SURVIVABILITY SIMULATION OF A WAVE ENERGY CONVERTER IN A NUMERICAL WAVE TANK

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1 Introduction

Wave energy from ocean waves is captured by wave energy converters (WECs) and converted into electrical power. WECs of the floating point absorber (FPA) type are selected which are heaving under wave loading. In this study, the numerical simulations of a WEC under operational wave conditions [1] are extended to a survivability simulation of a WEC under extreme design load conditions. Therefore, the WEC is subjected to breaking waves in a numerical wave tank (NWT).

2 Numerical framework

CFD-modelling is performed to study the behaviour of a floating WEC unit inside a NWT implemented in OpenFOAM. The two-phase flow field is resolved by the incompressible RANS equations together with a conservation equation for the volume of fluid (VoF) method. RANS turbulence modelling is applied by using a buoyancy-modified $k - \omega\ SST$ model developed by the authors [2, 3]. Wave generation and absorption at the boundaries of the NWT are adopted from the IHFOAM toolbox. The CFD-fluid solver is coupled to a motion solver in order to simulate rigid body motions. Only the governing motion of the WEC's behaviour is considered, the heave motion, allowing a reduction from a six to a one degree of freedom motion solver. The mesh motion is organised that only the highest and lowest row of cells is distorted (compressed or expanded) to prevent undesirable mesh deformations around the air-water interface. A coupling algorithm between the fluid and the motion solver is needed to obtain a converged solution between the hydrodynamic flow field around the WEC and the WEC's kinematic motion during every time step in the transient simulation. The coupling algorithm is using implicit coupling in the sub iterations by calculating a Jacobian, based on the available solutions of previous sub iterations for the acceleration of the floating body and the force acting on it, in order to minimise the number of sub iterations and consequently the CPU time [4].

3 Results & Discussion

This section presents two numerical results obtained in the NWT. Firstly, as a preliminary simulation, a two-dimensional (2D) NWT is considered without a floating WEC unit, i.e. an empty NWT. For a survivability simulation, breaking waves on the WEC are required. In order to trigger steepness-induced wave breaking in a constant water depth $d = 1.70\ m$, irregular waves are generated at the inlet by using three wave components and the method of wave focussing is applied. The surface elevations at the inlet ($x = 0\ m$) are calculated by superposition assuming linear wave theory:

$$\eta(x,t) = \sum_{i=1}^{3} \frac{H_i}{2} \cos\left(\frac{2\pi}{L_i}x - \frac{2\pi}{T_i}t + \phi_i\right) \tag{1}$$

in which H_i is the wave height, T_i the wave period, L_i the linear wave length and ϕ_i the phase of wave component i. Breaking waves are achieved by bringing the three wave components in phase at $x_f = 5\ m$ for $t_f = 10\ s$ by calculating ϕ_i of each wave component i as: $\frac{2\pi}{L_i}x_f - \frac{2\pi}{T_i}t_f + \phi_i = 0$ (linear wave theory). The numerical values for each wave component are as follows:

- $H_1 = 0.15\ m$; $T_1 = 1.00\ s \longrightarrow L_1 = 1.56\ m \longrightarrow \phi_1 = 42.71$;
- $H_2 = 0.10\ m$; $T_2 = 1.10\ s \longrightarrow L_2 = 1.89\ m \longrightarrow \phi_2 = 40.49$;
- $H_3 = 0.05\ m$; $T_3 = 1.20\ s \longrightarrow L_3 = 2.25\ m \longrightarrow \phi_3 = 38.38$;

Note that the wave periods are around the natural period of the WEC equal to $1.136\ s$, causing resonance of the WEC's heave motion. The three wave components are non-linear and therefore linear wave theory is not applicable and a non-linear fluid solver is required. Furthermore, waves generated with different wave periods generate new wave components which do not satisfy the linear dispersion relation. This is indicated in Figure 1 by the surface elevations over the length of the NWT at $x = 1\ m$, $x = 2\ m$, $x = 3\ m$, $x = 4\ m$, $x = 5\ m$ and $x = 6\ m$ for both the linear wave theory (dashed blue lines), equation (1), and the CFD result (solid red lines) during the first 30 seconds of the simulation. Due to the large wave steepness, wave breaking is induced between $x = 2\ m$ and $x = 3\ m$. This observation stresses the need for a CFD NWT to perform survivability simulations of a WEC subjected to breaking waves.

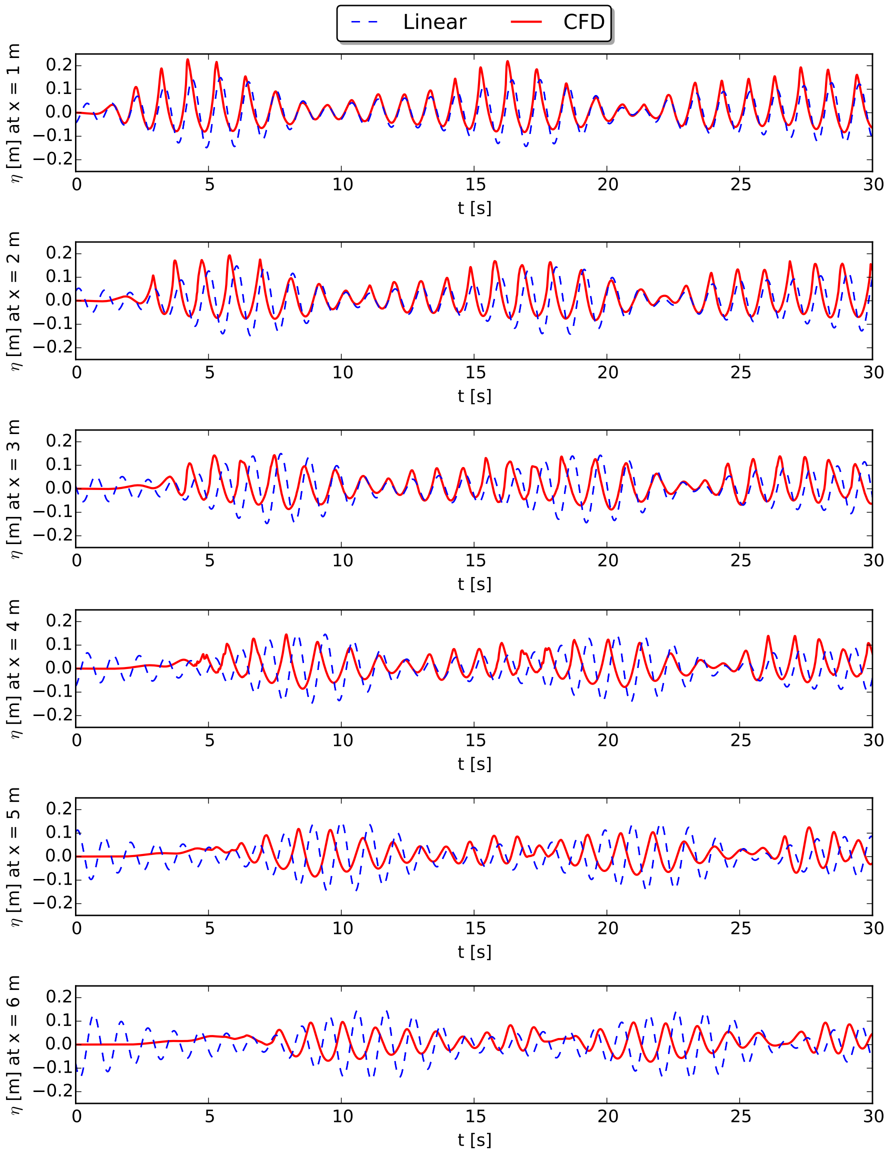

Figure 1: Surface elevations obtained with linear wave theory (equation (1), blue dashed lines) and in the empty CFD NWT (red solid lines).

For the second simulation, a WEC is installed in a three-dimensional (3D) NWT and the same irregular waves are generated. The WEC's centre is located at $x = 3\ m$, inside the wave breaking zone as found during the preliminary simulation using an empty NWT. A longitudinal symmetry plane is implemented to reduce the size of the computational domain. The NWT is $8\ m$ long, $1.6\ m$ heigh and $0.7875\ m$ wide. The computational domain has a vertical resolution of $1\ cm$ and a horizontal resolution of maximum $2\ cm$ around the free water surface. A detail of a longitudinal cross section around the WEC is visualised in Figure 2. The aspect ratio of the cells behind the WEC towards the outlet boundary on the right increases gradually which will cause numerical wave damping. This is however beneficial in order to avoid wave reflection from the absorbing outlet boundary. A maximum Courant number of 0.3 is used to limit the time step.
Figure 3 and Figure 4 visualise time series for the vertical position of the WEC z and the horizontal surge force acting on the WEC F_x respectively. Between $t = 5\ s$ and $t = 10\ s$ for example, the amplitude of the WEC's heave motion is

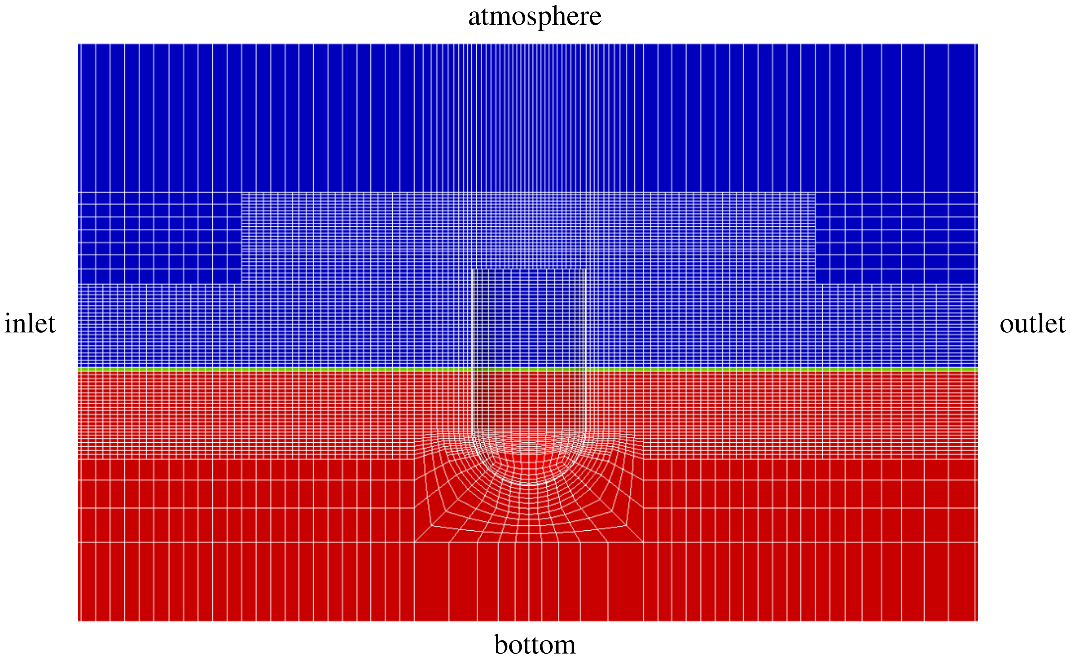

Figure 2: Cross section (XZ-plane) of the 3D computational domain in which a WEC is installed showing the initial condition for the volume fraction α at $t = 0\ s$ ($\alpha = 1$: water shown in red, $\alpha = 0$: air shown in blue).

gradually increasing due to resonance effects and the viscous damping force is important to predict correctly the WEC's heave motion. In Figure 4, the peaks observed in the time signal of the surge force on the WEC indicate the breaking wave impacts on the WEC. These forces obtained during a survivability simulation are important to quantify the design loading conditions on a WEC.

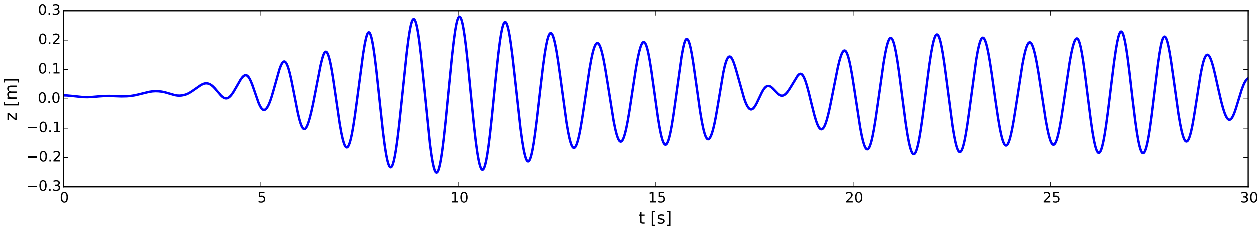

Figure 3: Vertical position z of the WEC subjected to breaking waves.

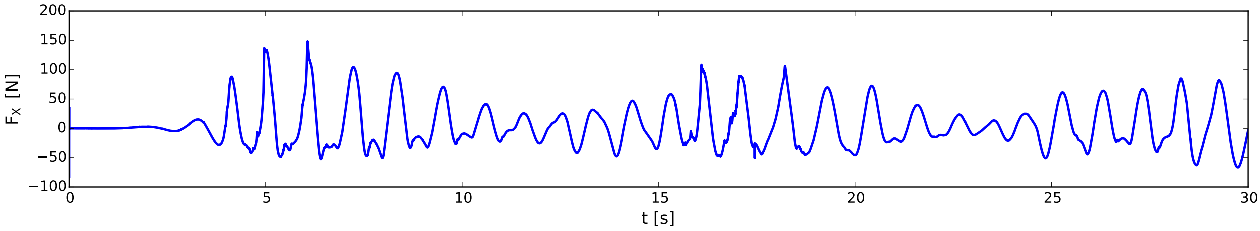

Figure 4: Horizontal surge force F_x acting on the WEC subjected to breaking waves.

Figure 5 depicts the number of sub iterations to achieve a converged fluid–motion coupling during every time step. Mostly two and occasionally three or more sub iterations are needed which indicates the successful application of the accelerated coupling algorithm for a survivability simulation of a WEC unit.

Finally, a snapshot of a breaking wave impacting on the WEC is visualised in Figure 6 at $t = 6.20\ s$. The wave starts to break in front of the WEC and the overturning volume of water is impacting on the WEC. Those highly non-linear and fully turbulent flows for breaking wave impact simulations are only possible by using a CFD NWT.

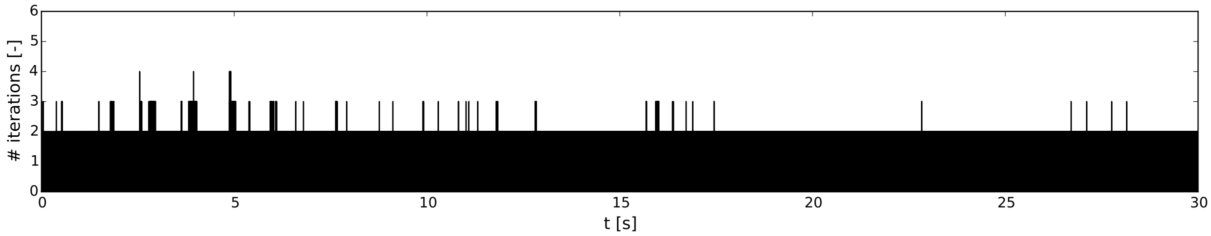

Figure 5: The number of sub iterations for every time step to have a converged fluid–motion coupling for the WEC subjected to breaking waves.

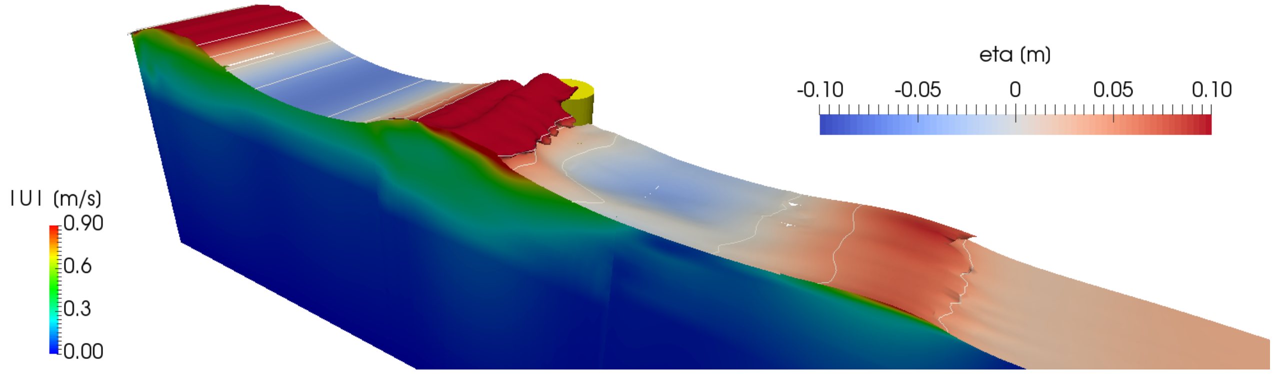

Figure 6: A snapshot at $t = 6.20\ s$ of a breaking wave impacting on the WEC in the NWT. Contour lines of the surface elevation $[m]$ are depicted on the isosurface for the volume fraction $\alpha = 0.50$. The vertical plane visualises the velocity magnitude $[m/s]$.

4 Conclusions

Based on this proof of concept study, we conclude that a CFD NWT is necessary to resolve non-linear wave–wave interactions during wave propagation and to simulate wave breaking events on a WEC for testing survivability conditions. Furthermore, it has been demonstrated that our coupling algorithm for the fluid–motion solver remains stable under extreme wave conditions and large displacements of the WEC by using few sub iterations during every time step. Future research is required to validate the numerical model for extreme wave conditions by using experimental measurements. In addition, a coupling between an accurate wave-structure interaction solver (e.g. OpenFOAM as a non-linear viscous NWT) and a fast wave-propagation solver (e.g. OceanWave3D as a non-linear potential flow NWT) will increase the efficiency of the numerical simulations by reducing the time-consuming 3D CFD domain.

Acknowledgments

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