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# EXPERIMENTAL STUDY OF MOTION AND MOORING BEHAVIOR OF A FLOATING OSCILLATING WATER COLUMN WAVE ENERGY CONVERTER

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## ABSTRACT

Floating Oscillating Water Column (OWC) type Wave Energy Converters (WECs), compared to fixed OWC WECs that are installed near the coastline, can be more effective as they are subject to offshore waves before the occurrence of wave dissipation of a nearshore location. The performance of floating OWC WECs has been widely studied using both numerical and experimental methods. However, due to the complexity of fluid-structure interaction of floating OWC WECs, most of the available studies focus on 2D problems with limited Degrees-Of-Freedom (DOF) motion while 3D mooring effects and multiple-DOF motion have not been extensively investigated yet. Therefore, in order to gain a deeper insight of these problems, the present study focuses on wave flume experiments to investigate the motion and mooring performance of a 1:25 scaled floating OWC WEC model. As a preparatory phase for the MaRINET2 EsfLOWC (**E**fficiency & **s**urvivability of **f**loating **OWC**) project completed by the end of 2017, the main purpose of this work is to test the OWC WEC response and mooring line tensions using two types of mooring materials, including iron chain and nylon rope. The experiments are carried out in the large wave flume of Ghent University (http://awww.UGent.be) and the following data has been obtained: multiple-DOF OWC WEC motions (through an optical measurement technique), mooring line tensions (through load cells) and wave heights (through resistive wave gauges). The tested wave conditions include regular wave periods ranging from 0.7 s to 2.1 s and wave heights ranging between 4.0 cm and 17.0 cm. It is observed that the OWC WEC motions exhibit strong nonlinear effects under large waves, and the use of soft mooring materials is associated with high heave motion response. The present data obtained at UGent together with the data from the EsfLOWC tests will provide a database for numerical validation of research on floating OWC WECs.

**KEWORDS:** Floating Wave Energy Converter, Oscillating Water Column, Wave flume experiment, Mooring, MaRINET2 EsfLOWC.

## 1 INTRODUCTION

The Oscillating Water Column (OWC) is a Wave Energy Converter (WEC) type which mainly consists of a chamber and an air turbine. The incoming waves lead to the variation of wave elevation inside the chamber, and introduce an air pressure variation which drives the air-turbine. Therefore, the wave energy is converted into pneumatic energy of the water column and then the mechanic energy of the turbine. This is the power-take-off (PTO) system of the WEC. A common way of installation is to fix the OWC WECs to the coast or nearshore seabed. This approach provides convenience in construction, operation and maintenance. However, the energy dissipation of the waves approaching the coast lowers the potential of energy output. Consequently, floating offshore OWC WECs are getting more attention as they are prone to have higher efficiency in exploiting the available wave energy resources at a larger sea area (Falcão, 2010).

A comprehensive review of the history and development of OWC WECs has been given by Falcão et al. (2016) where several floating OWC WEC concepts such as the Backward Bend Duck Buoy (BBDB) OWC (Masuda et al., 1987), the Spar Buoy (McCormick, 1974) and the U-Gen (Fonseca et al., 2013) WECs are introduced. Despite the functionality and mechanism of the different floating OWC WECs, the behavior of the coupled motion and mooring system are topics of interest in this field during the recent years. Various laboratory experiments have been carried out in both wave flumes and wave tanks. Meanwhile, different numerical models are established to simulate the dynamics of OWC WECs. Codes based on potential theory, such as WAMIT, are widely used for a fast prediction of the motion performance of different types of floating OWC WECs, e.g. the cylinder OWC WEC (Sheng et al., 2012), the BBDB WEC (Sheng et al. (2011), Bailey et al. (2016)) and the spar buoy OWC WEC (Gomes et al., 2016). Computational Fluid Dynamics method (CFD) is another powerful way to solve this air-fluid-mooring-coupling problem. Luo et al. (2014) reports a numerical simulation of a heave-only floating OWC WEC connected to spring mooring in numerical wave tank developed using the Fluent CFD software. Elhanafi et al. (2017a) thoroughly described a fully 3D numerical investigation on the hydrodynamic behavior of floating and moored OWC WEC by means of the STAR-CCM+ software and validated the results using experiments. The mooring lines in the employed tests are pretensioned and connected vertically to loadcells, which can be regarded as four vertical springs. The mooring survivability is investigated in Elhanafi et al. (2017b). Besides Eulerian based method, Lagrangian based methods are used as well. Crespo et al. (2017) presented a numerical model of a floating and moored OWC WEC via the Smoothed Particle Hydrodynamics (SPH) method coupled with the inelastic catenary theory. Other laboratory tests are also reported, e.g. in Fonseca et al. (2016) and He et al. (2017).

The concept of the OWC WEC model in this paper is based on the study by Crema et al. (2015) who presented the idea to assemble many single units of fixed OWC WECs to a very large floating system (VLFS) power plant for installation in Mediterranean Sea. The experimental studies have been carried out in the wave flume of the University of Florence (LABIMA) and the results show a large relevance between energy output efficiency and incident wave frequency. Further numerical studies of this OWC WEC type are completed using OpenFOAM and are presented by Simonetti et al. (2017). This study focuses on the parametric study of the main geometric characteristics and air damping coefficients of the PTO system, while the results have shown a good agreement between numerical modelling and physical tests. Inspired by this fixed OWC WEC, a floating OWC model has been re-designed based on the targets of the present study. To ensure the buoyancy and stability of the model, ballast iron weights and foam buoyancy blocks have been added, while mooring lines are applied to restrain the motion. As the dynamics of this type of floating OWC WECs and performance of the mooring lines is yet unknown, wave flume tests are essential to investigate the governing physical processes. Thus, the main objectives of this paper are to introduce this experimental work and to reveal the characteristics of the floating OWC WEC motion and mooring line behavior. In Section 2, the description is provided of the physical model set-up, of the instrumentation and of the test conditions. The results will be analyzed and presented in Section 3. In Section 4, conclusions are discussed.

## 2 EXPERIMENTAL SETUP

### 2.1 OWC WEC Model

A 3D sketch of the geometry of the 1:25 scaled OWC WEC model is presented in Figure 1(a) and a longitudinal cross-section A'A is shown in Figure 1(b). As the front and bottom openings are asymmetrical to the principle axis, the model is destabilized and extra ballast is required to lower down the center of gravity and prevent capsizing. Using a light PVC material with density of 570 kg/m$^3$ to build the main structure and light expanded polystyrene (EPS) foam blocks around the four sides, both the buoyancy and stability are enhanced to ensure a safe operation during the tests. Table 1 lists the geometric properties of the WEC model. To simulate the turbine PTO damping, an orifice of 5 cm diameter is drilled in the top plate, which indicates a 6 % orifice-to-top area ratio.

**Table 1. OWC WEC model geometric parameters.**

| Parameter | Symbol | Value | Parameter | Symbol | Value |
|---|---|---|---|---|---|
| Total Mass [kg] | m | 2.6 | X-Moment of inertia [kg·cm$^2$] | $I_X$ | 720 |
| Height (excl. ballast weight) [cm] | $H_{OWC}$ | 44.0 | Y-Moment of inertia [kg·cm$^2$] | $I_Y$ | 940 |
| Length (excl. foam) [cm] | $L_{OWC}$ | 20.0 | Z-Moment of inertia [kg·cm$^2$] | $I_Z$ | 564 |
| Width (excl. foam) [cm] | $B_{OWC}$ | 20.0 | Height of center of gravity [cm] | $d_1$ | 15.2 |
| Draft [cm] | $d_{OWC}$ | 26.0 | Distance from center of gravity to back panel [cm] | $d_2$ | 9.1 |
| Metacentric height [cm] | GM | 9.0 | | | |
| Orifice diameter [cm] | $D_O$ | 5.0 | Front opening height [cm] | $h_O$ | 19.0 |

### 2.2 Test facility and instrumentation

The experiments are performed in the 30 m long, 1.0 m wide and 1.2 m high physical wave flume of the Coastal Engineering Research Group at Department of Civil Engineering of Ghent University, in Belgium (http://awww.UGent.be). The maximum operating water depth is 80 cm. The wave flume set-up is indicated in Figure 2. An optical tracking motion system developed by Ctech Metrology (**Ctech, 2017**) and shown in Figure 3 is used to capture the 6-DOF motion. This tracking motion system consists of a camera, several marker receivers and dedicated processing software. The system defines the global coordinate system $O_0$-$X_0Y_0Z_0$ fixed to the bottom of the wave flume, with the positive direction of the $O_0X_0$ axis pointing to the wave paddle and the positive direction of the $O_0Z_0$ axis pointing upward vertically. The four marker receivers are attached to the front side of the floating OWC WEC and are used to build a rigid body. The local coordinate system O-XYZ is fixed to the center of gravity of the OWC WEC model. Based on the definition of the coordinate system, seven resistive wave gauges are installed along the wave flume to record wave elevation data where two of them are located in front of the model, three are located behind the WEC and two at the sides of the WEC model. The wave gauge locations in global coordinate system are listed in Table 2. One extra wave gauge (WG8) is installed inside the OWC WEC chamber. Using a body-fixed reference frame, WG8 provides information of the average water column height inside the chamber.

A four-point mooring configuration is adopted while each mooring line fairlead is fixed to a hook on the OWC WEC model and the anchor end is linked to a loadcell. The mooring system parameters are listed in Table 3. To investigate the influence of the mooring material, iron chains and nylon ropes have been tested. The elasticity properties of the two materials are acquired by tension tests performed at the laboratory of Ghent University. A sketch of the mooring system layout is displayed in Figure 4. Figure 5 illustrates the arrangement of the loadcells from a top view, where the loadcell is placed perpendicular to the mooring line direction to avoid the loss of transverse component of tension. The measurement range of the loadcell is 100 N and the sampling frequency is 1000 Hz, which is accurate enough to capture the snap load on the mooring line. In Figure 6, the moored OWC WEC model is presented.

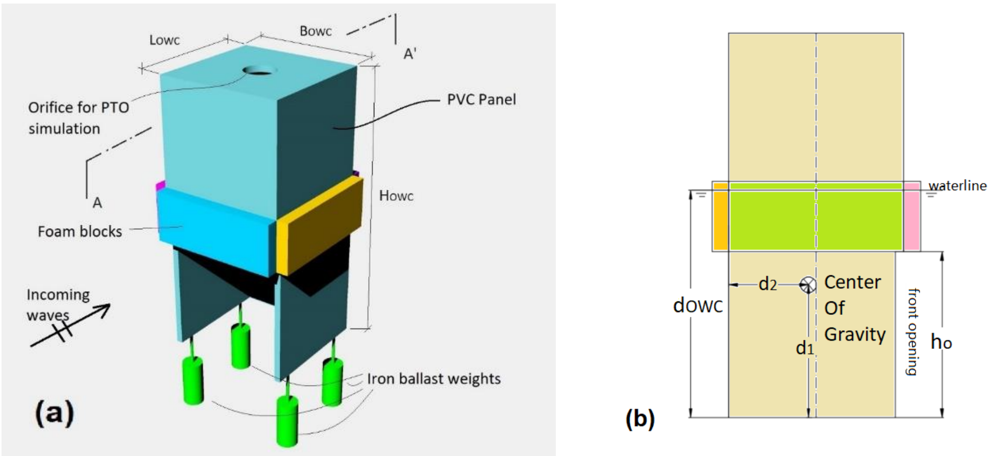


**Figure 1. Geometry of the OWC WEC model: (a) 3D Sketch. (b) Cross-section A'A.**

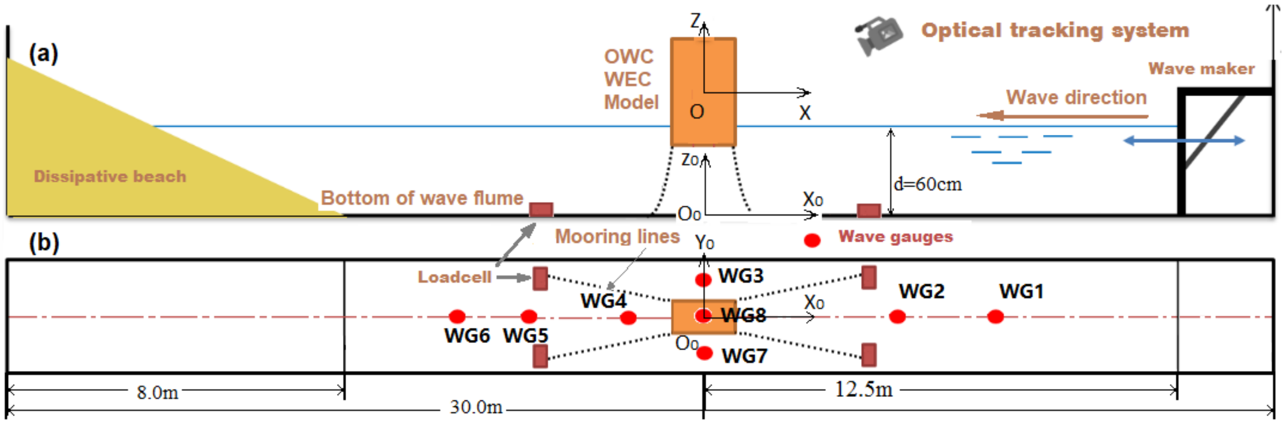


**Figure 2. Side view (a) and top view (b) of the experimental layout.**

**Table 2. Wave gauge locations in the wave flume: X and Y coordinate in global system $O_0$-$X_0Y_0Z_0$**

| Wave Gauge | WG1 | WG2 | WG3 | WG4 | WG5 | WG6 | WG7 | WG8 |
|---|---|---|---|---|---|---|---|---|
| X coordinate [m] | 5.55 | 2.74 | -0.07 | -1.9 | -2.9 | -0.55 | 0.05 | fixed to OWC |
| Y coordinate [m] | 0 | 0 | 0.36 | 0 | 0 | 0 | -0.26 | fixed to OWC |

**Table 3. Mooring system parameters of the tested OWC WEC model.**

| Mooring line properties | Symbol | Value | Mooring line properties | Symbol | Value |
|---|---|---|---|---|---|
| Total chain length [cm] | $L_C$ | 145.5 | Total rope length [cm] | $L_R$ | 144.0 |
| Length per chain segment [cm/seg] | $l$ | 0.8 | Rope elasticity [N/mm] | $k_R$ | 1.08 |
| Chain weight [g/cm] | $\omega$ | 0.607 | Fairlead height [cm] | h | 48.5 |
| Chain volume [cm$^3$/cm] | v | 0.105 | X distance between loadcells [cm] | $\Delta X_{LC}$ | 277 |
| Chain elasticity [N/mm] | $k_C$ | 18.95 | Y distance between loadcells [cm] | $\Delta Y_{LC}$ | 84.6 |

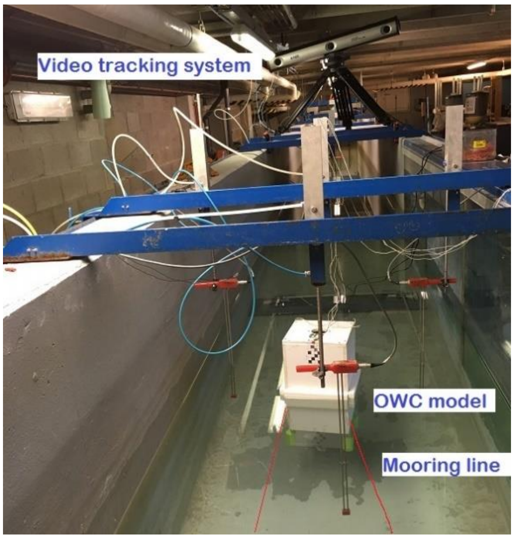


Figure 3. Optical motion tracking system.

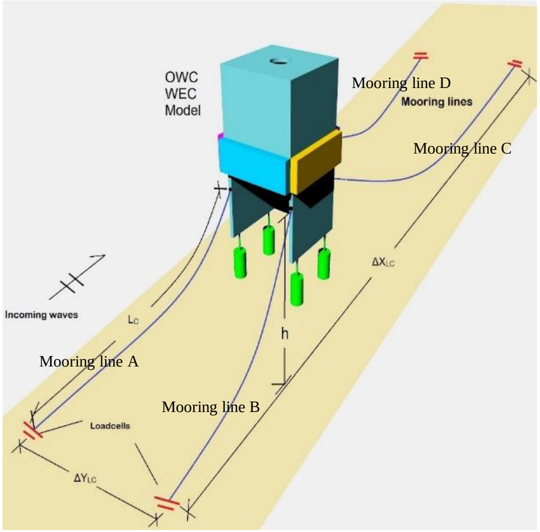


Figure 4. Moorings layout sketch.

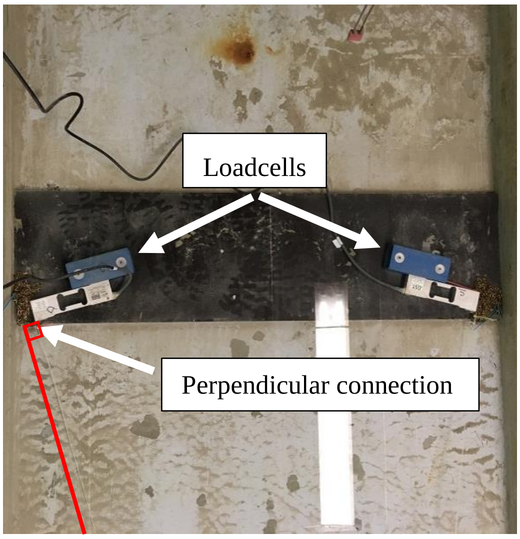


Figure 5. Load cells configuration on top view.

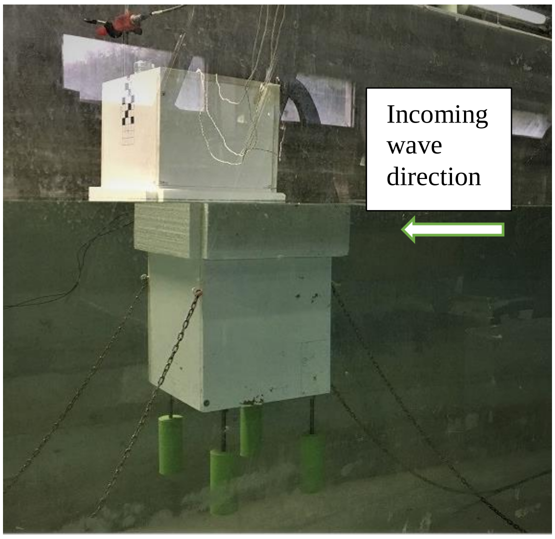


Figure 6. Side view of the mooring system.

### 2.3 Test conditions

Before testing the hydrodynamic behavior of the developed OWC WEC model, it is essential to obtain the natural frequency of the floating object system. Heave and pitch decay tests are performed to obtain the motion resonance characteristics. This information is important for determining the incoming wave frequencies range when testing the WEC response, as well as to determine the hydrodynamic damping of the WEC. The next step is to study the 6-DOF motion under waves and the mooring line tensions at the anchor points. Several objectives are considered in the set-up of the test matrix. Firstly, the frequency response of the WEC motion is tested using small amplitude linear regular waves. Note that $H$ is the wave height, $T$ is the wave period and $\lambda$ is the wave length. The wave period range is $0.7$ s $< T <$ $2.1$ s (corresponding to prototype wave period range from 3.5 s to 10.5 s). The wave heights are kept as $H < 8$ cm to ensure that wave steepness $H/\lambda < 1/30$.

The regular wave cases of $H = 11$ cm and $H = 14$ cm are tested, respectively, to acquire the mooring line loads in operational wave conditions. The maximum wave steepness $H/\lambda$ is 1/20. Then the comparison between nylon ropes and iron chain mooring lines is studied in small and medium wave height conditions. A sensitivity study of the mooring line imbalance is carried out as well.

The following data is acquired during each test:

1. Wave heights are recorded from each wave gauge.
2. 6-DOF motion time series.
3. The mooring line load acting on the normal direction of the loadcells.

## 3 RESULTS

The floating OWC WEC behavior under waves is post-processed according to the guidelines for tank testing of wave energy conversion systems (EMEC, 2009) and the ITTC (2014) seakeeping procedure. The results here presented focus on data acquired in small and medium wave height conditions, with wave heights H < 11cm. As an example, Figure 7 demonstrates the surge, heave and pitch motion history for waves of T = 1.7 s and H = 8 cm which correspond to a prototype wave condition of T = 6.5 s and H = 2 m. In the figure, $x$ denotes surge motion, $z$ is heave motion, $\theta$ is pitch motion and time is noted with $t$. The results of mooring line tensions and WEC motions when using different mooring line materials are investigated. It can be observed that in the small wave height conditions, both nylon ropes and iron chain mooring lines give similar results for the WEC heave motion. The WEC surge motion contains the components of wave frequency motion and low frequency motion. The wave frequency motion is excited by the first order wave force, meaning the floating object moves periodically with the same frequency of incoming waves. The low frequency motion is excited by the slow-varying wave drifting force and often happens in horizontal plane motion, such as surge, sway and yaw. The stiffness of the low frequency motion usually comes from the mooring system. Here, only the wave frequency motion is taken into consideration when analyzing the response amplitude of surge. The results show that the difference of the mooring line materials does not influence the WEC model motion behavior significantly. However, as the nylon rope mooring line stiffness only occurs when the rope is tight, and due to the coupling between heave and surge motion, the pitch motion of the rope-moored WEC model is not as harmonic as the chain-moored system.

The WEC model motion amplitude response of surge and heave are shown in Figure 8, in which $\eta_3$ is the measured wave amplitude from WG3, $x$ is the WEC model surge motion and $z$ is the heave motion. The bars stand for the average amplitude of each value. For the waves of T < 1.1 s, the wave heights of H = 4 cm have been applied to ensure non-breaking waves. For waves of T > 1.2 s, tests are carried out with H = 8 cm and H = 11 cm. The obtained results show obvious WEC model heave resonance at approximately T = 0.9 s to 1.0 s for all test cases. Meanwhile, in this frequency region, the WEC surge response is very low. This is because the iron chain mooring line stiffness becomes higher when WEC heave motion is severe. For longer waves, the WEC surge motion response increases as the wave period increases, however, the resonance period is not reached as it is far out of the test frequency range while the resonance amplitude is also restricted by the length of the mooring. Generally, under the condition of small amplitude waves, using the nylon rope mooring lines can obtain similar performance as using the iron chain mooring lines, but significant differences are observed in motion resonance regions and in long wave conditions.

The water surface elevation inside the chamber represents the air exchange rate through the orifice, which indicates the potential of energy output. As shown in Figure 9, noting the free-surface elevation with $\eta$, the water surface elevation inside the chamber (measured from WG8) is compared with the incident wave elevation (measured from WG3) under wave conditions of T = 0.9 s and T = 1.0 s, where the WEC model heave motion resonance occurs. The research from Crema et al. (2015) has shown that for the fixed OWC WEC with a similar geometry, the water column oscillation reaches resonance near wave periods at around T = 1 s. However, from the information provided in Figure 9, the oscillation resonance inside the chamber does not contribute as much as the heaving resonance does. It can also be observed that the in-chamber surface elevation is very sensitive to the incident wave period.

As for the larger waves with H = 14 cm, recording the mooring line tensions (noted as $F$) is one of the main objectives. The horizontal component of the mooring line load was measured by the loadcells installed at the wave flume bottom. To obtain reliable data, a careful preparation is needed to ensure the front lines (A and B lines in Figure 4) and back lines (C and D lines in Figure 4) are well balanced. The tests mainly focus on long waves with T > 1.5 s. A set of results under the wave condition of H = 14 cm and T = 1.7 s is plotted in Figure 10. According to the results, the horizontal mooring line loads are smooth and the tension amplitude is stable over the periods, the shock loads are not observed. The mooring line tension results will be validated by numerical models in future research.

## 4 CONCLUSIONS

This paper describes an experimental study of a floating oscillating water column wave energy converter performed in the wave flume of the Coastal Engineering Research Group at Department of Civil Engineering of Ghent University, in Belgium (http://awww.UGent.be). Due to the fact that the floating OWC WEC scale model is modified from a fixed OWC WEC scale model, the tests presented here have proven the feasibility of adopting the similar geometry of the two models to achieve wave energy conversion. Practical problems are encountered and solved during the tests while valuable experiences have been gained to proceed to the next stage of the tests within the MaRINET2 EsflOWC project, which has been performed after the tests reported in the present manuscript. The preliminary results obtained from the present tests have revealed the 6-DOF motion and mooring chain behavior of this type of device.

The linear motion response has indicated the optimum operating frequency of the studied floating OWC WEC. The heaving resonance occurs at the exciting wave period of T = 0.9 s. These conditions lead to intense in-chamber water column oscillation. It is also noticed that different mooring materials do not affect the linear motion behavior of the WEC model, but for the long wave conditions (T > 1.9 s), the soft nylon rope mooring lines can introduce significantly larger surge motion. Furthermore, the horizontal mooring line loads at the anchor points are measured by the loadcells mounted at the wave flume bottom. The results have shown a good force balance on the front and back mooring lines. With the iron chain as the mooring line material, shock loads are not observed in small and medium wave conditions.

In summary, as a preparatory experiment for the MaRINET2 EsfLOWC project, the presented tests have provided valuable information to deal with unclear physics questions of the floating OWC WEC. The following research will be carried out on the basis of the lessons learnt from this work.

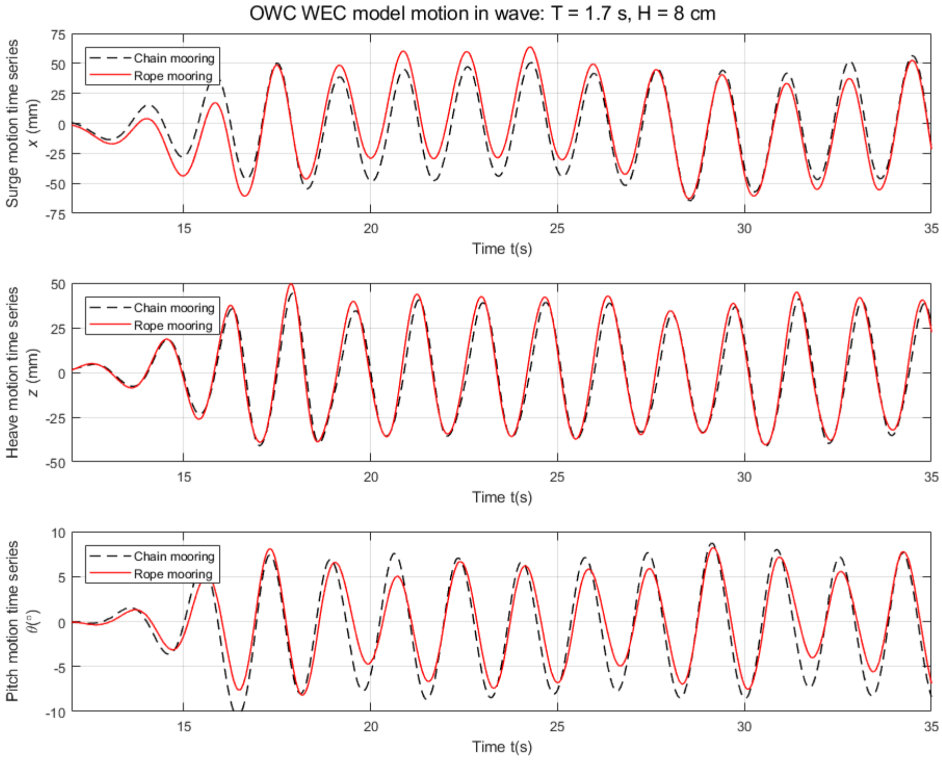


**Figure 7 Surge and heave motion response in small amplitude waves.**

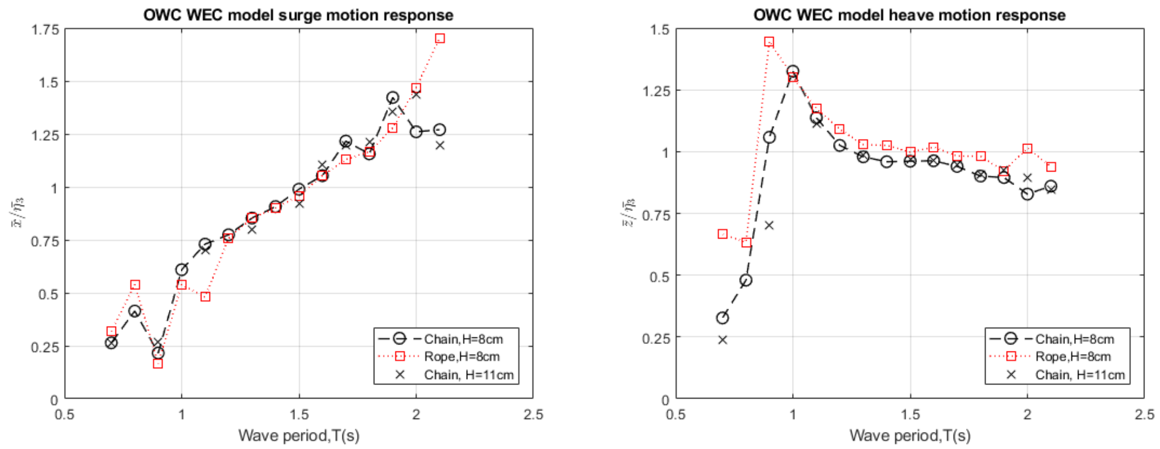


**Figure 8 OWC WEC model surge (left) and heave (right) motion amplitude response in small amplitude waves.**

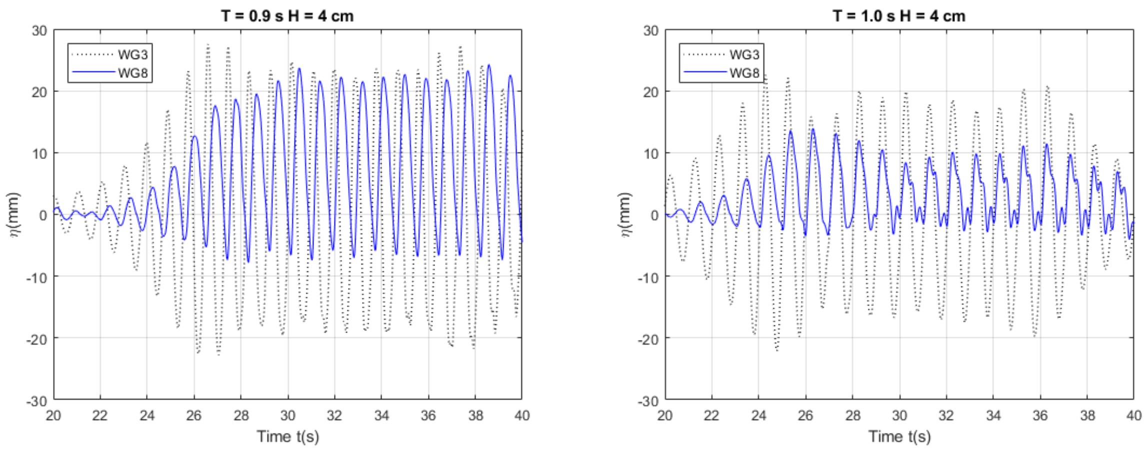


**Figure 9 Comparison between water column surface elevation inside OWC WEC chamber (WG3) and external wave surface elevation (WG8) near heave resonance zone T = 0.9 s (left) and T = 1.0 s (right).**

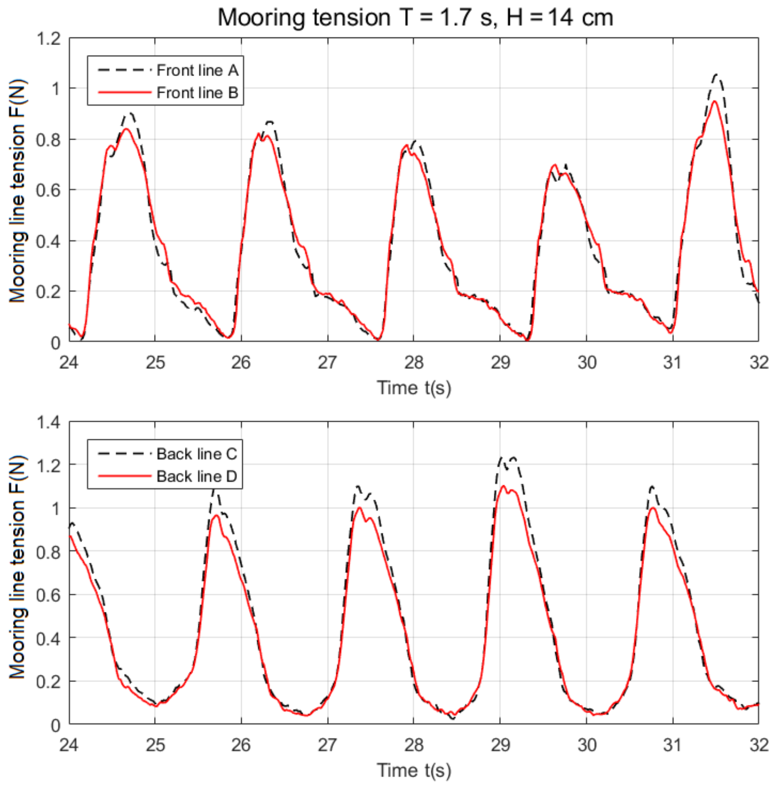


**Figure 10 Mooring line horizontal tension measured at the anchor point.**


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