Validation of Hydrodynamic Numerical Model of a Pitching Wave Energy Converter

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Abstract—**Validation of numerical model is essential in the development of new technologies. Commercial software and codes available simulating wave energy converters (WECs) have not been proved to work for all the available and upcoming technologies yet. The present paper presents the first stages of the validation process of a hydrodynamic numerical model for a pitching wave energy converter. The development of dry tests, wave flume and wave basin experiments are going to be explained, lessons learned shared and results presented.**

Index Terms—**WEC, wave flume, wave basin, modelling, validation**

Nomenclature

A_∞	Infinite-frequency Added Mass
B	Radiation Damping
C	Stiffness
COB_x	Centre of Buoyancy x coordinate
COG_x	Centre of Gravity x coordinate
F_b	Buoyancy Force
F_{exc}	Excitation Force
F_g	Gravity Force
F_{rad}	Radiation Force
g	Gravity
K	Kernel coefficient
M	Mass Matrix
t	Time
V	Volume
ζ_a	Wave amplitude
ρ	Density
ω	Angular frequency
$x(t)$	Displacement
$\dot{x}(t)$	Velocity
$\ddot{x}(t)$	Acceleration

I. Introduction

Significant hydrodynamic interactions occur when bodies are located close to the ocean surface. For the cases when linear potential theory is not suitable, numerical models that consider non-linearities are needed. Commercial software still have not been validated for enough wave energy devices, since wave energy is not a mature technology and the lack of published experimental data is a drawback. Yet numerical models to estimate loads and motions are essential to bring wave energy solutions and hybrid devices involving wave energy to a commercial maturity. This paper presents the early stages of validation of a F model of a pitching wave energy converter.

The case study is Floating Power Plant's wave energy converter. Floating Power Plant's device is a semisubmersible moored platform that hosts one wind turbine and four WECs (Ref. [1]). The WECs are moving in pitch motion around a shaft and are located in close proximity either to the main hull of the platform or to another WEC. This multi-body interaction will show a very interesting hydrodynamic behaviour. A single scaled WEC has been tested at the facilities of Aalborg University, in Denmark. Wave flume and wave basin experiments have been developed with several hydrostatic cases, surrounding substructures and two different incident wave angles.

The importance of the input parameters to the model will be discussed and conclusions drawn.

II. Hydrodynamic Numerical Model Description

The forces acting on the wave energy converter are:

- Excitation forces, which are forces on the floating body when it is restrained from motion and subjected to waves.
- Added mass forces due to having to accelerate the water along with the floater.
- Damping forces due to the oscillations creating outgoing waves which radiate energy away from the floater.
- Restoring forces due to bringing the buoyancy/weight equilibrium back to the floater.

The above forces can be assembled into an equation of motion:

$$\left[M + A(\omega)\right]\ddot{x} + B(\omega)\dot{x} + Cx = F_{exc}(\omega) \qquad (1)$$

Assuming $x = ae^{i\omega t}$, Eq.1 can be solved for a and the response amplitude operator (RAO) is then:

$$\mathrm{RAO}(\omega) = \frac{a}{\zeta_a} = \frac{F_{exc}}{C - (M + A(\omega))\omega^2 + iB(\omega)\omega} \qquad (2)$$

In the time domain, the model solves the dynamic equation of motion for a single degree of freedom implementing in Simulink the following equation:

$$\ddot{x} = \frac{F_{exc} + F_{rad} + F_b + F_g}{M + A_\infty} \quad (3)$$

Further details about the forces and equations can be found in Ref. [2].

A common approach is to use a hybrid frequency-time domain model based on Cummins equation with hydrodynamic inputs coming from linear wave theory (Ref. [3] and Ref. [4]). WAMIT has been used to obtain the hydrodynamic coefficients for a range of possible angles of motion, then by interpolation, the model takes as inputs the coefficients corresponding to the actual floater position. Later on, linear viscous forces will be considered to simulate friction effects. The values of the viscous coefficients have been tuned to match experimental results.

In the time domain model the radiation force has been included as a memory function approximated using Prony's method (Ref. [5]).

$$F_{rad} = -A_\infty \ddot{x}(t) - \int_0^t K(t-\tau)\dot{x}(\tau)d\tau \quad (4)$$

Also, the buoyancy force is calculated as:

$$F_b = -\rho \cdot g \cdot V \cdot COB_x \quad (5)$$

And similarly the gravity force is determined by:

$$F_g = M \cdot g \cdot COG_x \quad (6)$$

III. EXPERIMENTAL INPUTS TO THE NUMERICAL MODEL

A general overview of the experiments is going to be explained, see Ref. [6] and Ref. [7] for further details.

A. WEC Description

The pitching WEC is made of a PVC based foam with low water absorbency. It was decided a design able to perform experiments covering a wide range of hydrostatic situations, meaning different mass distributions capable to cover a wide range of natural periods. To accomplish this, the absorber has holes all over the body to host cylindrical ballast pieces, thus changing the mass and centre of gravity. It has also assembled seven pressure sensors in holes drilled perpendicularly to the WEC's surface. Fig.1 shows the main body of the wave energy absorber, with the lids that close the ballast holes in grey colour and the cables of the pressure sensors in black. Fig.2 shows two of the sensor heads. The top surface of the main body is protected with another piece of similar foam as the main body to avoid green water effects, as they entail modelling difficulties and therefore are desirable to avoid during these stages of the validation process. This overtop protection is screwed to the main body of the floater and taken into account during all the experiments, and is shown already assembled in Fig.2.

The absorber is suspended from a frame and moves in a single degree of freedom rotating in pitch motion around the
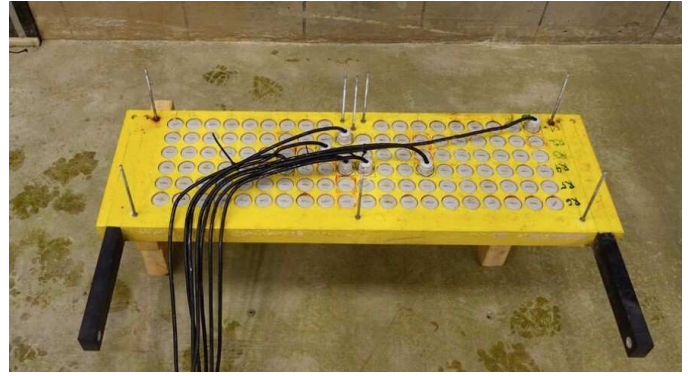

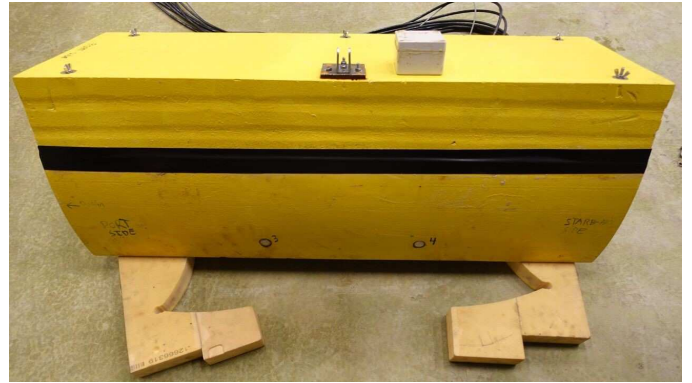Fig. 1. Top view of WEC without overtop protection

Fig. 2. Stern of WEC showing two of the pressure sensors

stainless-steel rod, inserted in the low friction Teflon bearings of the two hinge arms.

A power-take-off (PTO) can be connected. The PTO consists of an advanced linear electrical actuator and associated Linmot controller. The controller takes care of achieving the specified target position or force using position feedback from actuator or force feedback from an external force sensor.

B. Dry Tests

1) Geometry verification: The dimensions of the absorber were measured using a ruler and a calliper and compared to the original drawings for certainty. Small differences were found possibly due to the precision of the ruler and/or superficial irregularities in the floater due to painting or milling process. 3D CAD models were updated based on these new measurements. Table I gives an overview of the WEC's dimensions.

2) Mass: The cables of the pressure sensors lead to difficulties when weighing the body, since the position and the amount of cable considered may change significantly the total mass of the WEC. Fig.3 illustrates the cables standing out of the main body causing this problem. In addition, the material is not completely impermeable and watertight, hence the mass varies slightly depending on how dry the absorber is. An error of $\pm 300g$ has been defined accordingly.

3) Center of Gravity: The COG was determined using plumb line method by hanging the WEC from two separate

TABLE I
MAIN WEC DIMENSIONS

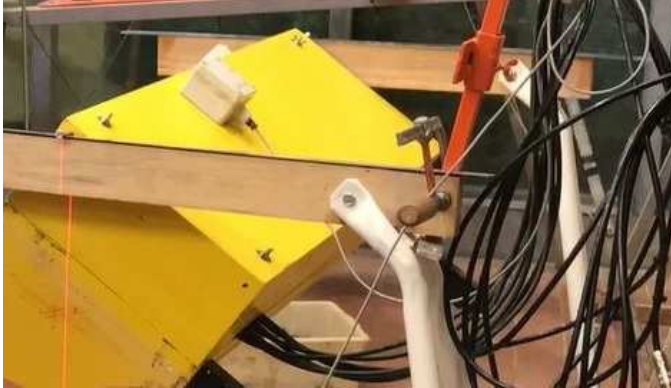|	
Width	1145.0 mm
Length of main body	343.5 mm
Length of hinge arms	228.5 mm
Height	423.0 mm

Fig. 3. Experimental method to calculate centre of gravity

points in two different positions and drawing vertical lines passing through the hanging point (Fig.3). As the figure illustrates, a laser was used to define the two vertical lines that define the COG at the cross point. A human error of $\pm 3mm$ on both horizontal and vertical coordinates of the centre of gravity was accepted for this method.

4) Moment of Inertia: The moment of inertia was determined using two methods. Firstly, with free oscillations in air and using the well-known pendulum equation. And secondly, applying fast enforced oscillations in air with the actuator.

C. Wave Flume and Wave Basin Experiments

The setup in the flume is shown in Fig.4. A piston type wave generator on the left-hand side generates the waves and an absorbing beach is placed on the right end. The absorber and the wave reference point was placed approximately in the middle of the flume, 10.25 m from the mean position of the wave generator. Thirteen wave gauges were distributed throughout the flume as shown in Fig.5. The setup with multiple wave gauges allows for accurately separating incident and reflected waves.

In the wave basin a bottom box, which is a type of surrounding substructure tested together with the WEC, was placed in the middle of the basin with the front side placed 4.86 m from the wave generator paddles, see Fig.6. A beach consisting of sea stones was absorbing the waves behind the device. Waves were generated using the software Awasys. The active absorption option was not used as reflection effects in the basin were much smaller than in the flume, and also a more accurate repeatability could be achieved in the basin when not in use the active absorption.

Tests performed for different ballast cases and set-ups in both wave flume and wave basin consisted of:

- Waves in empty facilities to perform reflection analysis.
- Decay tests.
- Regular waves with and without PTO.
- Irregular waves with and without PTO.

When simulating sea waves in flumes or basins, incident waves are affected by reflected waves. When it comes to validation of a numerical model, separating these two concepts is important. In order to know the incident and reflected waves at the reference location the following procedure was used:

1) Waves were generated and measured in the flume and basin with the WEC out of the water.
2) A wave analysis was performed to separate incident and reflected waves.
3) The same waves were repeated with the device in position, thereby getting measurements from the device.

The software "Awasys" from Aalborg University was used for wave generation including active absorption, and "Wave-Lab" for wave analysis. With WaveLab, performs a non-linear reflection analysis taking into account the propagation speed of the waves in a non-linear way. With this method was possible to get results of simultaneous water surface elevation at the selected location and pitch motion of the device.

1) Set-ups description: The WEC case study is the model-scale version of a wave energy converter that will be installed together with other three devices in a semi-submersible platform for a wind turbine. Hence, the WEC will interact with a surrounding structure. In this stage, this multi-body problem has been simplified to the cases of a single WEC interacting with different fixed surrounding structures.

In the wave flume:

- Single WEC moving in pitch (Fig.7).
- Single WEC moving in pitch with fixed submerged structure.

And in wave basin:

- Single WEC moving in pitch (Fig.8).
- Single WEC moving in pitch with fixed submerged structure.
- Single WEC moving in pitch with fixed submerged structure and short side walls (Fig.9).
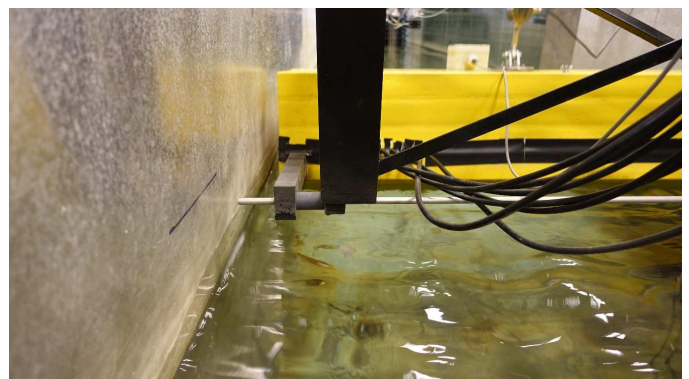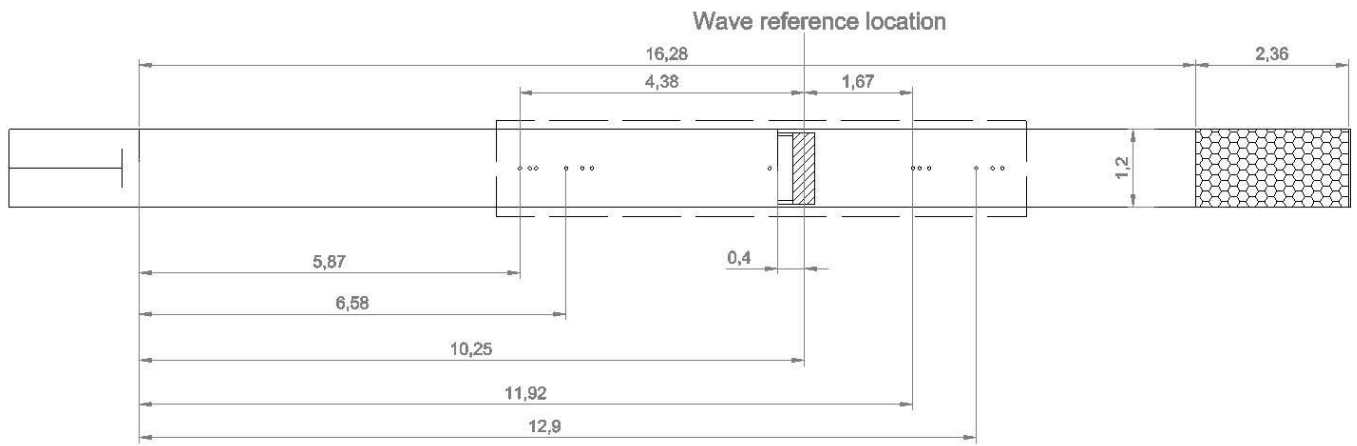

Fig. 7. Front view of WEC in wave flume

Fig. 4. Setup in the wave flume, measures in metres, birds eye view. The wave generator is on left and the beach (the honeycomb structure) is to the right. Location of the wave gauges is shown with small dots. The solid body in the centre represents the absorber.
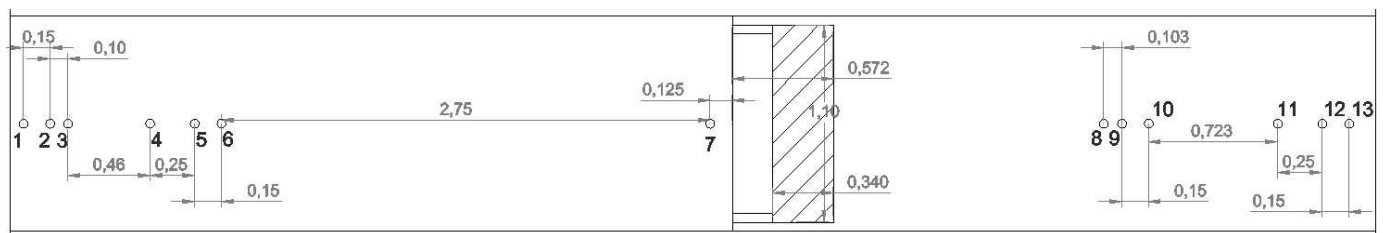

Fig. 5. Position of the wave gauges labelled from 1 to 13, bird's eye view. Measures in metres.
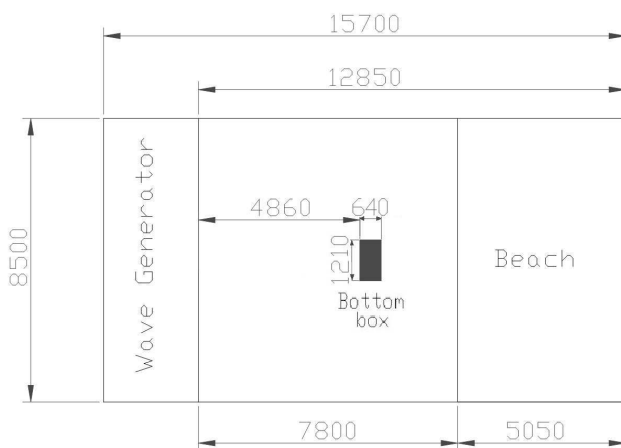

Fig. 6. Drawing showing position of bottom box in wave basin, bird's eye view, wave incidence 0 degrees, measures in mm.

Fig. 8. Experimental setup of single WEC in wave basin

2) Data acquisition: Data from the following sensors were collected:

- Pressure sensors on absorber and surrounding fixed structure.
- Wave gauges.
- Motion of WEC by a MTI sensor, particularly angular position.
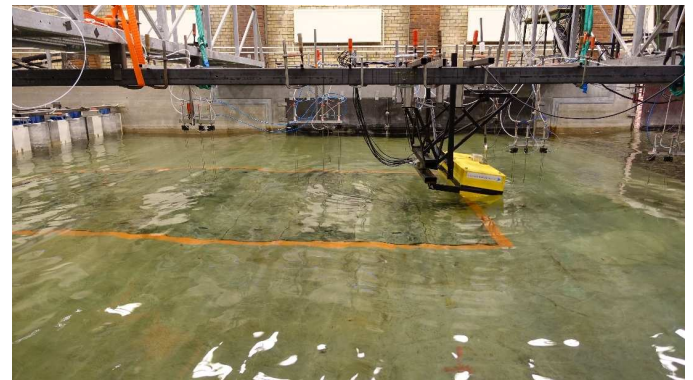- Wave trigger signal, which provides information about the starting time of the generator (used to synchronize data).
- Actuator position from Linmot system.
- Forces from the sensor by the electrical cylinder, i.e. the control force.
- Forces and moments from the 6-axis force sensor.

D. WEC position and rest angles

When the floater is in the rest position, the rest angle is measured using several methods:

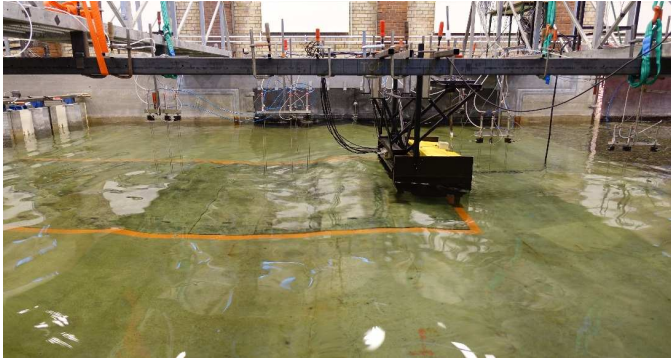- Linmot sensor, measuring the position of the power take off actuator.

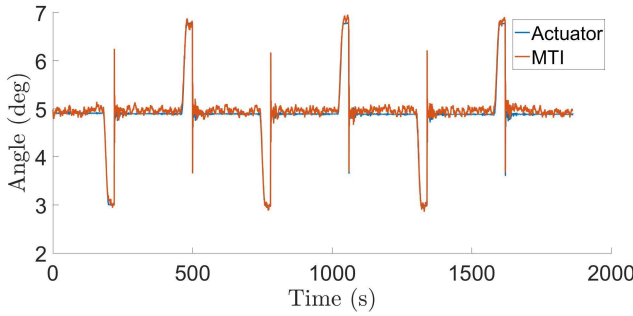Fig. 9. Experimental setup of single WEC with surrounding structure in wave basin

Decay nr.	T(s)	ζ
1	1.19	0.19
2	1.20	0.20
3	1.21	0.20
4	1.23	0.21
5	1.24	0.21
6	1.24	0.20
Mean	1.22	0.20

Fig. 10. Experimental data of decay tests of single WEC in wave basin

Fig. 11. Experimental decay data with calculated logarithmic decrement

- MTI sensor, which gives a direct angular measurement.
- A ruler to calculate the position geometrically using the distance from the hinge point and from the top of the converter to the water surface.
- Level app for smartphone.

The rest position is used to correct the mass and centre of gravity and analyse the hydrostatics. It is important to keep the water level constant, $\pm 1mm$ difference in water depth changes the body position ± 1degree. Since the objective is the validation of the numerical model, the highest accuracy level of the input data is needed.

A zoom in on the two first decay experiments is plotted in Fig.11 and Fig.12. For the same hydrostatic conditions is expected to get similar natural periods, damping ratios and rest angles, therefore a logarithmic decrement can be calculated to be suitable for all the experiments. As Table.II shows, a good agreement is achieved and the logarithmic decrement calculated from the mean values of the table is applicable for any of those experiments, as it is seen in the figures mentioned before.

IV. HYDRODYNAMIC INPUTS TO THE NUMERICAL MODEL

This section highlights the effect of the surrounding fixed structure affects on the hydrodynamic coefficients of the WEC due to the interaction between bodies.

E. Decay Tests

During decay tests, the absorber is moved away from its static position and released suddenly in calm water. When the absorber is released, it goes back to equilibrium after some oscillations. The oscillations are damped out relatively quickly and waves are radiated away from the absorber, this means that the potential energy disappears with the wave radiation. An example of a set of decay tests in wave basin is given in Fig.10.

F. Repeatability of experiments

One way to make certain that the experiments are performed correctly and results are reliable is by repeatability. In this section, a further analysis of the set of decay tests shown in Fig.10 is going to be done as example of consistency.
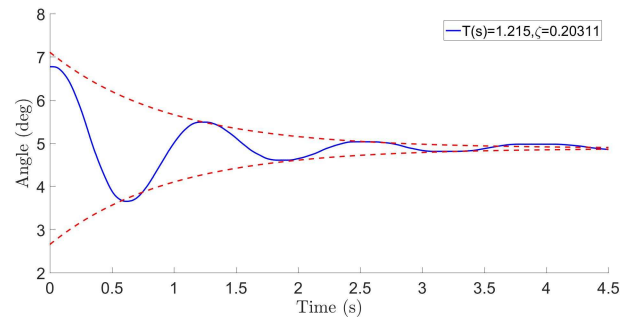

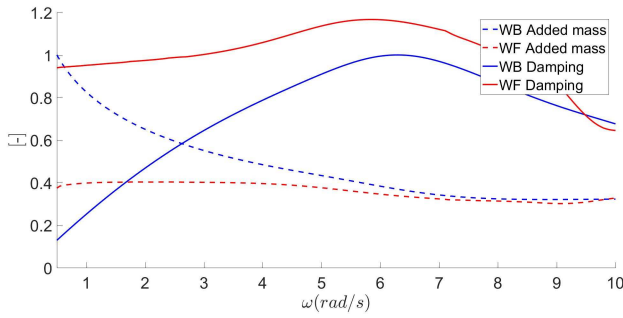Fig. 12. Experimental decay data for a different starting point with calculated logarithmic decrement

Fig. 13. Non-dimensional hydrodynamic coefficients for single WEC in wave flume and wave basin
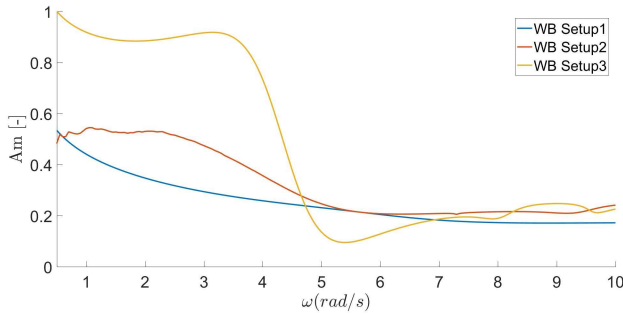

Fig. 15. Non-dimensional damping coefficients for different set-ups in wave basin

Fig. 14. Non-dimensional added mass coefficients for different set-ups in wave basin

Fig. 16. Walls effect on hydrodynamic coefficients

Results of the hydrodyamic coefficients simulated for the WEC in wave flume and wave basin with the same water depth and no other surrounding body are shown in Fig.13. For low frequencies, added mass coefficients are larger in the wave basin, even though this difference gets reduced when increasing the wave frequency. However, damping coefficients are greater in wave flume than in wave basin, but the difference is also reduced for higher wave frequencies.

Now a comparison of three different set-ups in the wave basin is presented. The different configurations are:

- Setup 1. Single WEC
- Setup 2. WEC with bottom fixed structure.
- Setup 3. WEC with bottom fixed structure and short side walls.

The third option is the most similar case to the full-scale configuration. However, for validation is important the build-up of the method and its analysis at every stage.

As shown before, discrepancy in the coefficients is larger for low frequencies in the case of added mass, see Fig.14. Important interactions occur with the side walls that make the added mass to be at least double than when the configuration does not include walls. The multi-body interaction makes damping coefficients larger for the intermediate range of frequencies, see Fig.15. According to this study, the wave energy converter performance is hugely affected by its surroundings.

Fig.16 shows the influence of the side walls. The wave basin set-up that includes short walls is compared to wave flume simulations, w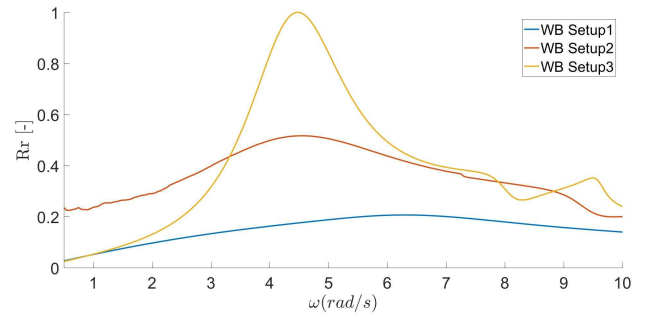hich can be considered as a configuration with long side walls. The non-dimensional coefficients change a lot depending on the frequency range.
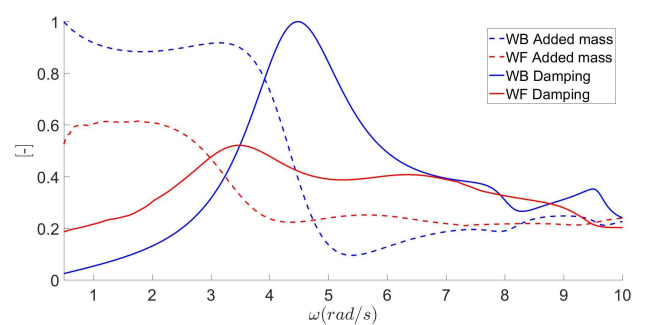
To sum up, a deeper study to get a better understanding of the interactions between bodies moving in close proximity is needed.

V. EXPERIMENTAL RESULTS

A. Importance on the multi-body interaction

Based on the differences in hydrodynamic coefficients for the different set-ups tested, a different performance of the WEC is expected. This statement is reasserted through experiments in this section.

Fig.17 shows the response amplitude operator obtained with regular and irregular waves for the device in the wave flume. The blue line refers to the single WEC, and the red line is used for the WEC with the bottom fixed surrounding structure. As it is shown, this interaction between bodies results on an optimal performance of the device for a wider range of wave periods.

The response amplitude operator of the single WEC in the wave basin and for the same water depth is presented in Fig.18, the RAO of the single WEC with bottom fixed surrounding structure in Fig.19 and finally a set-up that includes the surrounding structure plus side walls in Fig.20. The importance of the set-ups is evident, since there are changes in the amplitude of the motion, natural period and the width of the interval where the motion responses are larger.
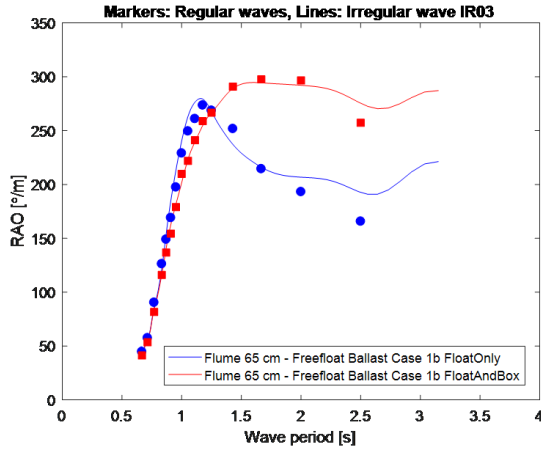
Fig. 17. Wave flume experiments with 0.65m depth for single WEC and WEC with surrounding bottom substructure
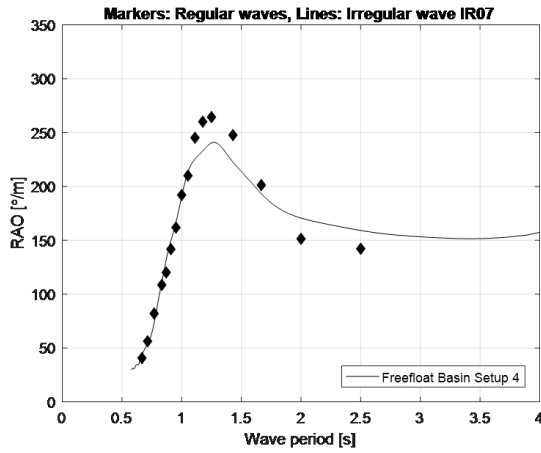

Fig. 18. Wave basin experiments with 0.65m depth for WEC with surrounding bottom substructure.
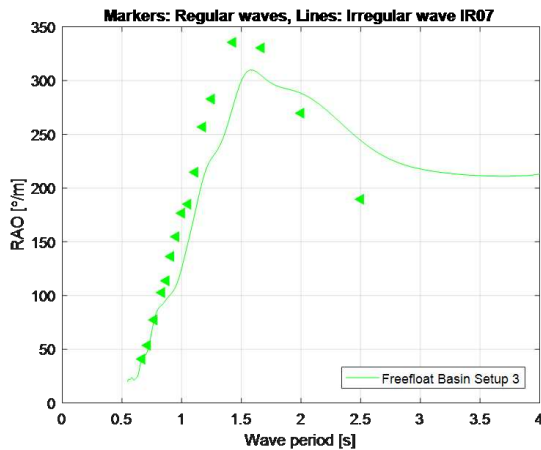

Fig. 19. Wave basin experiments with 0.65m depth for WEC with surrounding bottom substructure and side walls.
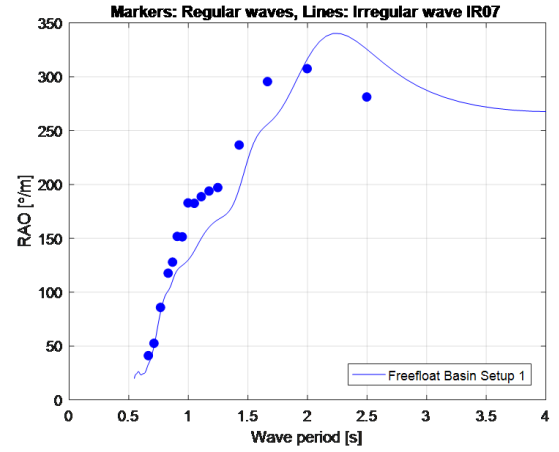
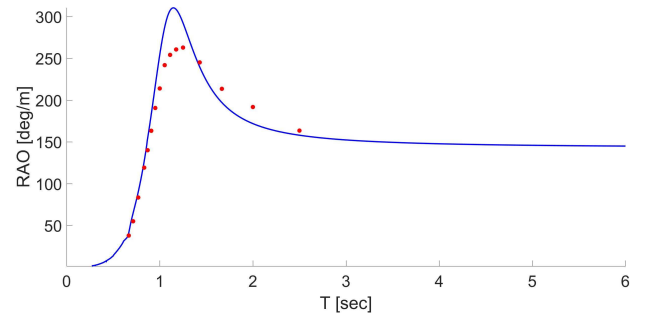

Fig. 20. Walls effect on hydrodynamic coefficients

Fig. 21. Response Amplitude Operator of single WEC in wave flume. (Solid line corresponds to numerical model and markers to experimental data)

VI. RESULTS

A. Response Amplitude Operator

In this section a frequency domain analysis is presented. The response amplitude operator (RAO) has been calculated in several cases to determine the likely behaviour of the converter when operating. Experimental data is used as comparison and to draw conclusions.

The RAOs of the single WEC are presented in Fig.21 and Fig.22.

Lastly, in Fig.23 experimental results for the setup with the bottom fixed substructure in wave flume are plotted together with the calculated RAO.

All the calculated solutions overestimate the pitch motion of the device, this is mainly due that no non-linearities have been included in the numerical model yet. However, natural frequencies seem to match and so does the shape of the curve when the fixed substructure is considered.

B. Decay Tests

Even though the model does not include any non-linearity yet, simulations of decay tests can be done since for decay tests no waves are needed. Fig.24 presents a decay tests with the model with and without friction. The friction effect has been included just as a linear force, that is a constant times velocity
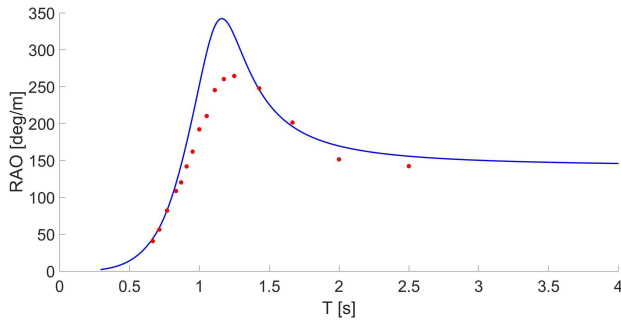
Fig. 22. Response Amplitude Operator of single WEC in wave basin. (Solid line corresponds to numerical model and markers to experimental data)
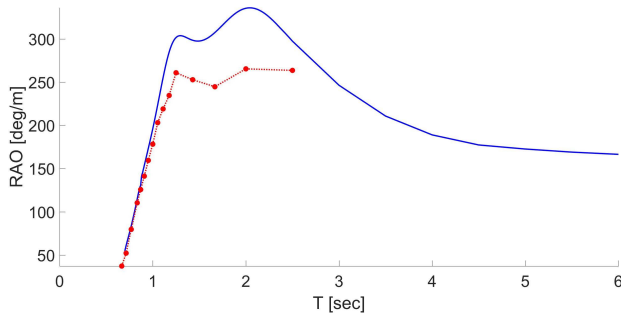

Fig. 23. Response Amplitude Operator of single WEC and surrounding structure in wave flume. Solid line corresponds to numerical model and markers to experimental data.

in pitch. Good agreement in period is found, however this set of experiments was not done with a trigger, so it was difficult to find the exact moment where the floater was released, hence the phase shift.
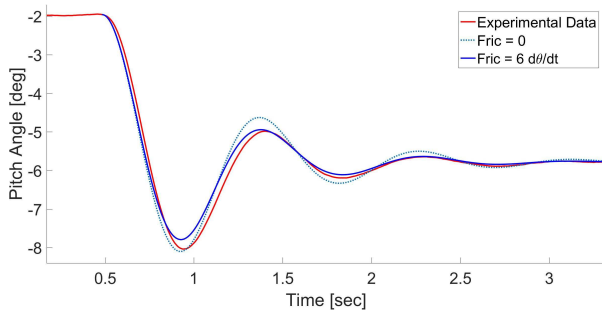

Fig. 24. Comparison between experimental data and simulated decay results

VII. CONCLUSION

The interactions between the wave energy converter and surrounding structures when are located in close proximity define the behaviour of the device, a deep study of this synergy is important to understand changes on the hydrodynamic coefficients and motions. For a validation process, is key to get reliable and consistent results from experiments, and a critical analysis on the methods and results is necessary to progress with certainty. The comparison of the numerical model results with experiments shows that the model predicts well the shape of the signals even though overestimates the motions, this is due to the lack of non-linearities such as non-linear excitation force and stiffness.

The experimental set of experiments is complete and reliable and is essential to develop and validate the hydrodynamic numerical model for a wave energy converter. As conclusion, the model at this stage is suitable for checking the correctness of the inputs. Nevertheless, it is not capable to simulate the motion of the pitching WEC accurately, still non-linearities need to be implemented to get a better agreement.

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