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Abstract

Integrating wave energy converters into an offshore wind turbine can potentially reduce the levelized cost of energy. The influence of the wave energy converters on the foundation, however, can worsen the wind turbine motion so that both the efficiency and the fatigue life of the wind turbine would be degraded. In this study, wave energy converters are devised as the suspension system of the floater, and the chamber pressures are controlled to help reduce the floater motion in waves. A numerical model taking account of aero-hydro-servo-mooring coupled dynamics is proposed and a numerical study shows the effectiveness of the control method.

Keywords : Hybrid wind-wave system, Oscillating-water-column wave energy converter, Motion reduction

1. Introduction

Ocean renewable energy is starting to play an increasing and significant role in mitigating global climate change. With increasing social acceptance and maturing technologies on reducing risk and cost, floating offshore winds are attracting a great deal of attention since the turbines can be installed in waters deeper than 60 meters and the accessibility to superior wind resources becomes available.

As waves are generated when wind moves over the ocean surface, areas with high potential of wind power are usually also rich in wave energy. Therefore, hybrid wind-wave systems have attracted the attention of academic communities and industry (Ragab *et al.*, 2021). Thanks to the technological simplicity and low maintenance costs, oscillating-water-column (OWC) wave energy converters (WECs) and oscillating-body WECs are the two types of WECs that usually applied for the integration. In (Sarmiento *et al.*, 2019, Zhu *et al.*, 2020), model tests were performed to investigate the effects of WECs on floating wind turbine, and it is reported that the natural frequencies of the combined system vary largely and depend on the openness of the chambers. Therefore, there are challenges to design hybrid wind-wave energy systems to avoid the interaction between the wind and wave energy harnessing.

In this study, a hybrid wind-wave system in which the OWC-type WECs are primarily devised as the suspension system of the floater is studied. The pressure in the chambers is regulated by controlling the air turbine rotational speeds and a by-pass vent valve of chamber. Therefore, the floater damping is expected to be increased. Concretely, a numerical WEC model which can simultaneously model the water column motion and chamber pressure variation is proposed. Then, a control method to regulate the air pressure in the chamber is studied.

2. Prototype and Experimental System

The prototype of the hybrid wind-wave energy system consists of: (a) a semisubmersible with one central column and three offset columns, (b) the NREL 5~MW wind turbine mounted on the central column, (c) a mooring system to secure the semisubmersible, and (d) three OWC-type WECs installed on the outboard of the offset columns, as shown in Fig. 1. Three offset columns are designed as quadrangular type prisms to facilitate the installation of WECs. Two sets of pontoons are employed to connect the columns. In addition, heave plates are installed at the bottom of the three offset

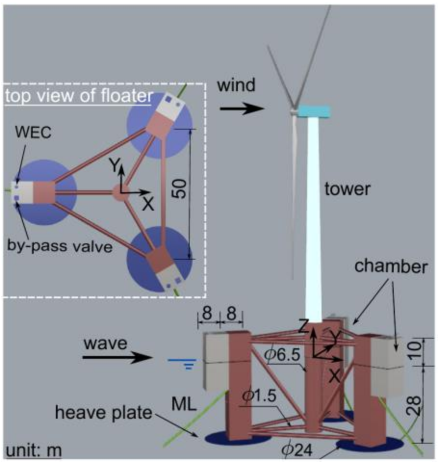


Fig. 1 Hybrid wind-wave prototype.

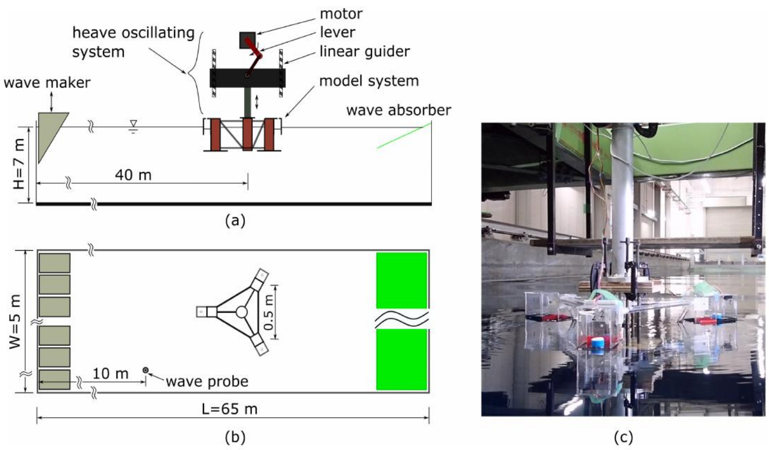


Fig. 2 Experimental system. (a) side view, (b) top view, and (c) model.

columns to increase the radiation-induced hydrodynamics. Three Wells turbines with a diameter of 2.3 m (rated power: 525 kW) are considered as the PTO of the WECs. In order to prevent the air turbine from overload and to secure the chambers from overpressure, each chamber is equipped with a by-pass valve. It is noteworthy that the WECs are designed to be neutral so that their installation and removal, i.e., during maintenance, would not affect the operation of the wind turbine.

A model (without wind turbine and Wells turbines) of 1:100 scale (based on the Froude scaling law) is developed to study the water columns behavior, and the overview of the experimental system is shown in Fig. 2. The platform is attached to a heave oscillating system so that it can be moved in heave direction with specified motion periods and amplitudes. The heave oscillating system can be manually rotated (in yaw) so that the experimental system under different angles of incident wave can be studied.

3. Modelling of Wave Energy Converter

The water column of a WEC is regarded as a rigid piston when studying its heave motion. Based on this consideration and taking account of the pressure perturbation in the chamber, the heave motion of the water column can be written as (Aalbers, 1984):

$$(\rho_w A(h_0 + h) + a_h)\ddot{h} + b_h\dot{h} + b_q\dot{h}|\dot{h}| + \rho g A h = F_{\mathrm{pt}_z} + F_{\mathrm{wav}_z} + F_{\mathrm{ch}_p}, \tag{1}$$

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_h the added mass, b_h and b_q the linear and quadratic damping coefficients, respectively, F_{wav_z} the wave exciting force at the inlet of OWC, $F_{\mathrm{ch}_p} = pA$ the force due to the pressure perturbation in the chamber, F_{pt_z} the hydrodynamic interaction induced by the heave motion of the platform.

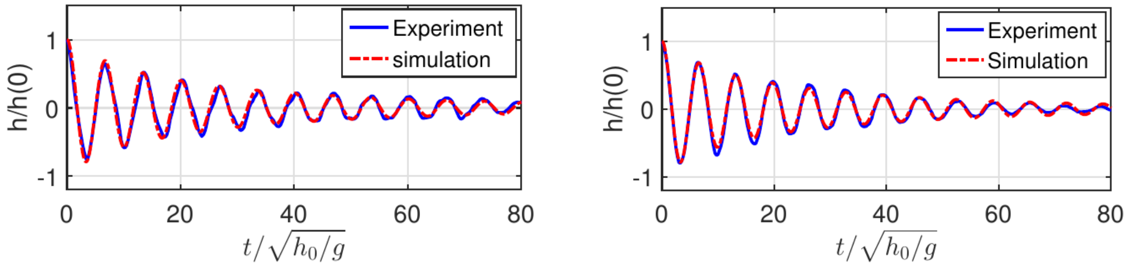
Wave excitation force F_{wav_z} and the hydrodynamic interaction load F_{pt_z} can be computed by

$$F_{\mathrm{wav}_z} = \sum_{j=1}^{N} |\Gamma_z(\omega_j)| \sqrt{2\boldsymbol{S}(\omega_j)\Delta\omega} \cdot \cos(\omega_j t + \angle\Gamma_z(\omega_j) + \epsilon_j), \tag{2}$$

$$F_{\mathrm{pt}_z} = -a_{z_\infty}\ddot{z} - \int_0^t K_z(t-\tau)\dot{z}(\tau)d\tau, \tag{3}$$

where $|\Gamma_z|$ and $\angle\Gamma_z$ are the amplitude and phase of the force response amplitude operators (force RAO) on water column, respectively, $\boldsymbol{S}(\omega)$ the wave spectrum, ω the wave frequency, ϵ the random phase angles, $\Delta\omega$ the constant difference between the successive frequencies, N the number of frequencies applied for dividing the wave spectrum for numerical computation, z the heave motion of the platform, a_{z_∞} the coupled infinite-frequency added mass, and $K_z(t)$ the corresponding retardation function.

The thermodynamic model in the chambers considering the air compressibility and the model for the Wells air turbines



(a) Draft $h_0 = 0.1$ m. (b) Draft $h_0 = 0.15$ m.

Fig. 3 Motion of water column in decay tests.

are developed according to the studies in (Falcao, 1999):

$$w + w_v = -\frac{dm}{dt} = -V\frac{d\rho}{dt} + \rho q, \tag{4}$$

where w and w_v are the mass flow rate through the air turbine and the by-pass vent, respectively, q the volume changing rate of the chamber, V the chamber volume, and ρ the air density. The terms in (4) can be expressed by

$$\frac{d\rho}{dt} = \frac{1}{\gamma R_0 T}\frac{dp}{dt},\ w = k_t \frac{D}{\omega_r} p,\ w_v = \mathrm{sign}(p)\,\epsilon\, A_v C_f \sqrt{2\rho|p|},\ q = A(\dot{h} - \dot{z}),$$

where p is the chamber pressure, R_0 the ideal gas constant, γ the heat capacity ratio, D the diameter of air turbine rotor, k_t a constant for a given turbine geometry, A_v the area of the by-pass vent, ϵ the opening ratio of the vent, C_f the flow coefficient, and ω_r the rotor rotational speed. The term $\mathrm{sign}(\cdot)$ is the sign function.

The parameters in (1) are identified by water column free-decay experiment, and the normalized results are $a_h^* = 0.196$, $b_h^* = 0.042$, and $b_q^* = 1.105$. The comparison between the experiment and the model under $h_0 = 0.1$ m and $h_0 = 0.15$ m is shown in Fig. 3.

4. Modeling of Floating Wind Turbine

Suppose that the floating wind turbine is rigid, and the motion is small, the motion equation can be expressed as (Fossen, 2011)

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{v}, \tag{5}$$

$$\left(\mathbf{M_{RB}} + \mathbf{A}_\infty\right)\dot{\boldsymbol{v}} + \left(\mathbf{C_{RB}}(\boldsymbol{v}) + \mathbf{C_A}(\boldsymbol{v})\right)\boldsymbol{v} + \int_0^t \mathbf{K}(t-\tau)\boldsymbol{v}(\tau)d\tau + \mathbf{D}\boldsymbol{v} + \mathbf{D_q}\boldsymbol{v}|\boldsymbol{v}| + \boldsymbol{g}(\eta) = \boldsymbol{\tau_m} + \boldsymbol{\tau_w} + \boldsymbol{\tau_a} + \boldsymbol{\tau_p} \tag{6}$$

where $\boldsymbol{v} \in R^6$ is the velocity vector expressed in the body-fixed coordinate frame, $\boldsymbol{\eta} \in R^3 \times S^3$ the position and orientation vector expressed in inertial reference frame, $\mathbf{J}$ the frame transformation matrix, $\mathbf{M_{RB}}$ the rigid-body inertia matrix, $\mathbf{C_{RB}}$ and $\mathbf{C_A}$ the Coriolis-Centripetal matrices due to the inertia and the added mass, respectively, $\mathbf{A}_\infty$ the infinite-frequency added mass matrix, the convolution term $\int_0^t \mathbf{K}(t-\tau)\boldsymbol{v}(\tau)d$ the *fluid-memory model* that $\mathbf{K}(t)$ represents the retardation function, $\mathbf{D}\boldsymbol{v}$ and $\mathbf{D_q}\boldsymbol{v}|\boldsymbol{v}|$ the damping forces, $\boldsymbol{g}(\eta)$ the hydrostatic restoring force, $\boldsymbol{\tau_m}$ the mooring force, $\boldsymbol{\tau_w}$ the wave excitation loads, $\boldsymbol{\tau_a}$ the aerodynamics on the wind turbine, and $\boldsymbol{\tau_p}$ the loads induced by the pressure variation of the chambers.

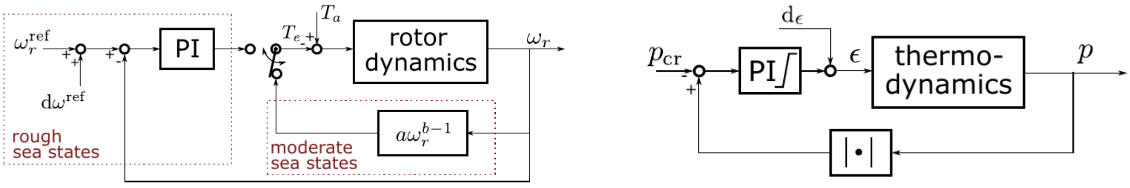
In this study, the mooring force is calculated based on the static mooring model MAP++ (NREL, 2015). The wave excitation force $\boldsymbol{\tau_w}$ is computed based on force response amplitude operators (force RAO) by

$$\boldsymbol{\tau_w} = \sum_{j=1}^{N} \left|\boldsymbol{\Gamma}(\omega_j)\right| \sqrt{2\boldsymbol{S}(\omega_j)\,\Delta\,\omega} \cdot \cos\left(\omega_j t - \kappa_j(x\cos\beta + y\sin\beta) + \angle\boldsymbol{\Gamma}(\omega_j) + \epsilon_j\right). \tag{6}$$

where $|\boldsymbol{\Gamma}|$ and $\angle\boldsymbol{\Gamma}$ are the amplitude and phase of the force-RAO, respectively. Potential flow program can be applied for solving the hydrodynamic coefficients. The aerodynamics $\boldsymbol{\tau_a}$ is calculated by $\boldsymbol{\tau_a} = F_t H_b$ in which H_b is the hub height and F_t is the thrust:

$$F_t = \frac{1}{2}\rho\pi R^2 C_t(\lambda,\beta)\left(v_{w_x} - v_{h_x}\right)^2. \tag{7}$$

The conventional control schemes for variable-speed pitch-regulated wind turbine are employed to regulate the rotational speed and the collective pitch.



(a) Air turbine rotational speed control.

(b) By-pass vent valve open ratio control.

Fig. 4 Controllers for air turbine and by-pass vent.

5. Floater Motion Reduction Control

In calm and moderate sea states, the motion of the platform are small. Both the wind turbine and the air turbines are expected to operate at their optimal rotational speed to maintain the optimal energy conversion efficiency. In rough sea states, the platform motion become large, WECs are preferred to work as a controlled suspension system, say, the rotational speed of the air turbines is controlled to adjust the rate of the air flowing in/out of the chambers to adjust the chamber air pressures. The speed of the air turbines can be tuned by considering the trade-off between the wave energy conversion efficiency and the air flow rate. The vent valves are expected to regulate the air pressure to help on stabilizing the platform motion and to secure the chamber against overpressure. Anti-windup Proportional-Integral (PI) controllers are designed to regulate the rotational speed of the air turbine and the stroke of the vent valves by considering both the robustness and the response performance. The block diagrams of the control system for air turbine and by-pass vent are shown in Fig. 4.

6. Results

A harsh environmental condition with a wind speed of 20 m/s, wave significant height of 8.5 m is studied. The wind and waves are set to travel from the same direction. The floater pitch motion without motion reduction control and with motion reduction control is compared in Fig. 5. It is observed that the motion can be improved to some extent with the help the control.

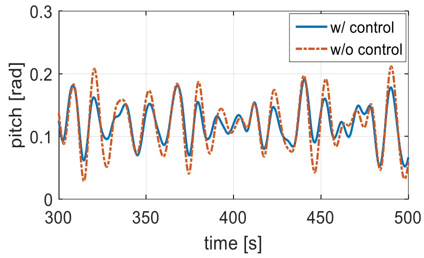


Fig. 5 Comparison of floater pitch motion.

7. Conclusion

A study on hybrid wind-wave energy system including the design and numerical model was performed. A 1:100 scale model was developed, and water tank tests were carried out to identify the numerical model. The controller for WECs on reducing the floater motion was devised and the effectiveness was illustrated under a harsh environmental condition. Detailed studies considering various ocean conditions will be performed in future.

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