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POWER PERFORMANCE OF THE COMBINED MONOPILE WIND TURBINE AND FLOATING BUOY WITH HEAVE-TYPE WAVE ENERGY CONVERTER

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ABSTRACT

This study deals with a new concept of near-shore combined renewable energy system which integrates a monopile wind turbine and a floating buoy with heave-type wave energy converter(WEC). Wave energy is absorbed by power-take-off (PTO) systems. Four different shapes of buoy model are selected for this study. Power performance in regular waves is calculated by using boundary element method in ANSYS-AQWA software in both time and frequency domains. This software is based on three-dimensional radiation/diffraction theory and Morison's equation using mixture of panels and Morison elements for determining hydrodynamic loads. For validation of the approach the numerical results of the main dynamic responses of WEC in regular wave are compared with the available experimental data. The effects of the heaving buoy geometry on the main dynamic responses such as added mass, damping coefficient, heave motion, PTO damping force and mean power of various model shapes of WEC in regular waves with different periods, are compared and discussed. Comparison of the results showed that using WECs with a curvature inward in the bottom would absorb more energy from sea waves.

Keywords: combined renewable energy, monopile wind turbine, heaving buoy, power take off

INTRODUCTION

Ocean energy resources have a great potential of providing renewable energy in the form of wind, waves and tidal currents. Over the last decade, among ocean renewable energy resources, offshore wind energy utilisation has been rapidly developed mainly in the form of the monopile fixed-bottom platform wind turbines (WT) in near shore wind farms. Other fixed-bottom platforms used in near shore wind farms are tripod and jacket ones[1].

Compared to wind, wave energy represents an energy resource with a higher power density. The wave renewable energy can be absorbed by using various wave energy converters (WEC) such as oscillating water column, oscillating body and overtopping [2]. Although various types of WEC systems have been proposed, this technology is actively developing and it is not mature enough for large-scale commercial application.

In a site where wind and waves coexist, it might be beneficial to combine a WT and a WEC system by sharing support structure and power substations. It would be beneficial for utilizing the ocean space more efficiently and reducing the cost of manufacturing, installation and maintenance.

So far, many studies on the combined concept of WT and WECs have been conducted and reported by several researchers. Most of the studies on such combined systems have been done for different floating support platforms and type of WECs.

Based on the semi-submersible floating platform, three combined WT and WEC systems have been proposed. Alves [3] studied the combined concept of WT and an oscillating water column WEC with a V-shape semi-submersible floating support structure. They showed that the economic cost could be reduced by sharing the mooring and power infrastructure. Other combined concepts were proposed based on the semi-submersible floating support structure of WT, which consists of three rotating-flap types WECs [4, 5], and a point-absorber WEC [6].

Bachynski and Moan [7] introduced a combined concept of WT and three point absorber WECs based on tension-leg-platform (TLP) floating support structure. In their work, the effects of point absorber WEC on TLP were studied in operational conditions.

Most of the studies on the combined concept based on floating support platform have been done for the spar-type platform. The spar - torus combination (STC) is consisted of the 5 MW WT of National Renewable Energy Laboratory (NREL) and a torus- point-absorber WEC, introduced and developed by Muliawan et al. [8, 9, 10]. Further numerical and experimental studies of the STC system in survival mode were conducted by Wan et al. [11, 12, 13, 14]. In their model tests they examined several phenomena such as Mathieu instability, wave slamming and vortex- induced motions.

There is limited number of research works about the conceptual design of the combined systems based on the fixed-bottom platforms in the shallow water zones. For the first time, a new concept of a combined fixed-bottom monopile WT and a heave WEC was proposed by Ren et al. [15]. This system is named 'MWWC' (Monopile-WT-WEC-Combination). Ren and Ma [16] compared numerical and experimental results of the MWWC system in both regular and irregular waves. In MWWC concept, the floating buoy can move along the monopile tower to absorb wave energy through a power take-off (PTO) system. A schematic picture of the MWWC system is shown in Fig. 1.

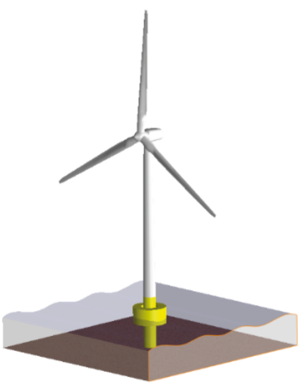

Fig. 1. A schematic picture of the MWWC system

In this paper, four different model shapes of WEC heaving buoys of the MWWC system are selected. At first, the function of the MWWC concept system is described and various model shapes of WEC are discussed. Then, the numerical results for one model of the WEC system are validated by the experimental data. Finally, the results of the main dynamic responses such as added mass, damping coefficient, heave motion, PTO damping force and mean power for various model shapes of WEC in regular wave with different periods are compared and discussed by using the ANSYS-AQWA software.

GEOMETRIC AND FUNCTIONAL DESCRIPTION OF THE MWWC SYSTEM

The MWWC concept considered in this study is inspired by the STC system developed by the Norwegian University of Science and Technology (Norges Teknisk Naturvitenskapelige Universitet = NTNU) [8, 9]. The monopile is a type of platform which is used for most of the offshore wind turbines in the shallow water zones [1]. Hence the spar floating platform in the STC system is replaced with the bottom- fixed monopile platform.

In this concept, the wind turbine is a 5 MW NREL reference turbine [17] (Notice that in the present study, the 5 MW NREL wind turbine is parked) and the WEC system is inspired by the 'Wavebob' solution developed in Ireland [18]. The Float which is the main component of the Wavebob is replaced by the monopile platform. Therefore, the floating buoy of the Wavebob is connected directly to the platform and it can be moved along the monopile tower.

The water depth for the operation of MWWC system is 15 m. The overall view of this system and the sketch of WEC are shown in Fig. 2, and the main characteristics of the system are listed in Tab. 1.

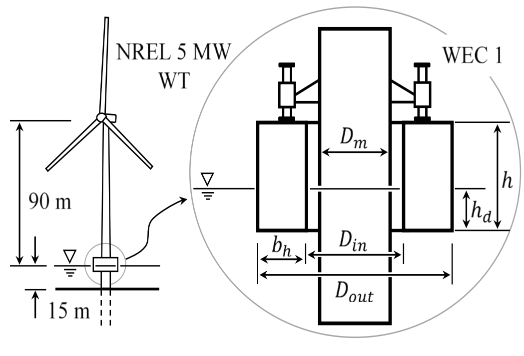

Fig. 2. The overall view of the MWWC system and the sketch of WEC system

Tab. 1. The main characteristics of the MWWC system

Parameters	Symbol	WEC1	Unit
Monopile diameter	D_m	6.0	m
Inner diameter	D_{in}	8.0	m
Outer diameter	D_{out}	16.0	m
Height	h	8.0	m
Draft	h_d	3.0	m
Bottom breadth	b_h	4.0	m

Parameters	Symbol	WEC1	Unit
PTO damping coefficient	B_{pto}	2.0e6	Ns/m
Centre of mass	*C.G*	(0,0,-1)	m

The wave energy is absorbed by the heave motions through a PTO system. In the STC system, the PTO system has been simplified by the linear PTO stiffness (K_{pto}) and linear PTO damper (B_{pto}) [10]. In MWWC system, just two linear PTO dampers (B_{pto} = 2e6 Ns/m) are used. A sketch of the PTO system is shown in Fig. 3.

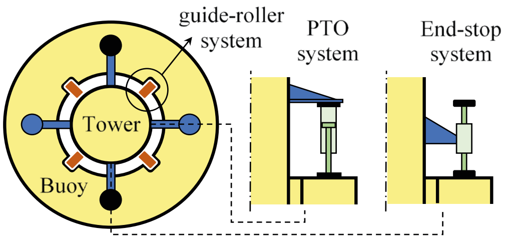

Fig. 3. A sketch of the linear guide-roller system and the end-stop system

Four linear guide-roller systems have been incorporated between the heave WEC system and the monopile. Therefore, the WEC system can move vertically along the monopile tower and its horizontal motions are limited. In addition, two end-stop systems have been used to limit the excessive heave motion in harsh environmental conditions. A sketch of the linear guide-roller system and end-stop system is shown in Fig. 3.

Three other shapes of WEC system , WEC2, WEC3 and WEC4 , have been selected to be compared with the WEC as WEC1, which were studied by Ren et al. [15] at first. The sketch of the three WEC systems is shown in Fig. 4. The similarities between all the models of WECs and the model of WEC1 consist in the same displacement, inner diameter, height, draft and location of centre of mass. On the other hand, the main differences are in their outer diameter and shape of their bottoms ; values of the parameters are listed in Tab. 2.

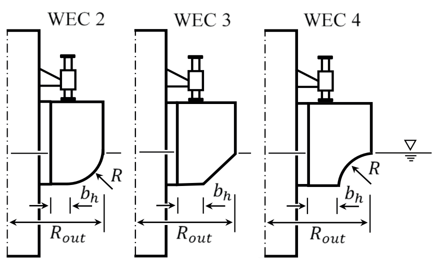

Fig. 4. The sketch of three different types of the WEC system

Tab. 2. The main characteristics of other types of WEC system (unit: meter)

Parameters	Symbol	WEC2	WEC3	WEC4
Outer radius	*Rout*	9.908	9.453	9.009
Curvature radius	*R*	5.0	–	5.0
Bottom breadth	b_h	2.908	2.453	2.009

NUMERICAL MODELLING

Dynamic responses and power performance of the MWWC system have been investigated in both time and frequency domains based on the boundary element method in ANSYS-AQWA software in which the hydrodynamic loads acted on the structures are calculated by means of the three-dimensional radiation/diffraction theory and Morison's equation.

In this simulation, two rigid bodies have been modelled as a fixed monopile platform wind turbine and a heaving buoy. The bodies are connected together by the guide-roller system at their interfaces, therefore the WEC system can be moved vertically by waves along the monopile tower.

The wave elevation in a regular linear Airy wave is expressed as follows:

$$\zeta(x,t) = \frac{H}{2} cos(kx + \omega t) \quad (1)$$

where H is the wave height; k is the wave number; ω is the wave frequency; t is the time. The wave number and wave frequency are expressed by wave length (λ) and wave period (T):

$$k = 2\pi/\lambda \quad , \quad \omega = 2\pi/T \quad (2)$$

The motion in heave direction of the WEC system is described by the equation (3):

$$[M + A_z]\,\ddot{z}(t) + [B_z + B_{PTO}]\,\dot{z}(t) + [C_z + K_{PTO}]\,z(t) = F_0 \cos(\omega t) \quad (3)$$

in which M and A_z are the buoy mass and the added mass in heave direction; $\ddot{z}(t)$, $\dot{z}(t)$ and $z(t)$ are the acceleration, velocity and displacement; B_z and C_z represent the hydrodynamic damping coefficient and the restoring stiffness of the buoy; B_{PTO} and K_{PTO} are the linear PTO damping and stiffness coefficients, respectively; F_0 is the amplitude of external excitation force in heave direction.The solution of the equation(3) for the steady condition is:

$$z(t) = z_a \cos(\omega t - \varepsilon) \quad (4)$$

where z_α is the amplitude of the WEC heaving motion, and is the phase angle of the WEC motion in relation to the exciting force. The amplitude of the WEC motion is given by:

$$z_a = \frac{F_0/(C_z+K_{PTO})}{\sqrt{(1-\Lambda^2)^2+(2\xi\Lambda)^2}} \quad (5)$$

in which Λ is the tuning factor, and ξ is the non-dimensional damping factor. They can be expressed as follows:

$$\Lambda = \omega/\omega_z \qquad (6)$$

$$\xi = \frac{B_z+B_{PTO}}{2\sqrt{(M+A_z)\times(C_z+K_{PTO})}} \qquad (7)$$

where ω_z is the natural frequency of heave motion and it can be calculated as follows:

$$\omega_z = \sqrt{(C_z + K_{PTO})/(M + A_z)} \qquad (8)$$

The damping force of the PTO system can be expressed as follows:

$$F_{PTO} = B_{PTO}\dot{z} \qquad (9)$$

and the WEC instantaneous power can be calculated by using the PTO damping force in the equation (9) as follows:

$$P_{WEC} = F_{PTO}\dot{z} = B_{PTO}\dot{z}^2 \qquad (10)$$

MESH STUDY

The ANSYS-AQWA software employs Hess-Smith constant panel method, hence the structure wetted surface is divided into triangular or quadrilateral panels. Hydrodynamic panel models which include WEC and a part of the substructure are shown in Fig. 5.

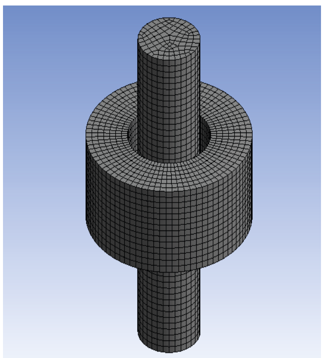

Fig. 5. MWWC panel models in ANSYS-AQWA software

In order to obtain the appropriate size of the elements to get accurate results from numerical simulation, the number of elements changed several times for both the WEC heave motion and the mean WEC power in typical regular wave case. The examined number of WEC elements in this study is illustrated in Figs. 6 and 7.

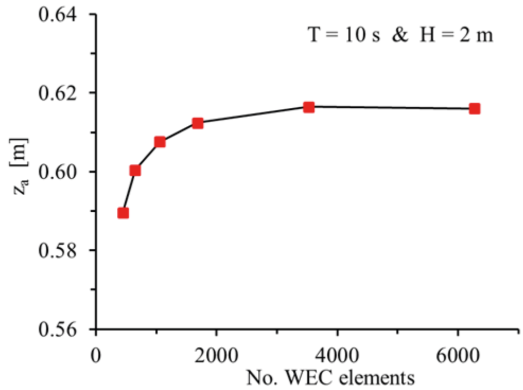

Fig. 6. Mesh study for heave motion of WEC in typical regular wave case

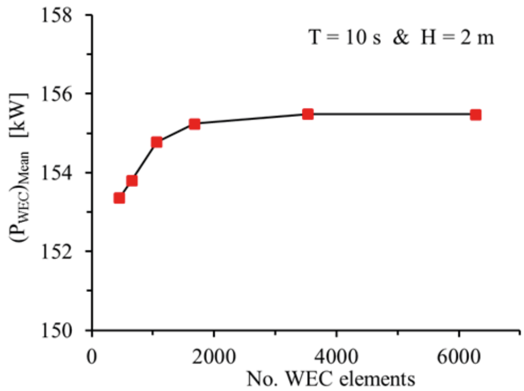

Fig. 7. Mesh study for mean WEC power in typical regular wave case

In Fig. 6 and Fig. 7 it can be seen that initially, with increasing the number of elements, changes in WEC heave motion and mean WEC power are significant. It is also clear that after applying more than 3528 elements for WEC, the changes in the parameters in question are reaching smaller and smaller values. Hence, numerical simulation of this model in ANSYS-AQWA software with using this number of elements will be of good accuracy.

VALIDATION

In order to verify the simulation results from ANSYS-AQWA software, the numerical results of the main dynamic responses of WEC1 have been compared with the experimental results obtained from the model test in State Key Laboratory of Costal and Offshore Engineering . The amplitude of WEC heave motion, the PTO damping force and the Mean power obtained from the comparisons for different regular wave periods and wave height,, are shown in Figs. 8, 9 and 10.

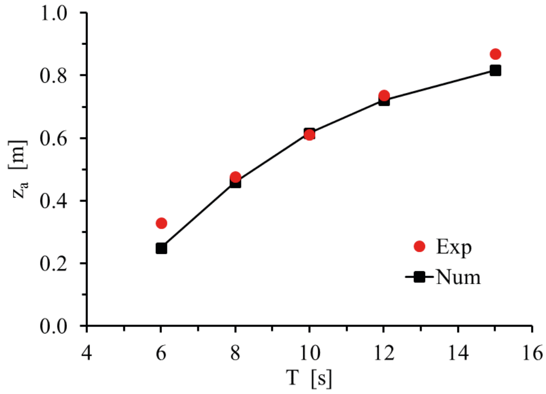

Fig. 8. Comparison of the WEC heave motion between experimental data and numerical results for typical regular waves (H = 2m)

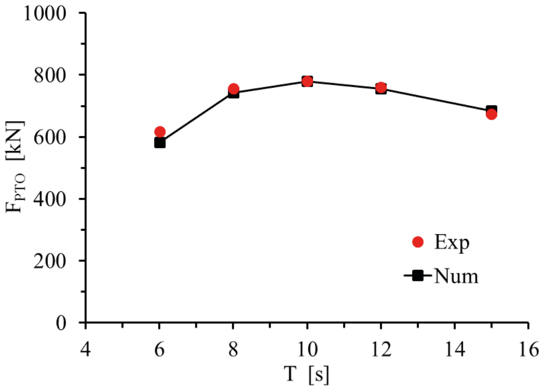

Fig. 9. Comparison of the PTO damping force between experimental data and numerical results for typical regular waves (H = 2m)

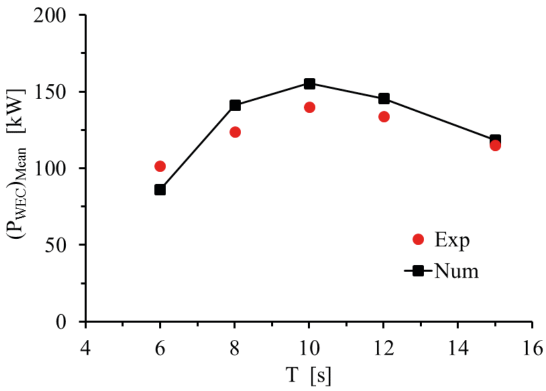

Fig. 10. Comparison of the mean WEC power between experimental data and numerical results for typical regular waves (H = 2m)

It is observable that the numerical result of WEC1 for the regular wave and the test data reported by Ren et al. [16] are in a good agreement. The main reason for the difference between numerical and experimental results is the viscous effect in the scale test model.

RESULTS AND DISCUSSIONS

To get the general performance of the different model shapes of WEC system, numerical results for regular wave conditions are compared and discussed. The simulations have been done for different wave periods and 2 m wave height. Added mass and damping coefficient of different shapes of WEC system are shown in Fig. 11 and Fig. 12.

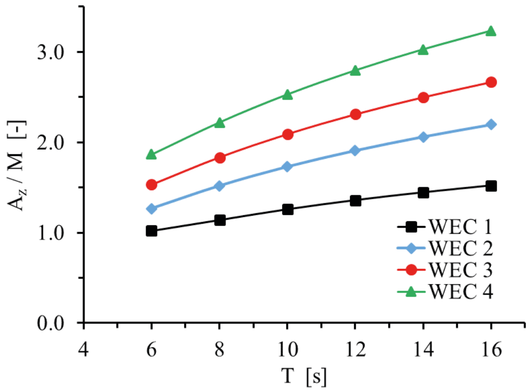

Fig. 11. Comparison of the buoy added mass for different shapes of WEC (H = 2m)

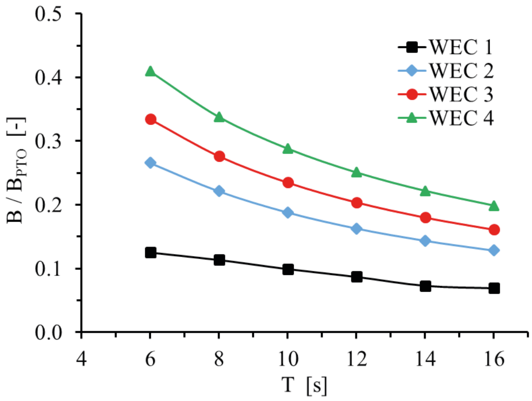

Fig. 12. Comparison of the buoy damping coefficient for different shapes of WEC (H = 2m)

In Fig. 11 it can be seen that the added mass of WECs gradually increases as wave period increases, while in Fig. 12 the damping coefficient gradually decreases for all the different shapes of WEC system. Also, it is clear that the model WEC4 has greater added mass and damping coefficient in comparison with the other model shapes of WEC system in the same conditions. In addition, the amplitude of WEC heave motion for its various shapes is illustrated in Fig. 13.

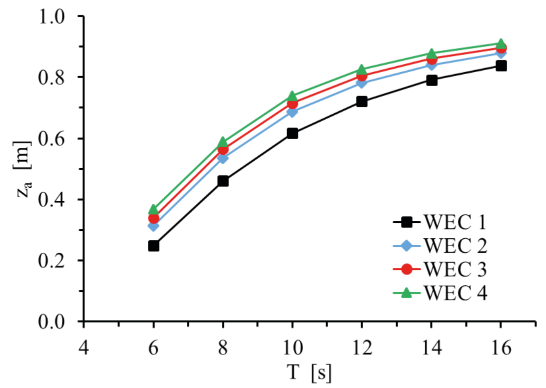

Fig. 13. Comparison of the heave motion for different shapes of WEC (H = 2m)

As shown in Fig. 13, the amplitude of WEC heave motion increases as wave period increases. In case of the larger wave periods, the amplitude of WEC heave motion gets closer to the amplitude of the regular wave. Also, it is clear that the model WEC4 has greater heave motion amplitude in comparison with the other model shapes of WEC system in the same conditions.

By using the equations (9) and (10), the PTO damping force and the mean power for various shapes of WEC system are calculated ; their amplitudes based on wave period are illustrated in Fig. 14 and Fig. 15.

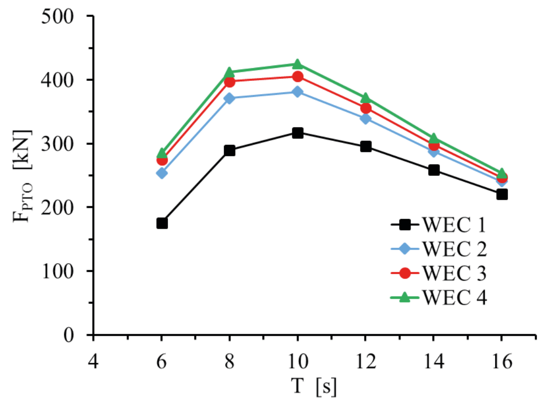

Fig. 14. Comparison of the PTO damping force for different shapes of WEC (H = 2m)

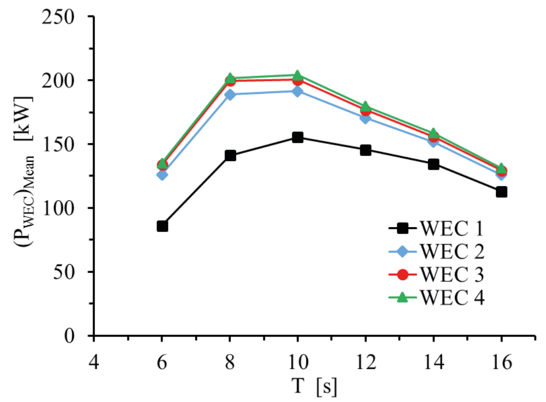

Fig. 15. Comparison of the mean WEC power for different shapes of WEC (H = 2m)

It can be seen that ,when the wave period increases, the PTO damping force and the mean WEC power first increase to the maximum value and then gradually decrease. This trend is similar in almost all model shapes of WEC. It is estimated that the maximum power generated by the WEC system is at about $T = 10\ s$ for all model shapes of WEC. Also, the model WEC4 has the best power performance in comparison with the other model shapes of WEC system in the same conditions.

The time history results obtained from ANSYS-AQWA for the typical regular wave case ($T = 10\ s$ and $H = 2\ m$) are presented in Figs. 16, 17 and 18. In the figures, the heave motion, damping PTO force and mean WEC power have been compared for different models of the WEC, whose amplitude have previously been displayed for different wave periods ($T = 6 – 16\ s$). It is obvious that the model WEC4 has a better performance than other model shapes of WEC system in the same conditions.

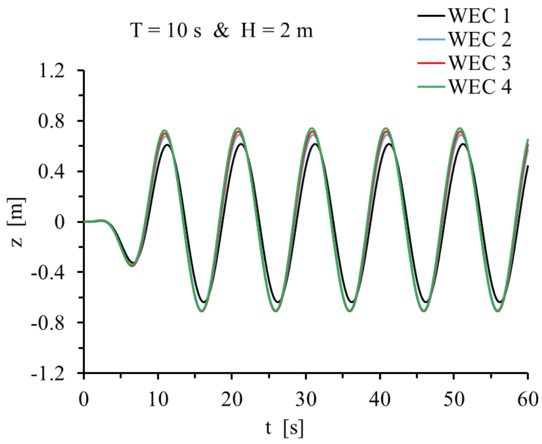

Fig. 16. Comparison of time histories of the WEC heave motion

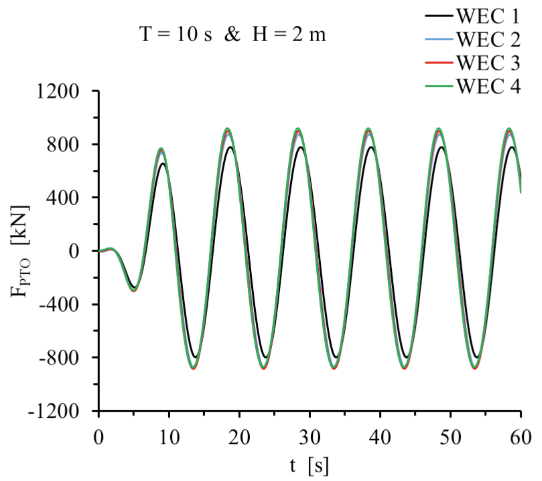

Fig. 17. Comparison of time histories of the PTO damping force

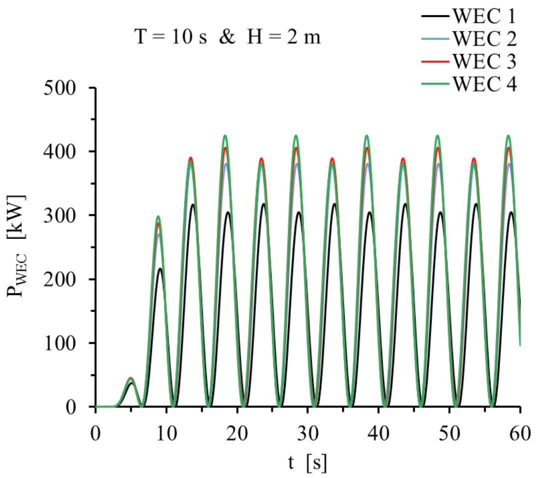

Fig. 18. Comparison of time histories of the WEC power

CONCLUSIONS

In order to observe the dynamic responses of the different shapes of WEC heaving buoy in regular wave conditions, numerical simulations have been performed by using ANSYS-AQWA software. The following conclusions can be derived from the study of numerical simulation results:

- The added mass of WECs and the amplitude of WECs heave motion increase as the wave period increases.
- The damping coefficient of WECs decreases as the wave period increases.
- The PTO damping force and the mean WEC power first increase to the maximum value and then gradually decrease as the wave period increases.
- The model shape of WEC4 has the best power performance in comparison with the other model shapes of WEC in the same conditions.

The comparison of the results of the numerical simulation showed that using WECs with a curvature inward in the bottom would absorb more energy from sea waves for the MWWC system.

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