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# Investigation of Model Validity for Numerical Survivability Testing of WECs

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*Abstract*—**This paper investigates the applicability of two numerical models to assess the survivability of Wave Energy Converters (WECs). Simulations using both a fully nonlinear Navier-Stokes solver (based on OpenFOAM) and WaveDyn (a linear time-domain model for multi-body interactions) are compared with physical experiments involving a free-floating buoy with a single mooring line. Events in which survivability is a concern are modelled using the focus wave-group NewWave. Two wave-groups (one steeper than the other) are used to identify the validity of each numerical model as a function of wave steepness. By taking into account the CPU cost and model validity, the range of applicability for both models is discussed. This constitutes the first step in future work: coupling the two numerical models to form an efficient modelling tool that benefits from the computational efficiency of WaveDyn while including the fidelity of a Navier-Stokes solver when required; therefore providing valuable information for WEC developers.**

*Index Terms*—**Floating body, OpenFOAM, NewWave, experimental validation, wave steepness**

## I. INTRODUCTION

Wave Energy Converter (WEC) developers consider reliability and survivability as key challenges in the design of their device. Existing research and standards concerning wave-structure-interaction (from oil and gas or offshore wind industries) seem unadapted to WEC design. Specifically, in the case of a point-absorber-type device, the structure cannot be considered to be fixed and, unlike traditional floating structures, the motion must not only be controlled to avoid damage but accentuated to generate power [1].

Present survivability design processes are based upon extremes, typically represented by single extreme wave events. Despite the characterization of these events being crucial, several mechanisms for their generation have been proposed (e.g. dispersive focusing or superposition) and a consensus on the description of an extreme event has yet to be found [2]. Furthermore, the peak loads on a WEC are not always the result of an extreme event, but can occur as a consequence of a particular series of smaller waves or, due to the motion history of the device [3].

Both numerical and physical modelling are widely used across engineering design [4]. The reliability of physical models is well established, and presently, the design and optimisation of WECs relies heavily upon them [5]. However, tank testing and physical experiments can be expensive and are typically limited to small scales (especially in the case of survivability studies). Numerical modelling is becoming increasingly important in the development of the offshore industry and WEC systems, where CFD-based Numerical Wave Tanks (NWT) have started to be recognized as design tools for survivability studies [6]. However, although a large number of design methods, and models, exist (with a wide range of fidelity), the limits and capacities of each are still unknown making selection of an appropriate model unclear [2].

Assessing the validity of a numerical code improves its reliability, as it defines a range of simulations and representations where the model can be used, and provides developers with certification for their models. 'Application of numerical models and codes' [7] classifies codes typically used in WEC development by physical process and the code capacity to accurately represent it by discerning a mark. However, precise measurements of code accuracy (or inaccuracies), using parametric criteria representing wave non-linearities - such as wave-steepness - instead of case-specific ones, are lacking. Also, WEC developers wish to perform accurate simulations with the least amount of CPU work [2]. Therefore, defining a code range of use improves efficiency as expensive codes will only be used to undertake survival testing, for example, whereas cheaper models will be used in more sedate cases, such as operational conditions. Also to ascertain the limit of use between those two numerical models, their validity is assessed against physical reference, with experiments that are representative of survival conditions.

The aim of this work is, therefore, to identify the validity of two numerical models, with different underlying physics, as a function of the wave steepness. The two software packages under investigation are:

- WaveDyn – a linear time-domain model for multi-body dynamics developed by DNV-GL [8], and;
- OpenFOAM - an open-source fully non-linear Computational Fluid Dynamics (CFD) code.

For each code, a numerical mirror of the Ocean Basin in the COAST Laboratory at Plymouth University [9] is generated. Simulations are performed to reproduce physical experiments involving the interaction of survival conditions - a focused wave event - with a simplified WEC system consisting of a floating buoy and a single taut mooring [3]. The accuracy and speed of the simulations are then discuss to identify the applicability of each numerical model as a function of wave steepness. This research is part of an overall project aiming to couple both numerical models, to provide an efficient numerical tool. It will take advantage of WaveDyn low computational cost to solve any cases, while being able to swap to OpenFOAM at any instant to assess local survivability event.

## II. REFERENCE MODELS

As part of an engineering design study for survivability, this study uses several models: a wave-model or design-wave, NewWave; a physical model, wave-tank plus buoy; and two numericals models, CFD with OpenFOAM and linear time-domain with WaveDyn.

### A. *Wave-model: NewWave*

This work is based on the generation of a focused wave group using NewWave theory. Introduced by [10], NewWave theory produces, for a given sea state, the average shape of the highest wave with a specified exceedance probability [11]. It is often used as a design wave across marine sector in both physical and numerical analysis: [12] compared loads using NewWave description with on-site measurement of a North Sea oil platform; [13] used NewWave to study over-topping of embankments; and in the WEC sector, [5] identified their design wave as similar to a NewWave one, and used this description for numerical simulations.

At first order the surface elevation $\eta$ of the generated focused wave is given by the addition of each wave component [14]:

$$\eta = \eta^{(1)} = \sum_{i=1}^{N} a_i cos[k_i(x - x_0) - \omega_i(t - t_0) + \epsilon_i] \qquad (1)$$

where $a_i$, $k_i$, $\omega_i$ and $\epsilon_i$ are the amplitude, wave number, wave frequency and phase of the $i^{th}$ component respectively. $N$ is the total number of wave components. Using NewWave theory, the amplitude of each wave component, $a_i$, are defined according to the spectral energy $S(\omega)$, and the amplitude $A$ of the main crest of the generated NewWave,

$$a_i = A \frac{S(\omega_i)\Delta\omega}{\sum_{p=1}^{N} S(\omega_p)\Delta f} \qquad (2)$$

where $A$ is defined using the zeroth moment of the spectrum $m_0 = (H_s/4)^2$, giving:

$$A = \sqrt{2m_0 ln(N)} \qquad (3)$$

An example of a NewWave wave focused group at the focus location, generated using a Pierson-Moskowitz spectrum, can be found in Figure 1.

The wave steepness is characterized by $kA$, where the wave-number $k$ corresponds to the peak frequency of the resulting wave groups spectrum assuming linear theory [3].

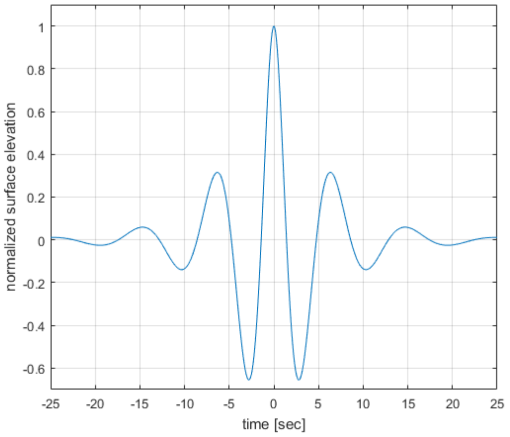


Fig. 1. Theoretical NewWave at focus location, generated by a Pierson-Moskowitz spectrum

### B. *Physical Model: OCEAN wave-tank*

This study uses the scale model of a 'generic point-absorber WEC' realised during the EPSRC X-MED project [3]. The absence of a PTO system removes more complexity, assures the model to be as generic as possible, and can also be considered as a WEC in survivability mode (PTO is off), therefore making this research meaningful to a wide panel of WECs. The overall validity of this study is assured by those simplifications, as attention if focus on validity of the two numerical model to represent motion. Also it constitutes a first step in an incremental investigation, where models can be made more complex in the future. The simple mooring line assures proportionality between motions and moorings loads; hence the second ones will be not be represented here.

The model consisted of a 0.5m diameter hemispherical with 0.25m high cylinder on top. The total dry mass of the model is 43.2kg. It is moored to the wave-tank ground using an universal joint to assure multi-directional movement. The mooring line consists of the succession, from top to bottom, of a 35kN/m stiff rope, with a 66.3N/m stiff spring, and with a load cell. It connects the model bottom to the universal joint. At resting position (a representation can be found in Figure 2), the spring is extended by 0.27m.

Tests were conducted in the 35mx15.5mx2.8m Ocean Basin at Plymouth University's COAST laboratory. 11 probes measure the surface-elevation at 128Hz, upstream of the model. An optical tracking system was used to record the 6 degree-of-freedom motion of the model, Figure 2.

### C. *Numerical Models*

Numerical models are used extensively throughout the wave energy sector, for almost every step in the development of WECs, from engineering to finance. Each can be very specific to a certain task or element of the WEC system. In the engineering design, for example, the estimation of mechanical loads on the structure alone, a wide panel of models is available for WEC developers. Capacities, limitations and

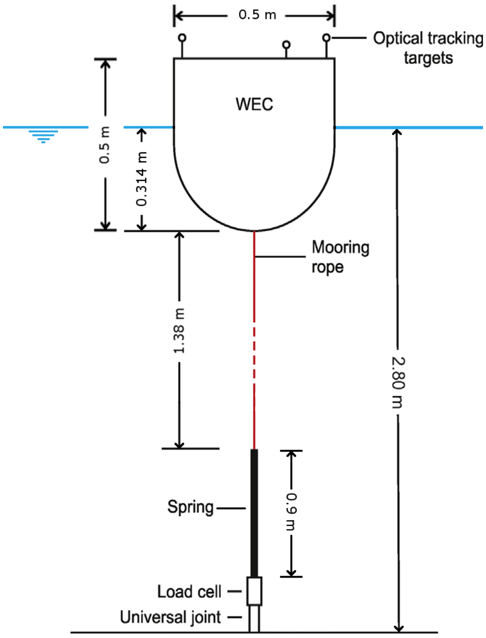


Fig. 2. X-MED model set-up and instrumentations

fidelity of those models are mostly unknown, even if the report realised through MERiFIC project started this investigation [7], however of great importance according to WEC developers [2].

Even if physical models are still required in the near future for WEC design [5], numerical models remain the solution to extrapolate and interpolate physical testing results, to full scale models or non-executable experiments (e.g. multi-directional waves, waves with different currents...).

### *1) OpenFOAM - Numerical Wave Tank:*

OpenFOAM is an open-source CFD code gaining popularity due to its range of applications, its possibility of being modified easily as it is written in the object oriented programming language C++, its active community, and of course its absence of licence fees. Also, some solvers solve the Navier-Stokes equations using the Finite Volume Method, which is the well-established technique also used by main commercial CFD codes [15]. This makes it attractive for both university research and industries. A well-made description of OpenFOAM solving WEC fluid structure interaction problem was realised for previous EWTEC conference [16], where the realisation of a NWT for WEC is explained in much details.

In this study, OpenFOAM (version 4.1) solves the Reynolds-Averaged Navier-Stokes (RANS) equations for two incompressible, isothermal, immiscible fluids (water and air) [17]. It uses a Volume Of Fluid (VoF) based method [15], to capture the interface. The movement of a solid body and its resulting mesh deformation is calculated using the internal libraries *rigidBodyDynamics* and *rigidBodyMeshMotion* respectively. These apply an interpolation of movement as function of distance to the object surface [18], using translation vector and rotation quaternion. The wave-generation toolbox *waves2Foam* [19] is adapted to the solver (*waveDyMFOAM*).

Based on its physical reference one, COAST, and in a similar manner, a Numerical Wave Tank (NWT) is realised and made of three regions (a schematic representation can be found in Figure 3):

- 1: the wave-maker: an extended boundary generating waves in the left-to-right direction, and absorbing in the right-to-left direction
- 2: the working-section: ruled by the solver
- 3: the relaxation-zone or beach: an extended boundary absorbing waves in the left-to-right direction

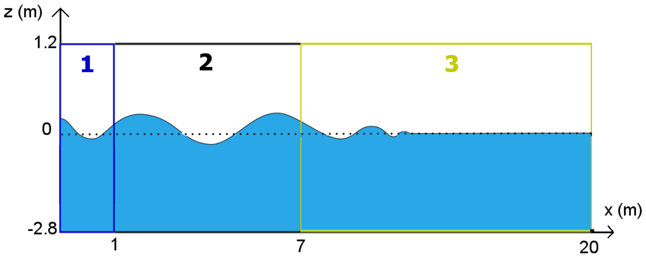


Fig. 3. The NWT schematic representation

The NWT uses a probe surface-elevation time-series as input for its wave-maker (1), by superposing linear wave components (Stokes $1^{st}$) obtained by a FFT decomposition of this signal. Then, the wave group spreads through the working-section (2) according to the solver. The beach (3) absorbs the incoming wave by applying a gradually increasing damping function.

Issues relative to the realisation of a non-case specific, in term of domain geometry, 2D-NWT with the ability to generate and absorb different wave conditions, such as NewWave focus wave-group are: reflected waves, grid refinement according to wave-height, laboratory experiments comparisons, and CPU cost [20]. A NWT with a non-specific domain geometry allows the user to run several tests in a similar manner than a physical one. Also, the best representation of the underlying physics was found using a fully squared cell grid [1]. As based on the COAST one, the working-section is set up to the distance from the model maximum surge to the first probe, 6m. A compromise on previous issues, results in a 20m long NWT with a 13m long beach, and with a resolution of at least three cells per wave-height.

Previous NWT is expanded to three dimensions, and the model is included in the mesh within a movement adaptive mesh area. Also comparatively to 2D simulations, 3D ones are computationally expensive. Square cells are conserved, but the mesh is now refined around the mean-water area, [-0.5m,0.5m], to save CPU, and on the model surface to improve its resolution. In order to represent COAST specifics behaviours, such as wave reflection from the side walls, the NWT wide is set to COAST one (15.5m) without the use of relaxation-zone on sides. Using the heave decay-test, explained later, a grid convergence study is realised, resulting in a 3 millions cells grid for the 20mx15.5mx2.8m (a cut along the length of this mesh can be seen on Figure 4).

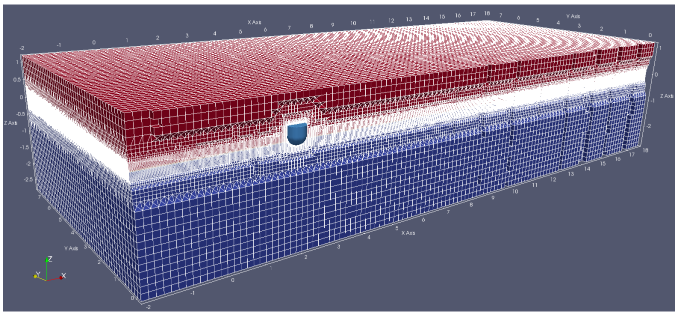


Fig. 4. OpenFOAM half-grid view – water is in blue and the wave spreads from left to right

The buoy model is defined by its mass, its centre of gravity, and its inertia matrix. The mooring line is represented by a 2.486m long spring with a 66.3N/m stiffness (rope stiffness influence is neglected).

*2) WaveDyn:*

WaveDyn is a performance and loading calculations tool for a range of WEC, developed by DNV-GL in Bristol [8]. It allows simulations of single or arrays of WEC. A device is constructed using a representative model made of specific bodies linked together with mass-less rigid links and adjustable joints.

Wave-structure interaction (WSI), in WaveDyn, is based on the Boundary Element Method (BEM). Each component is assigned with hydrodynamics properties, coming from a flow solver (AQWA or WAMIT). Body kinematics computes diffraction, radiation and buoyancy forces. This approach as a multi-body arrangement of Cummins equation, [21]:

$$(m_m + m_r(\infty))\ddot{x}(t) + f_{hs}(t) + \int_{-\infty}^{t} k(t-\tau)\dot{x}(\tau)\partial\tau = f_e(t) + f_{ext}(...) \tag{4}$$

Where $x$ is the body displacement from its equilibrium position, $m_m$ is the physical body mass, $m_r(\infty)$ is the theoretical added mass due to radiation force at infinite wave frequency, $f_{hs}(x)$ is the buoyancy force, the convolution-integral is the radiation force where $k(t)$ is the body impulse response function, $f_e(t)$ is the excitation force due to incident waves, and $f_{ext}(...)$ represents all additional non-hydrodynamics applied forces such as those due to moorings or Power-Take-Off (PTO).

X-MED WaveDyn model, Figure 5, is composed of three bodies (from seabed to the buoy):

- Seabed, the fixed datum,
- A slider - green diamond - representing the mooring line,
- the Buoy, where hydrodynamics forces comes from a WAMIT solver.

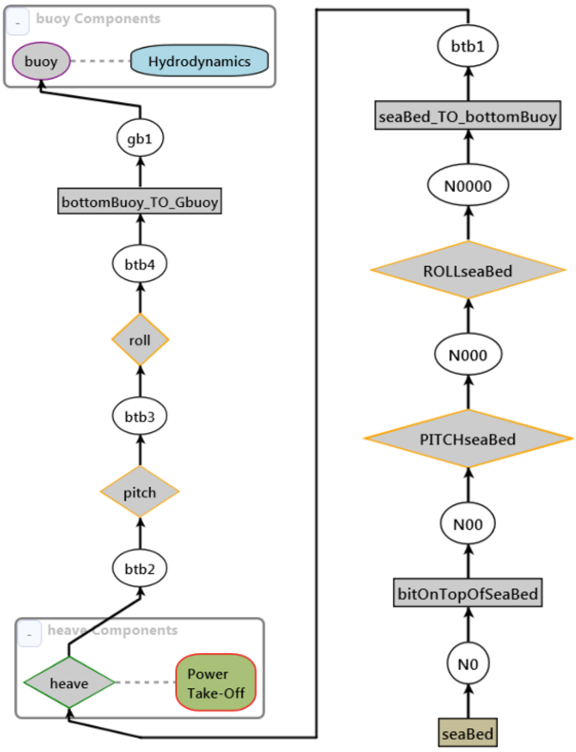


Fig. 5. X-MED WaveDyn model

Bodies are connected to each other with hinges - yellow diamonds -, and mass-less rigid links to represent the distance between two.

A wave spectrum described the decomposition into linear components of a sea-state using the probe at model location.

## III. Test plan

A heave decay test was performed in which the buoy was released from 0.204m from its resting moored position and the resonance frequency measured as 0.93Hz. This test is used for initial validation of the two numerical models.

Interaction of the taught-moored buoy in focused waves was then investigated. This study uses a Pierson-Moskowitz spectrum from a 100 year storm using hindcast data from the Wave Hub site ($T_z = 14.1$ s , $H_s = 14.4$ m, [22] p19). With this spectrum, a NewWave wave is defined, and generated at 50th scale with 1000 waves - a 3h sea-state [13]. Using Eqn.3, the largest crest amplitude is: $A = 0.267m$; and the first order wave components are found using Eqn.1 and in accordance to the COAST range of waves generation. This wave-group is defined as the reference case.

In order to assess the effect of wave-steepness on WEC movement, a steeper wave-group was created by increasing the reference peak frequency with a 1.09 proportional factor. This technique avoid the extra heave motion due to a steeper wave obtained by another technique which consists in increasing the crest amplitude while fixing the spectrum peak frequency [3].

But, please note, that the second wave-group can no longer be considered as a NewWave group.

Non-linear wave effects tend to shift the focus location [23] from its theoretical position. So a trial and error process was used during the experiments in order to focus wave groups where required. Waves groups were repeated three times to assess repeatability, where steepness and amplitude were measured. Table I sum up their characteristics, and figure 6 shows the surface-elevation, measured during the experiment, at focus location for both wave groups. The symmetry was considered when the two draught were at same depth.

TABLE I
CHARACTERISTICS MEASURED OF THE TWO WAVE-GROUPS

| Case | Measured steepness | Measured Amplitude (m) |
|---|---|---|
| ST1 | 0.167 | 0.285 |
| ST2 | 0.189 | 0.302 |

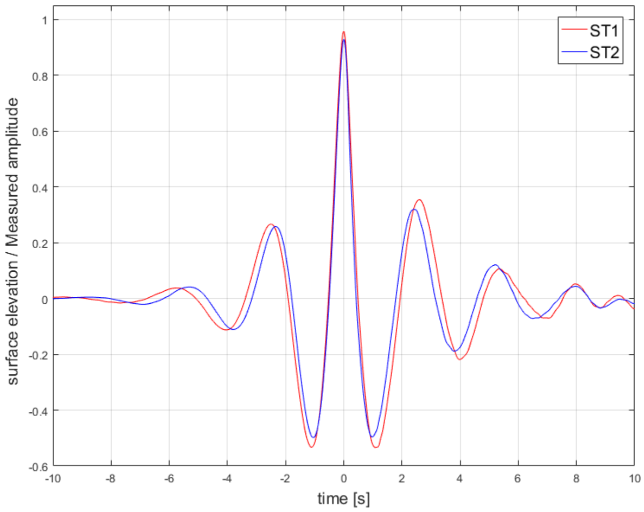


Fig. 6. Surface-elevation measured at focus location during the experiment

For the two wave-cases, surge and heave motion are compared, as they are of main importance for loads on the mooring line. Data are obtained from a Qualysis motion tracking system.

## IV. RESULTS AND DISCUSSION

### A. Decay test: results and discussion

Decay results are shown in Figure 7 and Figure 8, where the heave motion of the buoy is plotted against time as predicted by the two numerical modes and as measured in the laboratory experiment, using two different time scales. There is generally good agreement between the numerical predictions and the experiment data shown in both Figures. In term of resonance frequency, when considering only the first periods (Figure 7), OpenFOAM and WaveDyn find the same resonance frequency, $f$=0.91Hz, which is very similar to that measured in the experiment, $f$=0.93Hz. At later wave periods, the OpenFOAM prediction appears to deviate from the experiment and the period of oscillation lengthens.

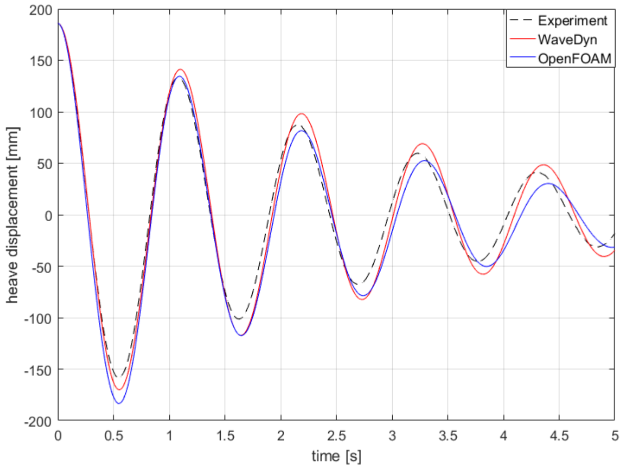


Fig. 7. First 5s for Heave decay test for moored X-MED

In terms of amplitude, both models over-estimate the heave motion in the first 5s, Figure 7, in both crest and trough. This over-estimation is seen throughout the WaveDyn simulation, whereas the amplitude of motion appears to be damped over time in the OpenFOAM simulation. OpenFOAM over-estimates mainly the trough amplitude, whereas WaveDyn over-estimates the amplitude in both crest and trough.

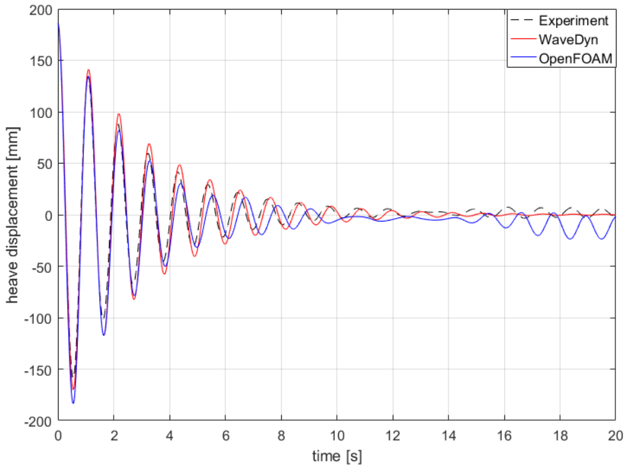


Fig. 8. Heave decay test for moored X-MED

After 14s, in Figure 8, experiment and OpenFOAM amplitudes of motion are amplifying again, whereas WaveDyn keeps following its normal decrease. This effect is probably due to waves generated by the buoy first oscillations, which are reflected by the side walls and come back at the model. As the WaveDyn BEM model do not represent the sides walls (the buoy evolves in an infinitely wide tank), those reflections effects could not be captured. Whereas the OpenFOAM NWT width was chosen accordingly to the physical one so to capture those effects; therefore this constitutes a success in representation. This side-reflection issue in WaveDyn model will not influenced futures results as reflections in the experiment are considered to happen after the main crest.

In comparing the CPU requirement of the two numerical models; WaveDyn requires less than a minute to simulate $25s$ on a desktop computer, whereas OpenFOAM requires 13h on the high-performance computing facility ARCHER, using 24 processors in parallel.

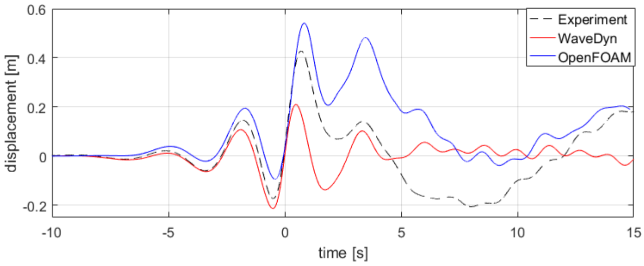
### *B. Wave-cases: results and discussion*

Viscosity is likely to have an influence on the results in situations where turbulence and flow separation are important. WaveDyn is a linearised model and is likely to predict poorly situations in which non-linear interactions between waves and structures occur. Thus we would expect to see greater difference for the steeper wave case.

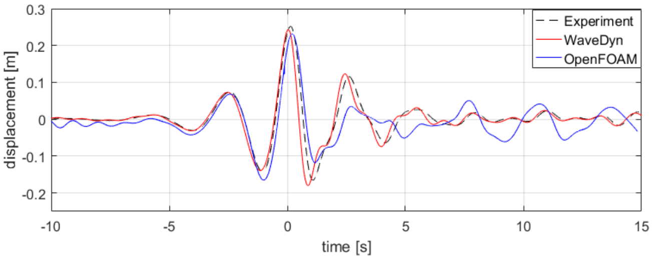
According to the experiments, shown as the black dotted line on Figures 9 and 10 - where both heave and surge motion of the buoy from the three models are plotted against time - the buoy movement can be decomposed into several steps, which appear to be correlated to the NewWave shape 1 (note that backward motion means towards the wave-maker, and forward motion is towards the beach):

1. Buoy is pushed forward and up - first NewWave peak
2. Buoy moves backwards and down - first trough of NewWave
3. Buoy is pushed up and forwards - Main crest left hand side
4. Buoy starts to regain its resting position - Main crest right hand side and second trough of NewWave
5. Buoy is briefly pushed forwards and up - second NewWave peak
6. Buoy regains its resting position with oscillations - after $5s$

Both numerical models manage to reproduce the general behaviour, and the heave motion is particularly well captured for both numerical models as shown in Figures 9(b) and 10(b). In heave, WaveDyn appears to predict more accurately step 5, which is in both cases under-estimated by OpenFOAM. This success is likely to be explained by the difference in surface-elevation generation: WaveDyn uses the surface elevation measured at the focus location during the experiment as input, and therefore it does not represent the propagation of the wave, but assures a perfect (at first order) representation of the free-surface. Whereas in OpenFOAM, the wave is propagating from its inlet boundary (left hand side of the tank), which is defined using an upstream wave gauge, towards the tank end. So at the inlet, the free-surface description is perfect - as in WaveDyn, as it uses also a sum of wave components - ; but at the focus location, the wave is the result of the wave-group spread, therefore inducing errors in the free-surface descriptions. Those are probably due to numerical diffusion, or due to the use of a linear decomposition for the description of a non-linear input.

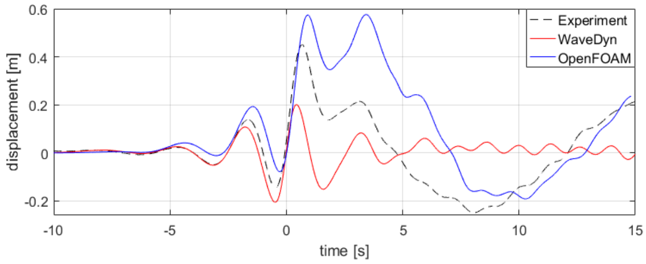


(a) Surge

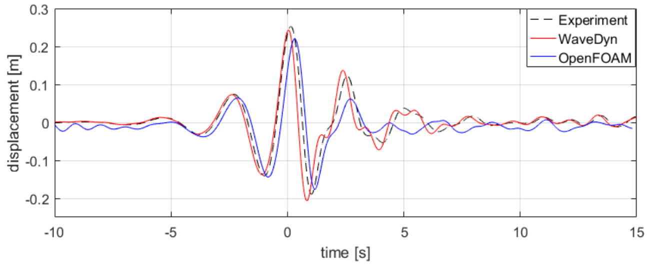


(b) Heave

Fig. 9. ST1 Experiment and numerical models comparison



(a) Surge



(b) Heave

Fig. 10. ST2 Experiment and numerical models comparison

In surge, figures 9(a) and 10(a), OpenFOAM over-estimated, whereas WaveDyn under-estimated the main surge peak. This motion - steps 3 and 4 - results from the push felt by the model due to the wave. Interestingly, step 5 is reproduced by both models, and it is overestimated in both cases. Step 6 in surge is not predicted by WaveDyn, possibly because the entire surge motion was underestimated. OpenFOAM manages to predict this pattern of oscillations, and captures even smaller ones. OpenFOAM represents the WSI in a fully-coupled way, where fields have a direct consequence on the buoy 6-DoF, and vice-versa. All buoy's degrees of freedom are coupled as well, so that the each influences the other. WaveDyn assumes linear hydrodynamics for WSI (diffraction, radiation and hydrostatic force), where no viscosity is taken into account, and movement are considered as small. Surge motion is appears a consequence of the wave passage, and therefore the viscosity plays a key role on its description; hence explaining OpenFOAM success comparatively to WaveDyn. Also, in a similar fashion to a surfer waiting for its wave, the buoy is carried by the heave motion resulting from the wave. This coupling between degree of freedom appears important for the surge description, and explains models differences.

whereas WaveDyn assumes linear theory for the water-column description as well. This difference in fluid motion under the free-surface is likely to explain those one in surge motion. But unfortunately, neither model managed to capture, at a same level of accuracy as heave, the surge motion.

### C. *Model validity*

Previous work on the X-MED buoy using NewWave, was published by Ransley [24], and shows similar behaviour in both heave and surge, which gives confidence to the OpenFOAM results presented here.

Carnegie [5] found their design wave as a combination of both maximum surge and heave motion. Therefore, the discrepancy found in the prediction of the surge motion by WaveDyn, even for the first wave group (ST1), might make the model inappropriate for wave groups of greater steepness for surge representation.

On the other hand, the OpenFOAM model still needs some improvements as there are some differences evident in the motion prediction for surge, which were unexpected. In the aforementioned study [24], surge motion was capture with a better accuracy by its OpenFOAM model. Therefore, some further development is required on the OpenFOAM model. For example, turbulences were not taken into account by the solver as the flow was considered as laminar. Turbulences models usually generates a damping of the motion as they decrease the fluid flow energy. Therefore, a possible development on the OpenFOAM model is to take into account those phenomenons by comparing turbulent models, which is likely to reduce surge motion.

## V. CONCLUSION AND FUTURE DEVELOPMENT

The two numerical models presented here are capable of reproducing movement of a floating moored buoy under two design-waves based on a NewWave representation for a 100 year event at WaveHub. However, both models shows some lacks compare to the physical model representation, used as reference.

Due to its linear wave generation representation (directly at focus location), WaveDyn represents very accuratetly the buoy heave motion, but lacks in accuracy for the surge motion, which seems to be more influenced by wave propagation and its influence on the water column description.

OpenFOAM appears to succeed to represent more accurately overall buoy behaviour, but with concerning inaccuracies. As previously stated and proposed by E.J. Ransley in [24], using linear superposition to generate highly non-linear waves is concerning. A higher order decomposition for NWT wave-maker boundary is required for development, and will hopefully over-come heave motion representation. Also, OpenFOAM model might be incomplete as no turbulences model was used, which might greatly helped to overcome the over-estimation of the surge motion representation. An OpenFOAM models comparison between the similar study [24], achieving better results, will constitute the first step of a future development.

Unfortunately, no concrete difference between the two wave group were found in this study, therefore limiting the investigations over wave-steepness. But the lack in accuracy of WaveDyn model in surge might suggest the use of a less steep wave group case for future investigations, as WaveDyn surge representation can be considered as inaccurate. Steeper wave group might also be useful to find an influence on heave representation. But due to WaveDyn wave generation, heave representation is expected to succeed as the long as buoy heave motion is similar in shape to the wave.

But in terms of the time allocated for design by WEC developers, OpenFOAM CPU cost [a week] can be put into debate as WaveDyn simulations [couple of minutes] are comparatively all but instantaneous. WaveDyn shows some great success in representing behaviour previous to the main event part, or considering heave motion only. Also, OpenFOAM has proven its capacities in many studies, such as [6], to represent well highly non-linear fluid-structure interaction (i.e. wave-breaking, large motion, over-turning surface...), to take into account turbulence models representing flow separation, and being able to handle geometries with non-linearities; different physical phenomenon present in extreme events that WaveDyn cannot represent.

Therefore, it is expected that there is a possible optimisation - if considering that OpenFOAM model can better succeed- , in terms of both CPU effort and accuracy, in which the appropriate model is selected according to the non-linearity present. This idea is also approved by B.F.M. Child [25], which research is linked to this work. Future work will consist of a coupling of these two models to realise such an optimisation and significantly reduce the computational overheads associated with survivability modelling of WECs. The idea is to use both software advantages: WaveDyn speed in weakly non-linear events; and OpenFOAM accuracy out of WaveDyn range of capacity (for highly non-linear events). The coupling is likely to be tight with WaveDyn having the supremacy. Simulation runs on WaveDyn until an out-of-range event (highly non-linear) occurs. At this moment, simulation swaps to OpenFOAM, so that this event can be represented with accuracy. It swaps back to WaveDyn once the event is finished, and in the range of WaveDyn capacity. This coupling benefits in term of CPU and accuracy, using best capacities of the two models. Therefore, accurate range of model validity, and a trigger for the swapping, are keys points for the coupling effectiveness.

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