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Integration of a Semisubmersible Floating Wind Turbine and Wave Energy Converters: an Experiment Study on Motion Reduction

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Abstract

The integration of wave energy converters and a floating wind turbine has the potential to reduce the cost of energy since they can share the mooring system and the infrastructure of the power grid. In this study, oscillating-water-column-type wave energy converters mounted on a semisubmersible-type floating wind turbine are presented. Water tank tests are carried out to illustrate that the wave energy converters can not only capture the wave energy but also help in reducing the motion of the floating platform when active control is applied. This study provides a new perspective on hybrid renewable energy application to widen renewable energy penetration by enhancing system reliability.

Keywords

Wave energy converter, floating offshore wind turbine, motion reduction, water tank test.

I. INTRODUCTION

The sustainable development of offshore wind energy requires reliable floating platforms. Although the platforms are usually designed with good sea-keeping performance and good stability, environmental forces induced by wind, wave and ocean current can, however, induce undesired motion of the platforms to deteriorate the fatigue life of wind turbines [1, 2, 3]. Suzuki and Sato have performed some pioneering work on investigating the effects of floater motion on the strength of offshore wind turbine blades, and it is reported that pitching with an amplitude of 5 degrees at floater would lead to a 50% increase of blade sectional modulus [4]. Although the floating platforms are designed with sophisticated analysis, Huijs *et al.* have reported that the maximum inclination of the floaters would also reach to 10 degrees according to model tests [5]. In order to further reduce the motions, various methods and state-of-art structures were proposed in the literature. In [6] and [7], novel water-entrapment plates with large horizontal skirts are proposed for a semisubmersible platform. The motion of the platform in heave, roll and pitch direction can be significantly reduced for the increase of the added-mass and viscous loads. In [8], Roddier and Cermelli proposed a new concept of motion reduction for a semisubmersible that the water can be pumped between the columns of the semisubmersible. Although the methods can reduce the motion of the platform, they would also increase the cost of energy and complicate the maintenance system.

The ocean waves are the primary source of inducing the floater motion, however, it is also a type of renewable energy resource with high power density [9]. The global gross theoretical resource is estimated at about 3.7 TW, a quantity that is comparable with the world's present power consumption. The technologies on the utilization of wave energy for electricity production are not yet mature. A number of demonstration projects exist, but these are generally still in the R&D phase and the cost of energy are multiple times greater than the target (market) level [10]. Various technologies, such as oscillating water columns [11], wave activated bodies [12], and overtopping [13] are applied with fixed structure or floating structure. Recent studies also put the effort in combining wave energy converters (WECs) with floating offshore wind turbine (FOWT) for better utilization of marine space and lower installation cost owing to the shared electrical grid connections and mooring systems [14, 15, 16, 17]. Though there are many advantages, the combination also introduces the interaction between WECs and FOWT that makes the whole system complex. Perez and Iglesias have reported that particular attention should be paid to the wind turbine foundation affected by the installation of the WECs since the inclination of the foundation may exceed the design limit [18]. Development of a hybrid wind-wave energy system which can not only extract the wave energy but also help in reducing the platform motion attracts our attention. In our previous studies in [19, 20], basic structural design and a motion reduction control method are discussed for a two-dimensional model consisting of a semisubmersible and WECs. The studies provide a perspective on this type of hybrid wind-wave energy system since the motion of the semisubmersible could be remarkably reduced by the proper control of the WECs from the simulation results.

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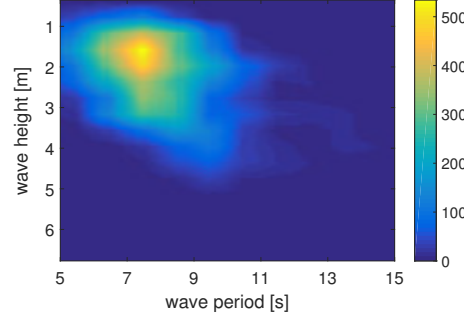


Fig. 1. Joint probability distribution of wave height and wave period.

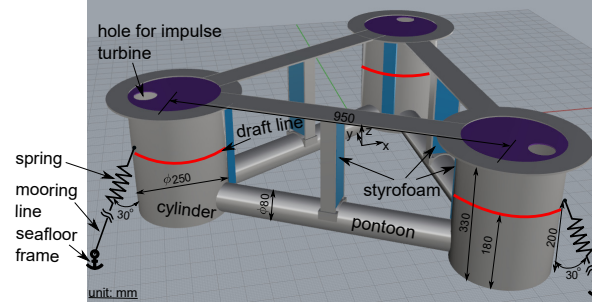


Fig. 2. Configuration of the semisubmersible and mooring lines.

To go a step further, a small experimental model is developed in this study. Tohoku Pacific coast area of Japan where Fukushima floating offshore wind farm demonstration project is currently in operation is considered as a typical location of this study, and the joint probability distribution of wave height and wave period is shown in Fig. 1 [21]. The wave period between 7 sec and 8 sec has a maximum occurrence frequency in this area. In the following, the floating platform and the WECs are designed based on the wave state to evaluate the efficiency of the WECs.

II. DESIGN ASPECTS

The experimental system consists of a semisubmersible with a mooring system, a wind turbine mounted on the semisubmersible, and three oscillating-water-column-type WECs installed at the vertices of the semisubmersible. The semisubmersible and the WECs are designed as a 1:50 model of the practical platform. For ease of explanation, the origin of the world coordinate system is set at the undisturbed free water surface beneath the tower. The x -axis is in wind direction and z -axis points upward normal to the water surface. The y -axis is defined to coincide with the right-hand rule.

A. Semisubmersible and Mooring System

The semisubmersible is a Δ -shaped platform made of acrylic resin. It consists of three hollow cylinders at the vertices of the platform, three pontoons to connect the cylinders and a set of three braces to strengthen the structure. The three hollow

TABLE I
PROPERTIES OF SEMISUBMERSIBLE

Property	Value
Floater draft (mm)	180
Elevation of platform (mm)	150*
Distance between Cylinders (mm)	950
Floater mass (kg)	12.24
Center of buoyancy (mm)	(0, 0, -124)*
Center of mass (mm)	(0, 0, -79)*
Moment of inertia (I_x, I_y, I_z) (kgm^2)	(1.45, 1.45, 2.15)**

* The values are with respect to the undisturbed water surface.

** The values are with respect to the center of mass.

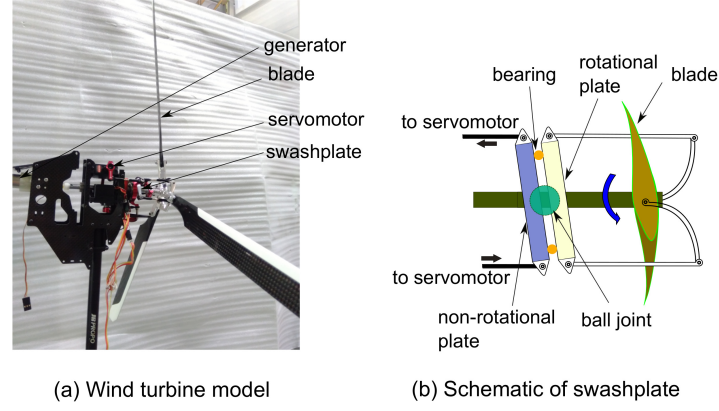


Fig. 3. Wind turbine for experiment.

TABLE II
PROPERTIES OF WIND TURBINE

Property	Value
Rotor diameter (mm)	720
Hub height (mm)	700
Rated rotor speed (rpm)	1400
Mass (kg)	0.61
Center of mass (mm)	(-20, 0, 630)*
Moment of inertia (I_x, I_y, I_z) (kgm^2)	$(4.72, 5.25, 3.45) \times 10^{-3}$ **

* The values are with respect to the undisturbed water surface.

** The values are with respect to the center of mass.

cylinders are reserved for the installation of WECs. The three pontoons are designed to provide the primary buoyancy for the system. A set of six square columns made of Styrofoam is mounted on the platform to adjust the waterplane area (as well as the natural periods) of the semisubmersible. The configuration of the semisubmersible is shown in Fig. 2. The properties of the semisubmersible are listed in Table I.

Preliminary numerical studies of the system indicate that the motion amplitudes of the semisubmersible caused by the incident waves are small in the experimental water tank conditions. Therefore, a set of three linear springs with stiffness of 0.08 N/mm is applied to approximate the anchor-chain mooring system. The mooring lines are connected to the outer wall of the hollow cylinders with an angle of 30 deg away from the centerline of the cylinders, as shown in Fig. 2.

B. Wind Turbine

A fixed speed wind turbine is applied for this study. The rotor of the wind turbine is remodeled from a helicopter (model: FORZA 450EX) with the rotor diameter 720 mm. The blades are non-tapered non-twisted blades with chord length 26 mm and thickness 3 mm. The pitch angle of the blades is controlled by three servo motor via a swashplate. The experimental wind turbine model and the schematic of swashplate are shown in Fig. 3. The generator is directly connected to the rotor by a coupling. The rotation speed of the wind turbine is set as 1400 rpm in the experiment. Other properties of the wind turbine are explained in Table II.

C. Wave Energy Converter

The schematic view of the WEC is shown in Fig. 4. A chamber is built by the hollow cylinder, floating platform, and the water surface. A self-rectifying impulse turbine with fixed twin guide vane at both sides of the turbine rotor is applied as the power-take-off (PTO) of the WECs. The configuration is shown in Fig. 5. The fluctuation of the water surface forces the air to flow in/out of the chamber to drive the impulse turbine. A brushed DC machine is applied as the generator of the WEC. According to the report in [22] that an oscillating water column type WECs has better primary wave energy conversion efficiency when the ratio between the wave length and the cylinder diameter is about 7 and the area ratio between the air hole and the cylinder is 1/200, the diameter of the hollow cylinder is set as 250 mm and the rotor radius of the impulse turbine and the length of rotor blade are set as 30 mm and 8.5 mm, respectively.

In order to regulate the air flowing in/out of the chamber so as to assist in controlling the motion of the platform, a butterfly valve is applied at the outlet of the impulse turbine for its compact. A digital servo motor is employed to control the disc of the valve. The mechanism of the valve is illustrated in Fig. 4(b).

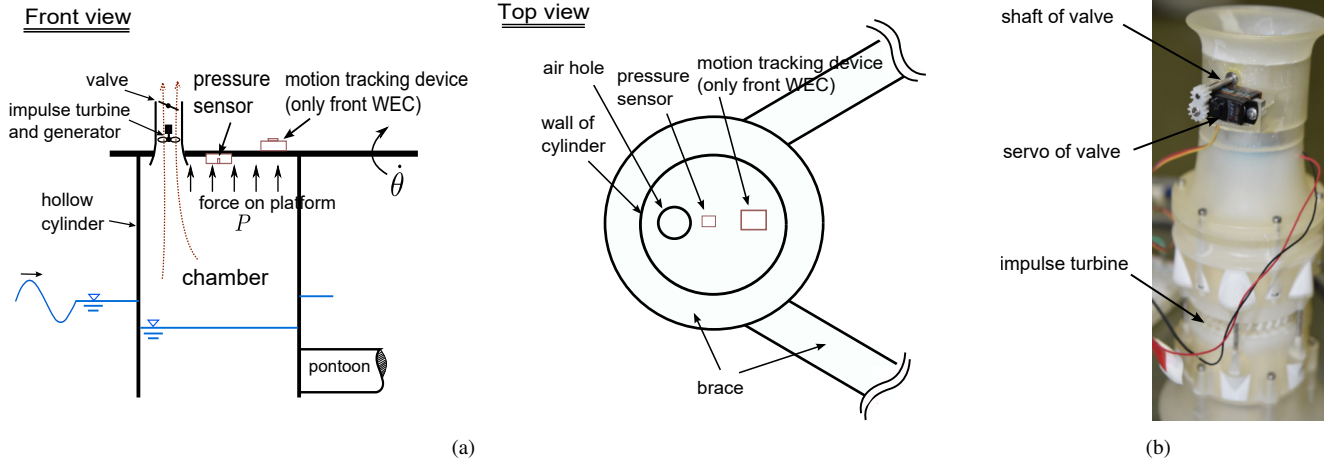


Fig. 4. Schematic of wave energy converter (a) and experimental setup of impulse turbine and valve (b).

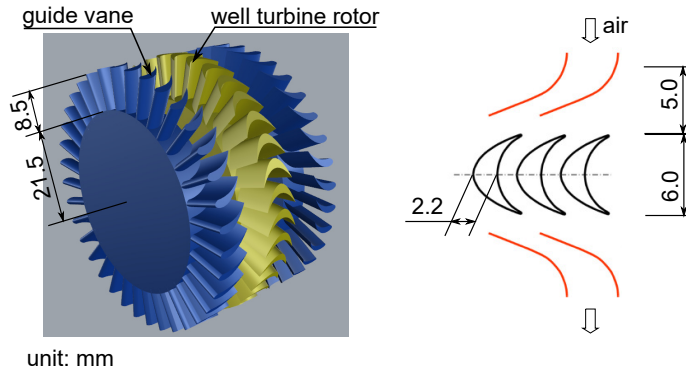


Fig. 5. Configuration of the impulse turbine.

The experimental model based on the aforementioned design is shown in Fig. 6. The mass of the whole system is 13.3 kg and its center of mass locates at (-1.1, 0, -41.2) mm. The longitudinal metacentric height of the floating wind turbine is 39.8 mm. In the following, the control system for motion reduction is presented.

D. Control System

Control system is designed for the valves of the WECs in order to help in reducing the motion of the platform. Owing to the nonlinear friction caused between the inner wall and the valve, the valve cannot move smoothly with small control demand. Therefore, the two-state Sky-Hook Control method [23] is applied to control the valves of the WECs based on the air pressure in the chamber and the gyro angular velocity of the platform. For the valve of the WEC at the upwind side of the semisubmersible, the control law is set by

$$\begin{cases} \dot{\theta} P_f > 0, & \text{valve=open,} \\ \dot{\theta} P_f \leq 0, & \text{valve=close,} \end{cases} \quad (1)$$

where $\dot{\theta}$ is the angular velocity of the platform in the pitch direction, and P_f is the gauge pressure in the front chamber. The valve is open to let the air flow in/out of the chamber to reduce the conjunction level between the water surface in the cylinder and the platform, while it is closed when the trapped air can provide a resistive force to the platform motion. To reduce the motion time, the open position of the valve is set at the position with an angle of 45 deg away from the closed position, as shown in Fig. 7. By the same consideration, the valves of the WECs in the downwind side of the platform are controlled according to

$$\begin{cases} \dot{\theta} P_r > 0, & \text{valve=close,} \\ \dot{\theta} P_r \leq 0, & \text{valve=open,} \end{cases} \quad (2)$$

where P_r is the corresponding gauge pressure in the downwind side chambers.

A computer-on-module (Intel® Edison Kit for Arduino) is applied for implementing the control algorithm. A set of three air pressure sensor (Adafruit BME280) is set at the top of the chambers of the WECs to measure the chamber pressure. Besides,

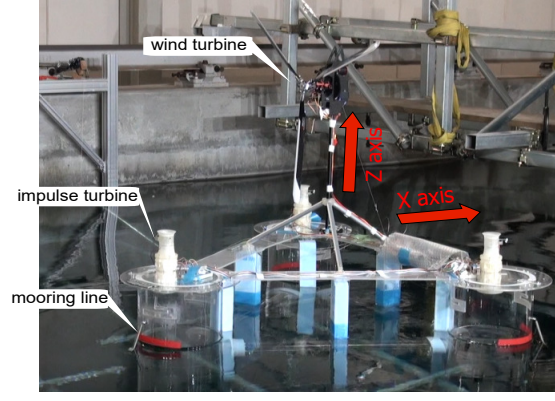


Fig. 6. Model for water tank test.

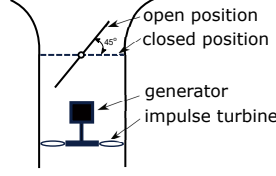


Fig. 7. Two state: open position and closed position of the valve for control.

a 9-axis motion tracking device (MPU 9150) mounted on the platform (on the front WEC chamber) is applied to measure the pitching angular velocity of the platform. The layout of the sensors is shown in Fig. 4(a). The pressure in the chambers of the WECs and the motion information of the platform are sent to the module by Inter-Integrated-Circuit (I2C) method. A first-order low-pass filter with the bandwidth of 2 Hz is applied to improve the signal-to-noise ratio (SNR) of the measured signals. The control period is set as 0.1 s considering the measurement delay of the sensors (including the signal transmission and signal processing) and the response of the digital servo motors.

III. RESULTS AND ANALYSIS

The model experiment is carried out in the water tank with length 65 m, width 5 m and depth 7 m at the Research Institute for Applied Mechanics (RIAM) of Kyushu University. A wind generator with 12 axial flow fans is installed on the tank, and it is able to generate a maximum wind speed of 5 m/s. A movable seafloor frame is installed in the water at the depth 0.9 m to set the mooring system. A high-speed digital video camera is applied to measure the motion of the floating wind turbine. In the experiment, wind and waves travel in the same direction along the positive x-axis. The full view of the experiment is shown in Fig. 8.

Free decay experiment is firstly carried out to measure the characteristics of the floating wind turbine with wave energy converters, and the results in time series are shown in Fig. 9. Owing to the symmetry of the platform, the free decay motion in surge, heave, and pitch are only investigated. The coupled natural frequencies of the motion are list in Table III.

Regular waves listed in Table IV are applied in the experiment. The wind speed is set as $V = 5$ m/s so that the wind turbine operates with tip-speed-ratio of $\lambda = 10$. In order to evaluate the wave energy conversion efficiency and the influence of the wind turbine on the energy conversion efficiency, the cases without wind turbine operation and with wind turbine operation are studied. Owing to the small scale of the model and the impulse turbines cannot rotate stably, the rotor of the impulse turbines are set to be halt and the primary energy conversion calculated from the air flowing in/out of the chamber is applied for evaluation. The flow rate of the air is estimated by

$$Q = C A_s \sqrt{2 \rho_a |P|}, \quad (3)$$

TABLE III
NATURAL PERIODS (COUPLED) OF THE FLOATING WIND TURBINE.

surge	heave	pitch
14.0 s	1.20 s	1.16 s

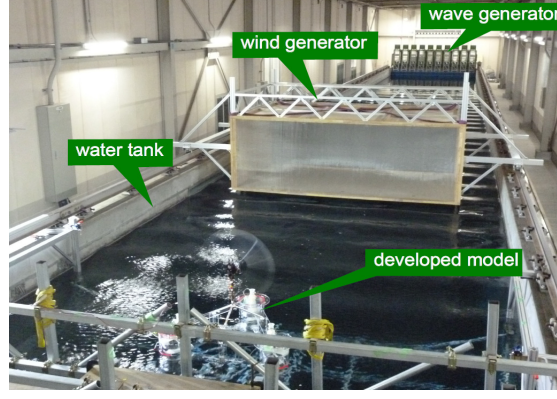


Fig. 8. Water tank and experiment in full view.

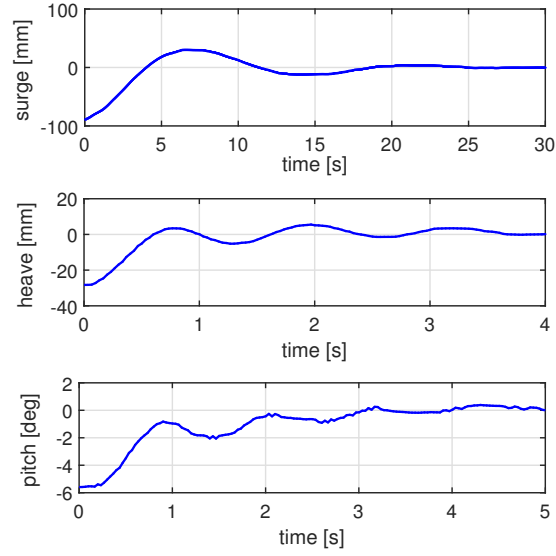


Fig. 9. Free decay motion of the floating wind turbine in surge (upper graph), heave (middle graph) and pitch (lower graph).

where C is the flow coefficient to be set as $C = 0.8$, A_s is the cross-section area of the impulse turbine, P is the gauge pressure of the chamber and ρ_a is the air density. The energy extracted from the wave by one WEC is calculated by

$$E_a = \int_0^T |P|Qdt, \quad (4)$$

TABLE IV
EXPERIMENTAL CONDITIONS

case	wave period [s]	wave height [cm]	Λ/D	Λ/L
1	0.90	1.25	5	1.55
2	1.13	2.00	8	2.44
3	1.39	2.00	12	3.70
4	1.60	2.67	16	4.91
5	1.79	2.50	20	6.14
6	2.00	3.13	25	7.66

Λ : wave length, D : diameter of hollow cylinder, L : length of the platform along wave direction.

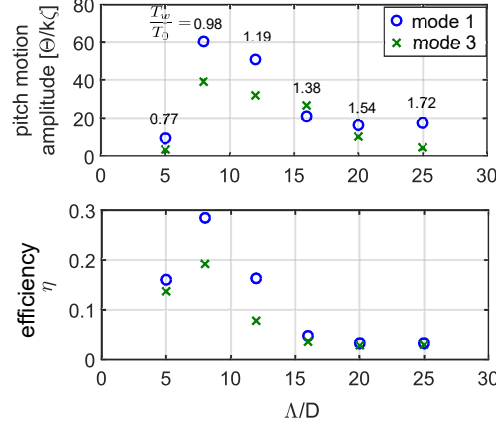


Fig. 10. Platform motion in pitch direction (normalized by $k\zeta$) and the primary wave energy conversion efficiency without wind turbine operation ('O' mark) and with wind turbine operation ('x' mark). The ratio of the wave periods to the natural period of the floating wind turbine in pitch direction ($\frac{T_w}{T_0}$) is also indicated for comparison.

where T is the time span of experiment. Therefore, the primary conversion efficiency is

$$\eta = \frac{E_{a_f} + E_{a_{r1}} + E_{a_{r2}}}{E_w}. \quad (5)$$

E_{a_f} and $E_{a_{rx}}$ ($x = 1, 2$) are the energy extracted by the front WEC and the rear WECs, respectively. E_w is the wave energy covered by the three cylinders calculated by

$$E_w = \left\{ \frac{\rho_w g^2 \zeta^2}{8\pi} T_w 3D \left(1 + \frac{2kh}{\sinh 2kh} \right) \tanh kh \right\} T, \quad (6)$$

where ρ_w is the water density, g the gravitational acceleration, ζ the wave amplitude, T_w the wave period, k the wavenumber, h the water depth and D the diameter of the hollow cylinders. In order to evaluate the wave energy conversion efficiency and the effectiveness of the valve control, the following four modes are studied:

- 1) Mode 1: regular waves without wind turbine operation, and without control (the valves are in open position);
- 2) Mode 2: regular waves without wind turbine operation, and with valve control of WECs;
- 3) Mode 3: regular waves with wind turbine operation, and without control (the valves are in open position);
- 4) Mode 4: regular waves with wind turbine operation, and with valve control of WECs.

The platform pitch motion and the primary wave energy conversion efficiency of Mode 1 and Mode 3 are shown in Fig. 10. The ratio of the wave periods to the natural frequency of the floating wind turbine in pitch direction is also indicated in the figure. Owing to the increase of air damping by the rotor of the wind turbine, the platform motion in pitch direction under wind turbine operation is smaller than the cases without wind turbine operation. The smaller platform motion in wind turbine operation cases also leads to the reduction of the wave power conversion efficiency. In addition, it is observed that the best wave energy conversion efficiency is obtained when the wave period is close to the natural period of the pitch motion of the floating platform.

In order to evaluate the effectiveness of the valve control, the platform pitch reduction ratio is defined as follows:

$$\text{pitch reduction ratio} = \frac{\Theta_{w/o \text{ ctrl}} - \Theta_{w/ \text{ ctrl}}}{\Theta_{w/o \text{ ctrl}}}, \quad (7)$$

where $\Theta_{w/o \text{ ctrl}}$ is the fundamental amplitude of platform pitch motion without control and $\Theta_{w/ \text{ ctrl}}$ is the fundamental amplitude with control. The results without wind turbine operation and with wind turbine operation are shown in Fig. 11 and Fig. 12, respectively. In the figures, the upper graphs show the platform pitch amplitude and the lower graphs show the pitch reduction ratio. It can be found that the platform pitch motion can be reduced in all of the cases when the controller of the valves is activated. However, the motion reduction ratio varies inversely with the motion amplitude of the platform. The reduction ratio is small when the motion amplitude is large (such as the results of case 2 and case 3), and large when the platform motion is small (such as the results of case 6). The capacity limitation of the WECs would be the primary reason for the phenomenon.

Owing to the fact that the valves of the WECs have only ON and OFF states, the performance of the WECs on wave power extraction would be remarkably deteriorated by the control. The primary wave energy conversion efficiency calculated by (5) is compared in Fig. 13. The results show that the efficiency decreases about 50% when control is activated. Therefore, a more sophisticated controller is required in the next phase of the study.

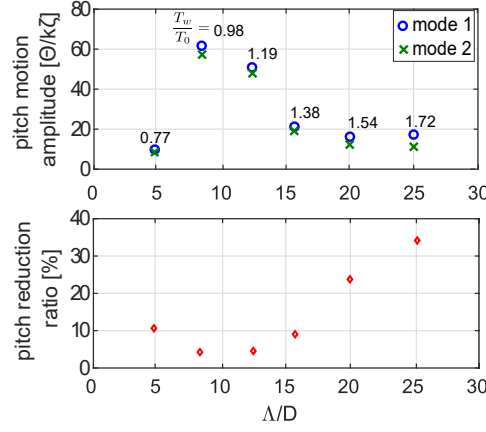


Fig. 11. The results of the floating platform pitch motion studies when the wind turbine is in parked condition. In the upper graph, the 'o'-mark shows the results without WECs valve control and the 'x'-mark shows the results with valve control of the WECs.

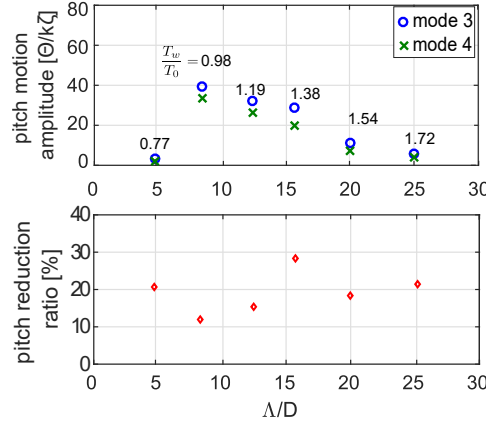


Fig. 12. The results of the floating platform pitch motion studies when the wind turbine is under operation. In the upper graph, the 'o'-mark shows the results without control and the 'x'-mark shows the results with valve control of the WECs.

IV. CONCLUSION AND FUTURE WORK

An experimental study on the integration of semisubmersible-type floating wind turbine and oscillating-water-column-type wave energy converters was performed. The wave energy converters were implemented not only to capture wave energy but also to reduce the pitch motion of the floating platform. The structure design and the controller for platform motion reduction were presented and the effectiveness of the controller was evaluated. Although the design of the integration system is still a big challenge, some important items can be concluded from this study:

- Design of wave energy converter should take into account the characteristics of the semisubmersible since the motion of the semisubmersible would significantly affect the wave energy conversion efficiency.
- A semisubmersible is usually designed with a small motion to prevent the wind turbine from becoming much more rigid in strength. However, the high efficiency of wave energy conversion requires a large motion of the platform. Instead of pursuing the wave energy conversion efficiency, an increase of damping effect or help in reducing the wave exciting force on semisubmersible would be the primary consideration of the integration.
- Cooperative control between the wave energy converters, the blade pitch and the rotor speed of the wind turbine should be considered together in order to reduce the platform motion.

In addition, two-state Sky-Hook control leads to large valves motion and sharp change of air pressure in chambers. Therefore, more sophisticated structure design and the robust controller is required for the practical situation.

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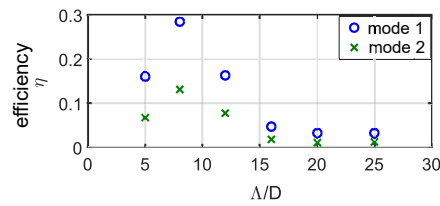


Fig. 13. The primary wave energy conversion efficiency without control of valves ('O'-mark) and with control of valves ('x'-mark) when the wind turbine is in parked condition.

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