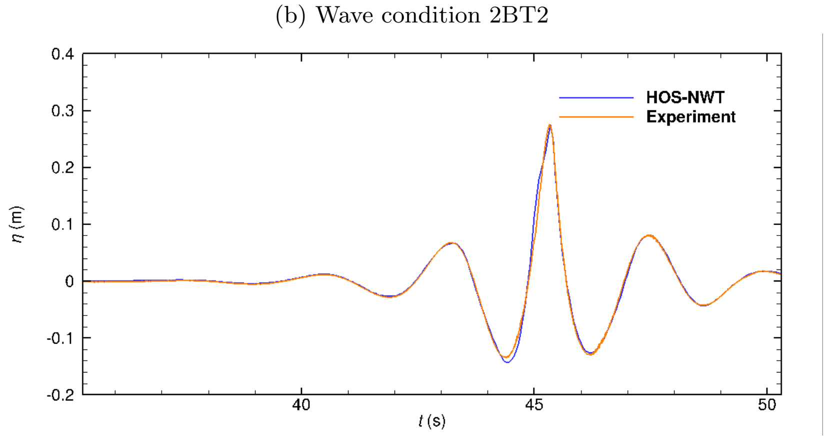
[11] V. Vukčević, H. Jasak, and Š. Malenica. Decomposition model for naval hydrodynamic applications, Part I: Computational method. *Ocean Engineering*, 121:37–46, 2016.



(a) Wave condition 1BT2

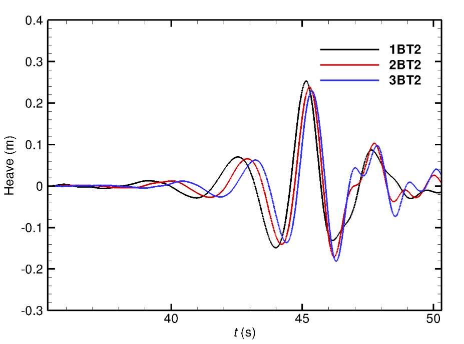


(b) Wave condition 2BT2

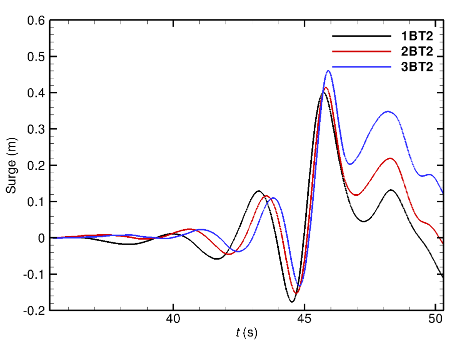


(c) Wave condition 3BT2

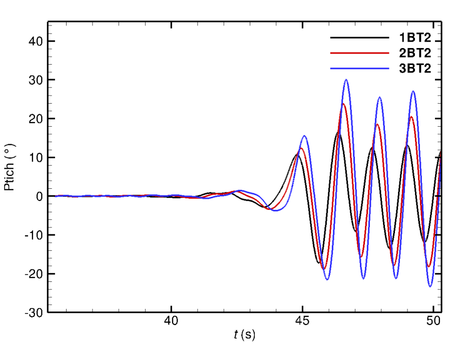
Figure 4: Comparison of the time evolution of the probe elevation between simulation and experimental data (probe No.5).



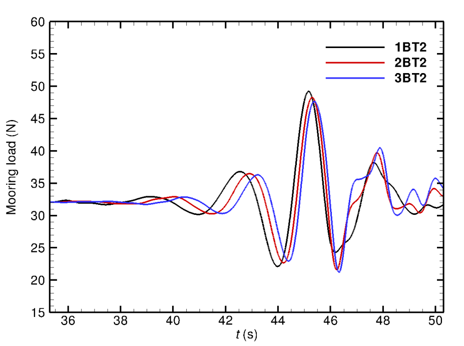
(a) Heave



(b) Surge



(c) Pitch



(d) Mooring Load

Figure 5: Simulation results of motion and mooring load.