Preliminary Design and Dynamic Response of Multi-Purpose Floating Offshore Wind Turbine Platform: Part 1

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Abstract: Floating offshore wind turbine foundations are based on platforms operated by the oil and gas industry. However, they are designed and optimized to meet the wind turbines’ operating criteria. Although Malaysia is considered a low-wind-speed country, there are some locations facing the South China Sea that are found to be feasible for wind energy harnessing. The average daily wind speed may reach up to 15 m/s. Therefore, designing a cost-effective platform that can operate in Malaysian waters which has less severe environmental conditions compared to the North Sea would be a prudent undertaking. In this study, a new design of a multi-purpose floating offshore wind turbine platform (Mocha-TLP) is presented. In addition, the dynamic response of the platform to wave loads was investigated using the Navier–Stokes code STAR CCM+ developed by CD-adapco. Moreover, free-oscillation tests were performed to determine the natural periods of the platform. Three approaching wave cases and two wave conditions (WC) were considered. The results show that the natural periods of the platforms were within the recommended range for pitch, roll, yaw, heave, sway and surge motions. The platform was stable in rotational motion within the three cases. However, it experienced a noticeable surge motion which was more critical with wave condition one (WC1) since the wavelength equalled the length of the structure. The dynamic response of the platform to wave loads was minimal and within the operational requirements for wind turbines.

Keywords: floating offshore wind turbine; renewable energy; offshore platforms; wind energy

1. Introduction

The power stations sector is one of the main sources of greenhouse gas emissions; it contributes 21.3% of the total gas emissions [1]. Many countries have made a significant effort to reduce the impacts of the emissions by placing investments in renewable energy sources. The sources of renewable energy include wind, wave and solar energy [2]. Solar and wind energy technologies are the fastest growing sources of clean energy, reaching 556 GW and 647 GW by the year 2019 for wind and solar energy, respectively, and these numbers are expected to reach 903 GW and 126 GW by the year 2023 [3,4]. Wind energy is a promising source for clean energy due to the improvement in the efficiency of wind turbines and the rising development of floating structures, which allow for large offshore wind farms to be built without disturbing the ecosystems [5,6]. Floating offshore wind turbine platforms are classified based on the way they are stabilized to achieve static stability. Types of stabilizing mechanisms include buoyancy, ballast and mooring lines. Semi-submersible, tension leg platforms, barges and spars rely on the above-mentioned mechanisms [7,8]. Spars are ballast-stabilized structures that have a large amount of ballast, which places the centre of mass below the centre of buoyancy. When tilting of the platform occurs, the rotational displacement is counteracted by stabilizing righting moment. Buoyancy (or waterplane)-stabilized structures such as barges have a large second moment of area with respect to the rotational axis, which creates a stabilizing righting moment in case of displacement. On the hand, mooring-stabilized structures such as tension leg platforms...
generate stabilizing moments by high-tension mooring lines [9]. Floating offshore wind turbine platforms are mainly based on existing structures in oil and gas industries [10]. The advantage of offshore wind turbines is that their capacity is higher and steadier than onshore wind turbines since the sea emplacement allows larger rotor diameters, and the speed of the wind is stronger and steadier [7]. In addition, wind farms can be located near high-demand coastal cities, which is cost-effective in terms of electricity transmission lines.

Floating offshore wind turbine platforms were designed to obtain wind turbines’ operating criterions. Professor William E. Heronemus introduced the idea of floating offshore wind turbines in the early 1970s [11]. However, FLOAT was the first research project to investigate the feasibility of operating floating offshore wind turbines in the 1990s [12], whereas the first offshore wind turbine was installed in Nogersund, Sweden, in 1990 at 6 m depth and around 250 m away from shore with a capacity of 220 KW [13]. The following year, the first wind turbine farm was installed in Denmark, containing eleven wind turbines with a total capacity of 4.95 MW (450 kw each wind turbine) [13,14]. The total capacity of installed wind turbines is rising worldwide with an average growth of 25% annually [15]. Most of the wind turbines built within the period were bottom-fixed, except for some farms, including Hywind in Norway with a 2.3 MW capacity, WindFloat in Portugal with a 2.0 MW capacity and Fukushima in Japan with a 2.0 MW capacity [13].

The design of a conceptual model of a floating offshore wind turbine platform such as a tension leg platform (TLP) requires the capability of achieving stability, displacement and a natural period. In addition, the design of tendons’ tension should not be zero to avoid slacking phenomena [16]. The natural period of floating offshore wind turbine platforms (TLP type) for surge and sway should be more than 35 s to avoid first-order wave excitation while heaving, and pitch-and-roll natural periods should be less than 3.5 s as well [17]. The area of the tendons must be sufficient to avoid yield (σ_y) within a given safety factor (SF) for tension up to twice the initial tension (T). In addition, the minimum displacement should be more than 2000 m^3 based on a study conducted by Bachynski and Moan [18] for TLP systems supporting 5 MW wind turbines so that they may survive the extreme wave and wind conditions and increase the stiffness of the system [19–21]. Moreover, it reduces the cost of the system by minimizing the materials' cost, tendon construction cost and installation cost [17].

The TLP concept is known for its stability, derived from the restoring moment due to the tension in tendons [22]. The first TLP platform built for the oil and gas industry was installed in Hutton, UK, in the North Sea, in 1984 [23]. Blue-H is a TLP prototype for a wind turbine that was installed in 2007. It was installed at 10.5 miles offshore the sea in Brindisi, Italy, at 111 m water depth. The purpose of Blue-H prototype was to prove the possibility of installing wind turbines in deep water with reliable and economically viable technologies [24]. PelaStar is another TLP design for offshore wind turbines developed by Glosten and Blue-H Group [25]. Several floating offshore wind turbine concepts have been proposed, and various of scaled-model experiments have been conducted in order to investigate the dynamic response of the structures to wave and wind loads. Jonkman and Matha conducted a numerical study to investigate the dynamic response of three offshore structural concepts, spar buoy, tension leg platform and barges, to support 5 MW wind turbines. A coupled hydro–aero–servo–elasto dynamic analysis was performed to determine the ultimate loads, fatigue loads and instability loads. The results show an increased load on the turbine components in comparison to land-based wind turbines [26]. It was reported that the loads in the barge were the highest among the three concepts while the differences in load between TLP and the spar buoy were insignificant, except for wind turbine’s tower loads, which were higher in the spar buoy concept [26].

Tracy conducted a parametric study to design a floating offshore wind turbine structure (MIT-TLP) based on concepts from oil and gas industries. This structure maintained good stability in calm seas without moorings when the wind turbine was not operating [27]. The design was based on 6 m and 10 m wave heights and a 200 m water depth. Two TLP designs were concluded for a 10 m wave height; the first TLP is a deep, slender structure
and the second one is a shallow draft barge. The shallow draft barge requires more pretension of the tendons in comparison to the spar-like structure to avoid slack in the leeward tether due to the large water plane area [27]. Matha optimized the MIT-TLP concept by altering the spokes' length and correcting faults through a coupled analysis using a FAST tool and then renamed it MIT/NREL TLP. It was the best concept compared to the ITI barge and spar buoy in terms of the ratios for ultimate and fatigue loads. The disadvantages of MIT/NREL TLP are the large amount of ballast, the expensive moorings and the length of the spokes, which is a source of failure [28]. Another study was conducted by Wang et al. to design a floating offshore wind turbine TLP based on the concepts of NREL-TLP and MIT-TLP, which was then named HIT-FOWT-TLP. The different features of this platform are its five-meter-high bevel shape and the concrete, which is located only at the base of the steel column, leaving the rest of the column space for water ballast. Besides that, the diameter of the spokes is larger, and they are welded to the steel column. It was found that the enhanced concept has more space for free ballast, which allows for the centre of gravity and centre of buoyancy to be adjusted according to the desired dynamic features [29]. It was also revealed that the effect of spokes should not be neglected as they may cause vertical incident wave exciting force. In addition, it showed better dynamic features of RAOs for pitch, sway and roll motions compared to the NREL models. Furthermore, the mass and displacement are only 27% and 49%, respectively, of the NREL models [29]. Murfet and Abdussamie conducted an experimental study on a NREL TLP concept developed by [30] to understand its motion and tendon response when subjected to unidirectional regular wave and wind with non-rotating blades. It was found that the static wind loads on the tower had an impact on the motion and tendon response with an increase of 13.1% in the heave direction, while it had a negligible effect on the surge motion and a slight decrease in tendon tension [30].

A way of minimizing the platform motion is by using Serbuoys; this concept was introduced by Ma et al. Serbuoys are submerged buoys normally placed below the wave trough and connected to the platforms by tendons. An experimental and numerical study was carried out by [31] for a proposed floating offshore wind turbine TLP associated with a series of buoys (Serbuoys-TLP). The coupled motion of the TLP and the buoys' system was investigated numerically and experimentally. Furthermore, the suppressive effect of buoys on the surge motion of the TLP response was investigated through several characteristics. It included the location of buoys, wave properties and submerged volume. The results show that the added series of buoys suppressed the surge motion effectively with a 60% suppression efficiency. It was also revealed that the location and displacement of the buoys have a great effect on its efficiency, where a larger displacement and lower position result in a longer resonance period, and the suppression effect is more remarkable [31].

Hybrid wind turbine platforms, or multi-purpose platforms, are designed to support wind turbines and other sources of clean energy converters such as wave energy convertor, current energy turbines or solar panels. Hybrid energy platforms are promising in terms of reducing the cost of produced energy and the variability of energy outputs [32,33]. The use of the hybrid concept reduces the cost of produced energy and utilizes the area of the ocean more efficiently [34,35]. Meanwhile, wave energy converters in combination with wind turbines provide the suppression of platform motion and can be controlled to minimize the systems' loads [35].

Malaysia is known for its calm weather, except the locations facing the South China Sea such as Kudat, Mersing and Kuala Terengganu [36]. The average daily wind speed may reach up 15 m/s during monsoon seasons. There are two monsoon seasons in Malaysia: one coming from the southwest from May to September and the other from the northeast from November to March. This study introduces a new design of a multi-purpose floating offshore wind turbine platform to be installed in Kudat, Malaysia, as it has feasible wind energy [37]. The structure was designed in a cost-effective manner and is stable enough to accommodate three wind turbines and more than 3000 square meters of solar panels. The structure was tested numerically based on the environmental conditions in Kudat,
Malaysia. The dynamic response to wave loads was investigated, and free-oscillation tests were performed to determine the natural periods of the platform in pitch, roll, yaw, heave, sway and surge motions.

2. Methodology

This study introduces a new multi-purpose platform that was designed in a cost-effective manner and easy to construct. It was designed to support three wind turbines and several solar panels. In addition, there is a possibility of installing wave energy converters at the sides of the pontoons. The structure was designed to obtain the requirements’ criterion to operate three wind turbines and support several commercial solar panels. SOLIDWORKS was used for the design of the platform, and the scale model of the platform and NREL 5 MW wind turbine. Furthermore, dynamic characteristics such as mass, moments of inertia and centre of mass (COM) were identified. The dynamic response of the platform to wave loads was investigated using the STAR CCM+ tool.

2.1. Design Configuration of the Floating Offshore Wind Turbine Platform

The structure consists of a triplex offshore platform containing three main polygonal pontoons connected to each other by self-floating trusses. It was designed to support three 5 MW wind turbines and around 1500 commercial solar panels. The pontoons were designed to be polygonal for the installation of wave energy converters at the sides of the pontoons. The trusses give more balance to the structure during the windy season and provide a large space for the installation of solar panels. Figure 1A,B illustrate the principal dimensions and artistic 3D view of the platform, while Figure 1C shows the pontoon’s compartments. The polygonal pontoons are divided into six chambers and a tower chamber for water ballasting in order to reduce the cost of the ballast by water ballasting and allow the adjustment of the dynamic properties of the platform. The truss was designed with four main tubular members; the lower two are ballasted with water to provide stability against overturning, while the upper two are hollow to allow the buoyancy of the truss. The blue surface in Figure 1B is the allocated surface for solar panels. The platform was designed with an operational draft of 12.5 m. However, the solar panels’ surface is six meters above the water surface in order to keep them away from splashing water.

![Figure 1. Cont.](image-url)
2.2. Scaling

The scaling of this study follows Froude’s scaling law for the floating platform and wind turbine. A scale ratio of 1:100 was considered, which is an acceptable ratio according to Chakrabarti [38]. The scale ratio was chosen to suit the depth of the UTP offshore wave tank for experimental purposes. Table 1 shows the dynamic characteristics of the whole assembly of the platform.

Table 1. Properties of Mocha-TLP prototype and 1:100 scale model.

| Item                           | Unit   | Prototype       | Scale Model          |
|--------------------------------|--------|-----------------|----------------------|
| Displacement                   | m³     | 24,639.0084     | 0.0246390084         |
| Mass of the platform           | kg     | 1,537,680       | 1.53768              |
| Mass of the ballast            | kg     | 7,425,360       | 7.42536              |
| Mass of wind turbine           | kg     | 697,460         | 0.74128              |
| Wind turbine rating            | MW     | 5               | -                    |
| Number of WT                   |        | 3               | 3                    |
| Number of solar panels         |        | 1661            | 1661                 |
| COM (m, m, m)                  |        | (37.131, 74.283, 19.98) | (0.37131. 0.74283, 0.1998) |
| Pitch inertia about COM        | kg·m²  | 45,100,000,000  | 4.51                 |
| Roll inertia about COM         | -      | 45,100,000,000  | 4.51                 |
| Yaw inertia about COM          | -      | 60,500,000,000  | 6.05                 |
| Number of mooring lines        | -      | 3               | 3                    |
| Line mass density              | kg/m   | 302.89          | -                    |
| Line extensional stiffness     | -      | 4,500,000,000   | 4500                 |
| Line pretension                | N      | 14,715,000      | 14.715               |
| Draft                          | m      | 12.5            | 0.125                |

2.3. Virtual Wave Tank Set-Up

A numerical simulation was conducted to investigate the dynamic response of the platform to regular a wave load using the Navier–Stokes CFD code STAR CCM+. The volume of fluid (VOF) multi-phase model was used to capture the distribution and movement of the interface between the immiscible phases of water and air. Volume fraction of air and water was used to express the physical properties of air and water. Free-oscillation tests were performed as well to obtain the natural periods of the platform.

A numerical wave tank with the dimensions of 20 m long, 5 m wide and 2.5 m deep was established, and the scaled model of the platform was placed at the centre as illustrated in Figure 2. A continuum rigid body was created and assigned to the platform. It allows
the calculation of the motion of the platform in response to the fluid forces and moments at the coupled boundary. The interaction between the body and the fluid in STAR CCM+ is called “dynamic fluid body interaction (DFBI)”. A local coordinate system was created and assigned to the DFBI model to track the motion of the platform in six degrees of freedom (6DOF). A spring coupling was made to model the tendons of the platform. Each tendon was modelled with a spring line with a stiffness of 4.5 N/mm and a pretension of 1.5 kg.

A 3D trimmer mesh with a prism layer mesher was used to generate the mesh. The surface mesh of the model was refined to 2 mm and 5 prism layers around the model. In addition, a volumetric control region was established for mesh refinement at the water surface. As a rule of thumb, anisotropic mesh refinements were set as 1/20 of the wave height in the vertical direction (z-axis) and 1/80 of the wavelength in the horizontal directions (x and y axes) based on the Star CCM+ guide [39]. An overset mesh refinement was set around the model as well. Figure 3 shows the mesh refinement of the model where Region A is the background, Region B is the refinement of the water surface and Region C is the overset mesh refinement.

Figure 2. Virtual towing tank set up.

Figure 3. Mesh setting and refinement of the model.
2.4. Boundary Conditions and Solution Setting

The boundary conditions were defined to model the appropriate wave with a specific height and period. Stokes’ fifth-order wave theory was used to model regular waves. Inlet boundary was specified at the left of the wave tank where the velocity field and volume fraction were defined by the appropriate wave theory (Stokes’ fifth-order wave theory). The pressure outlet was specified at the right of the wave tank. Wave forcing was used to prevent wave reflection at the sides of the wave tank and outlet.

The time step of the solution used was calculated by Equation (1) [39].

\[
\text{Time step} = \frac{P}{2.4n}
\]

where \( P \) is the wave period and \( n \) is the number by which we divided the wave length for mesh refinement, which is 80. For instance, the time step for a wave height of 0.0438 is about 0.0044 s.

2.5. Test Matrix

Based on previous studies, Kudat was selected as a suitable place for wind energy harnessing. Two wave conditions were selected for this study with three wave propagating cases as described in Table 2 and illustrated in Figure 4. The environmental conditions were based on the operational and 100-year storm event followed by the PETRONAS technical standards (PTS) code for the proposed location. Oscillation tests (decay test) on still water were performed to determine the natural periods of the platform. To perform free-decay tests, the model was excited with an initial velocity of 0.3 for heave and surge motions, and a 0.1 radian for pitch, roll and yaw motions.

Table 2. Metaocean conditions for Sabah and Sarawak water.

| Case No | Wave Condition | Wave Height | Wave Period |
|---------|----------------|-------------|-------------|
| Case No 1, 2 & 3 | WC1 | 4.38 (m) | 8.48 (s) |
| Case No 1, 2 & 3 | WC2 | 5.77 (m) | 11.65 (s) |

3. Result and Discussions

The results discuss the obtained natural periods of the model and its global response, which includes the dynamic motion and the tension of the tendons. Oscillation tests were performed in still water to determine the natural periods of the platform in the six degrees of freedom. The natural periods in heave, pitch and roll motions met wind turbine operational requirements with less than 3.5 s in heave, pitch and roll motions and more than 35 s in surge, sway and yaw motions as described in Table 3.
Table 3. Natural periods obtained for prototype and scale model.

| Degree of Freedom | Scale Model (s) | Prototype (s) |
|-------------------|----------------|---------------|
| Heave             | 0.21           | 2.1           |
| Pitch             | 0.19           | 1.9           |
| Roll              | 0.18           | 1.8           |
| Surge             | 8.72           | 87.2          |
| Sway              | 8.72           | 87.2          |

The results obtained by numerical simulation for the dynamic response of the floating offshore wind turbine platform show that the prototype can withstand the severe environmental conditions in Kudat in the three cases of wave advancement. Figure 5 shows the air–water interface visualization.

The platform experienced a slight rotational response in pitch motion in the three cases as shown in Figure 6A,B. However, yaw and roll motions were only significant in case one and steady in case two and three due to the uniformity of the model facing the wave in cases two and three and the rotational moment about vertical axes in case one. Roll motion in case one was a result of the tension exerted by tendons to resist the yaw motion. Figure 6C–F illustrate the roll and yaw motion for the three cases.

Heave displacement was almost identical within the three cases for WC1 and WC2. The displacement amplitude for WC2 was negative due to the large displacement of surge and the stiff tendons that pulled down the platform. Figure 7A,B show heave displacement for the scale model; it recorded the maximum displacement with WC2 as around 2.5 mm, which equals 25 cm for the prototype.
Surge displacement was the most severe motion among the six degrees-of-freedom motions. It is directly proportional to the wave height; it reached 30 mm with WC1 and almost 50 mm with WC2, which equal 3 m and 5 m, respectively, for the prototype. Despite that, it is still within the safe conditions for operating wind turbines. Surge motion is...
affected by the wavelength as well, as it is more dangerous when the wavelength is equal to the platform’s length as in WC1. In this condition, the wave hit the platform at the up-wave pontoons and the down-wave pontoons at the same time. This is applicable for case two and three. It can be seen in Figure 8A that case two and three experienced the most severe surge motion, with displacements of almost 20 mm and 12 mm, respectively. On the other hand, case one had the least severe surge motion because each pontoon was hit individually by the wave, which allowed tendons to resist the displacement more effectively. Figure 8B shows the surge displacement with WC2, and it is noticeable that the platform was displaced around 40 mm (4 m for the prototype) from the original position. However, the surge motion was less than WC1 since the platform is controlled by surge natural frequency. Figure 8C,D show the spectral density of the surge for both WC1 and WC2. The surge spectral response was almost identical in case two and three with both wave condition cases, whereas it was higher in case one for both wave conditions. The surge motion was dominated by wave loads, where it showed a higher wave frequency response in WC2 than WC1. Minor sway displacement was observed in case one, while it was stable in case two and three as shown in Figure 8E,F.

Figure 8. Time history of surge and sway motions for WC1 and WC2. (A) Surge displacement with WC1; (B) surge displacement with WC2; (C) surge spectral density with WC1; (D) surge spectral density with WC2; (E) sway motion with WC1; (F) sway motion with WC2.
Tendons must remain tense to avoid slacking; this was achieved by 1.5 kg of pretension applied to each tendon. The dynamic response of the tendons’ tension fluctuated almost in the same manner in case one, as shown in Figure 9A, while it was unlike the responses shown in case two and three, as illustrated in Figure 9B,C. The tension was higher with the singular tendon situated up-wave or down-wave such as tendon no 1 in case two as shown in Figure 10B and tendon two in case three as illustrated in Figure 10D. The highest tension occurred in case three with WC2 for tendon two, where it reached 45 N because it resisted double the loads that were on tendons one and three, as they are parallelly situated. The same scenario occurred for tendon one in case two, where it reached up to 40 N. Figure 10A–F illustrate the dynamic tension in tendons for the three cases and two wave conditions.

Figure 9. Time history of dynamic tension in tendons for case 1–3. (A) Tendons’ dynamic tension for case 1; (B) Tendons’ dynamic tension for case 2; (C) Tendons’ dynamic tension for case 3.
Figure 9. Time history of dynamic tension in tendons for case 1–3. (A) Tendons’ dynamic tension for case 1; (B) Tendons’ dynamic tension for case 2; (C) Tendons’ dynamic tension for case 3.

Figure 10. Time history of dynamic tension in tendons with WC1 and WC2. (A) Tendon 1 tension (up-wave tendon) with wc1; (B) tendon 1 tension (up-wave tendon) with WC2; (C) dynamic tension in tendon 2 (down-wave tendon) with WC1; (D) dynamic tension in tendon 2 (down-wave tendon) with WC2; (E) Dynamic tension in tendon 3 with WC1; (F) dynamic tension in tendon 3 with WC2.

4. Conclusions

The dynamic response of the model to wave loads was investigated. Free-decay tests were performed as well. The model showed a good stability in heave, pitch and roll motions. However, it experienced a significant rotation about the vertical axis (Yaw motion) in case one and a considerable surge motion in case two and three. The tendons remained tense in all cases due to pretension to avoid slacking. The worst scenario of tendon tension occurred in case two and three when two tendons stood parallel to each other with regard to wave direction, compared to one on the other side. The model satisfied the operational requirements for wind turbines in terms of natural periods for the six degrees-of-freedom motions and dynamic response to regular wave loads.

Author Contributions: Conceptualization, S.A.; methodology, S.A.; numerical simulation and data analysis, S.A.; writing—original draft preparation, S.A.; writing—review and editing, M.S.L. and L.E.S.; supervision, M.S.L. and L.E.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data are available within this manuscript.
Acknowledgments: The authors would like to express their gratitude to Universiti Teknologi PETRONAS for providing a good research environment.

Conflicts of Interest: The authors declare no conflict of interest.

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