A Control Approach on Hybrid Floating Offshore Wind Turbines for Platform and Generated Power Oscillations Reduction at Below-rated Wind Speed

Payam Aboutalebi, Fares M'zoughi, Irfan Ahmad, Aitor J. Garrido and Izaskun Garrido

Abstract This paper presents the use of four oscillating water columns integrated into the platform of a barge-type floating offshore wind turbine. A control strategy has been proposed to decrease the system's oscillations and generated power fluctuations by adequately controlling the opening of the airflow valves. The switching time for below-rated wind speed has been calculated using the platform's pitch response amplitude operator. The blades' pitch has been adjusted to harness the maximum energy at below-rated wind speed and a constant torque method has been employed for the generator. A comparative study has been carried out between uncontrolled traditional barge-type and controlled oscillating water columns-based barge floating offshore wind turbine to determine the performance of the control technique. The findings demonstrate that the suggested control approach can effectively decrease both the oscillations in the system's states and the fluctuations in the generated power. The results show a 26.6% fluctuation reduction in the generated power for the controlled OWCs-based barge platform, compared with the standard barge platform.

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1 Introduction

Although the use of conventional fossil fuels such as oil, gas, and coal may promote economic growth, excessive use of nonrenewable sources emits a large amount of carbon dioxide into the atmosphere, likely to result in global warming. Policy initiatives have resulted in the development of renewable energies in recent years, giving rise in the harness of wind and wave energies. As a result, the configuration of floating offshore wind turbines (FOWT) has been growing substantially throughout the world in order to achieve a low-carbon society and improve the utilization of sea spaces [6].

The oscillations caused by waves and winds on the FOWT states are a challenge in the offshore wind field. These oscillations may cause mechanical problems by putting undesired loads on the blades, rotor shaft, yaw bearing, and tower, decreasing aerodynamic performance, tower fatigue life and generated power [4]. Oscillating Water Columns (OWC), one of the most studied Wave Energy Converters (WEC), could be incorporated inside the floating platform to decrease the vibrations in the system cite.

Researchers have proposed hybrid FOWT-WECs to harvest energy from both wave and wind. For example, a structure of three rotating-flaps WECs attached on a semisubmersible FOWT [7], a hybrid tension leg platform-type FOWT and three point-absorber WECs [3], and a hybrid model of a spar-type FOWT and a torus-shaped point-absorber [8]. Several documents have described how to modify the structure of FOWTs to prevent vibrations in the system. M. Palraj et al. introduced in [10] the use of a gyro-stabilizer installed in the barge of a FOWT to control the vibrations. J. Yang et al. in [12] installed a tuned mass damper inside the barge platform to decrease the vibrations.

On the other hand, J. Jonkman constructed a square-shaped moonpool placed in the center of the barge, designed to allow the integration of an OWC inside the wind turbine's tower [5]. P. Aboutalebi et al. [1] evaluated the dynamics of hybrid barge-type FOWT-OWCs in different sea states. F. M'zoughi et al. in [9] designed a linear model of combined two OWCs-based FOWTs, controlled by a PID controller for the FOWT stabilisation. P. Aboutalebi et al. in [2] developed a switching control strategy based on Response Amplitude Operators (RAO) to improve the overall performance of system in the absence of wind. This paper describes a control strategy based on RAOs that takes into account different wave periods as well as the wind at below-rated wind speed. In addition to designing a controller for OWCs, a second and third controllers for the blades' pitch and generator have been developed to maximize the energy harness at below-rated wind speed.

This paper is organized as follows: Section 2 describes the equations of motion for the system. Section 3 explains the problems and challenges due to the platform's oscillations. In Section 4, the control strategies have been examined under different sea states and below-rated wind speed. Finally, Section 5 presents the conclusions of this paper.

2 FOWT model

In this paper, the full nonlinear equations of motion for a 5-MW offshore wind turbine mounted on a barge have been studied. Four OWCs have been integrated inside the barge platform, as shown in Fig. 1, in order to reduce the oscillations in the system's states and generated power.

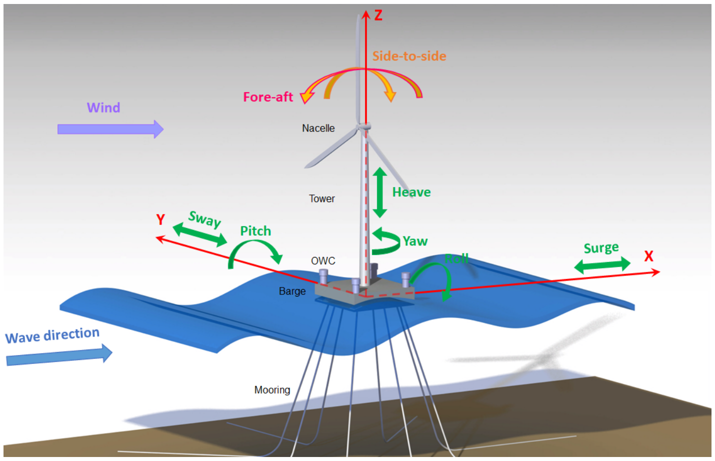

Fig. 1 Barge-type FOWT equipped with four OWCs.

The full nonlinear equations of motion in time domain for the coupled floating wind turbine, support platform system and OWCs may be described as follows:

$$M_{ij}(q,u,t)\ddot{x}_j = f_i(q,\dot{q},u,t) \tag{1}$$

where M_{ij} (kg) expresses the inertia mass elements and x defines the states of the system. u describes the control inputs. The external forces of aerodynamic loads on the blades and nacelle, hydrodynamic forces on the platform, elastic and servo forces and Power Take Off (PTO) have been described as f_i on the right hand-side of Eqn. 1.

The equation of motion in frequency-domain may be described as [1]:

$$I_{FOWT}(\omega)\ddot{q} + B_{FOWT}(\omega)\dot{q} + K_{FOWT}q = \mathbf{f}_{FOWT}(\omega) + \mathbf{f}_{PTO}(\omega) \tag{2}$$

where I_{FOWT}, B_{FOWT} and K_{FOWT} stand for the inertia elements, damping components and stiffness matrix, respectively. $\mathbf{f}_{FOWT}(\omega)$ expresses the hydrodynamic force, viscous drag and aerodynamic loads. $\mathbf{f}_{PTO}(\omega)$ denotes the load caused by the PTO equipment and ω denotes the wave frequency. The term q in Eqn. 2 is described as [11]:

$$q = \begin{bmatrix} surge & sway & heave & roll & pitch & yaw & fore\text{-}aft & side\text{-}to\text{-}side \end{bmatrix} \quad (3)$$

The inertia elements of FOWT is described by:

$$I_{FOWT}(\omega) = A_{Hydro}(\omega) + M_{Platform} + M_{Tower} \quad (4)$$

where $M_{Platform}$ (kg) is platform mass and M_{Tower} (kg)is tower mass and A_{Hydro} expresses the platform's added mass, may be calculated by the panel radiation program namely WAMIT.

The stiffness matrix K_{FOWT} may be defined as follows:

$$K_{FOWT} = K_{Hydro} + K_{Mooring} + K_{Tower} \quad (5)$$

where K_{Hydro}, $K_{Mooring}$ and C_{Tower} describe the platform' hydrostatic restoring matrix, the mooring lines spring stiffness elements and the tower stiffness coefficients, respectively.

The damping coefficients can be described as:

$$B_{FOWT}(\omega) = B_{Hydro}(\omega) + B_{Tower} + B_{viscous} + B_{chamber} \quad (6)$$

where B_{Hydro} is platform's damping elements, B_{Tower} is damping matrix of the flexible tower and $B_{viscous}$ is the viscous drag. $B_{chamber}$ describes the the PTO's effect.

Thus, the equation of motion in frequency domain for the FOWT is obtained as follows, as described in Equation 2:

$$I_{FOWT}(\omega)\,\ddot{\hat{q}} + (B_{FOWT}(\omega) + B_{PTO}(\omega))\,\dot{\hat{q}} + (K_{FOWT} + K_{PTO})\hat{q} = \mathbf{f}_{FOWT}(\omega) \quad (7)$$

In order to define the geometry of the platform, MultiSurf has been used. Fig. 2a, 2b and 2c demonstrate three platforms including standard barge platform, closed OWCs-based barge platform and open OWCs-based barge platform, respectively.

3 Problem Statement

The FOWTs' Oscillations are undesirable because they have a negative impact on the system, consisting of stress on the system's structural components, a significant reduction in wave and wind energy harvest, and fluctuations in the generated power. Increased maintenance costs could also decrease the system efficiency. To tackle the problem, a switching control strategy has been proposed based on the RAOs. In this section, first the RAOs are evaluated, then the control strategy is described.

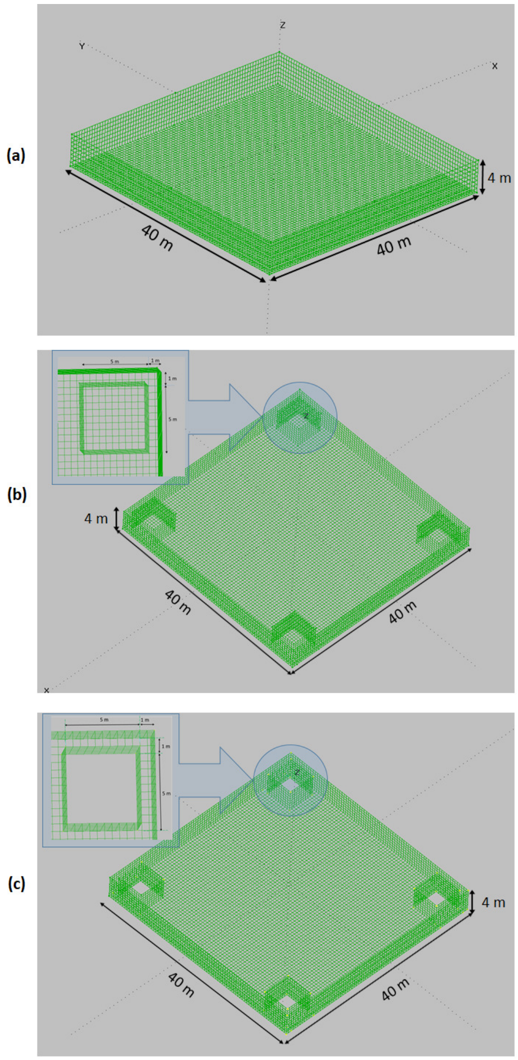

Fig. 2 Platforms' design for (**a**) Standard barge platform. (**b**) closed OWCs-based barge platform. (**c**) open OWCs-based barge platform.

3.1 RAOs evaluation

It is essential to use RAOs in order to assess the movement of FOWTs in different sea conditions. The procedure for plotting the RAOs for different states of the input-output system is explained in this section. Using MultiSurf, WAMIT, FAST and MATLAB and the following equation the RAOs can be achieved:

$$RAO = \frac{S_{xy}(\omega)}{S_{xx}(\omega)} \tag{8}$$

where $S_{xy}(\omega)$ and $S_{xx}(\omega)$ are the cross-spectral and auto-spectral densities of the wave elevation input $x(t)$ and the system's stats output $y(t)$, respectively.

The system states' RAOs with respect to the wave period are presented at below-rated wind speed of 8 m/s, showed in Fig. 3. Platform pitch and fore-aft states are significant because these states are the most altered modes by the wave and wind that are aligned with the surge mode. Oscillations occur in the platform pitch, showed in Fig. 3f for below-rated wind speed.

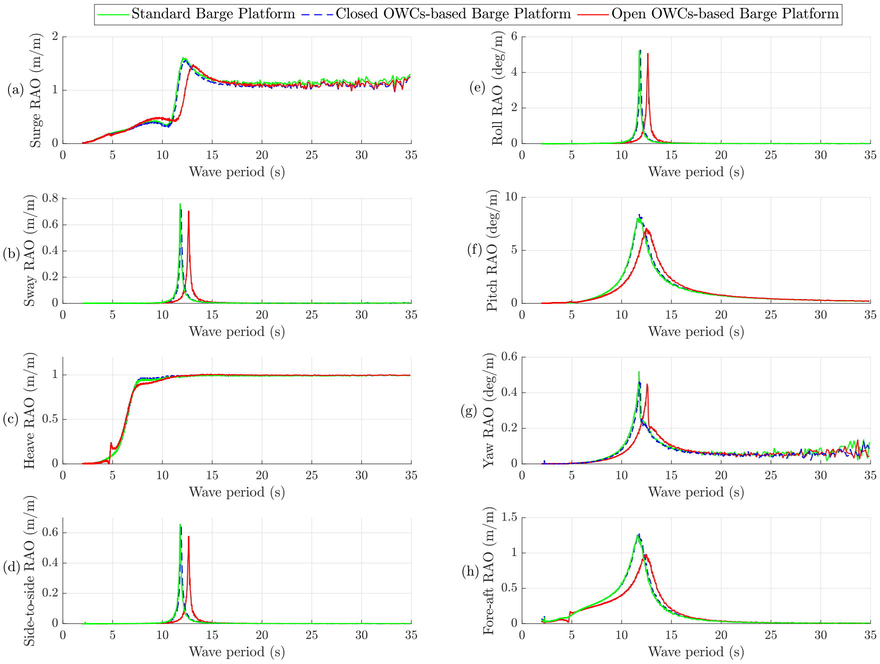

Fig. 3 RAOs at the below-rated wind speed of 8 m/s for (a) Surge. (b) Sway. (c) Heave. (d) Side-to-side. (e) Roll. (f) Pitch. (g) Yaw. (h) Fore-aft.

3.2 Control Statement

A control method is introduced to reduce the oscillations in the FOWT's states as represented in Fig. 4. The proposed control method is based on the analysis of the platform pitch RAOs, illustrated in Fig. 3f at below-rated wind speed. As it is seen in the figure, the platform pitch RAO for the open OWCs-based barge platform crosses the platform pitch RAO for the closed OWCs-based platform at a wave period called switching point. The switching point is the wave periods 12.37 s for the wind speed of 8 m/s. Therefore, the switching controller opens the valves for waves with the periods lower than the switching point and closes the valves for waves with higher periods than the switching point. The equation for the switching technique is defined as follows:

$$u(T_w) = \frac{e^{(T_w - T_{sp})}}{e^{(T_w - T_{sp})} + 1} \tag{9}$$

where $u(T_w)$ represents a sigmoid function of the closing and opening valves' control input. T_w and T_{sp} express the wave period measured by a sensor and the switching point from platform pitch RAO, respectively.

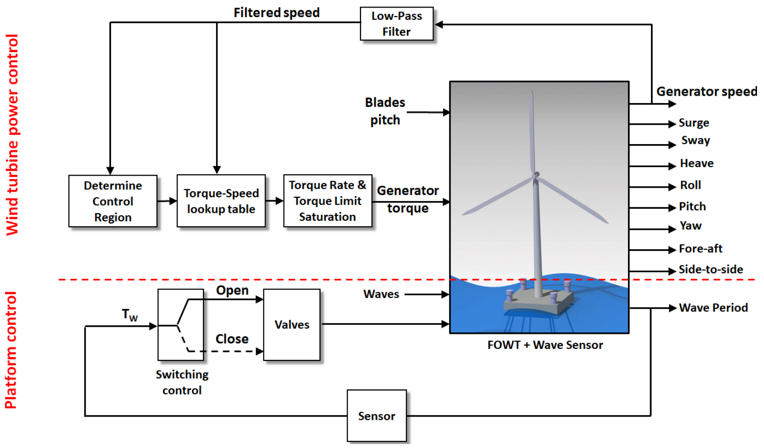

Fig. 4 Control scheme for the OWCs-based platform with wind turbine power control at below-rated wind speed.

In this article, blade-pitch angle is adjusted at zero to extracted the most energy from wind at below-rated wind speed. Also, variable-speed operation mode based on the generator torque manipulation have been employed in order to evaluate the performance of the switching control technique on the generator power output. The operation regions are divided into five modes including the regions 1, 1 $^1/_2$, 2, 2 $^1/_2$ and 3 (see Fig. 5). In region 2 (below-rated wind speed), the generator torque is proportional to the the filtered generator speed in order to keep an optimal tip-speed ratio. For more details of the variable-speed control of the generator, refer to [5].

4 Results

To show the performance of the controlled OWCs-based barge platform compared to the uncontrolled standard barge platform, a time-domain simulation has been

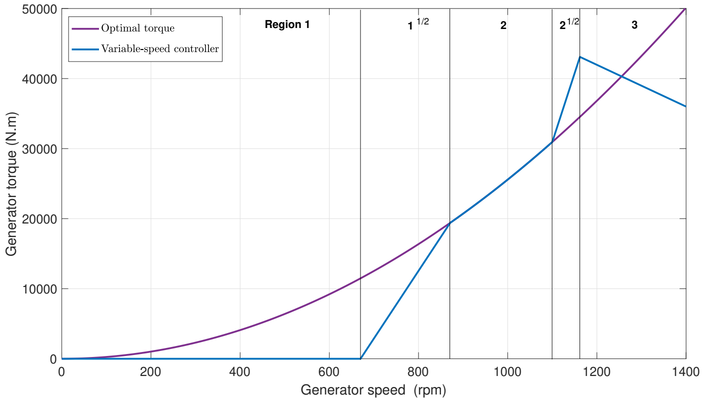

Fig. 5 Generator toque versus generator speed.

performed. The regular wave with an amplitude of 0.9 m has been considered, showed in Fig. 6a.

Based on the pitch RAO at the wind speed of 8 m/s, the switching controller acts to open the valves for the periods less than 12.37 s and to close the valves for the periods higher than 12.37 s. Here the OWCs’ valves transition from closing to opening at 600 s.

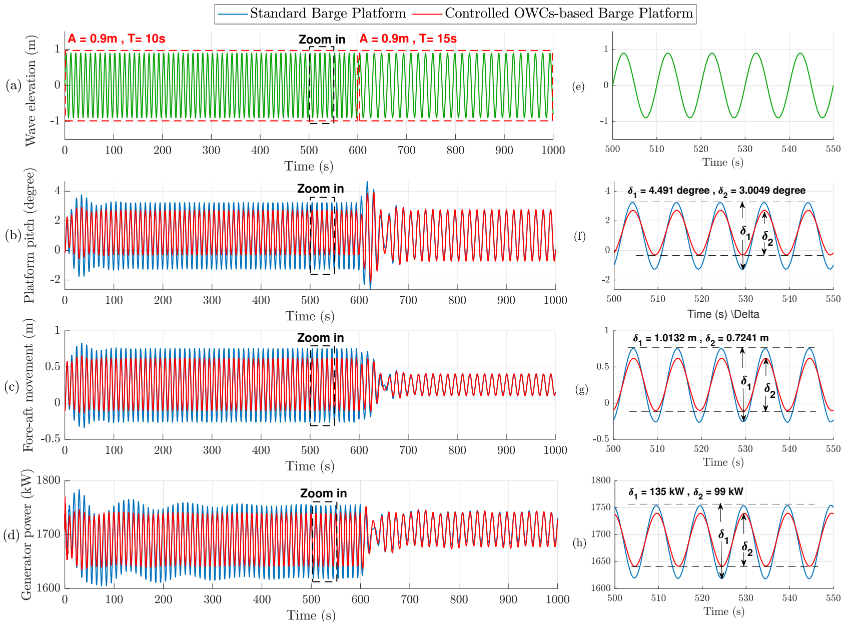

Fig. 6 First scenario at below-rated wind speed. (a) wave elevation. (b) platform pitch. (c) fore-aft movement. (d) generator power.

The standard barge platform and controlled OWCs-based barge platform are represented in blue and red respectively. As it can seen in Fig. 6b, the controlled OWCs-based barge platform pitches by 3.0049 degrees while the standard barge platform pitches by 4.491 degrees. This shows that the pitch oscillations in the controlled OWCs-based platform are drastically lower than the standard barge platform by 33% after transient time. Both controlled OWCs-based and uncontrolled standard barge platforms' pitch curves are almost identical with very slight difference after 600 s when the OWCs' controller manages to close the valves. Fore-aft motion, showed in Fig. 6c, shows the same behaviour as the platform pitch angles for both controlled OWCs-based and standard barge platforms.

Fig. 6d indicates the generator power controlled by variable speed method. It is observed from the figure that there is a relationship between the platform pitch and fore-aft oscillations with generator power fluctuations. Before 600 s, the generator power in controlled OWCs-based barge platform fluctuates for 99 kW whereas the generator power in the standard barge platform fluctuates for 135 kW. This shows a 26.6% fluctuation reduction in the controlled OWCs-based barge platform, compared with the standard barge platform.

5 Conclusions

A control method was introduced to increase the stability of the FOWT by deduction of the oscillations in the platform and tower modes. The system was evaluated in various sea states and below-rated wind speed. The transition between opening and closing valves has been conducted by analysing the platform pitch RAOs. The platform pitch RAO provides the data for analysing the behaviour of the FOWT. To capture the wind energy, the blades' pitch were adjusted to zero degrees at below-rated wind speed and a variable speed controller was designed for the generator.

The results showed that the proposed switching control technique in OWCs' valves was able to decrease the oscillations in the system effectively. The performance of the controlled OWCs-based barge platform in terms of oscillations reduction was better, overall in different environmental conditions, compared to uncontrolled standard barge platform. Moreover, the generator power fluctuations decreased efficiently.

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