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Modelling of a Floating-Type Hybrid Wind-Wave System with Oscillating Water Column Wave Energy Converters: A Study Towards Floater Motion Reduction

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Abstract. The integration of floating offshore wind turbines with wave energy converters is regarded as a promising solution for offshore renewable energy development. Given the early stage of wave energy conversion technologies and the substantial influence of control methods on overall system dynamics, a faithful aero-hydro-thermo-elastic-servo-mooring coupled model, along with an engineering environment offering high flexibility for control implementations, is essential. To address the requirement, a numerical modeling framework is developed in this study based on Simulink, known for its superiority in control design and implementation, and OpenFAST, which offers a reliable floating wind turbine model. The model incorporates the thermodynamics of the air in chambers, power take-off dynamics, and oscillating water column dynamics. Furthermore, bypass valves are utilized for the wave energy converters to adjust chamber pressure and reduce floater motion, with a control law proposed to regulate the valve opening ratio. A case study is conducted under harsh ocean conditions to validate the model. The numerical results not only demonstrate the feasibility of the model but also underscore the effectiveness of the control law in improving floater motion performance.

1. Introduction

Ocean renewable energy is increasingly playing a significant role in mitigating global climate change. With growing social acceptance, maturing technologies on risk and cost reduction, and the development of supply chains, floating offshore wind turbines (FOWTs) are regarded as a more feasible solution than bottom-fixed alternatives in deep-water areas. However, FOWTs still face a high levelized cost of energy (LCoE) attributed to the costly floating foundation and mooring system. To address this issue and lower the LCoE, numerous studies have been conducted to explore the versatile use of ocean space [1, 2, 3, 4, 5].

As waves are generated when wind moves over the ocean surface, regions with high wind power potential are usually rich in wave energy. Consequently, the combined utilization of offshore wind and wave energy has been proposed as one potential way of reducing cost. Typically, oscillating-water-column type (OWC-type) and point absorber type (PB-type) wave energy converters (WECs) are considered for hybrid integration due to their technological simplicity and ease of maintenance [7, 8, 9, 10]. While the integration of floating wind turbines and wave energy converters can enhance energy output per square meter through shared ocean space, their interaction may adversely impact floater motion. In [12, 13, 14], experiments have been conducted to investigate the effects of OWC-type WECs on floating wind turbines, and it was reported that the natural frequencies of the combined system, especially in heave, roll and pitch, may approach the wave frequencies. Hence, the hybrid system would become more susceptible to the wave-induced loads.

To address the issue, several studies have been performed focusing on floater motion reduction by the control of WECs. In [15], an optimal design method was developed to determine the mechanism connecting the floater and WECs. The mechanism is modeled as a linear spring-damper system, and the $\mathbf{H}_\infty$ loop-shaping method is applied to design the spring and damping coefficients. In [16, 20], WECs are considered as actuators for reducing floater motion, and model predictive control methods have been studied for the power take-off (PTO) control of WECs. The results demonstrate that floater motion can be effectively suppressed by a sophisticatedly designed control system. In [14] and [17], a two-state control method and several improved methods were studied for regulating the chamber pressure of OWCs for floater motion reduction. The results also demonstrated that floater motion could be improved through the control of WECs.

There are some other issues regarding the hydrodynamic model test experiments for hybrid energy systems. Although model test experiments are essential for prototype development, uncertainties arising from model setup and measurement, and the scale effects, may lead to erroneous results. For example, in model testing, structures subject to wave action are in general designed based on Froude similarity, which will cause the model-prototype disimilarity for chambers and air turbines owing to their different similarity criteria [21]. The spring-like effect of air compressibility in the chamber, which is known to significantly affect the power performance of the full-sized converter, would not be properly accounted for. Therefore, theoretical/numerical modeling should be the first step in the study of such kind of offshore energy converter.

In this study, a faithful aero-hydro-elastic-servo-mooring coupled model is developed taking into consideration the compressibility of the air in WECs. The model is established based on Simulink [18], known for its superiority in control design, and OpenFAST, which offers a reliable floating wind turbine model. The model and the engineering environment can introduce tremendous flexibility in control implementations for both wind turbine and WECs. In the numerical model, an OWC-type WEC is modelled through the combination of water column dynamics, thermodynamics of the air in the chamber, and air turbine dynamics. Moreover, a bypass valve is introduced for each WEC to prevent chamber from overpressure and assist in regulating floater motion. To demonstrate the feasibility of the established model, a semisubmersible FOWT combined with three OWC-type WECs is presented, and a control method for floater motion reduction is proposed as the study case in this work.

The remainder of this paper is organized as follows. Section 2 describes the proposed numerical model for a floating type FOWT-WEC system. A control law for the bypass valves on reducing floater motion is presented in Section 3. Section 4 studies a numerical example to illustrate the feasibility of the model and the effectiveness of the control law. The conclusions are given in Section 5.

2. Numerical model

In this section, the numerical model of a floating type hybrid wind-wave system with OWC-type WECs is explained. For the purpose of control of WECs to reduce floater motion, the system is expected to comprise one floating foundation and at least three radially distributed OWC-type WECs. The model is established within Simulink environment, and the dynamics of FOWT are analyzed by OpenFAST through its Simulink interface. The WECs are modelled by the combination of the water column dynamics, thermodynamics of the air in OWCs, air turbine (applied as PTO) dynamics, and by-pass valves control. The overview of the proposed model is shown in Fig. 1. The foundation position, velocity, and acceleration at each time step are extracted from OpenFAST for calculating WEC dynamics and controls. Simultaneously, the forces induced by WEC pressure variations and hydro interaction between OWCs and foundation are transferred to OpenFAST for calculating the structural dynamics of FOWT. Additionally, to avoid the synchronization issues with wave-induced loads between FOWT and WECs, the waves are generated in advance and the wave elevation at the origin of the inertial frame coordinate system in time series is provided for OpenFAST.

2.1. Floating Wind Turbine Modelling

As one of the state-of-the-art nonlinear aero-hydro-servo-elastic-mooring coupled simulators for FOWT developed by the National Renewable Energy Laboratory (NREL), OpenFAST is extensively used by academia and industry. It facilitates the analysis of various wind turbine configurations, including two- or three-blade horizontal-axis rotor, pitch or stall regulation, rigid or flexible structures (including blades, drivetrain, and tower), and upwind or downwind rotor. The wind turbine can be mounted on land or offshore on fixed-bottom or floating foundations. The OpenFAST modules that have been coupled to our numerical model are InflowWind for processing spatially and temporally varying wind-inflow, AeroDyn for calculating aerodynamic loads on both the blades and tower, HydroDyn for the hydrodynamic loads on floating foundation, mooring analysis modules (MAP++, MoorDyn, and FEAMooring) for the mooring force on floating foundation, ElastoDyn for the structural dynamics, and ServoDyn for the wind turbine control. It is noteworthy that the wind turbine control input can also be set to be from Simulink through the FAST S-Function block.

In ServoDyn module, there is a Structural Control submodule that provides an option for applying time-series load at a specified location. The force can be applied on the nacelle, tower, blade, or platform. In this study, this submodule is modified to enable the input of time-series force from Simulink. This modification allows the force generated by pressure variations in the chambers of WECs and the coupled hydro loads to be integrated into the OpenFAST routines for calculating the structural dynamics of FOWT.

Since there is hydro interaction between the OWCs and floating foundation, potential flow programs, such as WAMIT, can be applied for calculating the hydrodynamic coefficients. In potential flow program, the OWCs can be modeled as pressure surfaces or moonpools.

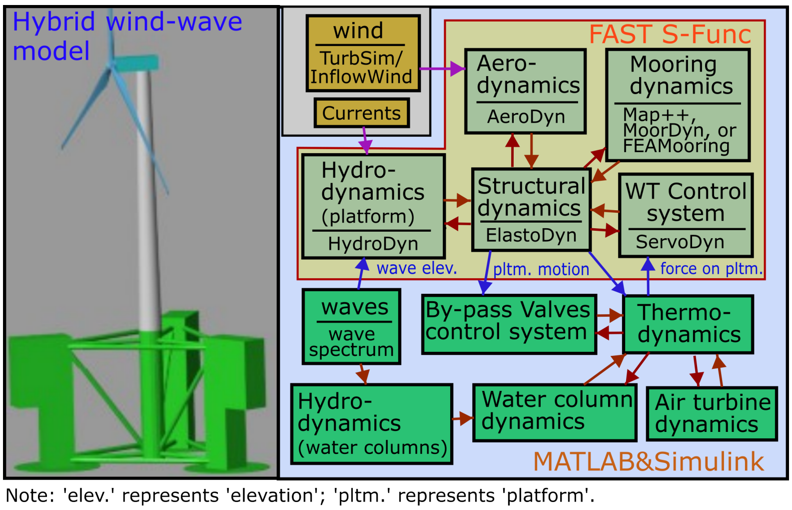

Figure 1: Framework of numerical model in Simulink.

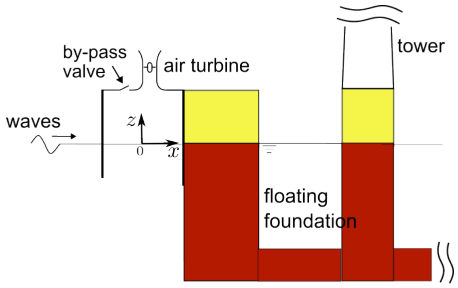

Figure 2: Cross-sectional view of OWC type WEC.

2.2. Wave Energy Converter Modelling

For the convenience of WEC modelling, the origin of coordinate system $(o - xyz)$ is defined on the centerline of its OWC, coinciding with the still water surface. The coordinate system allows us to disregard the roll and pitch motion of the water column during the modelling. The schematic view of a WEC installed on the external column of a semisubmersible wind turbine is illustrated in Fig. 2. Apart from the air turbine mounted on the top of the chamber, a bypass valve is employed to prevent the chamber from over- or under-pressure and to introduce additional flexibility for floater motion suppression.

2.2.1. Water Column Motion Suppose the dimension of the chamber is small compared to the wavelength of ocean waves, which is usually the case, the water column is treated as a rigid piston when studying its oscillating motion. Like common offshore structures, the hydrodynamics consist of the forces acting on the water column when it is restrained from oscillating (with incident waves and other hydrodynamic interactions related to wave effects) and the forces when the water column is forced to oscillate (without incident waves). The latter is typically characterized by added mass, damping and restoring terms. Referring to the study on the water motion in a moon pool in [27] and taking into account the pressure perturbation in the chamber, the oscillating motion of the water column is written as:

$$(\rho_w A(h_0 + h) + a_{z\infty})\, \ddot{h} + b_z \dot{h} + b_q \dot{h}|\dot{h}| + \rho_w g A h = F_{\text{pt}} + F_{\text{wav}_z} + F_{\text{ch}_p}, \tag{1}$$

where ρ_w is the water density, A the cross-sectional area of the OWC, h_0 the average draft, h the water elevation, $a_{z\infty}$ the added mass, b_z and b_q the linear and quadratic damping coefficients, respectively, F_{wav_z} the wave exciting force at the inlet of OWC, $F_{\text{ch}_p} = pA$ the force due to the pressure perturbation p in the chamber, F_{pt} the hydrodynamic coupled load induced by the motion of the floating foundation. The terms F_{wav_z} and F_{pt} can be calculated based on the pressure Response-Amplitude-Operator (RAO) at the OWC inlet, the coupled added mass, and potential damping coefficients.

2.2.2. Chamber Thermodynamics Suppose w and w_v are the mass flow rate through the air turbine and the by-pass valve, respectively, the variation of the air mass in the chamber can be expressed by

$$w + w_v = -\frac{dm}{dt} = -V\frac{d\rho}{dt} + \rho q, \tag{2}$$

where m, ρ, V are the air mass, density, and volume of the air in the chamber, respectively, q is the volume changing rate of the chamber that can be approximated as $q = A(\dot{h} - \dot{z})$ where z is the heave motion of the WEC frame. The volume V is represented as $V = V_0 + A(z - h)$ where V_0 is the chamber volume in the initial state.

Suppose that the air is ideal gas and changes of the air specific entropy and enthalpy is ignored, the thermodynamic state of the air in the chamber can be described by

$$\frac{d\rho}{dt} = \frac{1}{\gamma R_0 T}\frac{dp}{dt}, \tag{3}$$

where R_0 is the ideal gas constant, T the thermodynamic temperature, and γ the heat capacity ratio. The equation (2) can be rewritten as

$$\frac{V_0}{\gamma p_a}\frac{dp}{dt} + \frac{1}{\rho_a}(w + w_v) - q = 0, \tag{4}$$

by applying the ideal gas law $(p_a+p)/\rho = R_0 T$. The term p_a represents the atmosphere pressure.

According to [22], the air flow rate w and w_v can be expressed as functions of chamber pressure p, as described as follows:

$$w \approx k_t \frac{D_{\text{at}}}{\omega_r} p, \tag{5}$$

$$w_v \approx \text{sign}(p)\ \epsilon A_v C_f \sqrt{2\rho_a |p|}, \tag{6}$$

where ρ_a is the density of open air, D_{at} is the diameter of air turbine rotor, ω_r is the rotational speed (radians per unit time), k_t is constant for a given turbine geometry, A_v and ϵ $(0 \leq \epsilon \leq 1)$ are the flow area and opening ratio of the by-pass valve, respectively, and C_f is the flow coefficient.

2.2.3. Power Take-off Modeling Air turbines are typically applied as the power take-offs for OWC-type WECs. Suppose that permanent-magnet synchronous machines (PMSMs) are employed as the generators and the drivetrain flexibility is ignored, the rotor dynamics can be expressed by

$$J_r \dot{\omega}_r + B\omega_r = T_a - T_e, \tag{7}$$

where J_r is the moment of inertia of the rotational components including the air turbine rotor and the generator rotor, B is the damping coefficient, T_a and T_e are the aerodynamic torque and electromagnetic torque, respectively. Neglecting the mechanical friction losses and generator windage losses, the following speed control law which can achieve the optimal power conversion efficiency of air turbine is applied [24]:

$$T_e = \min\left(a\omega_r^{b-1}, \frac{P_{\text{rated}}}{\omega_r}\right), \tag{8}$$

where a and b are constant and P_{rated} is the rated power of air turbine. The aerodynamic torque on the air turbine can be computed by

$$T_a = \frac{P_t}{\omega_r} = \Pi(\Psi)\rho_a \omega_r^2 D_{\text{at}}^5, \tag{9}$$

where P_t is the power captured by the air turbine, Ψ and Π are dimensionless coefficients of pressure and power that are defined as

$$\Pi = \frac{P_t}{\rho_a \omega_r^3 D_{\text{at}}^5}, \qquad \Psi = \frac{p}{\rho_a \omega_r^2 D_{\text{at}}^2}. \tag{10}$$

In the model, the power coefficient $\Pi(\Psi)$ as a function of Ψ can be given as a look-up table. More details can be referred to the study in [22].

3. Control Law for Bypass Valves

In calm and moderate sea states, the floater motion is small. Both the wind turbine and air turbines are expected to operate at their optimal rotational speed to maintain optimal energy conversion efficiency. In rough sea states, the platform motion becomes large, leading to increased wind speed variation in the rotor plane. The situation can diminish wind power conversion performance and shorten the operational lifetime of the wind turbine. Therefore, WECs are preferred as damping system for the floater in such rough sea states. In the following, a hybrid system with three radially and symmetrically distributed WECs, which is applicable for a semisubmersible foundation with three external columns, is taken into account. In the cases that the number of the WECs are more than three, the control system can be treated as a redundantly actuated system and a proper mapping method can be applied to reduce the design flexibilities.

The following control law is proposed to help increase the damping ratio of floater motion:

$$\begin{cases} \epsilon_1 = \mathrm{sat}_{[0,\,1]}\left(\mathrm{sign}(p_1)k_c\frac{P_{\mathrm{rms}}}{\sqrt{|p_1|+\nu}}\dot{\theta}\right), \\ \epsilon_2 = \mathrm{sat}_{[0,\,1]}\left(\mathrm{sign}(p_2)k_c\frac{P_{\mathrm{rms}}}{\sqrt{|p_2|+\nu}}(-\frac{\dot{\theta}}{2}-\frac{\sqrt{3}\dot{\phi}}{2})\right), \\ \epsilon_3 = \mathrm{sat}_{[0,\,1]}\left(\mathrm{sign}(p_3)k_c\frac{P_{\mathrm{rms}}}{\sqrt{|p_3|+\nu}}(-\frac{\dot{\theta}}{2}+\frac{\sqrt{3}\dot{\phi}}{2})\right), \end{cases} \tag{11}$$

where $\dot{\phi}$ and $\dot{\theta}$ are the floater angular velocity in roll and pitch, respectively, $k_c > 0$ is a control parameter to be tuned, ν is a positive constant applied to prevent the opening of the valves from varying significantly at low chamber pressure, P_{rms} represents the root-mean-square (RMS) value of the chamber pressure, and $\mathrm{sat}_{[0,\,1]}(\cdot)$ is the saturation function, limiting the opening ratio of the valves to the range [0 1]. The subscript $_j$ (j=1, 2, 3) indicates the settings for the j-th WEC. The WECs are symmetrical about the X-axis of the inertial frame coordinate system. The first WEC is located in the opposite direction of the X-axis, while the other two WECs are numbered counter-clockwise in top view. Further details on numbering can be found in the numerical example in Section 4. The equation (11) is to linearize (6) for ease of parameter design.

Suppose that ν is small and the opening ratio of the bypass valves does not reach its bounds, the chamber thermodynamics can be expressed as a switched system. The following equation shows the thermodynamics of the air in the first WEC:

$$\begin{cases} \frac{V_0}{\gamma p_a}\frac{dp_1}{dt} + \frac{w_1}{\rho_a} + \sqrt{\frac{2}{\rho_a}}k_c A_v C_f P_{\mathrm{rms}}\dot{\theta} = q_1, & p_1\dot{\theta} > 0 \\ \frac{V_0}{\gamma p_a}\frac{dp_1}{dt} + \frac{w_1}{\rho_a} = q_1, & \text{others.} \end{cases} \tag{13}$$

The equations for other two WECs can be obtained in a similar form. Considering the control of WECs for reducing roll and pitch motion of the floater (ignoring the motion in other degree-of-freedoms), a linearized model to express the floater roll and pitch motion can be expressed by

$$(I_x + \boldsymbol{A}_{44})\ddot{\phi} + \boldsymbol{D}_{44}\dot{\phi} + \boldsymbol{C}_{44}\phi = F_{4_{\mathrm{dist}}} + (p_3 - p_2)\frac{\sqrt{3}L'}{2}A, \tag{14a}$$

$$(I_y + \boldsymbol{A}_{55})\ddot{\theta} + \boldsymbol{D}_{55}\dot{\theta} + \boldsymbol{C}_{55}\theta = F_{5_{\mathrm{dist}}} + \left(p_1 L' - (p_2 + p_3)\frac{L'}{2}\right)A, \tag{14b}$$

where I_x and I_y are the moment of inertia of the hybrid system in roll and pitch, respectively, $\boldsymbol{A}_{jj}$, $\boldsymbol{D}_{jj}$, and $\boldsymbol{C}_{jj}$ (j = 4, 5) are the jj-entry of the matrices of the added moment of inertia

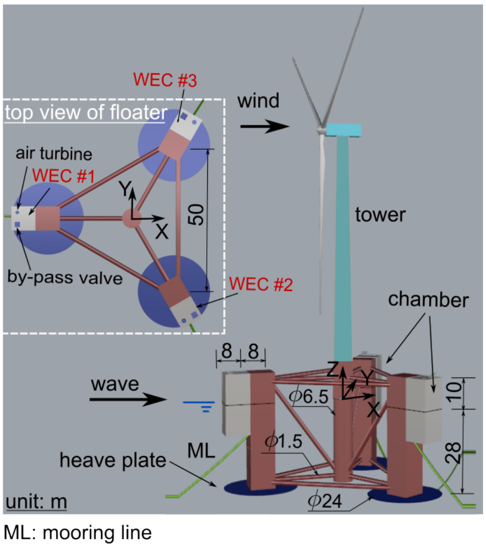

Figure 3: Schematics of the hybrid wind-wave system.

Table 1: Properties of the hybrid system

(a) Properties of the semisubmersible

Property	Value
Mass (with ballast water) (kg)	6,245,126
Center of mass (m)	[0 0 -20.44]
Draft (m)	28
Offset column side length (m)	8
Center column diameter (m)	6.5
Displacement (m^3)	6,859
Center of Buoyancy (m)	[0 0 -14.83]

(b) Properties of WEC

Property	Value
Mass (kg)	53,340
Center of mass (m)	[0 0 0.28]
Center of Buoyancy (m)	[0 0 -5.0]
Draft (m)	10.0
Volume of chamber (m^3)	640
Air turbine diameter (m)	2.30
By-pass valve area (m^2)	1.13

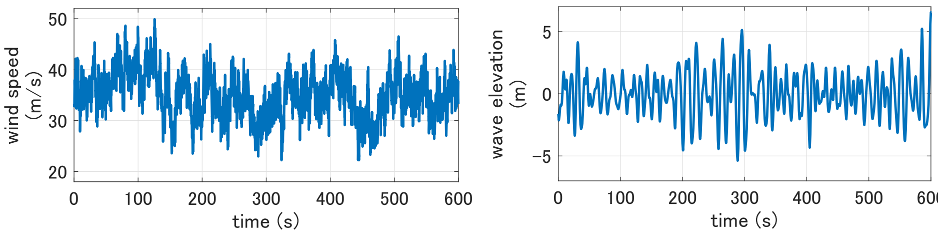

Figure 4: Time-series wind speed and waves for numerical study.

$\boldsymbol{A}$, damping coefficient $\boldsymbol{D}$, and restoring coefficient $\boldsymbol{C}$ of the floater, respectively, $F_{j_{\text{dist}}}$ the j-component of external disturbance. The terms $\boldsymbol{D}_{jj}$ and $\boldsymbol{C}_{jj}$ can be identified using OpenFAST model. The parameter k_c can be designed to improve the damping ratio of the floater motion via pole placement method.

4. Numerical Examples

The hybrid system with a semisubmersible type FOWT using NREL offshore 5MW baseline wind turbine [25] and three OWC-type WECs installed on the outboard of the semisubmersible

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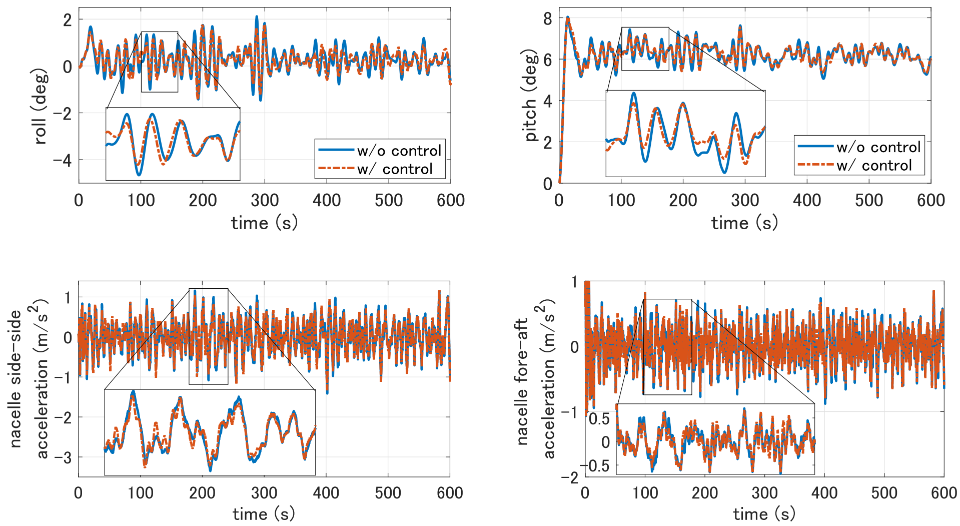
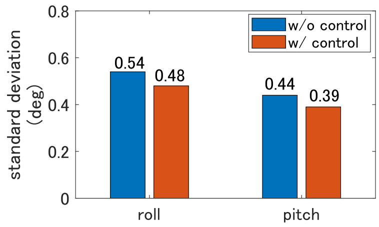
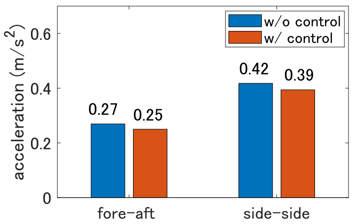


Figure 5: Floater motion in roll and pitch; Nacelle acceleration in side-to-side and fore-to-aft.



(a) Floater roll and pitch.



(b) Nacelle acceleration.

Figure 6: Standard deviation of the roll and pitch motion of the floater, and the nacelle acceleration during 100 s and 600 s.

is employed for this work. The overview of the system is shown in Fig. 3. The major properties of the FOWT and WECs are given in Table 1. It is noteworthy that the air turbines are referred to the one used in the Pico plant and the associated control system presented in [23] is implemented in this study.

In this numerical study, a harsh sea condition at Akita port, Japan, where several offshore wind farm projects are being planned, is considered. The conditions include a wind speed (10-minute averaged) at hub height of 36 m/s and a significant wave height of 8.0 m, with a peak wave period of 14 s. TurbSim [26] with IEC Kaimal turbulent model is applied to generate wind field, and the modified Pierson-Moskowitz (MPM) Spectrum is applied to calculate the wave profile. Both the winds and waves propagate along the positive X-axis direction. The time-series wind speed and wave elevation are shown in Fig. 4. Additionally, the parameters for the control of the by-pass valves are $P_{\text{rms}} = 5 \times 10^3\ P_a$ and $\nu = 3 \times 10^3$. The control gain k_c is set to $k_c = 40$ to improve the damping ratio of the floater in roll and pitch from 0.31 to 0.40. The rate command for the opening ratio ϵ is limited to 0.25.

Numerical simulations, both without and with by-pass valve control, are carried out using the proposed model. The floater motion in roll and pitch, the nacelle acceleration, and the states of WEC#1, are shown in Figs. 5∼ 7. From the simulations, it can be confirmed that the numerical model can be stably solved. By Fig. 5, it can be observed that the control of the by-pass valves

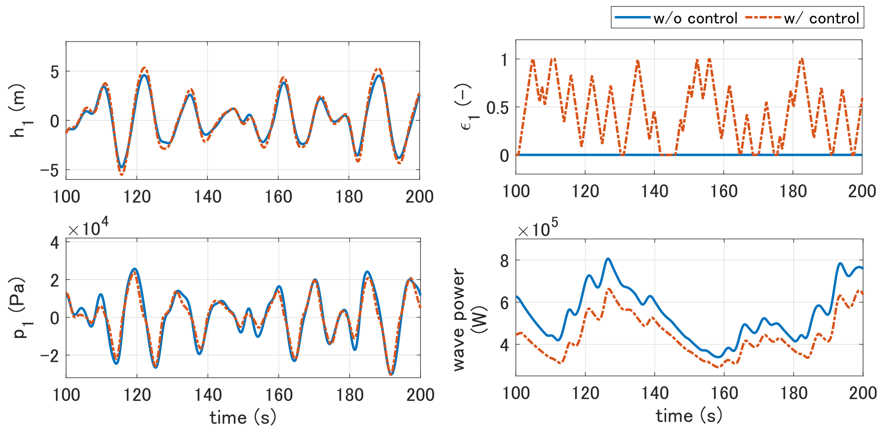


Figure 7: Time-series of (a) water elevation, (b) pressure, (c) opening of by-pass valve of WEC#1, and (d) wave power captured by WEC#1 during 100 s and 200 s.

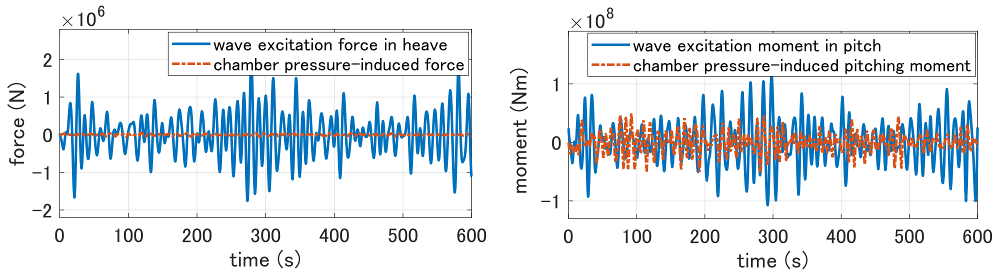


Figure 8: Time-series wave excitation force on floater and chamber pressure-induced loads.

can help improve the floater roll and pitch motion as well as reduce the mechanical loads on the wind turbine. The standard deviations of the roll and pitch motion, and the nacelle fore-aft and side-side acceleration are compared in Fig. 6. The standard deviation can be reduced by 11% for floater rotational motion and by 7% for nacelle acceleration with the control of WECs.

In Fig. 7, the elevation of free surface, the chamber pressure, the valve opening ratio, and the captured wave power are illustrated. It can be seen that the pressure in the chamber is slightly reduced and the motion amplitude of the water column is enlarged when the by-pass valve is controlled. This is trivial since air can flow in/out of the chambers through the by-pass valves. It is noteworthy that the valves opening rate is almost consistently saturated under the control. This saturation would largely limit the control performance. To address the issue, by-pass valves with larger flow area can be considered for the system. In addition, it can be observed that the efficiency of the wave power conversion is reduced under the by-pass valve control. The decrease is somewhat greater compared to the decrease of the chamber pressure. This would be cause by the fact that the air turbine is not operated at its optimal rotational speed when valve control is implemented. Further studies on air turbine control considering the coupled effects need to be performed in future work.

The chamber pressure-induced loads on the floating foundation, compared to the wave excitation loads, is shown in Fig. 8. It is obtained that although the total force on the floater is small, the moment is large since the WECs are installed away from the floater center and the arm length is large. The results can corroborate that the chamber pressure control is able to enhance floater stabilization.

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5. Conclusion

In this paper, a numerical model for a hybrid wind-wave energy system with OWC type WECs was proposed. The model, established within MATLAB&Simulink environment, enhances flexibilities in control design and implementations. With this model, both the floating wind turbine dynamics and the WEC dynamics can be predicted. Furthermore, a control system utilizing the WECs as actuators to stabilize floater motion was explored. Simulation results confirmed the effectiveness of the control system. From this study, it can be concluded that:

- Load transfer between OpenFAST and Simulink with the addition of WECs in Simulink is applicable. Numerical example results illustrate that the dynamics of floater motion can be stably analyzed.
- With the active control of WECs, the floater motion can be reduced to some extent even under harsh ocean conditions. The combination of FOWT and WECs presents a promising solution for offshore renewable energy, as power supply can be maintained by WECs even when wind speeds are above the wind turbine cut-out speed.

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