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Numerical calculation and experiment of a heaving-buoy wave energy converter with a latching control

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Abstract. Latching control was applied to a Wave Energy Converter (WEC) buoy with direct linear electric Power Take-Off (PTO) systems oscillating in heave direction in waves. The equation of the motion of the WEC buoy in the time-domain is characterized by the wave exciting, hydrostatic, radiation forces and by several damping forces (PTO, brake, and viscous). By applying numerical schemes, such as the semi-analytical and Newmark β methods, the time series of the heave motion and velocity, and the corresponding extracted power may be obtained. The numerical prediction with the latching control is in accordance with the experimental results from the systematic 1:10-model test in a wave tank at Seoul National University. It was found that the extraction of wave energy may be improved by applying latching control to the WEC, which particularly affects waves longer than the resonant period.

Keywords: heave motion; model test; power extraction; latching control; latching duration

1. Introduction

A simple point absorber WEC extracts power through the heaving motion of a cylindrical buoy moored to the sea bottom or the relative motion between two separate buoys. The PTO system converts either the oscillating motion of a floating buoy or the relative motion between two separate buoys into electricity. There are two typical PTO. One involves hydraulic rams that drive a hydraulic motor, and the other utilizes a direct linear electric generator composed of magnets and an amateur coil. To enhance the power extracted through the PTO system, the resonance condition must be satisfied. In the resonance condition, the motion and velocity responses of WECs may be maximized, but the power extraction efficiency rapidly decreases for off-resonance wave frequencies. Some control techniques are required to create resonance-like effects, especially at wave frequencies far from resonance. Consequently, the control technique helps absorb wave energy effectively in as wide a range of frequency as possible.

Previous studies on control techniques focused on using mechanical impedance-matching schemes in order to maximize velocity, leading to maximizing the power captured from waves. Despite former attempts to utilize this method, there is a critical flaw. This method generates immense oscillation amplitude that is realistically inapplicable for physical constraint handling or

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nonlinear PTO systems (Falnes 2002a). The incorporation of latching control strategies were then integrated into the field of wave energy utilization. As such, there have been a number of significant studies conducted on latching control. One example is Budal and Falnes (1975), who introduced the concept of latching control to a point absorber WEC for the very first time. Hoskin and Nichols (1986) focused on latching control strategy and determined the optimal latching and releasing time by applying Pontryagin's maximum principle. Eidsmoen (1995), followed by Greenhow and White (1997), provided a theoretical, detailed explanation of this issue. Korde (2002) furthered this research by conducting practical studies as well. Barbarit and Clement (2006) specifically studied the latching control of WECs in irregular waves. They also went a step further and applied latching control strategy to SEAREV WEC. Falcao (2008) also worked on this subject and implemented latching control to oscillating-body converters that were equipped with a high-pressure hydraulic PTO system. Recently, a new latching control technology has been proposed by Sheng *et al*. (2015a, b). It has been confirmed that the newly proposed latching control technique allows for a significant improvement in wave energy conversion efficiency in regular and irregular waves. With this new methodology, they were able to specifically devise a method of reaching a phase optimum condition in which the latching duration can be easily deduced based on the wave period for either regular waves or, in the case of irregular waves, the spectral characteristic period. Giorgi and Ringwood (2016) used fully nonlinear computational fluid dynamics (CFD) to verify the nonlinear effect of a WEC under latching control and investigated the differences between linear and nonlinear simulation models.

Unfortunately, experimental tests have not been widely performed because they are time consuming, expensive and require a large-scale wave tank. Bjarte-Larsson and Falnes (2006) tested latching control on an axisymmetric floating body in a wave tank and verified that the application of latching control increased the extracted power up to 4.3 times. Durand *et al*. (2007) compared numerical results with experimental results that were obtained from the model test of the SEAREV device with a latching control mechanism in a wave tank. Latching control increased the energy production by up to ten times for regular waves, and from 50% to 86% for irregular waves.

In the present study, the latching control strategy was applied to a heaving WEC buoy with a direct linear electric PTO system. The linear electric PTO system may be modeled as a linear damper. Latching control can be achieved by imposing a discrete on/off braking force to the equations of motion. Time domain analysis is applied to analyze the heave responses of the WEC buoy with latching control in both regular and irregular waves, and the numerical solution of the WEC with latching control is validated through experimentation. A scaled model test ($\lambda = 1/10$) was conducted in both regular and irregular wave conditions at the wave tank at Seoul National University. The objective of the present paper is to develop simple and efficient latching control method of practical importance that can be applied to various sea states instead of developing continuous time-varying wave-by-wave real-time optimal control scheme. The present paper is organized as follows: Sect. 2 presents the mathematical and computational description and latching control strategies, while Sect. 3 introduces the model tests. In Sect. 4, results and discussions are presented, and Sect. 5 provides some conclusions and final remarks.

2. Mathematical formulation

2.1 Dynamic equation of motion for latching control

Consider the heaving WEC buoy represented in Fig. 1. The WEC buoy is subjected to the wave-exciting force $F_E(t)$, hydrostatic force $F_S(t,z)(=-\rho gSz)$, radiation force $F_R(t,\dot{z},\ddot{z})$, and several damping forces (viscous damping, mechanical damping, brake damping, PTO damping). Under the assumption of inviscid and incompressible fluid and irrotational flow, the equation of heave motion for the present WEC system can be described by Newton's second law

$$m\ddot{z} = F_E(t) + F_S(t,z) + F_R(t,\dot{z},\ddot{z}) + F_v(t,\dot{z}) + F_M(t,\dot{z}) + F_{Brake}(t,\dot{z}) + F_{PTO}(t,\dot{z}) \tag{1}$$

where m and S are the mass and water plane area of the WEC buoy, respectively.

Under the assumption of potential theory, the viscous effects are included in the equation of motion by means of the empirical prediction based on Morison's equation

$$F_V(t,\dot{z}) = -\frac{1}{2}\rho C_d A|\dot{z}|\dot{z} \tag{2}$$

where C_d is the drag coefficient, and A is the projected area.

On the other hand, the viscous force can be linearly described by

$$F_v(t,\dot{z}) = -b_v\dot{z} \tag{3}$$

where b_v is calculated from $b_v = \dfrac{2\kappa\rho gS}{\omega_N}$, and κ is the dimensionless damping factor, which can be obtained from free-decay test (Sow *et al*. 2014). $\omega_N \left(= \sqrt{\dfrac{\rho gS}{m + a(\omega_N)}}\right)$ is undamped heave natural frequency, where $a(\omega_N)$ is the added mass at heave natural frequency. In the present study, the linear viscous model expressed by Eq. (3) was used with the viscous damping coefficient obtained from free-decay test.

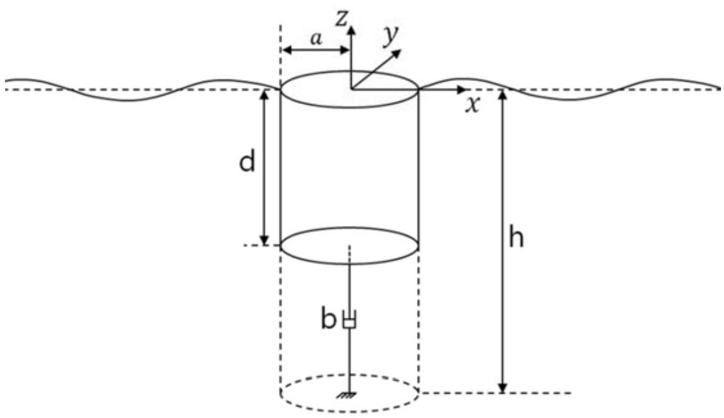


Fig. 1 Definition sketch of a heaving WEC buoy

$F_M(t,\dot{z}) = -b_M\dot{z}$ is the mechanical damping force due to the friction, and $F_{PTO}(t,\dot{z})$ is the PTO damping force, which is modeled as an equivalent linear damping force as a linear damper with PTO damping coefficient, as follows

$$F_{PTO}(t,\dot{z}) = -b_{PTO}\dot{z} \tag{4}$$

The optimal PTO damping coefficient in Eq. (4), which is tuned to produce maximum wave energy conversion at a particular frequency, is set to be equal to the sum of the viscous damping(b_v) and radiation damping(b) at resonant frequency, $b_{PTO} = b_v + b$ (Falnes 2002b).

The braking force, $F_{Brake}(t,\dot{z})$ is applied for latching and is modeled as

$$F_{Brake}(t,\dot{z}) = -b_{Brake}(t)\dot{z} \tag{5}$$

The brake damping coefficient, $b_{Brake}(t)$, is defined as a cubic function of time to ensure a continuous transition between zero and the maximum value

$$b_{Brake}(t) = \begin{cases} C_{\max}\left[3(t/t_{\max})^2 - 2(t/t_{\max})^3\right], & 0 \le t \le t_{\max}. \\ C_{\max}, & t \ge t_{\max}. \end{cases}, \tag{6}$$

where $t_{\max}$ is the target brake time since the braking command instant. The $t_{\max}$ and maximum brake damping coefficient, $C_{\max}$, should be properly selected for prompt and complete locking of the WEC buoy at the desired time and position.

The radiation force is calculated in the time domain as

$$F_R(t,\dot{z},\ddot{z}) = -\int_{-\infty}^{t} K(t-\tau)\dot{z}(\tau)dt - a(\infty)\ddot{z}(t) \tag{7}$$

The integral in Eq. (7) is a memory term expressing the radiation damping, where the impulse response function, $K(\tau)$, can be calculated by functions of buoy frequency response by the inverse Fourier transform,

$$\begin{aligned} K(\tau) &= -\frac{2}{\pi}\int_0^\infty \left(a(\omega) - a(\infty)\right)\omega\sin(\omega\tau)d\omega \\ &= \frac{2}{\pi}\int_0^\infty b(\omega)\cos(\omega\tau)d\omega \end{aligned}, \tag{8}$$

where the added mass $a(\omega)$ and radiation damping coefficient $b(\omega)$ of the present WEC buoy were computed by eigenfunction expansion method. For the evaluation of the impulse responses function in Eq. (8), we used the semi-analytical method (Cao 2008).

The real sea-state is made of the superposition of a large variety of waves with different amplitudes, frequencies, and phases. We use the energy density represented by the frequency spectrum $S_\eta(\omega)$ to describe irregular waves. In this situation, the first-order wave excitation forces can be expressed as

$$F_E(t)=\sum_{n=1}^{N_w}\left|X(\omega_n)\right|A_n\cos\left(\omega_n t+\chi_n(\omega_n)+2\pi\varepsilon_n\right),\text{ with } A_n=\sqrt{2S_\eta(\omega_n)\Delta\omega} \tag{9}$$

where ε_n is a random number generator between 0 and 1. N_w is the number of equally spaced frequencies in wave spectrum $S_\eta(\omega)$. $(\left|X(\omega_n)\right|,\chi_n(\omega_n))$ are the modulus and phase angle of the wave exciting force on the WEC buoy by a wave of unit amplitude and frequency ω_n. In the present calculation, $\Delta\omega=3.0/N_w$ rad/s with $N_w=300$.

The equation of motion for the heaving WEC buoy in the time domain is then rewritten as (Cummins 1962)

$$(m+a(\infty))\ddot{z}+(b_M+b_{PTO}+b_{Brake})\dot{z}+\int_{-\infty}^{t}K(t-\tau)\dot{z}(\tau)d\tau+\rho gSz=F_E(t)+F_V(t,\dot{z}) \tag{10}$$

The system of differential equations of heaving the WEC buoy in time-domain was solved by Newmark's β method with the initial conditions z(0)= 0, $\dot{z}$ (0) = 0 (Newmark 1959).

The time-averaged power extraction from t_1 to t_2 is defined as

$$\overline{P}=\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2}b_{PTO}\dot{z}^2dt \tag{11}$$

2.2 Latching duration

For a latching control, it is a well-known fact that latching occurs when the device velocity reaches zero or a sufficiently small value. However, the unlatching time may differ depending on the latching control strategies utilized (Babarit *et al*. 2006, Hals *et al.* 2012). The latching control avoids the phase difference between the wave excitation forces and the velocity of the WEC to maximize the extracted power like resonance. Nearly all existing latching control strategies require the short-term prediction of the wave information of at least a few seconds or more in advance in order to determine the unlatching instant. With this in mind, Sheng *et al.* (2015a, b) proposed a method for deciding the latching duration from the optimal control condition. The latching duration is affected by wave period and natural period of the WEC alone and is calculated as

$$T_{latch}=\frac{T_W-T_N}{2} \tag{12}$$

where T_{latch} is the latching duration, $T_N(=2\pi/\omega_N)$ the natural period, and T_W the wave period. In irregular waves, the peak period T_P or the energy period T_E is used as a statistical value for real waves instead of the wave period T_W. Eq. (12) implicitly implies that the latching control strategy must be applied when the wave period is larger than the natural period.

When the latching duration in Eq. (12) is put into consideration, the unlatched time can be calculated with the following simple equation, irrespective of regular and irregular waves: $T_{unlatch}=(T_W-2T_{latch})/2=T_N/2$. The starting time of latching is not arbitrary. We start latching when heave motion amplitude near peak period is at its peak (heave velocity is zero), which can be determined from motion sensors, then hold until heave wave force becomes close to maximum, as specified by (12). Subsequently, we apply T_{latch} and $T_{unlatch}$ repeatedly as given in the above.

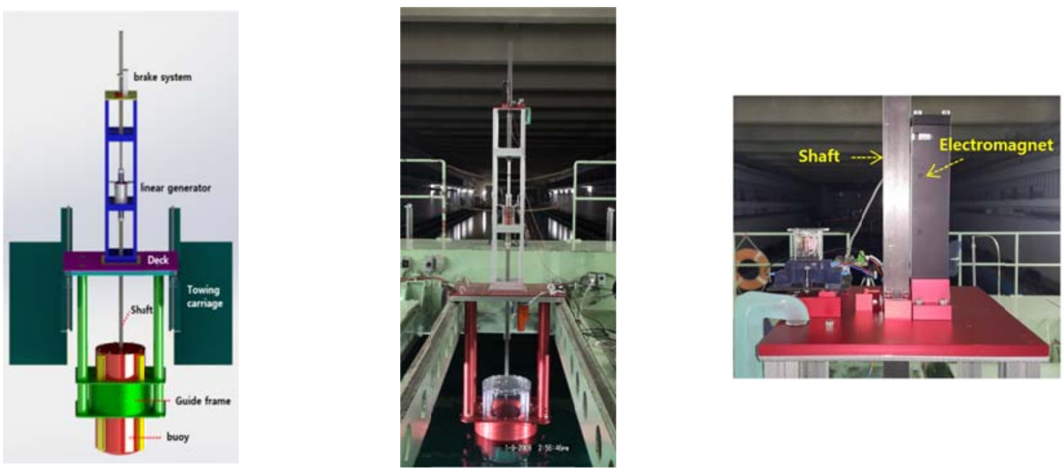
3. Model test

The WEC model with latching control system consists of heaving WEC buoy, fixed external guide frame, linear electric generator, and brake device as seen in Fig. 2. Only WEC buoy is allowed to move vertically with the help of guided frame fixed to towing carriage and rectangular shaft made with alloy steel. The low-friction plates are installed at the lower and upper sides of the guide frame to reduce the frictional forces between the WEC buoy and guide frame. By this arrangement, WEC buoy moves through the guide frame where pure heave motion is allowed. During latching, the WEC buoy kept in locking position by switching on the brake device. The specifications of a WEC buoy model are tabulated in Table 1. The draft of the WEC buoy is d = 54 cm and the radius is a = 20 cm, respectively. The heave natural period of the WEC buoy model can be obtained from Eq. (13).

$$T_N = 2\pi\sqrt{\frac{m+a}{\rho g S}}, \tag{13}$$

Table 1 Specification of WEC model

Item	Radius [cm]	Draft [cm]	Freeboard [cm]	CoG. (from SW.) [cm]	Mass [kg]	Natural period [sec]
WEC buoy	20	54	38	38.9	67.13	1.56
Guide frame	26.5	15	15	-	57.9	-



(a) (b) (c)

Fig. 2 (a) 3D drawings of WEC model for experiment (b)Photograph of experimental model in wave tank (c)Brake system using electromagnet

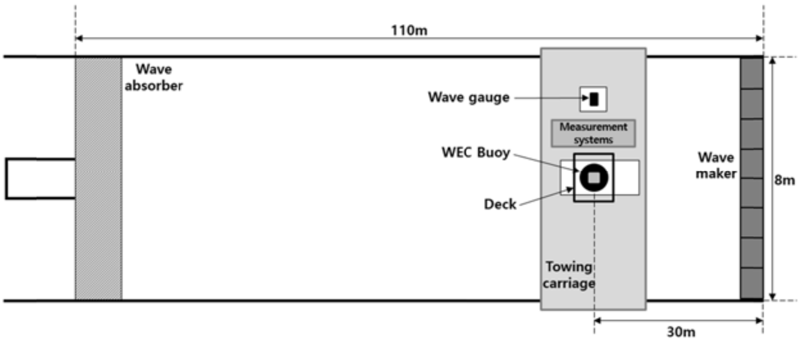


Fig. 3 Schematic sketch of the experimental set-up

By substituting the values in Table 1 to Eq. (13), the heave natural period of WEC buoy ($T_N = 1.56\text{s}$) can be calculated.

The model test was conducted in the towing tank at Seoul National University. The length of the tank is 110 m, width is 8 m, and water depth is 3.5 m. At the one end of the tank, eight sets of plunger-type wave-makers, which can generate either regular or irregular waves, are installed. The beach-type wave absorber is installed at the other end to reduce the reflected waves. The WEC buoy was installed through the hatch of the towing carriage and placed 30m away from the wave maker. The servo type wave gauge was installed at the same distance from the wave maker to measure the incident waves. Since the model size is quite small compared to the tank width, the effect of the tank wall is expected to be minimal.

Fig. 3 shows the configuration of the experimental set-up and position of the wave gauge. To measure the heave motion of the WEC buoy in waves, both the accelerometer (AS-1GB) and ultrasonic displacement meter are used independently for cross-checking. To investigate the effect of latching control from WEC buoy dynamics in waves, the model test was conducted without the PTO system.

To involve the effect of viscous and mechanical damping in the present potential theory, free-decay tests were conducted twice. First, the typical free-decay test was accomplished with the WEC buoy without a guide frame to obtain the viscous damping coefficient, b_v. The mechanical damping coefficient, b_M, could be readily obtained by comparing the difference of the decay rate between with and without the external guide frame. The damping coefficients of each item are listed in Table 2. From the free-decay test, the measured damped natural period is the same as that calculated from Eq. (13), which is exact only if damping is absent or negligible.

The wave period range for a regular wave test was taken as $1.36\text{s} \le T \le 2.36s$, which includes the heave natural period ($T_N = 1.56s$) of the WEC buoy; a total of 13 wave periods were selected within the test period range. A total of four cases of irregular wave were generated based on the JONSWAP spectrum with various peak periods and fixed significant wave height of 0.1 m. The regular and irregular wave conditions for latching control are summarized in Table 3. The effective experimental data was obtained by excluding the reflected wave effect from the wave absorber, and the sampling frequency was 100Hz.

Table 2 Results of free-decay tests

Case	Damper natural period [sec]	Measured damping factor (κ-value)	Damping coefficient [kg/sec]	Each damping coefficient [kg/sec]
Without guide frame	1.56	0.0299	19.5(①)	Viscous damping 19.5
With guide frame	1.56	0.0458	29.8(②)	Mechanical damping 10.3(②-①)

Table 3 wave conditions for regular and irregular waves

Regular waves					
Case	1	2	3	4	5
A [m]	0.036	0.045	0.054	0.043	0.05
T_w [sec]	1.76	1.96	2.16	2.36	2.56
T_{latch} [sec]	0.1	0.2	0.3	0.4	0.5
$T_{unlatch}$ [sec]	0.78				
Irregular waves					
Case	201	202	203	204	
H_s [m]	0.1				
ω_p	3.38	2.98	2.84	2.50	
T_{latch} [sec]	0.15	0.275	0.325	0.475	
$T_{unlatch}$ [sec]	0.78				

4. Results and discussions

To estimate the performance of the WEC buoy according to with and without the latching control, a simple heaving cylinder buoy with a radius a= 2 m and drafts d = 2, 4, 6 m was used in present study. The water depth is 80 m. To maximize the wave energy production by the WEC, the optimal PTO damping coefficient ($b_{PTO} = b(\omega_N)$) is applied first. The idealized PTO system can provide the required optimal damping, and it will be shown that how the PTO can maximize wave energy production.

Figs. 4-6 show the time series of the heave motion and its velocity with and without a latching control. The viscous damping forces are ignored. When motions are greatly exaggerated near the resonance, as shown in these figures, more reasonable motion amplitudes can be obtained by including the quadratic damping effects with the drag coefficient, C_d=0.5, illustrated in Fig. 4. The incident waves are monochromatic waves with amplitude A = 1 m and period $T_W = 7s$. The optimal PTO damping coefficients are 4.64, 2.44, and 1.57kN/(m/s) according to 2, 4, and 6 m drafts, respectively. The undamped natural periods as a function of draft are 3.52s, 4.57s, 5.39s, respectively; therefore they do not satisfy the resonance condition that the period of incident waves agrees to the heave natural period. The latching control technique that consists of locking the motion of the WEC buoy at the very instance at which its velocity vanishes and then releasing allows for obtaining a phase optimum in waves, which results in a significantly improved wave energy conversion.

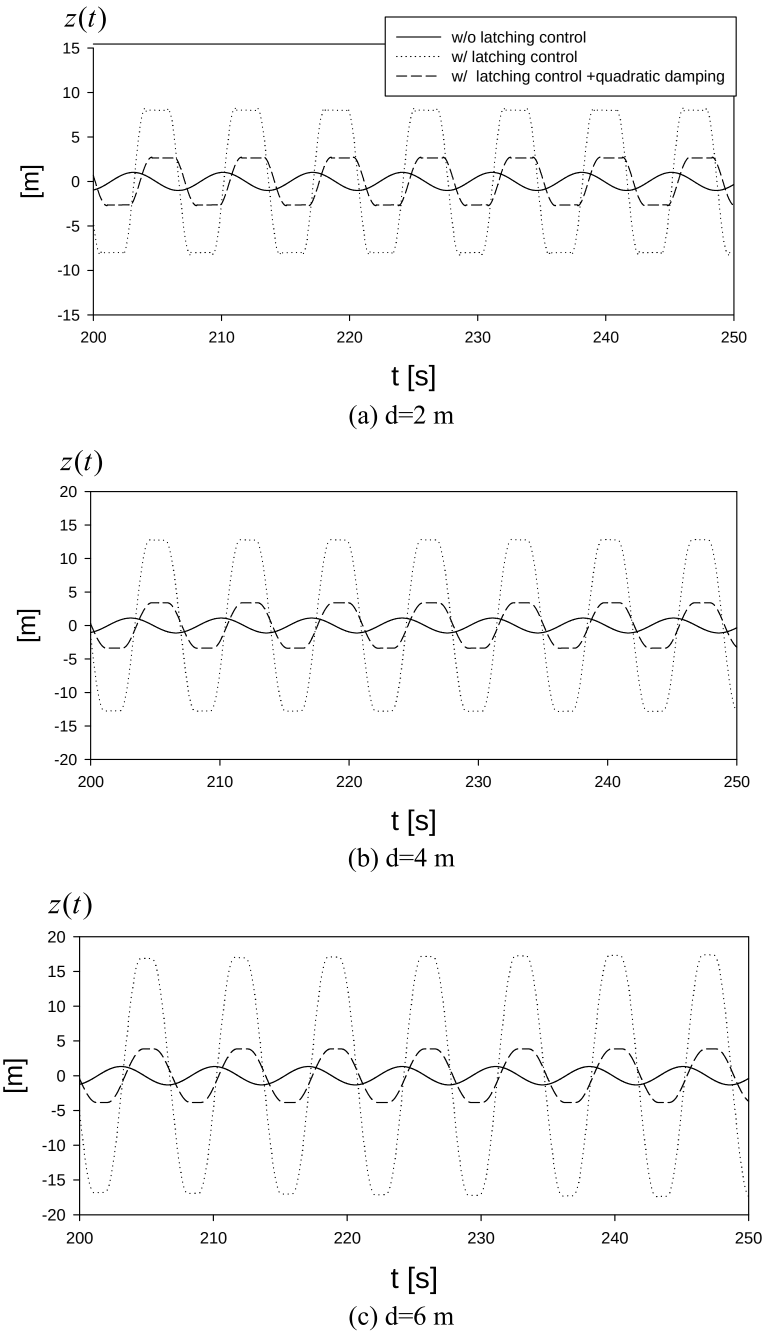


Fig. 4 Heave motion amplitude of WEC buoy with and without latching control in regular waves (A = 1 m , T_W = 7s)

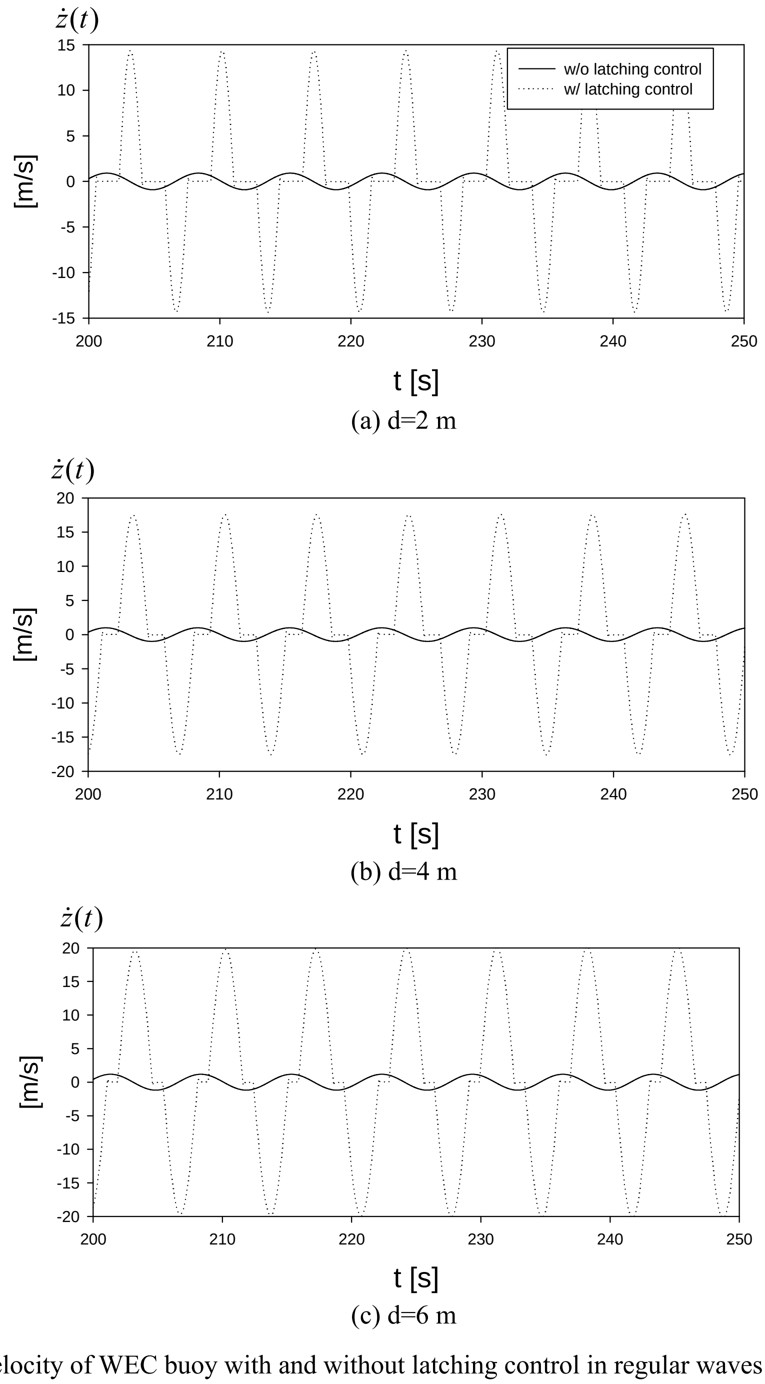
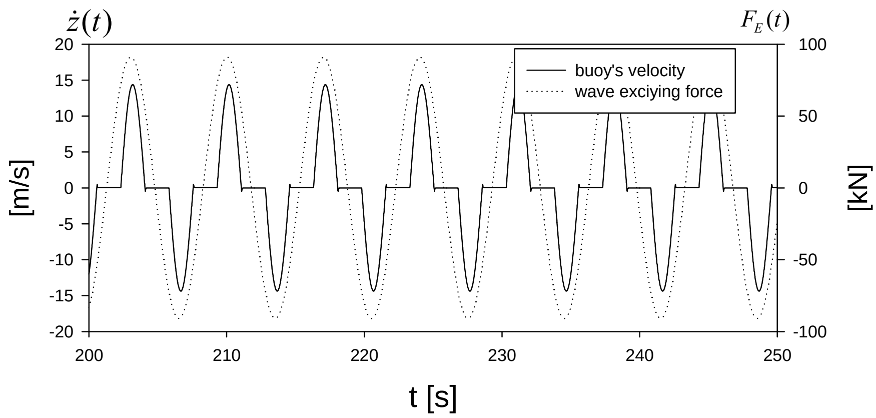
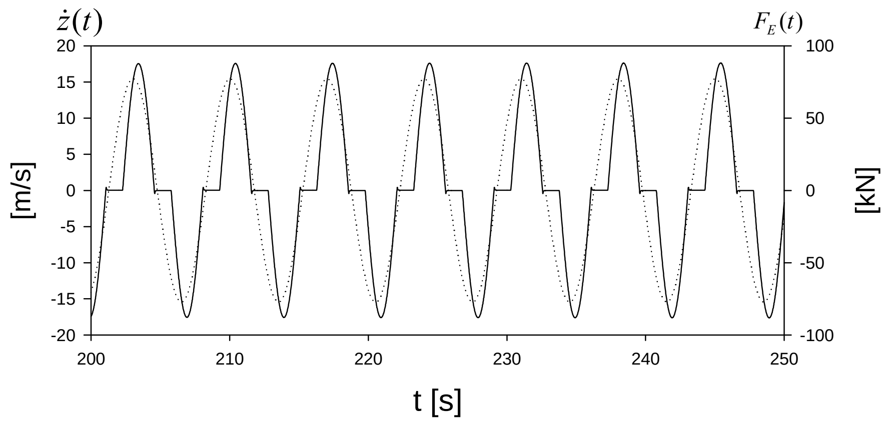


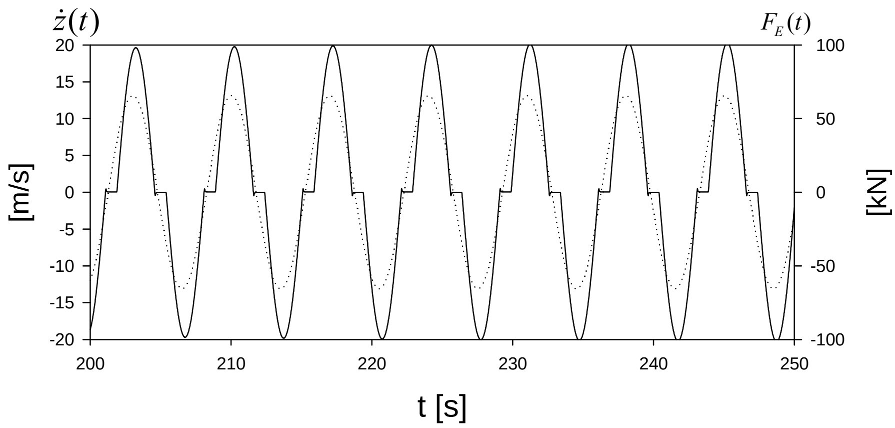
Fig. 5 Heave velocity of WEC buoy with and without latching control in regular waves (A = 1 m , T_W = 7s)



(a) d=2 m



(b) d=4 m



(c) d=6 m

Fig. 6 Phase comparison for the vertical velocity and wave exciting force of WEC buoy with latching control in regular waves (A = 1 m , T_W = 7s)

As shown in Figs. 4 and 5, the latching control has changed the phase of heave motion and velocity greatly. Therefore, it can be concluded that, due to latching control, the heave motion and velocity amplitude have been notably increased, regardless of the draft. The increased velocity of the WEC buoy by latching control contributes to enhancement of the extracted power greatly. Fig. 6 exhibits the comparison between heave velocity (with latching control) and wave excitation force. It is quite obvious that applying the latching control caused the velocity to become in phase with the wave excitation force. In this regard, the phase optimum equivalent to the resonance condition is said to be achieved.

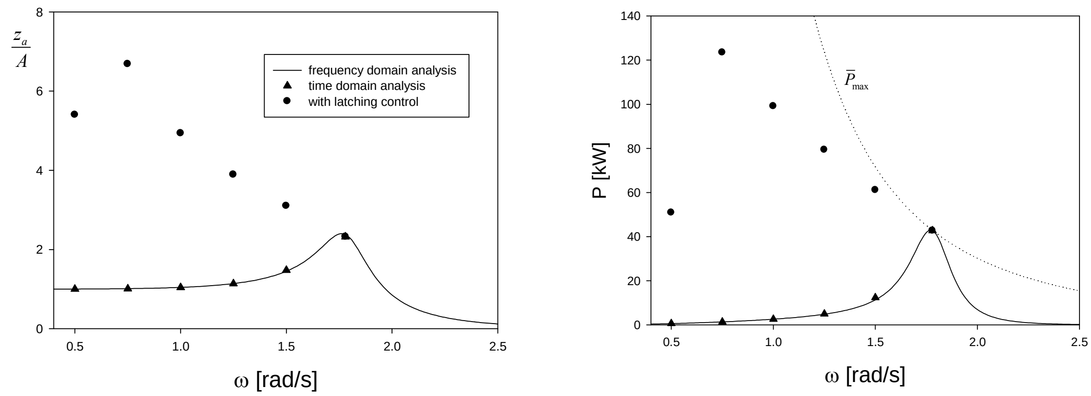
Fig. 7 shows the comparison of the heave RAO and extracted power for three different drafts, d=2,4,6 m, in regular waves without and with a latching control. The optimal PTO damping is equal to the radiation damping coefficient at the natural frequency for the maximum power conversion. Here, the solid line is the numerical solutions in the frequency domain analysis, and the symbols are the time-domain solutions (●: with latching control, ▲: without latching control). The time-domain solutions with no latching control agree well with the frequency-domain solutions. In the wave region longer than the natural period (3.52s, 4.55s, 5.37s), latching control is helpful in extracting more energy up to the incident wave period of 8s. If the wave period is further increased to 13s, the heave RAO and extracted power are reduced, though not lower than those at resonance frequency. From the comparison of the extracted power, it can be concluded that latching control is remarkably effective in improving wave energy conversion, especially in long waves.

When the latching control technique was applied in irregular waves of the JONSWAP spectrum with the significant wave height H_S = 1 m and peak period $T_P = 6.67s$, regardless of the difference in each individual wave of the wave train, the latching duration will remain a constant ($T_{latch} = \frac{T_P - T_N}{2}$) for the specified sea state. When considering each individual wave, the wave amplitude and frequency varies from wave to wave, whereas in this case, the wave spectrum is significantly steadier and statistical values often stay fixed for some period of time.

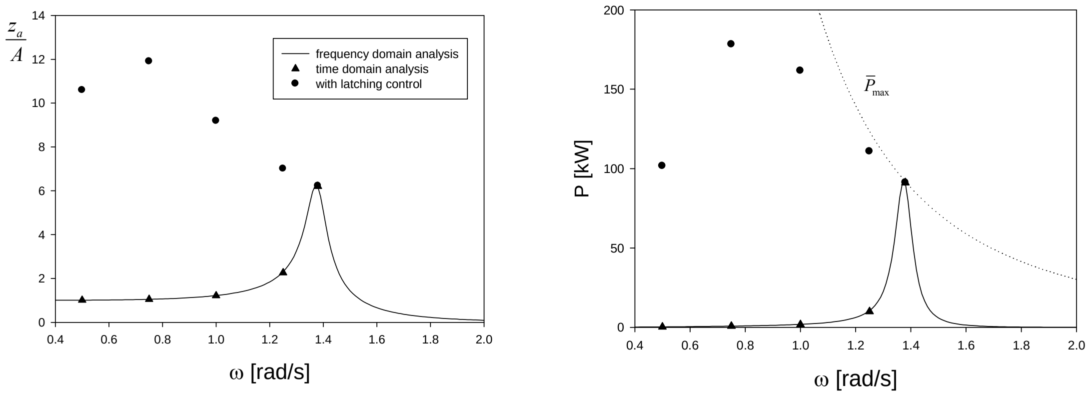
For the WEC buoy (a= 2 m, d = 5 m) in such a sea state (H_s= 1 m = T_P= 6.67s), the latching and unlatching durations are given by $T_{latch} = 0.84s$ and $T_{unlatch} = 2.49s$, respectively. The value of PTO damping is set equal to that of the optimal damping for a maximum power conversion (i.e., $b_{PTO} = 19.3kN/(m/s)$). Fig. 8 compares heave motion amplitude between with and without a latching control in irregular waves. From the second enlarged figure, with latching control, the maximum amplitude was doubled in comparison to without latching control.

Fig. 9 shows the phase comparisons for the velocity and wave excitation force. It shows that the velocity is much in-phase with the wave excitation force after applying with latching control, especially for larger wave groups. The extracted power conversion with latching control applied shows a distinct improvement, as illustrated in Fig. 10, despite the fact that the phase control cannot be completely executed in irregular waves. As a result of the latching control, the average power conversion has increased from 1.11 kW to 2.22 kW, which is an increase of 100%. Under circumstances where the wave period (peak period) is longer, the latching control's contribution to increasing the wave energy extraction can be more prominent.

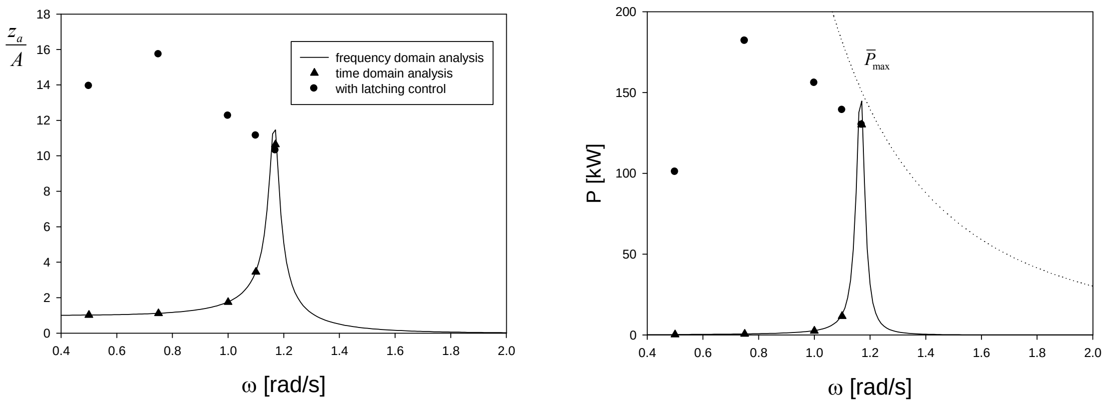
The experimental results of regular wave tests are expressed as RAOs (z_a / A), which can be defined by the ratio between incident wave amplitude (A) and buoy-heave amplitude (z_a). Fig. 11(a) shows comparisons between experimental and numerical results without and with latching control, when each damping coefficients (Table 2) obtained from a free-decay test were applied.



(a) d=2 m



(b) d=4 m



d=6 m

Fig. 7 Comparison of heave RAO and extracted power of WEC buoy between frequency-domain and time-domain analysis

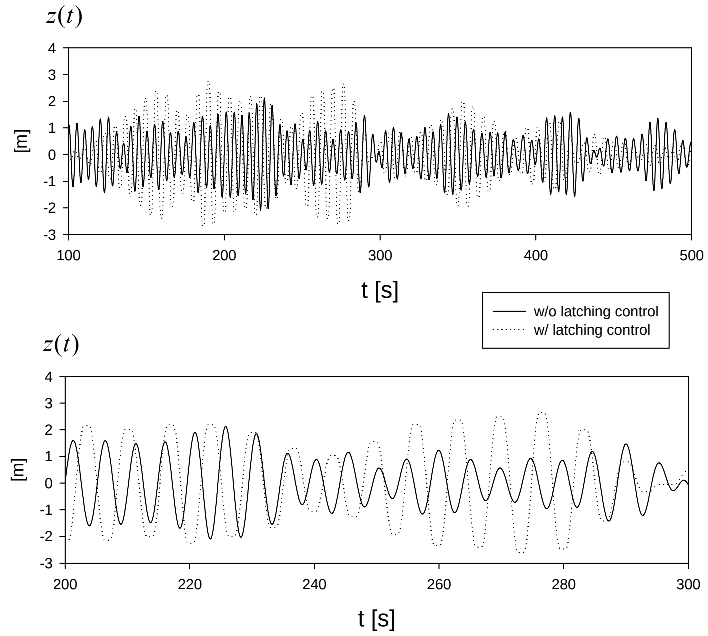


Fig. 8 Heave motion amplitude of WEC buoy with and without latching control in irregular waves for $T_{latch} = 0.84s, b_{PTO} = 19.3kN/(m/s), H_S = 1m, T_P = 6.67s$

The comparisons with no latching control show that the general trend of the experimental and numerical results is very similar and that their correlations are very reasonable. From the comparison of heave RAO with latching control, latching control is indeed very effective in increasing heave motion amplitude of the WEC buoy, especially in the long wave region. The significant differences between the numerical and experimental test results after the application of latching control results may be attributed to more complex nonlinear phenomena. The inclusion of nonlinearities (e.g., nonlinear Froude–Krylov effects) in the present linear model will contribute to enhancing the model accuracy.

Fig. 11(b) shows the times series of heave motion obtained in the model tests with and without latching control. With latching control, the heave motion amplitude is amplified more than double in spite of lower amplitude of incident wave. As the extracted power is normally proportional to the square of motion amplitude, much higher power conversion is expected through the latching control.

For irregular wave tests, JONSWAP wave spectrum with the peakedness factor $\gamma = 3.3$ was used. First, for the verification of the irregular wave tests, time series for heave motions are selected and their respective spectra are calculated using Fast Fourier Transform (FFT). The heave motion spectrums of WEC buoy for each irregular are plotted in Fig. 12 without and with latching control. The latching control can increase the heave motion greatly in irregular waves, as shown in Fig. 12.

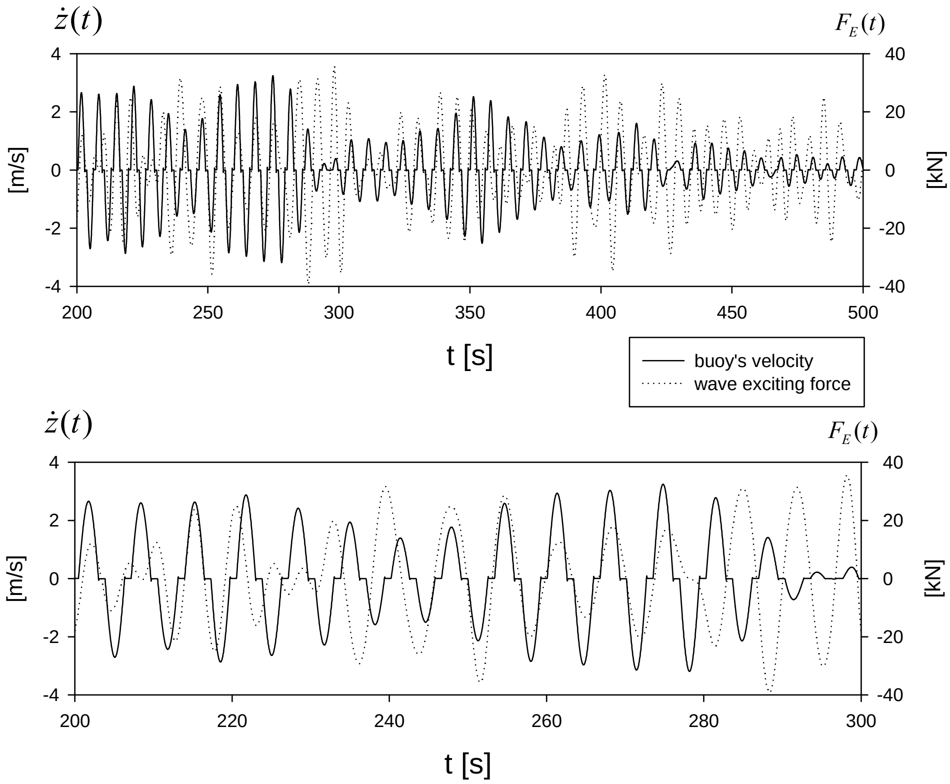


Fig. 9 Phase comparison for the vertical velocity and wave exciting force of WEC buoy with latching control in irregular waves for $T_{latch} = 0.84s, b_{PTO} = 19.3kN/(m/s), H_S = 1m, T_P = 6.67s$

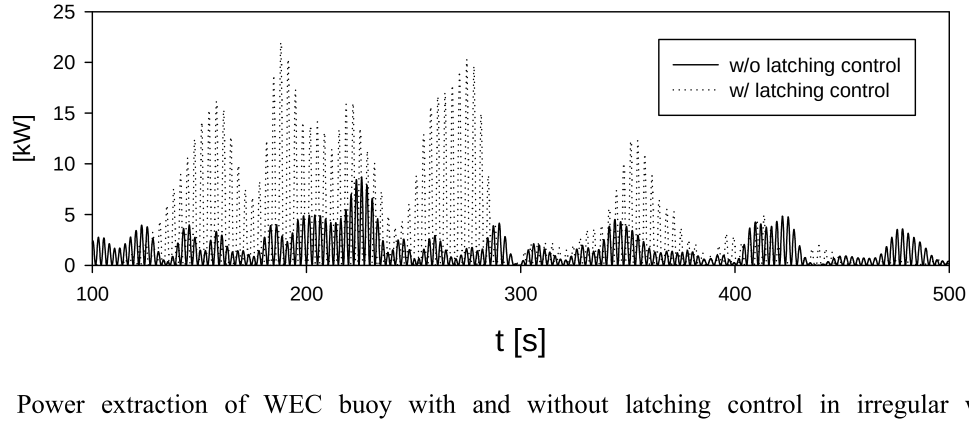
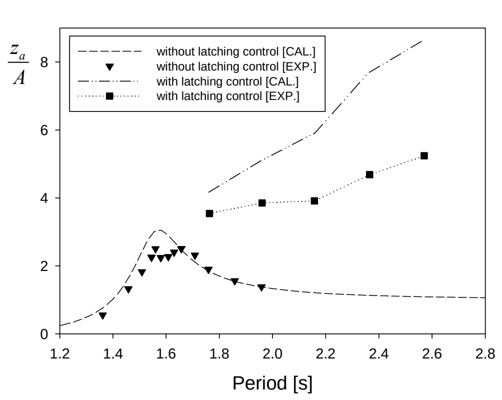
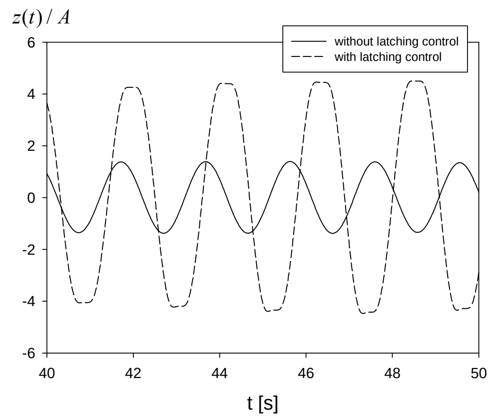


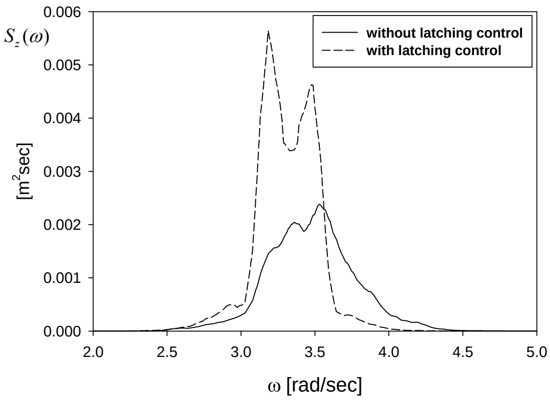
Fig. 10 Power extraction of WEC buoy with and without latching control in irregular waves for $T_{latch} = 0.84s, b_{PTO} = 19.3kN/(m/s), H_S = 1m, T_P = 6.67s$



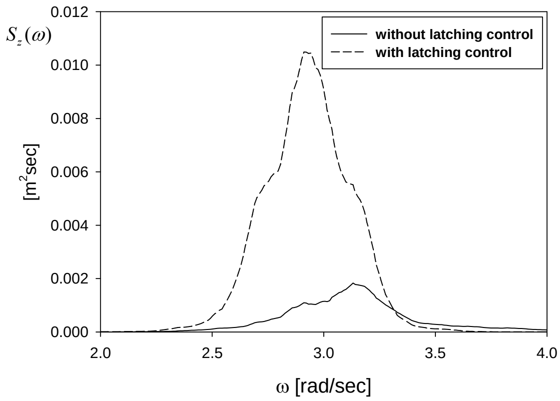


(a) (b)

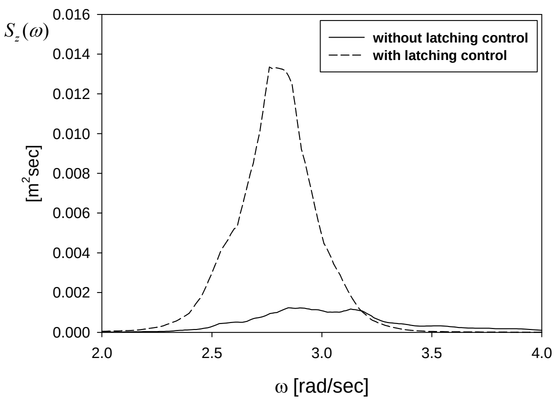
Fig. 11 (a) Heave RAO of WEC buoy with and without latching control and (b) Heave motion amplitude of WEC buoy with and without latching control(w/ latching: A =0.045 m, T_W= 1.96 s, w/o latching : A =0.06 m, T_W= 1.96 s)



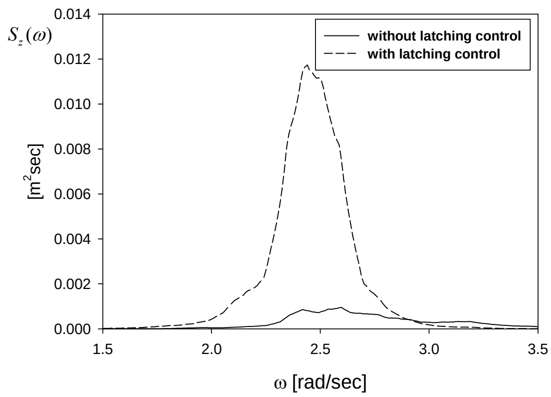
(a) Case 201



(b) Case 202



(c) Case 203



(d) Case 204

Fig. 12 Heave motion spectrum of WEC buoy with and without latching control

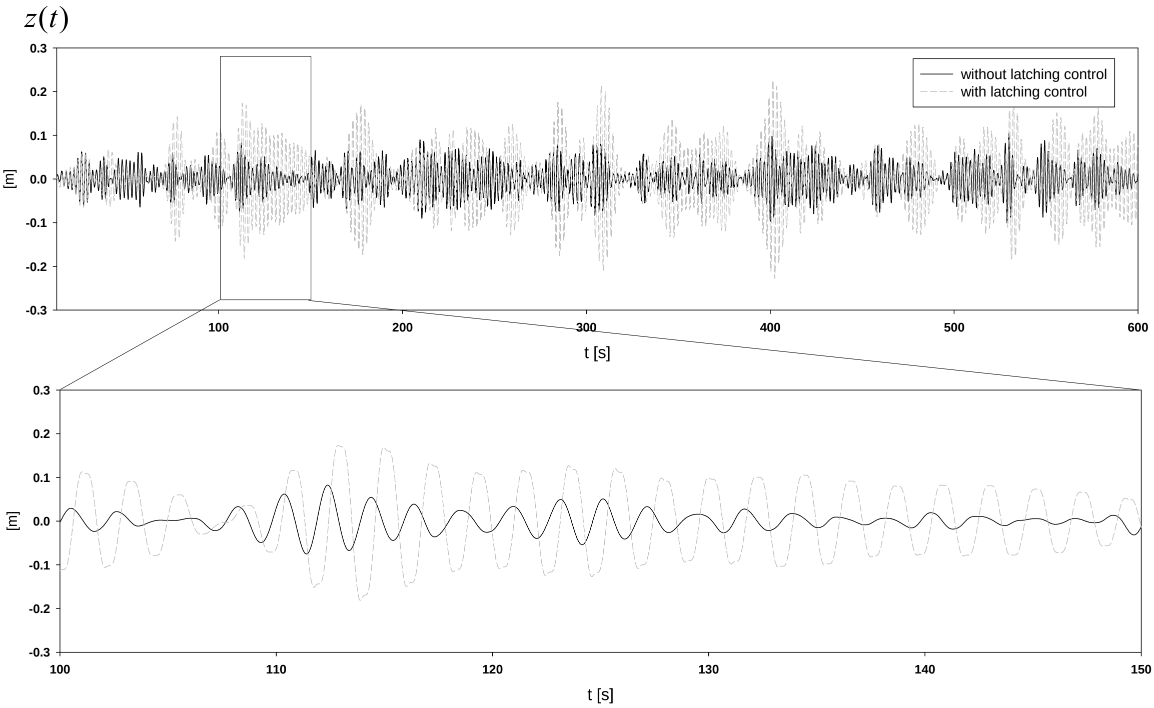


Fig. 13 Time series of WEC buoy with and without latching control for case 202

To further analyze the irregular wave tests, the time series (Case 202) of heave motion of the WEC buoy are taken with and without latching control. Fig. 13 shows that the latching control changed the motion phase greatly, similar to the regular wave test, and the buoy motion was significantly increased when the period of the individual wave in the wave train is longer than the natural period.

5. Conclusions

The present study is focused on determining how the application of latching control can contribute to the improvement of wave energy conversion, numerically and experimentally. For these purposes, the equation of heave motion involving the brake system for locking the WEC buoy has been established. Well-applied latching control can shift the entire dynamic system into resonance, especially if the wave period is longer than the natural period of the system. This enables one to attain an optimal phase condition equivalent to the resonance condition. In determining the latching duration, the methodology proposed by Sheng *et al.* (2015a,b) is adopted, which may be dependent on both the natural period and the wave period of the sea state. When latching control is applied to regular waves, the WEC is able to enhance its energy extraction from longer waves up to a certain wave period. In the example, the significant increase of wave energy conversion can be seen from the natural period to 8s. Latching duration for irregular waves was calculated according to the peak period.

In the model test, the linear viscous and mechanical damping coefficients were calculated through the free-decay tests. The brake device to implement latching control consists of a strong electromagnet for locking the WEC buoy. From the regular wave test, the amplified heave motion of the WEC buoy was observed at the natural period of the WEC buoy without latching control. By applying latching control at a longer period region than the natural period, heave response increases highly. In addition, with latching control, the areas of heave motion spectrum in irregular wave tests increase greatly. When it comes to the practicality of applying latching control to WEC, some problems remain unsolved. Two of the most pressing challenges include determining future information of incoming waves based on wave measurements in front of the WEC in order to select the unlatching instant, and developing the discrete on/off locking mechanical device. Future wave information is also necessary for selecting the optimal PTO damping force because both the wave height and the wave period of the sea state can potentially affect its value.

Acknowledgments

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