Mitigating Undesirable Oscillatory Behavior in Barge-type Floating Offshore Wind Turbines through Oscillating Water Columns

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***Abstract*—This paper addresses the challenge of reducing undesired oscillations in barge-type floating wind turbines (FWTs) caused by wind and wave forces, which result in fluctuations in generator power and system oscillations. These oscillations can negatively impact the system's lifespan, power generation, maintenance costs, and component stress. To mitigate these issues, oscillating water columns (OWCs) are integrated within the FWT substructure. A control strategy is proposed for the OWCs based on response amplitude operators, aiming to minimize oscillations in a 5 MW wind turbine structure. A considered case study is conducted for above-rated wind speeds to evaluate the effectiveness of the controllers and to compare the performance of an uncontrolled FWT against a controlled FWT integrated with OWCs. The findings demonstrate the efficacy of the control strategy in pitch oscillations reducing for 29.9% and generated power fluctuations reducing for 23.03% and highlight the advantages of integrating OWCs in floating offshore wind turbines.**

I. Introduction

Aligned with the objectives of the European Green Deal, which strives to decrease greenhouse gas emissions by 55% by 2030 and elevate the proportion of renewable energy to constitute 40% of the overall EU energy consumption, the implementation of innovative technologies such as floating wind turbines can play a pivotal role [1]. These turbines offer a promising avenue for generating clean and sustainable energy. Additionally, improving energy efficiency by 36% in terms of final energy consumption and 39% in terms of primary energy consumption is essential in meeting the goals outlined in the European energy plan. By harnessing the power of offshore wind resources, floating wind turbines can contribute significantly to achieving these targets, providing a reliable and environmentally friendly solution for meeting Europe's energy needs while reducing dependence on fossil fuels.

The offshore wind sector has emerged as a pivotal contributor to the global transition towards sustainable and renewable energy sources. However, the unique challenges posed by the marine environment have prompted a deeper exploration of the stability and efficiency of FWTs. The intricate interplay of waves and winds can produce oscillations that have profound repercussions on the mechanical performance and energy generation of these systems. The resulting oscillatory motions can lead to structural tension on vital components such as blades, rotor shafts, yaw bearings, and tower. This not only diminishes aerodynamic performance but also curtails the overall fatigue life of these components, jeopardizing the long-term viability of offshore wind energy systems.

To surmount these challenges and optimize the performance of FWTs, innovative solutions are being explored to mitigate oscillations and enhance energy capture. One particularly promising avenue is the integration of OWCs within the FWT substructures. As a subset of Wave Energy Converters (WECs), OWCs present an opportunity to counteract the oscillations induced by waves and winds. By capitalizing into both wave and wind energy sources, hybrid systems can simultaneously stabilize FWTs and elevate the consistency and quality of energy transmitted into the grid. This integration, notably within barge-based FWTs, offers a pragmatic approach, streamlined integration, and the potential to harness wave energy by the mean of controlled compression/decompression of air within OWC chamber [2].

In the pursuit of harnessing the combined potential of wave and wind energy, researchers have proposed innovative hybrid systems that integrate FWTs with OWCs. These hybrid FWT-WEC configurations represent a promising avenue to optimize energy efficiency and system stability. For instance, Michailides et al. in [3] explored the integration of rotating-flaps WECs onto a semisubmersible FWT, while Bachynski et al. in [4] examined a hybrid configuration involving a tension leg substructure type FWT combined with point absorber WECs. These innovative approaches underscore the drive within the research community to enhance energy capture and overall system performance.

Advances in control methodologies have been pivotal in this endeavor. Shah et al. [5] classified control strategies for FWTs into categories focused on the maximisation and regulation of power with load mitigation. These strategies encompass both blade pitch-based and mass-spring–damper based approaches tailored to FWT designs. Concurrently, researchers have explored modifications to FWT structures to counteract vibrations. Yang et al. [6] implemented tuned mass dampers (TMDs) within barge substructures to dampen vibrations. The application of wing motion stabilizers to spar-type FWTs was proposed by Yang et al. [7]. Kluger et al. [8] employed a combination of surge mode internal TMDs, heave type internal TMDs, and the use of several heave type WECs to enhance system stability. However, the integration of WECs into barge-based FWTs to enhance stabilization remains relatively unexplored.

While some researchers have ventured into the realm of hybrid FWT-OWCs, particularly with linear models, there remains a dearth of comprehensive explorations into addressing nonlinear equations of motion. As an illustration, Jonkman [9] innovatively introduced a central moonpool integrated into the barge structure, facilitating the incorporation of an OWC inside the substructure. This advancement, however, primarily focused on feasibility rather than enhancing system stability. Aboutalebi et al. [10] conducted a dynamic evaluation of hybrid barge-type FWT-OWCs across varying marine conditions. Although they compared standard and OWC-based barge substructures in the absence of wind, the influence of controlling airflow within OWC chambers to dampen oscillations was not examined. Furthermore, Aboutalebi et al. [11] presented an innovative control strategy employing response amplitude operators (RAO) to optimize the efficacy of barge substructures equipped with four OWCs. The primary focus was on minimizing oscillations, thereby enhancing the overall operational efficiency.

The endeavor to create efficient hybrid FWT-WEC systems is marked by complex challenges that call for inventive control strategies. This article aspires to unravel the dynamic intricacies of such systems, offering a comprehensive approach to support the stability of FWTs and heighten energy capture. The study delves into the intricate interplay between oscillations, wave frequencies, wind loads, and their combined impact on mechanical and electrical components as well as power generation. Through the deployment of several of controllers, including a switching controller for OWC valves, a blade pitch adjustment controller, and a generator power controller, the research endeavors to mitigate oscillations, fortify system stability, and sustain a consistent power output.

In the ensuing sections, this paper provides a detailed analysis of the technical facets of the research. Section II gives an overview of the equations governing the model of FWT-OWCs. Section III navigates through the intricacies engendered by oscillations and introduces control strategies to address these multifaceted challenges. The efficacy of these strategies is subjected to rigorous examination across diverse sea states and above rated wind speeds in Section IV. In Section V, the research concludes the findings and underscoring the pivotal role of the proposed control strategies in advancing the stability and efficiency of hybrid FWT-WEC systems.

II. FWT'S EQUATIONS OF MOTION

Figure 1 depicts a barge-type FWT integrated with OWCs, showcasing the intricate balance between harnessing wind and wave energies while confronting hydrodynamic and aerodynamic forces. For station-keeping purposes, eight catenary mooring cables are connected to the substructure. The FWT's substructure is characterized by translational and rotational modes.

Elaborated attributes of the 5 MW wind turbine with the substructure are available for reference in [12]. The substructure size and OWC chamber size are 40m × 40m × 10m and 5m × 5m × 10m, respectively.

In accordance with Airy wave theory, input wave conditions are modeled as unidirectional regular waves, described as:

$$z(t) = A\sin(\omega t) = A\sin(2\pi f t) = A\sin\left(\frac{2\pi}{\lambda}ct\right) \quad (1)$$

here, c represents the wave propagating speed. Symbol A represents the wave amplitude, while λ represents the wavelength, indicating the span between consecutive wave crests. ω stands for wave frequency.

The characterization of frequency dominant equations of motion may be articulated as follows:

$$\begin{aligned} I_{FWT}(\omega)\ddot{x}(\omega) + B_{FWT}(\omega)\dot{x}(\omega) + K_{FWT}x(\omega) \\ = \vec{f}_{FWT}(\omega) + \vec{f}_{PTO}(\omega) \end{aligned} \quad (2)$$

where I_{FWT}, B_{FWT}, and K_{FWT} are the inertia, damping, and stiffness matrices respectively. $\vec{f}_{FWT}(\omega)$ and $\vec{f}_{PTO}(\omega)$ express hydrodynamic forces, aerodynamic loads, and PTO-induced loads respectively. Note that all the aerodynamic

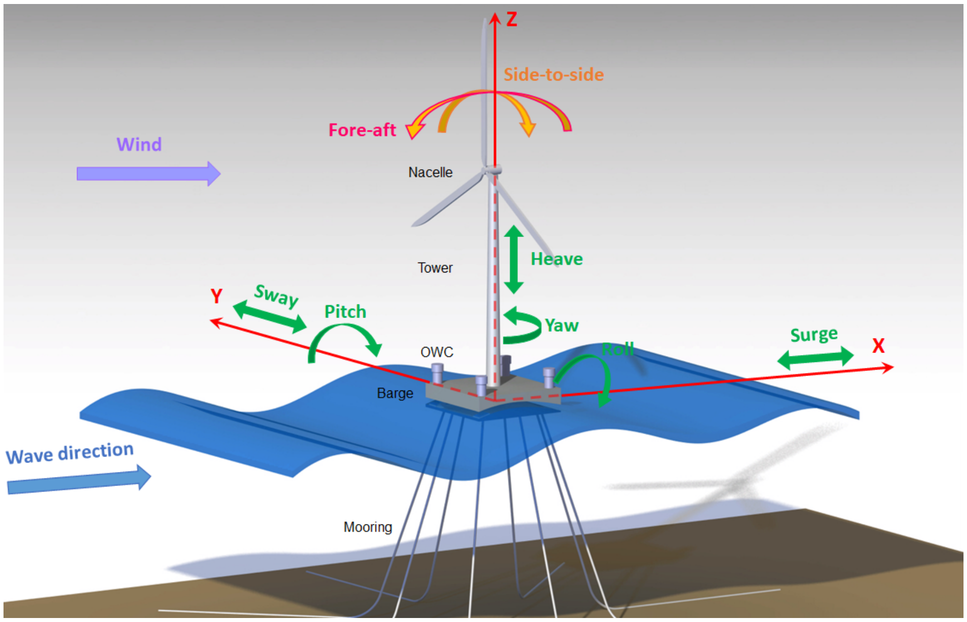

Fig. 1: Barge-type FWT-OWCs configuration.

and hydrodynamic loads are linearized loads, which are not dependent on the motion status *x*. The state vector *x* in eq. 2 is defined by eq. 3:

$$x = \begin{bmatrix} \text{surge} \\ \text{sway} \\ \text{heave} \\ \text{roll} \\ \text{pitch} \\ \text{yaw} \end{bmatrix} \tag{3}$$

The FWT inertia elements are given by:

$$I_{FWT}(\omega) = A_{Hydro}(\omega) + M_{FWT} \tag{4}$$

here, A_{Hydro} represents the added mass of the substructure, which can be achieved using the WAMIT program. M_{FWT} denotes the FWT mass.

The stiffness matrix K_{FWT} is composed of hydrostatic restoring matrix and mooring lines spring stiffness:

$$K_{FWT} = K_{Hydro} + K_{Mooring} \tag{5}$$

Damping coefficients in $B_{FWT}(\omega)$ include hydrodynamic damping, tower damping and PTO-induced damping, described as following equation:

$$B_{FWT}(\omega) = B_{Hydro}(\omega) + B_{viscous} + B_{chamber} \tag{6}$$

It is assumed that the viscous and PTO damping coefficients are linearized damping coefficients.

In this study, the substructure's geometry was defined using MultiSurf software. The design included three types of substructures: a standard barge substructure, a barge substructure with closed OWCs, and a barge substructure with open OWCs. The substructures' geometry was established considering their undisplaced position with a fixed draft of 4 meters.

Subsequent to the MultiSurf design, the matrices (A_{Hydro}, B_{Hydro}, K_{Hydro}, and f_{Hydro}) were computed by WAMIT.

Throughout the research, simulations were conducted using OpenFAST and MATLAB to model the barge-based FWT and implement control strategies for OWCs' valves, blades' pitch adjustment, and generator's torque control. This was accomplished across diverse sea and wind conditions, encompassing above-rated wind speeds.

III. Control Statement

This paper introduces a novel switching control strategy aimed at mitigating oscillations within the states of the FWT. The introduced control strategy is founded on the evaluation of substructure's pitch RAOs exhibited in Fig. 3f across wind speeds of above-rated condition. Notably, the substructure's pitch RAO of the open OWCs-based barge substructure intersects with that of the closed OWCs-based substructure at a specific wave period named the switching point. These RAOs play a crucial role in assessing the system's behavior under different valve configurations of the OWC-based barge substructure, allowing the determination of these switching points.

In this context, the paper primarily employs two substructures, the standard substructure, and OWCs-based substructure. The switching points have been identified at wave periods of 13.1 s for the wind speed of 18 m/s. Consequently, the switching controller activates valve opening for wave periods lower than the switching points and valve closing for periods exceeding the switching points. The anticipated outcome from the substructure pitch RAOs is that the controlled OWCs-based structure will emulate the behavior of the standard barge substructure for wave periods beyond the switching points,

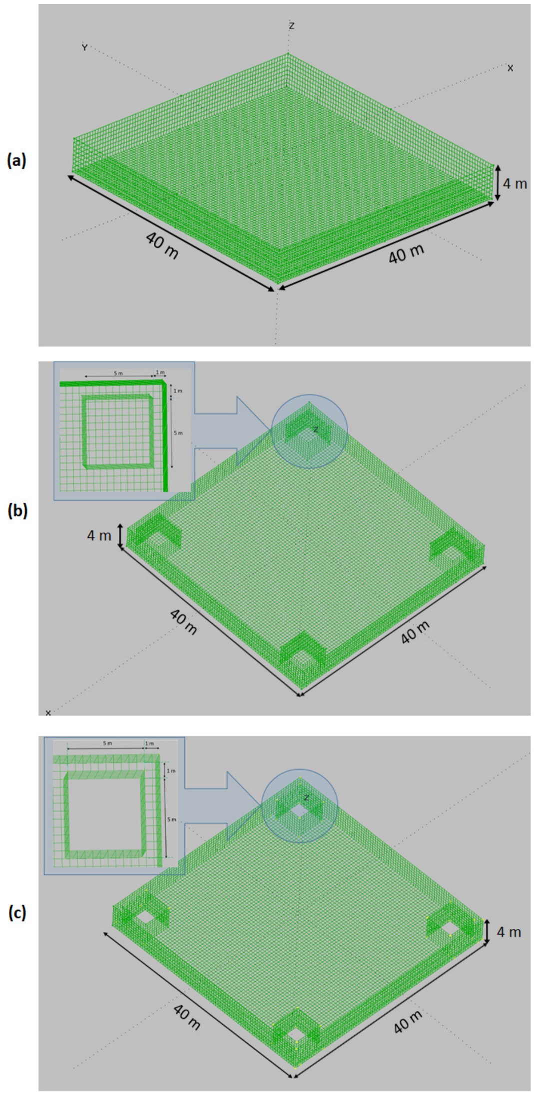

Fig. 2: Substructures configuration (**a**) Standard barge substructure. (**b**) closed OWCs-based barge substructure. (**c**) open OWCs-based barge substructure.

whereas displaying reduced substructure pitch oscillations for periods shorter than the switching points.

This study employs a blade-pitch angle emulation method and a variable-speed operation state that involves manipulating the generator's torque. These techniques are utilized to assess the control strategy impact on the output of the generator's power .

IV. Results and discussion

To gauge the efficacy of the OWCs-based barge substructure under control as opposed to the uncontrolled substructure, a time-dominant simulation was carried out.

The performance of the switching controller was evaluated under above-rated wind speeds and different sea conditions. The wind and wave directions were both adjusted at zero deg, and the wind speed was fixed at 18 m/s. only the substructure pitch movement, fore-aft displacement, and generator's power were monitored. A wave amplitude of 1.5m was introduced to change at 600s, transitioning from a wave period of 10s to 15 s, as illustrated in Fig. 4.

As depicted in Fig. 4b, the controlled OWCs-based barge substructure exhibited 29.90% less oscillation in substructure pitch than the uncontrolled substructure for a wave period of 10s. For the longer period of 15s, the controlled OWCs-based and standard substructures showed nearly identical substructure pitch behavior, aligning with expectations from the substructure pitch RAO.

Similar trends were observed in the fore-aft movement. The controlled OWCs-based barge substructure demonstrated 24.50% less oscillation in fore-aft displacement than the standard barge substructure, particularly during the time before 600 s beyond the transient stage. Beyond that, both substructures exhibited nearly equivalent vibrations in the fore-aft movement, showed in Fig. 4c.

For the above-rated wind speed of 18m/s, the blade's pitch was set to 14.92 deg. to maintain a rated generator power output of 5MW, while the generator torque remained constant at 43093.55 N·m. Fig. 4d illustrates the controlled OWCs-based barge substructure's reduced generator power fluctuations, outperforming the standard substructure by 23.03%. Nevertheless, after the switching time of 600 s, both substructures exhibited similar generator power fluctuations with a slight disparity.

V. Conclusion

This research delved into the implementation of control strategies to address the wind-wave presence affecting FWTs. A novel switching control strategy was proposed as a means to enhance FWT stabilization by mitigating vibrations in substructure and tower movements. This approach involves the manipulation of OWCs' valves, employing a dynamic switch between open and closed states.

The study focused on evaluating the system's response under aligned wave and wind directions in various sea conditions and above-rated wind speeds. Consequently, some modes remained unprovoked, with emphasis placed on pitch and fore-aft displacements. The transition points for valve operations were derived from pre-processed substructure pitch RAOs. These RAOs offer crucial insights into FWT behavior and guided the establishment of switching points for OWCs' valve control.

Using the obtained substructure's pitch RAOs, switching points for above-rated wind speeds were identified at periods of 13.1 s. These switching points triggered the transition of OWCs' valves between open and closed states, corresponding to wave periods below and above the designated switching points.

The outcomes demonstrated the effective reduction of system oscillations across varying environmental conditions using the introduced switching control method for OWCs valves. Overall, the controlled OWCs-based substructure exhibited superior performance in terms of oscillation reduction in comparison with the uncontrolled standard barge structure, across

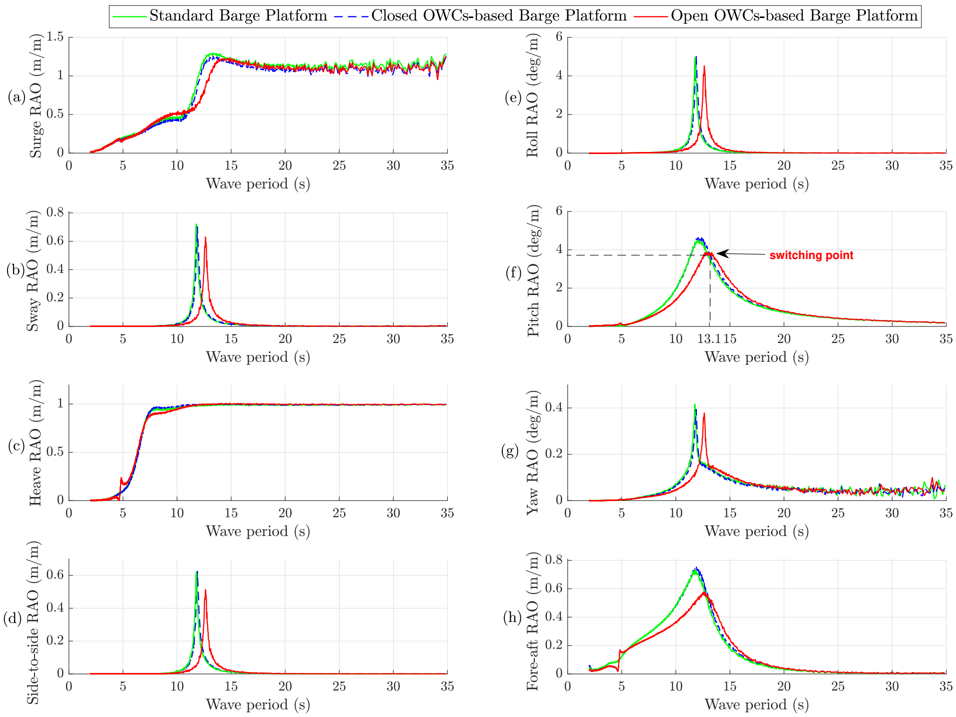

Fig. 3: RAOs at the wind speed of 18 m/s and the wave direction of zero deg. for the following motions: a) Surge. b) Sway. c) Heave. d) side to side movement. e) Roll. f) Pitch. g) Yaw. h) Fore-aft.

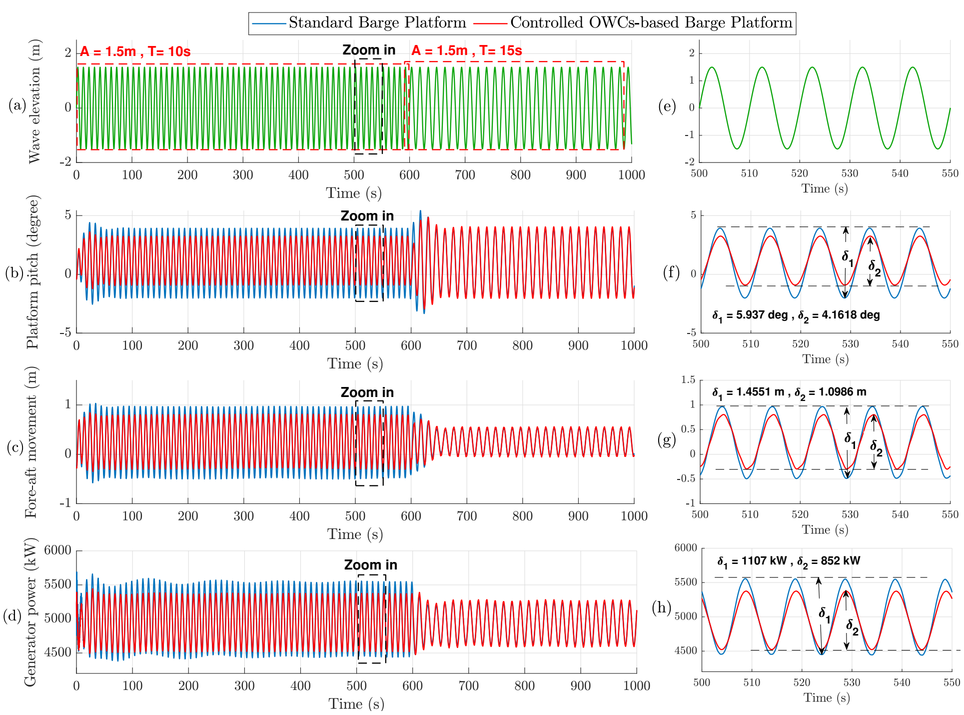

Fig. 4: Condition observed at above-rated wind speed of 18 m/s: a) Wave amplitude. b) Substructure's pitch. c) Fore-aft movement. d) Generator's power.

diverse environmental scenarios. Additionally, the technique proved efficient in mitigating fluctuations in generator power.

These findings serve as a foundation for the future application of the proposed strategy to irregular waves, which typically involve modified regular waves and varying wind conditions. Furthermore, the controller's efficacy in turbulent wind conditions will be verified, further validating its potential for practical implementation.

ACKNOWLEDGMENT

Partial support for this project was provided through funding from the PID2021-23543OB-C21 and PID2021-123543OB-C22 projects (MCIN/AEI/10.13039/501100011033/FEDER, European Union). Additionally, financial assistance was received from the Basque Government's research groups, specifically IT1555-22, and the Margarita Salas MARSA22/09 initiative (UPV-EHU/MIU/Next Generation, European Union).

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