On the experimental study of a concentric wave energy array adapted to an offshore floating platform

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Abstract— **Experimental results of the dynamics of a small scale concentric wave energy converter array adapted to a floating offshore platform are presented. A small scale prototype is tested without and with twelve conical heaving point absorbers. The free decay and regular wave tests are carried out in an ocean basin to understand the hydrodynamic interactions between various elements of the floating offshore platform and wave energy converter array. Meanwhile, the heave motions of the buoys are observed in regular waves with and without dampers for the initial estimation of power take-off damping as a pitch control module. The results show the improvements in heave, pitch, and roll performance of the platform due to the interaction between the buoys and platform.**

Keywords— **Concentric array of wave energy converters, Floating offshore platform, Pitch performance, Heaving point absorber, Hydrodynamic interactions.**

I. INTRODUCTION

THE mean annual power absorption of individual large or small wave energy converter (WEC) is usually limited to hundreds of kW [1]. Thus, WECs are commonly arranged in bigger farms where their total power absorption is maximized [2] and their operational and capital costs are minimized [3]. Moreover, WECs can join in wave arrays in two main categories, fixed and floating farms. The fixed array is usually a group of bottom referenced heaving buoys that are arranged in rows and columns and the floating layout is a group of floaters attached to a floating offshore platform or pontoon structures (e.g. PPC concept [4] and Wavestar [5]). The first category, as expected from its name, is more applicable in near shore region and the former one is compatible with offshore region with higher depth and harsher wave climate. Waves in the offshore region are generally multidirectional and the layout of WEC farms can considerably affect the power absorption performance. Thus, the concept that is studied in this paper is an offshore located type of arrays because the idea is to deploy the WEC array in region with high wave climate.

Meanwhile, instead of having a single application platform only for wave energy extraction, the WECs can unite with other offshore renewable energy concepts and propose a multipurpose platform. Utilizing these combined offshore energy concepts can reduce the levelized cost of energy by sharing power transmission equipment, mooring lines and floating structure. Meaning a more power production with lower capital and production costs as well as shared operational and maintenance costs. Returning to the main objective of this study, the combined wind-wave platform deployed in a high wind and high wave region (offshore) can be a promising concept as an offshore renewable technology.

Similar to the classification of WECs [6], [7], the combined platforms are commonly classified based on their technology (wind-wave, wave-tidal, wind-tidal, etc.), or location of deployment (offshore, nearshore, or onshore) [8], [9]. The numerical studies on point absorber farms shows a considerable difference between concentric and linear arrangements [10]. It is reported that the performance of the circular array is higher and a better control on the PTO parameters is expected [11]. Also, these platforms have a great potential for combining with a wind turbine that may be located in the platform center.

The concentric layout is adapted from a hybrid wind-

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wave concept [12] developed for deep offshore regions. A conical buoy is considered as a heaving point absorber. The hydrodynamic of this WEC is studied using different BEM software [11] and [13]. Regarding the floating platform, the primary hydrodynamic studies are carried out in [14] and a simplified frequency domain approach for studying the WEC-structure interactions was adopted [15]. The main objective of this study is to understand the interactions between the buoys, the floating offshore platform and other components that cannot be covered by numerical simulations.

The prototype and WEC concept are explained in Section II. The experimental setup and model installation in the basin as well as the wave characteristics are explained in Section III. Then in Section IV, the methodology and test plans are presented. The experimental results are presented in Section V. Finally, in Section VI the conclusions are presented.

II. CONCEPT AND PROTOTYPE

The advantages of using WECs arranged in circular arrays is demonstrated in the literature. The studies from Engström et. al., [16] shows that the concentric array of WECs presents a smoother power production compared to the rectangular arrangements. Balitsky et. al., [17] proved that the circular arrays are less sensitive to location of the platform, wave direction, and suggest a more predictable power in offshore region. Moreover, concentric arrays may offer more efficient cost structure including lower levelized cost of energy. Also, the concentric design can contribute to a significant savings in capital costs (CAPEX) during the production phase [10].

In the previous studies related to this issue [18] a cone-cylinder buoy presented a better power absorption compared to the hemisphere-cylinder and hemisphere floaters, due to its hydrodynamic properties and coefficients. These cone shaped buoys are also studied in circular arrays with 12 WECs where buoys with different diameters were simulated, and a better absorbed power was recorded from larger diameters [10]. The circular array of WECs provides a better power quality and there is a consistency in the PTO control parameters of all individual floaters. Meaning that the circular array is easier to control in offshore located arrays with hydraulic PTO.

A higher level of stability is expected from a concentric solution because of mitigating the excitation and diffraction forces induced by incoming waves on the platform and improving the contributions of the floaters to the restoring moment of the platform. Thus, in comparison with conventional ballast distribution approach for pitch control of floating platforms, this solution might offer a more dynamic and adaptive reaction to platform pitch motions. Meanwhile, if the circular array is supposed to be seen as a control unit (as a secondary objective of the system), the power production of WECs adds another value to the system, which is self-powering of control system.

The concept shown in Fig. 1-a, is designed based on the procedures presented in [19, 20] and a simplified small-scale prototype is designed (Fig. 1-b) using Froude scaling method (Table I). Also, the prototype is fabricated with the geometric properties illustrated in Table II. The mass of the prototype in zero ballast condition is 31.3 kg, while the displacement at operative water line (18 cm below the deck of the structure) is around 70 L. Therefore, 20 L of reserve buoyance are designed as ballast inside the lateral and central calumns of the prototype including 18.5 kg of lead blocks fixed in the lowest radial calumns of the platform to provide the required mass, draft, and CG.

Also, the platform is designed compact and agile while steel damping plates are fixed bellow each column, mainly to damp the heave motion of the platform. In addition, a wind tower with an equivalent mass of nozzle is installed on the deck to fairly simulate the combined platform for the tests.

(a) (b)

Fig. 1. Conceptual model (a) and small scale prototype (b) of the concentric WEC array combined with offshore wind platform.

TABLE I
SCALING FACTORS

$\lambda = 27$			
Variable (units)	Dimensions	Scale Ratio	Scale Factor
Length (m)	L	λ	2.70E+01
Mass (kg)	M	λ^3	1.97E+04
Angle (rad)	None	1	1.00E+00
Acceleration (m/s^2)	L/T^2	1	1.00E+00
Angular Acceleration (1/s^2)	1/T^2	λ^{-1}	3.70E-02
Angular Velocity (1/s)	1/T	$\sqrt{\lambda}^{-1}$	1.92E-01
Force (Kg× m/s^2)	M×L/T^2	λ^3	1.97E+04
Wave Height (m)	L	λ	2.70E+01
Wave Period (s)	T	$\sqrt{\lambda}$	5.20E+00
Velocity (m/s)	L/T	$\sqrt{\lambda}$	5.20E+00
Moment of Inertia (kg×m^2)	M×L^2	λ^5	1.43E+07

TABLE II
GEOMETRICAL PROPERTIES OF THE SCALED MODEL

Property	Value	Unit
Platform		
Diameter of central column	160	mm
Diameter of lateral columns	110	mm
Diameter of radial columns	50	mm
Height	1100	mm
Draft	950	mm
Disp.	70.1	L
Mass	69.8	kg
CG	370	mm
CB	480	mm
Wind Tower Height	760	mm
Wind Tower Mass	0.40	kg
Equivalent turbine Mass	1.10	kg
Buoy		
Draft	111	mm
Mass	1.8	kg
Disp.	1.8	L
CG	950	mm
Arm		
Length	400	mm
Mass	0.40	kg
CG	1050	mm
Angle with Platform	67.1	deg
Angle with buoy	22.9	deg

The deck of the platform is made by steel frame that also include connections for 12 aluminium arms that are attached to the WECs. It should be indicated that, 12 dampers are installed in the joints of the arms to the hexagonal deck. These friction type rotary dampers with a maximum angular velocity of 30 rpm [21] are supposed to play the role of PTO system for WECs.

Dampers are unidirectional (counter clockwise direction) and they can handle the maximum torque of 50 Ncm. The prototype built for this experiment is capable of fast assembly and detachment [22].

III. TEST SETUP

The tests are carried out in the Lir - National Ocean Test Facility in Cork, Ireland. The wave tank dimension is 25 m × 17 m with a variable depth up to 2.5 m that is set by a mobile floor (Fig. 2). The wave makers can produce waves with the Hs = 0.16 m, T_p = 1.4 s and H_{max} = 0.32 m, which is reasonably good for small scale models up to 1:50. Moreover, active and passive wave absorption shores can guarantee an advanced wave simulation and shorter settling time.

As shown in Fig. 3, the model is set up in the center of wave basin while three catenary mooring lines (steel chain with a specific mass of 0.0713 kg/m, with no springs and dampers) are applied to moor the prototype to the moveable floor (shown by dashed lines in the figure). As seen in the figure the length of the mooring lines is not equal and in the fore direction is 5.6 m and in the stern sides are 3.36 m. To monitor the mooring forces, load cells are applied in mooring lines. Wave tests are performed for one directional regular waves (zero angle) that are scaled before being employed in the experiments by adapting methods from [23].

Fig. 2. The Lir NOTF wave tank in MaREI center in Ireland, Cork.

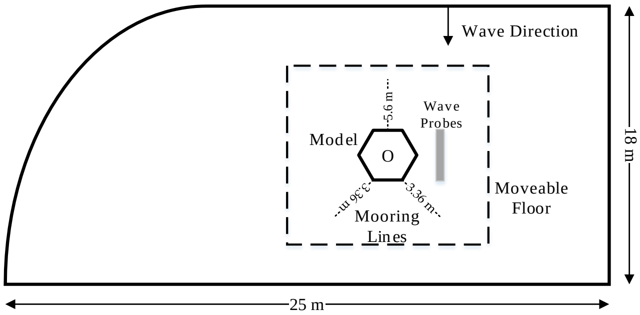


Fig. 3. XY plane diagram of the prototype installation in the Lir ocean basin.

Table III reveals the simulated regular waves. The wave heights considered for this study are 1, 2 and 4 cm and the periods vary from 0.6 to 4.0 s. As seen in Fig. 3, a series of 4 wave probes were placed beside the prototype and 1 m away from the platform starboard to calibrate the wavemakers and control the produced waves.

TABLE III
THE REGULAR WAVE PARAMETERS

Regular Waves		
Height (cm)	Period (s)	Duration (s)
1.00	0.6 to 4.0	
2.00	0.6 to 4.0	128
4.00	0.6 to 3.0	

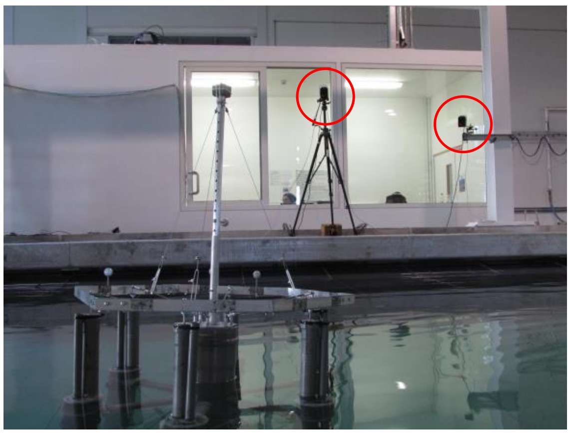


Fig. 4. The schematics of the installation of the prototype on the moveable floor of the basin.

IV. METHODOLOGY

The motions of the platform are captured by the 6-DoF Qualisys motion cameras shown in Fig. 4. A set of 4 tags named as starboard, port, stern and top are placed on the aft side of the deck. Also, the optical cameras placed in the aft side of the platform can detect the position, velocity and acceleration of mentioned tags installed on the structure. Actually, the outputs of the motion detection system are highly depending on the position of the camera tags in respect to the platform CG.

Because the rotational velocity and accelerations are calculated and transformed by the borders (relative distance and angles) connecting tags to the CG of the platform. One may notice that in Fig. 4, the camera tags are installed on the deck of the platform but then they were moved to a T-section because of the sensitivity of the cameras to the vibration of the tags. The vibration of the deck during free decay tests resulted some data losses but the tests were repeated with camera tags on T-section.

Also, to observe the heaving motion of buoys, 8 tags are considered on the deck and buoys in the aft side of the platform (4 tags on top of Buoys and more 4 tags on the columns). The blue tags (named as C_{11}, C_{12}, C_{21}, and C_{22}) shown in Fig. 5 are responsible for monitoring the motions of the deck (where the arms are attached to deck) and the red ones (named as B_{11}, B_{12}, B_{21}, B_{22}) for observing the movements of buoys.

Tests were performed based on the scenarios presented in Table IV to study the behaviour of WEC array adapted to a floating offshore platform. As mentioned above, all tests were performed with the presence of a wind turbine considering that the thrust force on the turbine and nozzle is not simulated. In this study all the regular waves are generated at zero-angle.

As seen in Table IV, the investigation of the platform hydrodynamic is carried out in two main test cases, “Without WECs” and “With WECs”. The main difference between these test cases is the array that is added in the second case. Two scenarios are tested in the first case including without and with mooring lines. The main aim of this test is to have a primary analysis on the hydrostatic and hydrodynamic performance of the platform and the contribution of mooring system in these characteristics.

Also, two scenarios are considered for the second case, without and with dampers. The main goal of this case is to monitor and measure the effects of the WECS and equivalent PTO system on platform hydrodynamics.

Related to the first test case of the platform, the first scenario is mainly focused on the free decay tests in 3 DoFs, while the second scenario considers both free decay (in 6 DoFs) and regular wave tests. Regarding the second test case, in the first scenario, WECs are freely mounted to the edges of the hexagonal deck frames, while in the second scenario one damper is applied in the joint of the WEC arm and platform.

Decay tests are carried out at the beginning of the experiments to study the eigen periods of various DoFs in free floating condition. Then, these tests are repeated for all other conditions that include adding components to the platform. The free decay tests are carried out by induced inclining forces in the desired direction (DoF) of the platform and then the tests are repeated for reducing the uncertainty factors in the test. It should be indicated that, for the analysis of the free decay tests results, an automated procedure presented in [24] is used.

Then the regular wave tests are performed considering that the main objective of these tests is to determine the heave response amplitudes and monitor the response amplitude operations (RAOs) of the model in various test cases and conditions. In order to measure the motion RAOs, the mean response amplitude in regular waves is divided by the wave amplitude. To avoid transient effects in the basing, the data of the first 10 × T seconds are not considered for the calculation of response amplitudes.

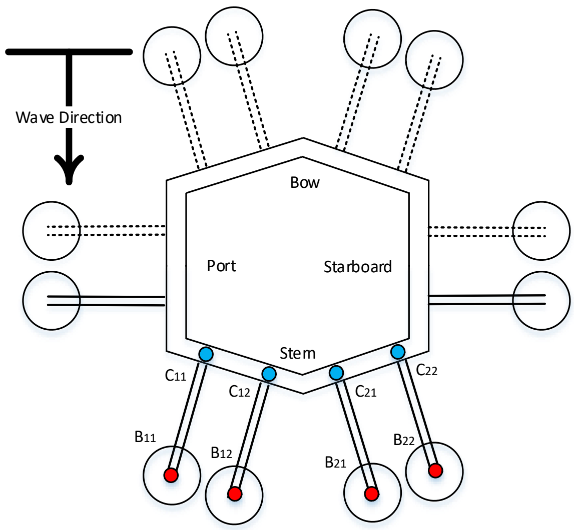


Fig. 5. The 2D diagram of the WEC array and the position of camera tags on buoys and deck.

TABLE IV
DEFINED TEST PLAN OF EXPERIMENTAL STUDIES.

	Test case	Scenarios	Tests	Details
Floating Platform	Without WECs	Without mooring	Free decay	3 DoF (Roll, Pitch, Heave)
		With mooring	Free decay	6 DoF
			Regular wave	H = 1, 2, 4 cm and T = 0.6 – 4.0 s
	With WECs	Without dampers	Free decay	6 DoF
			Regular wave	H = 1 cm and T = 0.6 – 4.0 s; H = 2, 4 cm and T = 1.4 s
		With dampers	Free decay	6 DoF
			Regular wave	H = 1 cm and T = 0.6 – 4.0 s; H = 2, 4 cm and T = 1.4 s

V. RESULTS AND DISCUSSION

The exploited results of this study are separated in two different categories, free decay and regular wave results to provide a better understanding of all results.

A. *Free decay tests*

To compare the eigen periods of important DoFs of the platform in different case studies, the results of the decay tests are presented in Table V. One may notice that the eigen period of roll and pitch have relatively equal eigen periods all test cases while in the last case the roll response is faster than the pitch. The reason behind this difference is understandable by looking at Fig. 5 where the number of WECs contributing to the restoring moment of roll are more than the ones in pitch motion.

The comparison between different rows of the Table V shows the effect of mooring system on the eigen period of heave, roll and pitch as the most important DoFs of a floating offshore platform. Adding mooring lines to the system decreased the eigen period of heave by 2 %, roll by 10 % and pitch by 13 % compared to the without mooring scenario. Because of the arrangement of the mooring lines, it is expected that the effects of this element on the pitch is more than on the roll.

Also, the comparison shows that the WECs have a considerable effect on the eigen period of the platform. Especially in “with dampers” scenario the presence of the WEC array decreases the eigen period of heave motion by 6 %. As illustrated in the Table V, the roll and pitch motion are more affected by adding mooring and WECs to the platform by around 44 % and 33 %, respectively.

The mentioned differences in eigen periods are due to the effects of restoring forces of the mooring system. Also, adding WECs to the platform caused some changes in the displacement and CG of the platform (the CG is increased after adding the WEC layout). This change can also be responsible for decreasing the eigen periods.

Meanwhile, the effect of restoring moment produced by dampers is considerable in the last scenario. Meaning that the role and pitch motion have faster responses in presence of WEC layout “with dampers”.

TABLE V
RESULTS OF THE DECAY TEST FOR DIFFERENT TEST CASES.

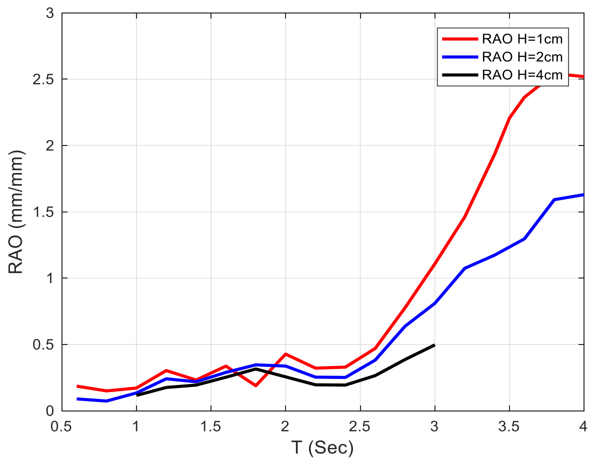
DoF	Eigen Period (s)	Full Scale Eigen Period (s)
without WECs and moorings		
Heave	3.66	19.01
Roll	7.06	36.64
Pitch	7.03	36.48
without WECs and with moorings		
Heave	3.57	18.52
Roll	6.29	32.64
Pitch	6.11	31.71
with WECs, moorings and dampers		
Heave	3.45	17.90
Roll	3.51	18.21
Pitch	4.07	21.12

B. *Regular wave tests*

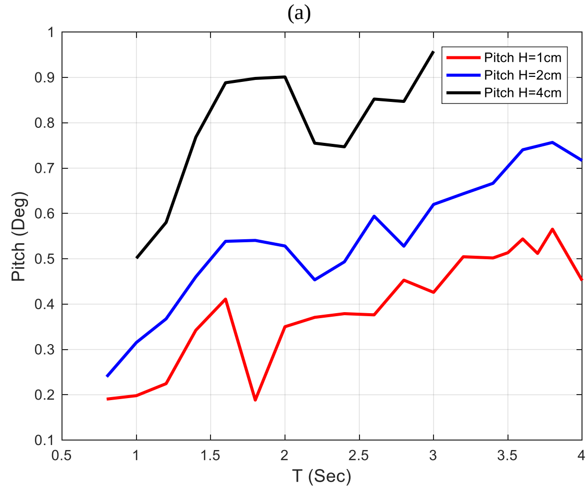
The floating platform is tested in regular waves with two different scenarios (presented in Table IV). In the Fig. 6-a, the heave RAO of the platform in “without WEC” case is shown in three different wave heights. As revealed in this figure, a considerable nonlinearity is recorded in heave motion especially near the resonance periods. This nonlinearity is mainly because of the nonlinear viscous damping effects induced by small components underwater and especially the ones that cross the free surface. In addition, the compactness of the prototype with a considerable number of joints and submerged components can increase this nonlinearity.

One may notice that the RAOs of heave and pitch do not change linearly with the wave amplitudes. For instance, a comparison between H = 1.0 cm and 2.0 cm shows that peak of heave RAO (Fig. 6-a) drops almost by 36 %. The Fig. 6-b illustrates that the amplitude of the pitch increases by wave amplitude while the trends are not linear.

In addition, the “without WEC” and “with WEC” cases are compared. It should be indicated that in the “with WEC” case, the “with damper” scenario is considered to observe the interaction between WECs and platform in productive conditions.



(a)



(b)

Fig. 6. heave (a) and pitch (b) RAOs of the platform in “without WEC” case.

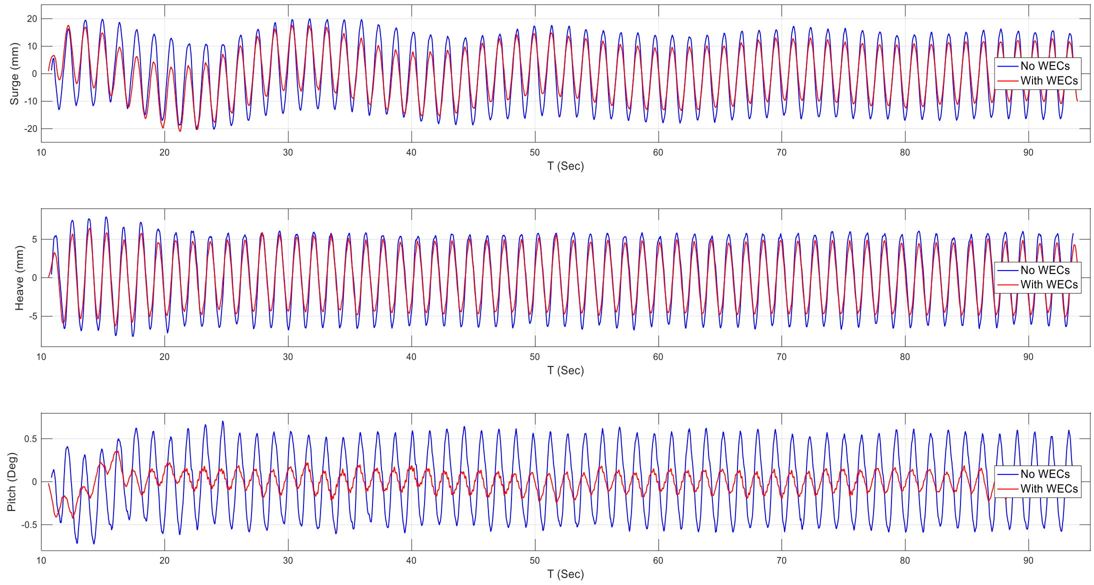
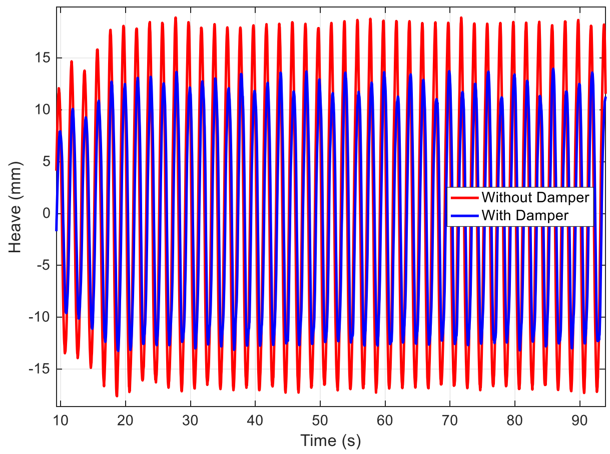


Fig. 7. The surge, heave and pitch responses in “without WEC” compared with “with WEC” (“with damper” scenario) cases in H = 4 cm and T = 1.4 s.

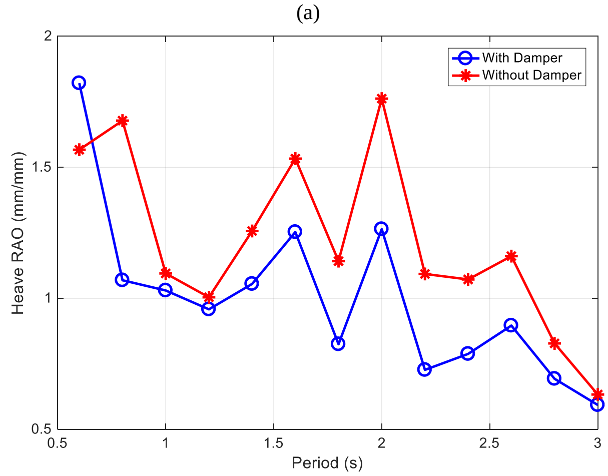
Fig. 7 presents platforms’ surge, heave, and pitch motions in regular waves (H = 4 cm and T = 1.4 s). It shows that the amplitudes of motions are reduced in the second case compared to the first one (the surge amplitude by 30 %, heave amplitude by 14 %, and pitch amplitude by 80 %). The radiation damping and restoring moment of the floaters performing in productive situation with a PTO system attached to their arms (rotational damper) are the main reasons for this decrease in motion amplitudes.

Moreover, the heave RAOs of buoys are investigated in regular waves and a comparison is made between different scenarios. As mentioned, two conditions are taken into account for these tests, floaters without and with PTOs. For this section, the motions of the B_{12} tag and corresponding tag C_{12} attached to the platform deck are considered for the study. Indeed, the relative motion of the buoy and deck are applied for determining of RAO of buoys. Fig. 8-a shows the heave response amplitude of buoy B_{12} in regular waves (H = 1 cm and T = 3 s) and Fig. 8-b shows the corresponding heave RAOs of B_{12} in these two scenarios in regular waves with a period range of 0.6 s to 3 s. It is also noticeable in Fig. 8-a that the difference between the peaks of heave amplitudes are not equal to the difference between its’ troughs. The reason for this observation is because of the unidirectional dampers that are applied for these tests that only act in counterclockwise directions.

As seen in the Fig. 8-b, dampers are not affecting the RAO of the floaters in different periods, persistently, while a 36 % increase is recorded in T = 0.8 s and there is also a 16 % increase in T = 0.6 s. The test results are also indicating that the RAO of the buoy, in H = 2 and 4 cm, in “without damper” and “with damper” conditions are slightly close to the values in H = 1 cm.



(a)



(b)

Fig. 8. The comparison of B_{12} heave response in regular wave (H = 1 cm and T = 3 s) in without and with damper scenarios (a) and the B_{12} heave RAO in various wave periods (b).

VI. Conclusions

The conclusions of this study addresses the decay and regular wave test outcomes. The free decay test results indicate that adding mooring lines and installing WECs to the platform can reduce the natural period of heave, roll, and pitch while arrangement of mooring lines can affect this reduction for pitch and roll motions. This means that an axisymmetric arrangement of moorings may suggest equal reductions in amplitudes of these motions. Also, the WEC array had a positive effect on the stability of the floating platform while a faster response to the pitching is observed due to restoring moments produced by PTO system (motion of WECs).

Moreover, the regular wave test results indicate that the motion amplitudes are significantly decreased after the attachment of circular WEC layout to the platform, considering that the applied dampers are unidirectional and no active control approaches are used for changing the PTO parameters during the tests.

On the other hand, monitoring the motions of the floaters show that a decrease in RAO is recorded after the deployment of rotational dampers on the arms. Meaning that the energy absorption by PTO system has a direct relation with the heave response amplitudes of the WEC that is also affecting the motions of the platform by producing restoring moments. It can be concluded that tuneable PTO parameters (damping and stiffness) may improve contribution of the WEC in energy absorption and motion control as well as the platform hydrodynamic performance.

The future studies related to this work will be dedicated to analysis of motions in irregular waves and considering survivability conditions for the combined platform.

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