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Hydrodynamic Analysis of a Modelling Approach of Oscillating Water Columns Integrated in a Barge-based Floating Offshore Wind Turbine

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Abstract. The integration of Oscillating Water Columns (OWCs) into Floating Offshore Wind Turbines (FOWTs) offers a promising hybrid renewable energy solution. Accurately modeling the hydrodynamic response of these systems is essential for performance assessment and design optimization. This study compares two numerical models, i.e. standard ITI Energy barge and the same one with four integrated OWCs. Using WAMIT, the hydrodynamic analysis of both platforms was carried out including the added masses, damping coefficients, and Response Amplitude Operators (RAOs). The results highlight the advantages and limitations of both platforms, providing insights into their suitability.

Key words. Floating Offshore Wind Turbine, Hydrodynamic Modelling**,** ITI Energy Barge**,** MultiSurf Oscillating Water Columns, WAMIT

1. Introduction

The depletion of fossil fuel resources and the increasing concerns over climate change have accelerated the global transition toward renewable energy sources [1]. Sustainable alternatives such as wind, solar, and wave energy have gained significant attention as viable solutions to reduce carbon emissions and meet the growing global energy demand by 2050 [2]. Among these renewable sources, wind energy has emerged as a key player in the global energy transition, offering a clean, abundant, and economically viable solution for electricity generation [3]. With continuous advancements in turbine technology and energy storage systems, wind power has become a major contributor to global electricity production, reducing dependence on traditional fossil fuels [4].

While onshore wind farms have seen widespread adoption, offshore wind energy has emerged as a promising alternative due to its higher wind speeds, lower land-use constraints, and increased energy generation potential. FOWTs provide an innovative solution for deploying wind energy in deep waters, where fixed-bottom structures are not feasible. Recent research and industry efforts have focused on optimizing FOWT designs to enhance stability, energy capture efficiency, and structural resilience.

The development of Floating Offshore Wind Turbine (FOWT) systems has brought significant attention to structural challenges arising from wind and wave loads. These dynamic loads increase stress and the risk of structural failures, reducing efficiency and lifespan. To address this, two main load mitigation strategies have been proposed. The first approach uses aerodynamic control to reduce platform pitch by generating restoring torque through rotor thrust. This is typically achieved via blade pitch adjustments. Jonkman et *al.* developed the FAST tool and implemented gain-scheduled PI control for blade pitch across different FOWT types [5,6]. Lackner et *al.* [7] adjusted rotor speed to induce restoring torque, while Staino et *al.* [8] combined passive pitch with active tendons in the blades. Yang et *al.* [9] proposed a hybrid platform design integrating spar- and semi-submersible features for improved stability. The second approach involves structural control. Lackner et *al.* [7,10] developed FAST-SC, incorporating a passive Tuned Mass Damper (TMD) in the nacelle and optimizing it for barge-type platforms. Luo et *al.* [11] used a Tuned Liquid Column Damper to reduce surge motion, and Hu et *al.* [12] implemented a stroke-limited Hybrid Mass Damper with a linear-quadratic regulator for active vibration control.

These methods contribute to enhancing the dynamic performance and longevity of FOWTs under harsh offshore conditions.

A growing trend in renewable energy is the hybridization of FOWTs with complementary energy sources such as solar, tidal, and wave energy. These hybrid systems not only improve overall energy production and enhance platform utilization but also reduce costs by leveraging shared infrastructure. Additionally, they enable more reliable power generation by combining multiple energy sources with different availability patterns. Among these configurations, integrating OWCs with FOWTs offers a promising approach to harnessing both wind and wave energy within a single floating platform. However, accurately modelling the hydrodynamic interactions of such systems remains a complex challenge that requires advanced numerical simulations.

This study compares two numerical models, i.e. standard ITI Energy barge and the same one with four integrated OWCs. Using WAMIT, the hydrodynamic analysis of both platforms was carried out including the added masses, damping coefficients, and Response Amplitude Operators (RAOs). The results highlight the advantages and limitations of both platforms, providing insights into their suitability. The findings will provide insights into the suitability of these methods for frequency-domain simulations and lay the foundation for future work incorporating OpenFAST for coupled aero-hydro-elastic modeling.

2. Hybrid Wind-Wave FOWT Model

The FOWT under study is the NREL offshore 5MW baseline wind turbine [13]. The turbine is a three-bladed, upwind, variable speed, pitch-controlled turbine. The blades drive a generator installed at the top of the tower in the nacelle. The wind turbine is mounted on a ballasted barge platform moored by catenary lines to reduce drifting and improve stability as shown in Fig.1. The adopted barge model is the ITI Energy barge, a simple square platform which is commonly used for research in the literature for load analysis and conception verification of offshore wind turbines.

The complete nonlinear time-domain equations of motion of the coupled floating wind turbine, support platform system and OWCs are of the general form:

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

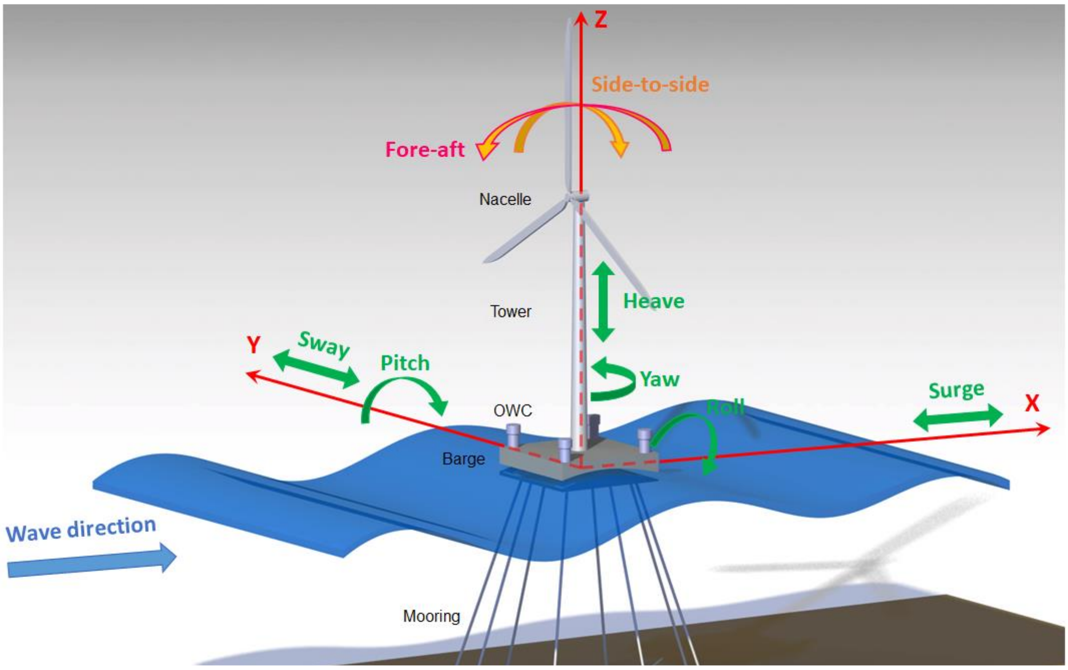

Fig.1: Barge-based floating offshore wind turbine with four OWCs.

where M_{ij} is the (i,j) component of the inertia mass matrix,u is the control inputs, t is time, $\ddot{q}_j$ is the second time derivative of the j^{th} DOF and f_i is the component of the generalized external force, including aerodynamic load on the blades and the nacelle, hydrodynamic force on the platform, elastic and servo forces associated with DOF i.

This study does not consider wind and servo forces for yaw, pitch and generator control of the wind turbine. Hence, the total number of DOFs evaluated is ten consisting of surge, sway, heave, roll, pitch and yaw. The origin of the coordinate system is at Still Water Line (SWL).

The system linear equation of motion in frequency domain is expressed as [14]:

$$I_{FOWT}(\omega)\ \ddot{q} + B_{FOWT}(\omega)\ \dot{q} + C_{FOWT}(\omega)\ q = \vec{f}_{FOWT}(\omega) \quad (2)$$

where I_{FOWT}, B_{FOWT} and C_{FOWT} are inertia, damping and stiffness matrixes respectively. and q is the vector of motion (DOF) is defined as:

$$q = \begin{bmatrix} surge \\ sway \\ heave \\ roll \\ pitch \\ yaw \end{bmatrix} \quad (3)$$

The inertia matrix is defined as follows:

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

where $M_{Platform}$ is the platform mass matrix, M_{Tower} is tower mass matrixes and contains the coupling of the elements of tower bending modes with the platform and A_{Hydro} (ω) is the platform's and OWC's added mass calculated by WAMIT from the panel radiation program and it is frequency-dependent.

The damping matrix is defined as:

$$B_{FOWT}(\omega) = B_{Hydro}(\omega) + B_{Viscous} + B_{Tower} \quad (5)$$

where B_{Hydro} (ω) is the platform's damping matrix, $B_{Viscous}$ is the nonlinear viscous drag on the platform and B_{Tower} is the tower's damping matrix.

The stiffness matrix C_{FOWT} is defined as:

$$C_{FOWT}(\omega) = C_{Hydro} + C_{Mooring} + B_{Tower} \quad (6)$$

where C_{Hydro} is the platform's hydrostatic restoring matrix, $C_{Mooring}$ is the mooring lines' stiffness coefficients and C_{Tower} is the tower's stiffness matrix.

The term on the right-hand side of equation (2) f_{FOWT} is defined as:

$$\vec{f}_{FOWT}(\omega) = \vec{f}_{Hydro}(\omega) + \vec{f}_{Viscous}(\omega) + \vec{f}_{PTO}(\omega) \quad (7)$$

where $f_{viscous}(\omega)$ is the viscous force, $f_{Hydro}(\omega)$ is the hydrodynamic force of the waves on the platform and $f_{PTO}(\omega)$ is the counter forces induced by the added OWCs.

Assuming that the internal water free surface behaves like a piston, the pressure is uniform inside the chamber [15]. Hence the PTO force may be defined as:

$$\vec{f}_{PTO}(\omega) = -p(\omega)\, S \quad (8)$$

where p is the pressure drop across the turbine and S is the internal free surface area.

3. Materials and Methods

The standard barge platform is the ITI Energy barge, a simple square platform ballasted and moored by eight catenary mooring lines to reduce drifting and improve stability. The proposed platform adopts the ITI Energy barge and integrates four OWCs in each corner. The geometric modeling of both barge platforms has been carried out using MultiSurf [16].

In accordance with linear wave theory, only the wetted surface of the structure, in its undisplaced position, is modeled and meshed using MultiSurf [5]. The four OWCs are represented by four moonpools. Fig. 2 shows the geometric design of the ITI Energy barge platform in Multisurf while Fig. 3 shows the proposed ITI barge with four integrated moonpools.

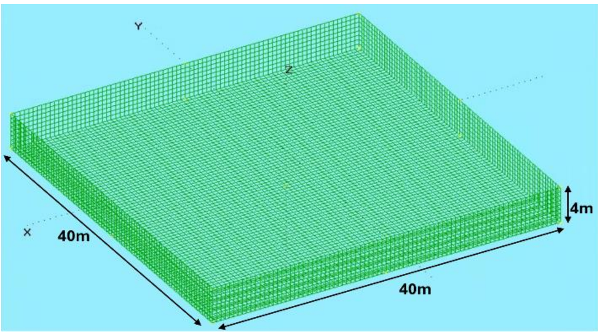

Fig. 2. Geometry of the ITI Energy Barge in MultiSurf.

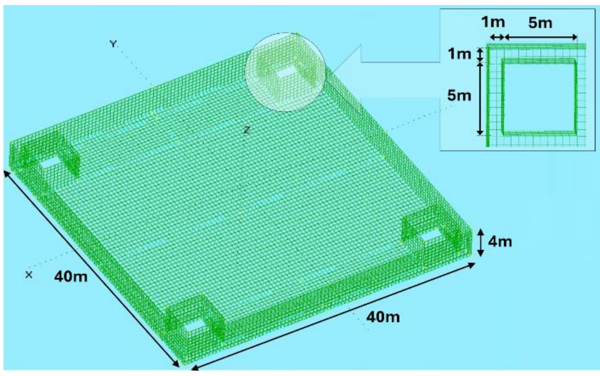

Fig. 3. Geometry of the ITI Energy Barge with 4 moonpools.

In this work, the draft of the barge platform is determined to be 4 meters. The standard ITI Energy barge geometry, exhibiting symmetry about both the *x*-axis and *y*-axis, is represented using 2,240 rectangular panels over one-quarter of the structure while the second platform with four moonpools is modeled using 9840 rectangular panels.

The hydrodynamic analysis of the barge was conducted using WAMIT (Wave Analysis Massachusetts Institute of Technology) software. WAMIT employs the three-dimensional Boundary Integral Equation Method (BIEM), commonly referred to as the panel method, to address linearized hydrodynamic radiation and diffraction problems in the frequency domain [17]. This method is specifically designed to analyze the interaction of surface waves with stationary offshore structures, assuming zero forward speed. By applying Green's theorem, the Laplace equation is reformulated into boundary integral equations to determine the unknown velocity potential on the submerged body. The BIEM approach is then used to compute the velocity potential and the resulting pressure distribution on the structure. The hydrodynamic behavior of the barge, both with and without a moonpool, was evaluated using WAMIT under different wave directions.

Specifications of the 5 MW wind turbine and the ITI barge can be found in Table I and Table II [5], [13].

Table I. - Parameters of the ITI Energy barge platform.

Feature	Value
Platforms' size (W×L×H)	40 m × 40 m × 10 m
OWCs' size (W×L×H)	5 m × 5 m × 10 m
Platforms' Draft, Free bord	4m, 6m
Water displacement in standard barge	6400 m^3
Water displacement in proposed barge	6000 m^3
Platform mass in standard barge	5 452 000 kg
Platform mass in proposed barge	5 111 250 kg
CM Location below SWL in standard barge	0.281768 m
CM Location below SWL in proposed barge	0.167333 m
Roll Inertia about CM	726,900,000 kg.m^2
Pitch Inertia about CM	726,900,000 kg.m^2
Yaw Inertia about CM	1,453,900,000 kg.m^2
Anchor depth	150 m
Number of mooring lines	8
Line diameter	0.0809 m
Line mass density	130.4 kg/m

Table II. - Parameters of the NREL 5 MW wind turbine.

Feature	Value
Base line control	Variable speed, collective pitch
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Tower mass	347 460 kg
Nacelle mass	240 000 kg
Hub mass	56 780 kg
Blades mass	53.22 kg
Rotor diameter	126 m
Hub height	90 m
Center of mass location	38.23 m

4. Results and Discussion

The designed platforms were simulated for wave-structure interaction in WAMIT to analyse the hydrodynamic behavior.

To indicate the performance of the proposed model, the following conditions are considered:

- No wind was imposed on the turbine
- Regular waves with a direction of 0 degree.

Figure 4 shows the hydrodynamic results obtained for both platforms in a side-by-side comparison.

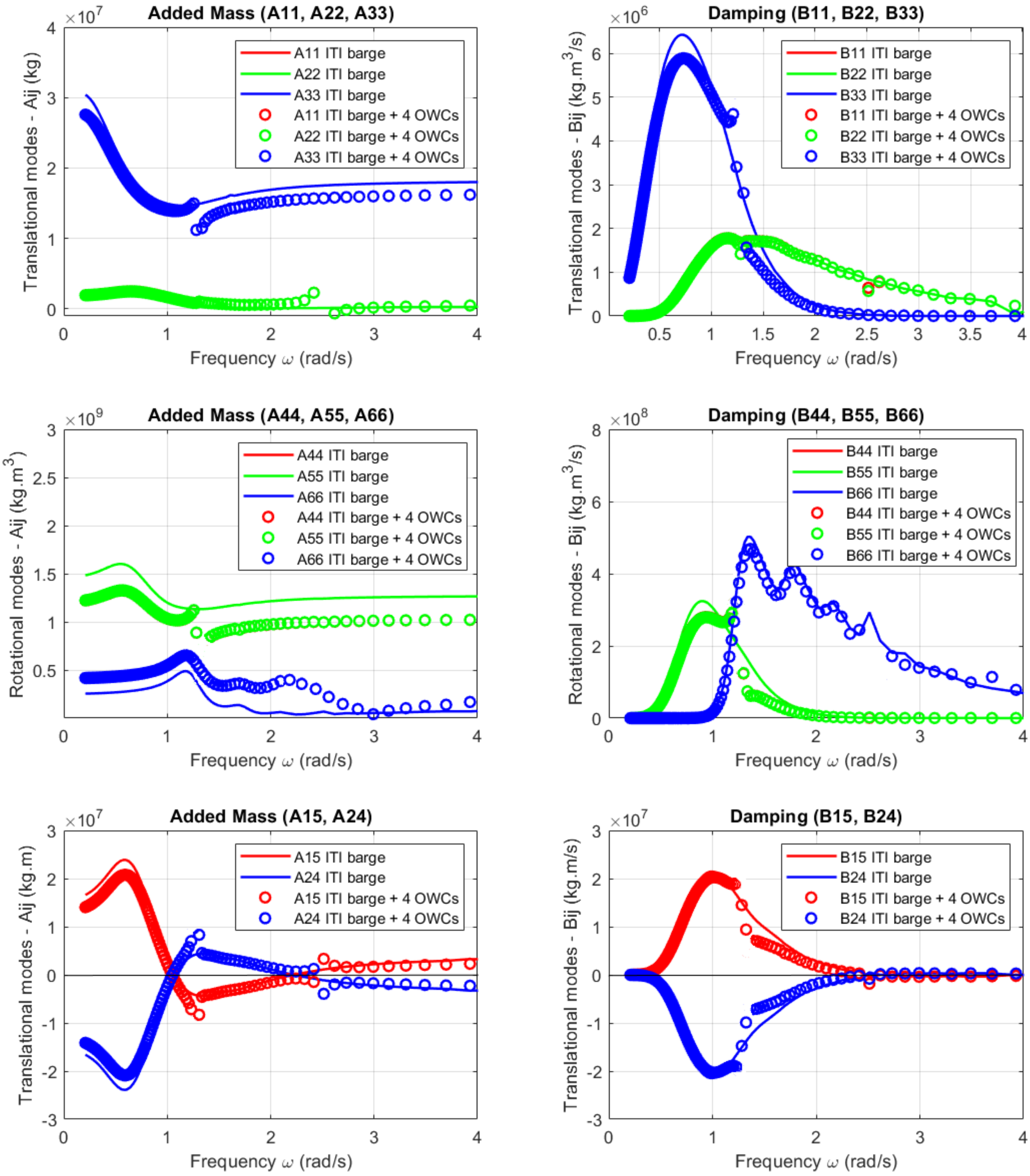

Fig. 4. Hydrodynamics of the standard ITI Energy barge vs the proposed 4 OWC-barge.

Only the upper triangular matrix elements are shown because the hydrodynamic-added-mass and -damping matrices are symmetric in the absence of sea current or forward speed [5]. Also, because of the barge's symmetries, the surge-surge elements of the frequency-dependent added-mass and damping matrices, A_{11} and B_{11}, are identical to the sway-sway elements, A_{22} and B_{22}. Similarly, the roll-roll elements, A_{44} and B_{44}, are identical to the pitch-pitch elements, A_{55} and B_{55}. Other matrix elements not shown are zero-valued or very close to being zero-valued.

The results obtained for the standard ITI Energy barge are in solid lines. As expected, all matrix elements peak out at some intermediate frequency and level out at higher frequencies. The results were analyzed and compared to Jason Jonkman's works and were found to match the ones obtained in [5].

The results of the proposed barge with four integrated OWCs, are presented with the circular marker. It may be observed that the curves are similar to that of the standard ITI barge but with slight difference, peaks and dips at certain frequencies which indicates sloshing resonance inside moonpools. By looking into the translational modes (ij= 11, 22, 33), it may be observed that for the surge-surge and sway-sway the added masses A_{11} and A_{22} and the damping coefficients B_{11} and B_{22} maintain similar behavior to those of the standard barge but with the appearance of slight peaks and dips at the frequencies ω_1=1.25 rad/s and ω_2=2.5 rad/s. However, when it comes to the heave-heave, we see a slight decrease and a peaks and dips at ω_1=1.25 rad/s in both the added mass A_{33} and the damping coefficient B_{33} due to the moonpools' displaced volumes and the decrease of mass.

On the other hand, looking into the rotational modes (ij= 44, 55, 66), it may be observed that for the roll-roll and pitch-pitch the added masses A_{44} and A_{55} and the damping coefficients B_{11} and B_{22} decreased a little compared to those of the standard barge and with the appearance of slight peaks and dips at the frequency ω_1=1.25 rad/s. However, in the case of the yaw-yaw we can see that the added mass A_{66} increased but the damping coefficient B_{66} is maintained.

To evaluate the motion response of the platforms, Response Amplitude Operators (RAOs) calculated by WAMIT are analyzed.

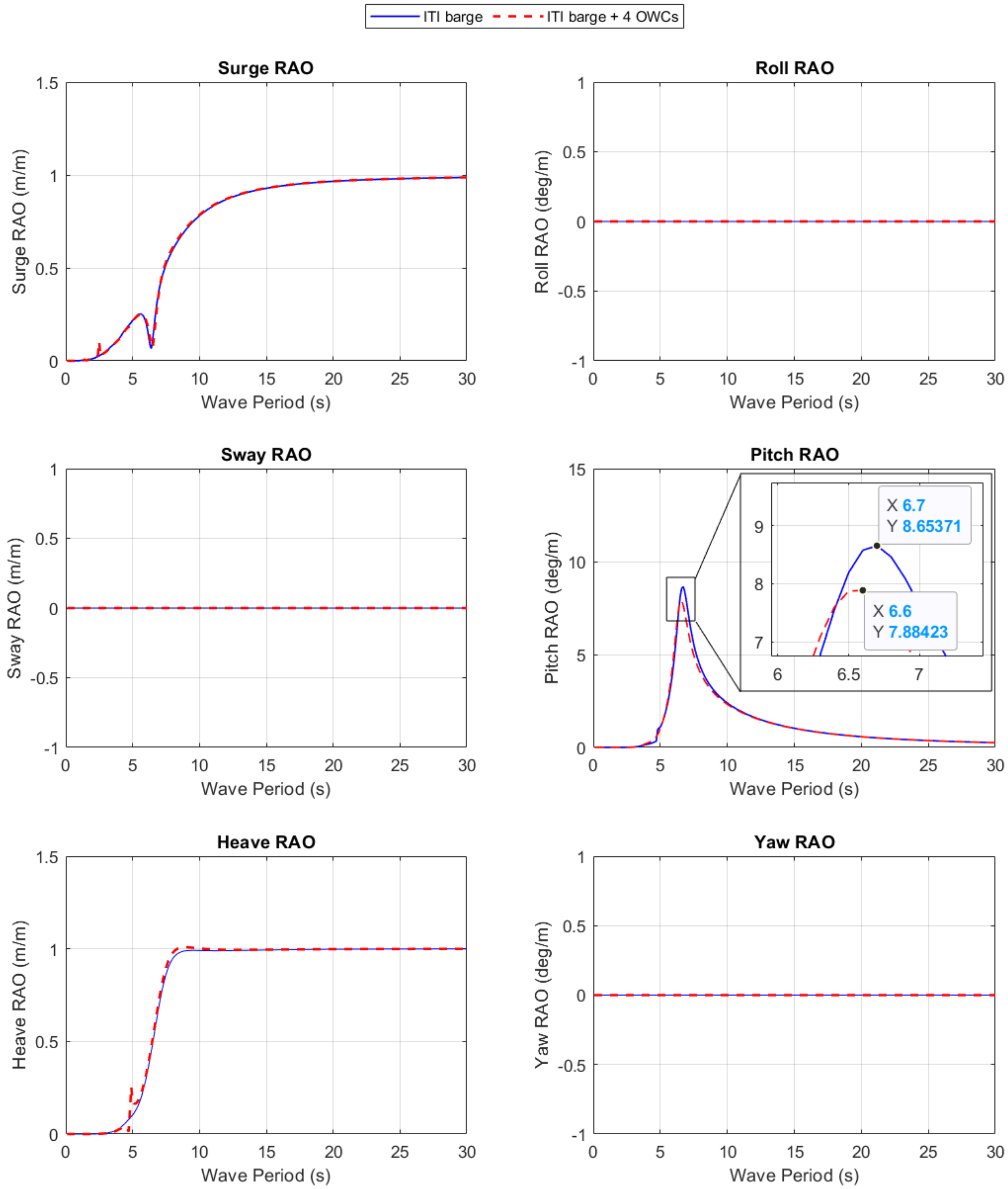

Fig. 5. Translational and rotational RAOs for the standard ITI Energy Barge vs the proposed 4 OWC-barge.

RAOs corresponding to the system's dynamic modes provide valuable insight into the platform's performance under different sea state conditions, enabling comparative assessment of stability and behavior. In this study, a WAMIT simulation using regular waves with a 0 deg incident wave heading and no wind are considered.

Figure 5 illustrates the RAOs of the translational and rotational modes obtained from the WAMIT simulation for both the standard ITI Energy barge platform in blue solid line curves and the proposed barge with four integrated OWCs in red dashed line curves.

Looking into the RAOs of the surge, heave and pitch of both platforms, we can see a good agreement indicating similar behaviors. However, in all three modes we notice small peak at the wave period T=5.026s which corresponds to the sloshing resonance frequency inside the moonpools ω_1=1.25 rad/s. Moreover, looking closely at the pitch RAO, it's observed that it has decreased from 8.65 deg/m to 7.88 deg/m.

The sway, roll and yaw RAOs are zero because of the 0 deg incident wave heading and no winds.

5. Conclusion

In this paper, a novel hybrid wave-wind floating offshore wind turbine has been proposed by integrating four Oscillating Water Columns into an ITI Energy barge platform.

The standard ITI barge and the proposed barge with 4 OWCs were designed in MultiSurf using manel methods. Then a wave-structure simulation has been carried out in WAMIT for hydrodynamic analysis of both models.

Results of the added masses and damping coefficients showed a small decrease in the case of the translational modes whereas in the rotational modes, it may be observed that for the roll-roll and pitch-pitch the added masses and the damping coefficients decreased a little compared to those of the standard barge and with the appearance of slight peaks and dips at the frequency ω_1=1.25 rad/s. However, in the case of the yaw-yaw we can see that the added mass A_{66} increased but the damping coefficient B_{66} is maintained. These results are due to the reduction of the mass, the displaced volume and the water sloshing inside the OWC chambers. A second comparative study focusing on the RAOs further confirmed the appearance of the sloshing peaks at the indicated resonance frequency. Moreover, the pitch RAOs showed that it has decreased in the case of the proposed barge platform.

It can be concluded that the integration of the OWCs has introduced the sloshing resonance frequency inside the capture chambers at a low frequency which are small as shown in the RAOs. However, on the other hand it introduced a reduction of the pitch mode which is responsible for the vibration of the tower and hub.

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