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A comparison of the dynamic characteristics of the spar and TLP offshore structures under irregular waves, experimentally

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ABSTRACT

In the field of renewable energy, floating offshore wind turbines (FOWT) are currently a hot topic. Numerous numerical and experimental investegations have been developed to model the performance of FOWTs under wave forces in order to design and optimize them. A comparsion of two types of FOWT was disscuesd experimentally.

To guarantee accurate results for the responss comparison, two experimental models were created, first a simulation of tension leg platform eind turbine by 1/100 scale factor , second a 1/300 scale model of a 3-leg catenary mooring spar buoy platform model.To simulate real-world conditions, irregular wave states were generated in the Benha Faculty of Engineering laboratory where the models experiments were carried out. Our findings demonstrate that The models responds well in the surge directions, For spar model, in comparison to the surge, pitch, and heave responses, the sway, roll, and yaw responses are very small, For TLP model, in comparison to the surge, sway, and roll responses, the heave, pitch, and yaw responses are very small.

Keywords

Floating Offshore structures ,Wind Turbines ,OC3-Hywind spar platform,Tension leg platform

1- INTRODUCTION

It is well known that utilizing wind energy at sea is better than on land, and over recent years the wind turbines are becoming one of a the most important solutions to the energy problem. Therefore, the offshore wind turbine is the more feasible solution to the energy problem. While a rich wind resource lies untapped off the Gulf of Suez coasts of Egypt, the application of offshore wind turbine will be successful as a solution of the energy problem of Egypt. Due to the scarcity of land, fixed offshore wind turbines have been installed in shallow waters recently. The tension leg platform (TLP) with different shapes (rectangular, triangular, and hexagonal) and the spar type system are the two most popular types of offshore supporting wind turbine structures for deep-sea locations with abundant wind. In our study, a expermentally comparsion of the spar type responses with the TLP type responses was looked at.

The floating platforms can be modeled as a rigid body with six degrees of freedom (6-DOF). Heave, roll, and pitch motions make up the vertical degrees of freedom while surge, sway, and yaw motions make up the horizontal degrees of freedom. Several studies on the dynamic behavior FOWT have been conducted.

[1] have developed an experimental study of the HYWIND 5mwspar-buoy type FOWT in 1:47 model scale which was carried out by Hydro Oil & Energy at MARINTEK's Ocean Basin Laboratory in Trondheim, Norway in 2005. Experiment was performed to investigate the design under a wide range of environmental conditions. In addition to this, wind turbine control schemes were also tested. [2] Carried out an experimental study using a 1:67 scale model of their semi-submersible wind float concept in order to confirm the accuracy of the numerical model developed for the engineering design. The concept has a three-legged foundation and is designed to carry a 5–8 MW wind turbine; the first full scale windfloat was deployed in November 2011. The paper describes the numerical hydrodynamic model of the platform and its mooring system, wave tank testing which included a simplified aerodynamic model of the wind turbine and the development of the coupled model using FAST.

A TLP, a spar-buoy and a semisubmersible in Maritime Research Institute Netherlands (MARIN) have investigated three FOWT concepts of at 1:50 scale, To better understand the behavior of FOWT's and assess their advantages on the system performance experiments (each carrying the NREL 5 MW reference turbine), They found that for a TLP type wind turbine, although the wind loading increases the pitch response of the system, the pitch response is still very small. It was observed that the operating wind turbine damped the second order pitch response of the spar buoy and the semisubmersible. The results in their paper are constrained within the specific load and design cases, therefore the results cannot be generalized. [3]

[4] Presented a tank test results for a 1:100 scale TLP type FOWT incorporating three rotating blades. Tests were carried out in both waves and wind force. Like [3] their results showed that the blade-wind interaction has a beneficial effect of reducing the floater pitch motion and in addition also decreases the mooring line vibrations. [5] Investigated the hydrodynamic performance of a TLP FOWT. Regular, operational, survival, failure and transport tests were performed for a simulated 80 m water depth. The paper presents the experimental setup, free decay tests, regular wave motion RAO’s, irregular wave responses, tendon loads and accelerations. In order to include wind effect into the tests a calibrated turbine was used and controlled with the data measured through a real time platform motion tracking. They also compared their results with available in-house numerical simulations and other results found in literature. Their experimental results indicated that the natural periods and damping values are similar to those published in the literature. The surge values were slightly smaller than reference values which was put down to the reduced water depth. All the RAO’s were very small except surge which is typical for TLPs. Due to the coupling of surge and heave motions, the heave motion response contained components at twice the fundamental wave frequency. It is also reported that no slack in the tendons occurred during the testing period.

An investigation of the experimental and numerical response of a 6 MW spar-type FOWT constructed for a depth of 100 m. For the experiment, a scaled model was created with an aspect ratio of 65.3 and created a numerical model using the Fatigue, Aerodynamics, Structures, and Turbulence (FAST open-source platform). According to experimental and numerical investigations, they are dependable and consistent for the needed 6MW spar-type FOWT [6]. At the DHI tidal basin in Horsholm, Denmark, an experiment of an offshore spar buoy wind turbine's dynamic response was carried out under various wind and wave conditions. Uniform and unsteady waves with constant wind loads were forced to a scale model with a Froude ratio of 1:40. Before analysis, all experimental data were scaled to full scale using Froude scaling [7]. The study of the dynamic behavior of a triangular, square, and pentagon TLP supporting a 5MW wind turbine exposed to multidirectional uniform and random waves that the environmental loads have been evaluated in accordance with the Egyptian Metrological Authority's data for the northern region of the Red Sea. The analysis was conducted using the ANSYS-AQWA, FAST, and MATLAB programs. Their findings improved our knowledge of dynamics and platform stability [8].

The investigations of the dynamic responses of triangular and square tension leg platforms under hydrodynamic forces using MATLAB software were carried out. Both studies were conducted to investigate the consequences of nonlinearities generated by hydrodynamic forces in the time domain, as well as the conjunction effect between surge, sway, heave, roll, pitch, and yaw degrees of freedom on the dynamic behavior of TLPs. The investigation only took into account unidirectional waves in the surge direction, and the responses of the two shapes were contrasted [9], [10]. Creating a 1/300 scale model with a 3-leg catenary mooring allowed us to assess the OC3-Hywind spar platform's performance for the study, to simulate real-world conditions, irregular wave states were generated in the Benha Faculty of Engineering laboratory where the model experiments were carried out. The results demonstrate that the surge, sway, heave, roll, pitch, and yaw responses of the model were accurately predicted by the Ansys-Aqwa numerical software. Moreover, the numerical software accurately predicted that the sway, roll, and yaw responses were significantly lower than the surge, heave, and pitch responses. [11]

This study compares experimental responses of TLP platform model and Spar buoy model. In the offshore structures engineering lab of the Benha Faculty of Engineering, model tests were done with a 1/100 and 1/300 scale ratio respectively to investigate the wind turbine dynamic characteristics under irregular waves. Since it is very expensive to have a towing tank, the other objective of the experiment is to show that a small flume (with an ingenious system to reduce wave reflection) can gain a set of experimental data still suitable to calibrate the comparison and give good results.

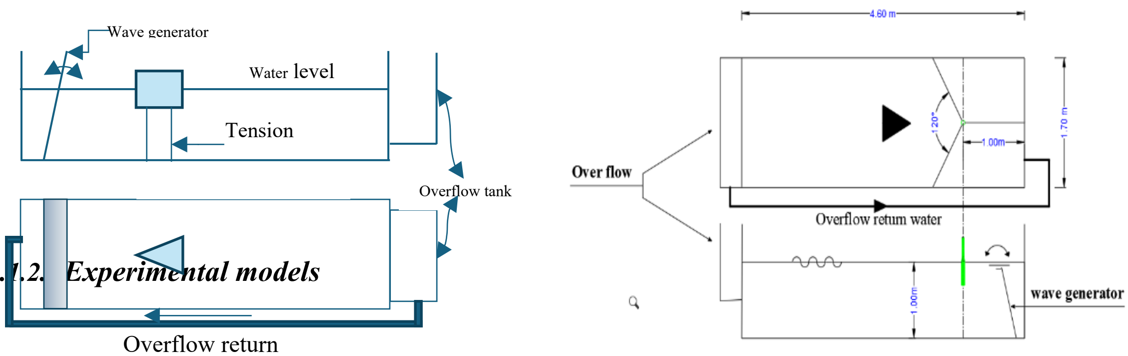
2- EXPERIMENTAL SETUP

With growing interest in floating offshore wind concepts, experimental tests will continue to play an important role in investigating the performance of Floating Offshore Wind Turbine (FOWT)

2.1. Model Scaling

2.1.1. Wave Basin

In the present study, to compare the responses of two types of FOWT physical models at a reduced scale have been used in the investigation. A prototype of Tension Leg Platform (TLP) and OC3-Hywind SB (Spar Buoy) prototype model has been taken as a reference. The experiments have been performed at benha faculty of engineering. The wave basin is 4.6 m long and 1.7 m wide with an overall water depth of 1 m Figure 1. The TLP models have been placed at the centre of the basin 1.5 m from the wave maker but the spar model was 1 meter from the wave maker.



a. TLP model b. Spar model

Figure 1: A Schematic diagram for the wave tank

2.1.2. Experimental models

In our study two models Figure 3 and Figure 3were tested. There is triangle shape of TLP scaled model of 1:100 scale factor and Spar Buoy is a scaled model of 1:300 scale factor of the prototype models. Models were manufactured in Faculty of Engineering lab, Benha University by 3D printer with PLA plastic material, Table 2and Table 1shows the geometry properties of the experimental models.

Table 1: The SB-OC3 Hind's geometric properties. Length Scale 1:300

SB OC3-Hywind	Full scale Dimension (m)	Scaled model Dimension (m)
SB diameter	15	0.05
Depth of floater base below SWL (total draft)	120	0.4
Tower height	88.50	0.295
Tower diameter	6	0.02
Hub diameter	3	0.01
Radius of fairleads	15	0.05
Depth of fairleads	70	0.23
Blade length	63	0.21

Table 2: The TLP geometric properties. Length Scale 1:100

Properties of the 5-MW wind turbine Triangle TLP			Full scale Dimension (m)	Scaled model Dimen-sion (m)
Length of the side			40	0.4
Floating system	Main column	NO	3	3
		Diameter	10	0.1
	Connecting beam	No	6	6
		Diameter	2	0.02
Super structure	Main beam	NO	3	3
		Diameter	2	0.02
	Bracing	No	6	6
		Diameter	1.5	0.105
Cables		No	3	3

Figure 3: TLP experimental

Figure 3: Spar experimental model

The presence of the mooring system aims to provide the platform with the necessary restoring forces to avoid excessive motions under the action of waves and also, to keep the angles and the displacements of the structure inside the operational and safe range of the turbine, during the action of extreme loads.
For the TLP, the mooring line system consisted of tension legs made of aluminium wire, the lower ends of the mooring lines have been anchored to the bottom of the pit in the wave basin to simulate the TLP foundation, and their top ends have been attached to the model. The spar platform model is tethered to the ground by a set of three catenary lines through a circular connection. The fairleads are positioned 0.025 m from the centre of the platform and 0.23 m below the SWL. The nominal orientation of one of the lines is parallel to the positive X-axis (in the surge direction). At the platform, the two remaining lines are evenly separated by a 120° angle.

2.2. Wave data

A liquid level sensor was used to measure the current wave data (Figure 4). The time history for the irregular wave is shown in Figure 5. The average wave height is 2.1 cm, and the time period equals 3.2 sec which equal to the real sea min.

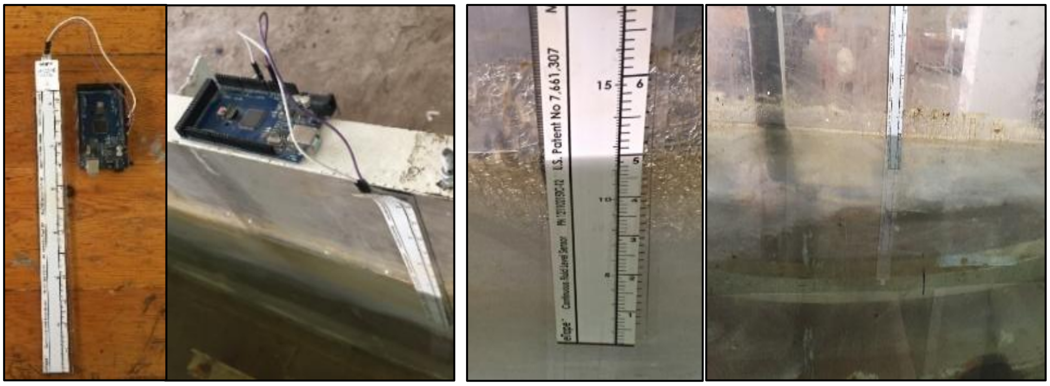


Figure 4: Liquid level sensor

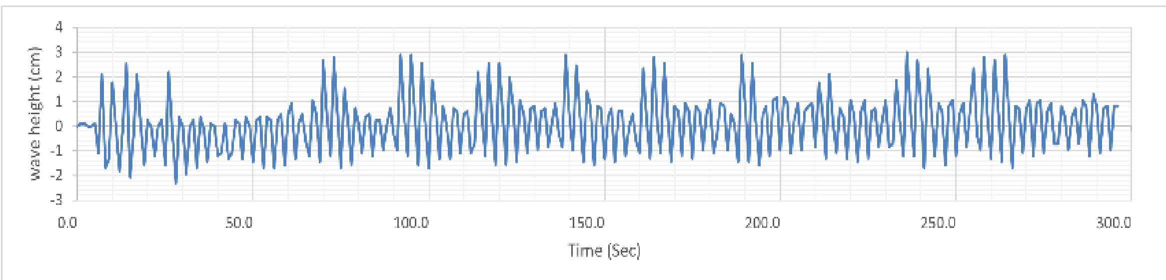


Figure 5: Time history for wave excitation

2.3. Instrumentation

Hinged-flap type wave maker (Figure 7) is made with flat vertical plate hinged at the bottom and rotating around its axis so when driven with an oscillatory motion it partially rotate in a fore and aft arc. It is suited for physical modelling of deep-water waves, where the water is barely perturbed at the lower depth of the tank. The pitching motion about the submerged hinge is regarded as more inductive to quickly produce the correct water particle orbital profiles which also exhibit the required exponential diameter decay with depth. The wave maker can generate irregular waves. To minimize reflected wave (back wave) (Figure 7), an opening located at the end of the tank (opposite to the wave maker) was made where water is circulated to return the overflow water behind the wave generator. The water level gauge Figure 4 has been located aligned to the structure to measure the wave height to define the wave profile.

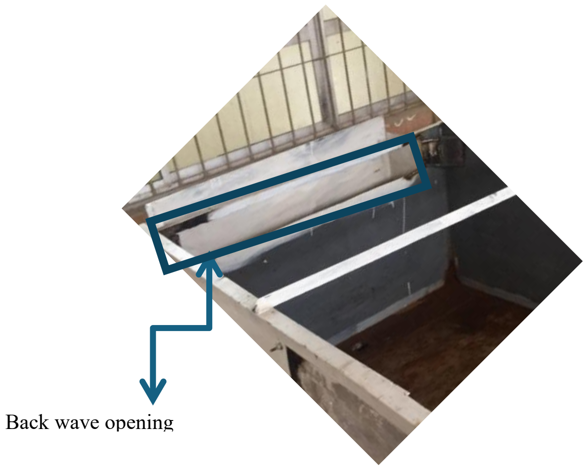


Figure 7: The overflow section with the back-wave opening

Figure 7: Wave generator with its supporting system

In order to conduct a detailed study of the stability of the TLP type platform and spar type platform, it was necessary to measure accelerations and inclinations of the platform at the centre of gravity, A 9DOF Inertial Measurement Unit (IMU) sensor module called GY-85 (has three-axis gyroscope, tri-axial accelerometer and 3-axis magnetic field), For the TLP platform model The IMU was connected to a wireless transmitter that sent real-time data to a receiver at the laptop which was connected to lab-view for recording the measurements. In order to generate a wireless signal, sensors had to be connected to a microcontroller directly on the model. An Arduino atmega328 microcontroller was used to provide the power to the sensors, process the analog signals, and output the signals to the wireless card. The wireless signals were sent and received using two CSR popular Bluetooth chip Figure 8. For the spar model The Esp32- Arduino is a family of inexpensive, low-power systems on a chip with dual-mode Bluetooth and integrated Wi-Fi that is used to receive data from the IMU (gy85) sensor and send it to the laptop via Wi-Fi so that the experiment's results (real-time recording of data) operation can be seen on the screen. The IMU settled inside the spar model near the center of mass and connected to the Esp32- Arduino. Figure 9 displays a schematic diagram for the electronic sensor system and the process of measuring the responses during the experiment.

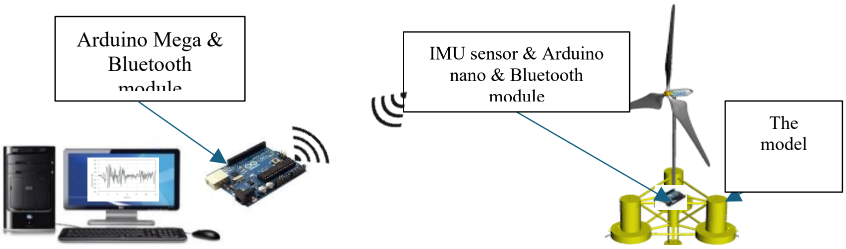


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Figure 8: Schematic diagram for the TLP experiment measuring system

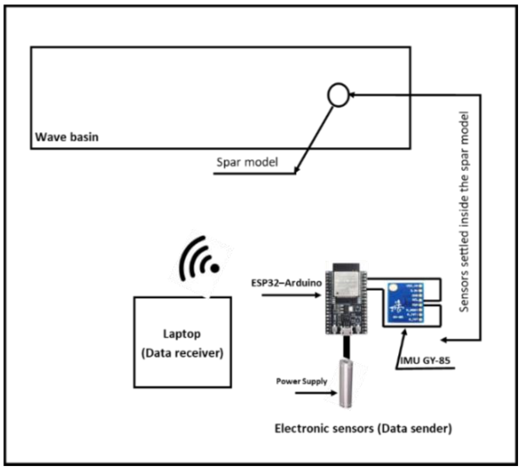

Figure 9: : Schematic diagram for the Spar experiment measuring system

3- EXPERIMENTAL TEST

3.1 Triangle TLP model:

The triangular model was placed in the centre of tank width with one and half meter away from the wave maker, shown in Figure 10.

Figure 10: TLP model Real test

3.2 Spar Buoy model:

As shown in Figure 11, the spar model was positioned in the middle of the tank's width, one meter away from the wave generator.

Figure 11: Spar buoy model Real test

4- RESULTS AND DISCUSSION

Many trials of experiments were created to compare the responses of the two models. Data has been collected for the 6 DOF for a long time. While there are numerous data points from the experiment model, only the most important ones are shown. In case of TLP model the wave direction is important than the case of Spar model because the spar model is symmetric. So, the wave direction for the TLP model is on the surge DOF direction.

4.1 Surge responses

A sample of the time history is shown in Figure 13 and Figure 13 for experimental results. It should be mentioned that the experimental data were scaled according to the Froad scaling factor. Also, a portion of the time series (experimental data) were shown because of the back-wave interference with the generated wave that accumulated after 180 sec and caused a chaotic motion in the response. Figure (b) show that the response of Spar model is bigger than the response of TLP model. Since the structure is constraint by tension cables in case of TLP catenary to a free one in the case of the spar model. Also, the rate of semi periodic motion in case of spar platform is greater than the TLP platform. It should be mentiond that Surge responses have more energy content than any other responses as expected since the wav e is in the surge direction.

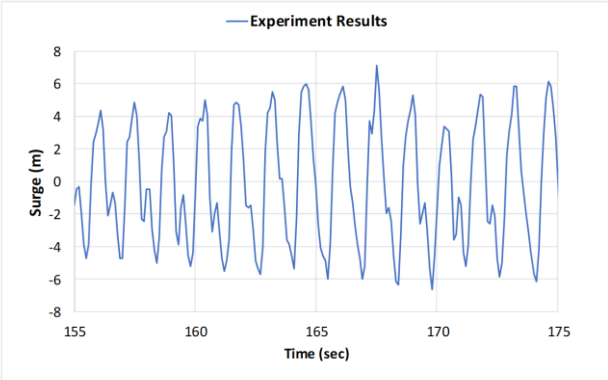

Figure 13: Time history of surge response for Spar model

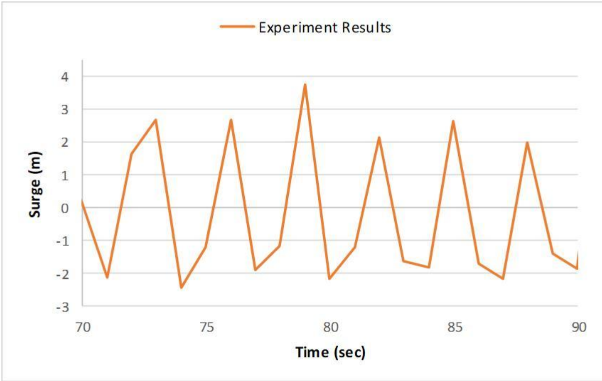

Figure 13:Time history of surge response for TLP model

4.2 Sway responses

Since the wave excitation is irregular a very small sway response can be observed. **Error! Reference s ource not found.** show that the Spar model response is small than the TLP' response. The whole energy is taken of the surge direction for the spar since it is free.

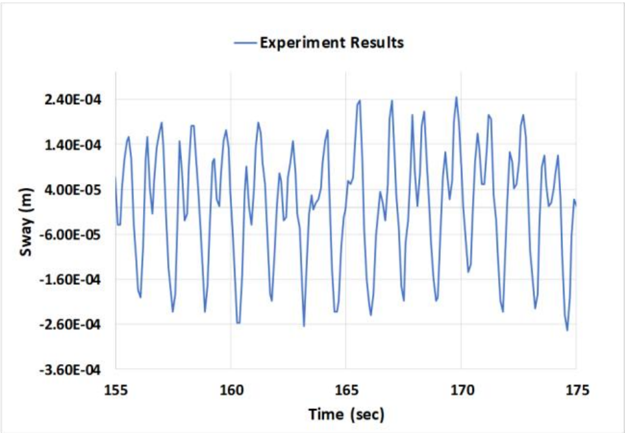

Figure 15: Time history of sway response for Spar model

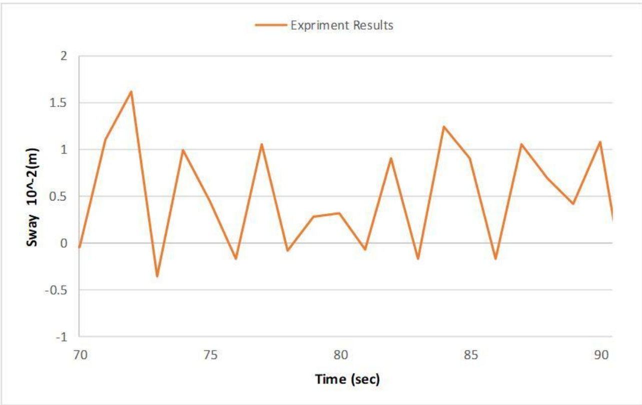

Figure 15: Time history of sway response for TLP model

4.3 Heave responses

As seen in Figure 17 and Figure 17 , the heave responses for the TLP model are extremely small due to the cables restrain (heave is stiff DOF) compared of the Spar model. It should be mentioned that all heave response is in the negative direction, which is logically acceptable because of coupling between the surge and heave motion. it is clear that the heave motion has a smaller energy content than the one in surge response, which is good for the stability of the floating structure.

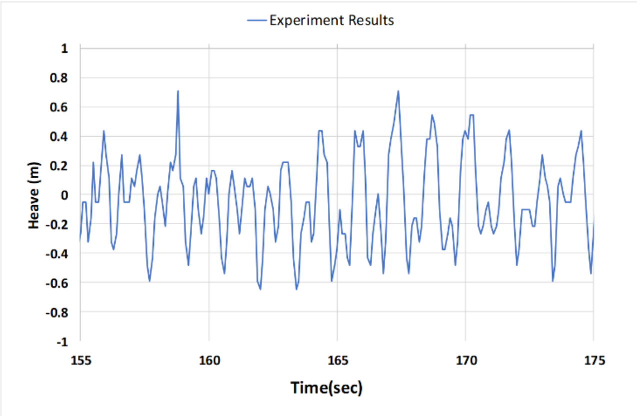

Figure 17: Time history of heave response for Spar model

Figure 17: Time history of heave response for TLP model

4.4 Pitch response

The TLP is very stiff in pitch because of the effect of the tension cables; hence a small range of pitch motion is expected for this degree of freedom. But pitch response of the Spar model is larger than the TLP model because it's self-stability. As seen in Figure 19 and Figure 19.

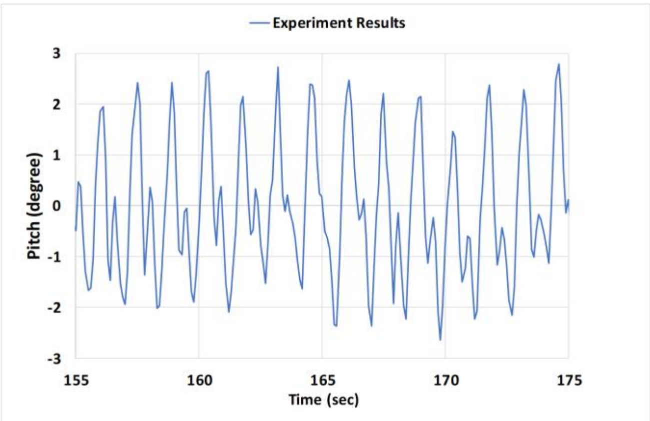

Figure 19: Time history of pitch response for Spar model

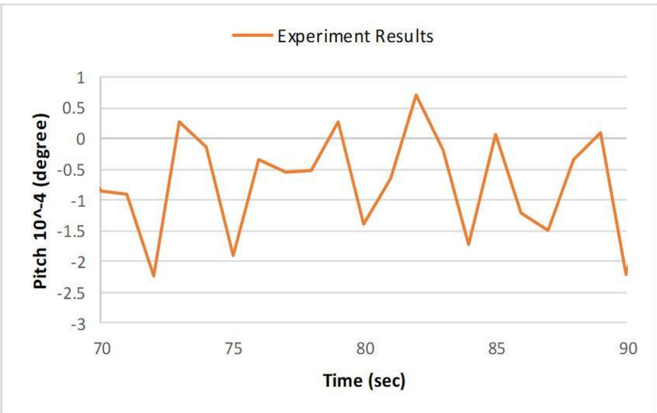

Figure 19: Time history of pitch response for TLP model

4.5 Roll response

In this DOF direction the responses is very small for the two models because the direction of the wave is in the surge direction, as shown in Figure 21 and Figure 21.

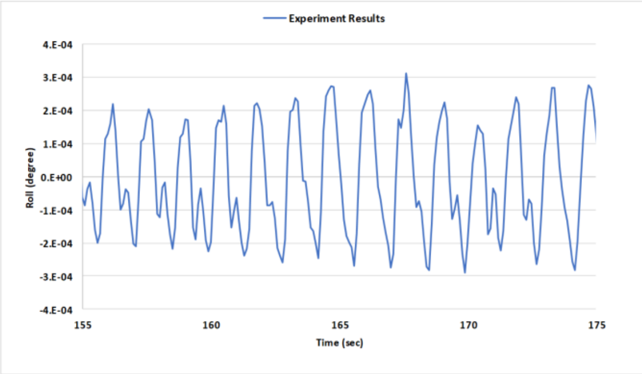

Figure 21: Time history of roll response for Spar model

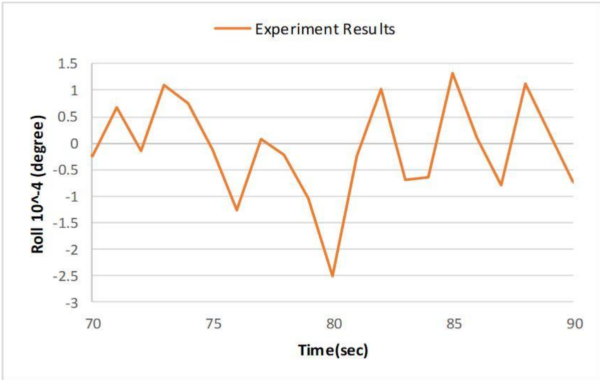

Figure 21: Time history of roll response for TLP model

Yaw response

Also, a very small response occurs in the yaw direction. Figure 23 and Figure 23**Error! Reference source not found.** show that the response of the Spar model is larger than the TLP model because that the TLP platform attached to the ground with the tension cables.

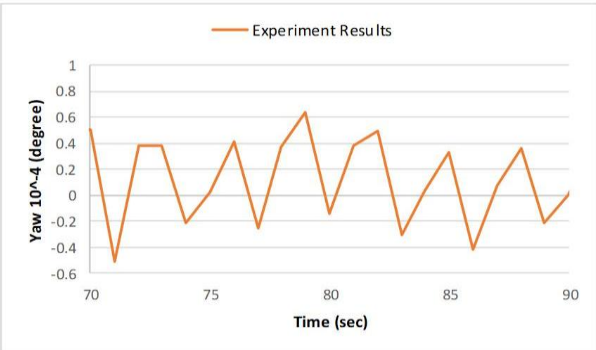

Figure 23: Time history of yaw response for TLP model

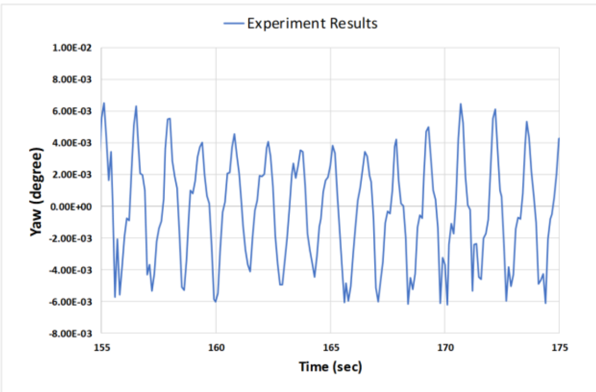

Figure 23: Time history of yaw response for Spar model

5- CONCLUSIONS

In this paper, a 1:300 spar OC3 model and a:100 TLP platform model was investigated experimentally at the Benha faculty of engineering lab under irregular waves. The conclusions listed below can be drawn based on the results presented in this manuscript:

1) The models responds well in the surge directions.

2) For spar model, in comparison to the surge, pitch, and heave responses, the sway, roll, and yaw responses are very small.

3) For TLP model, in comparison to the surge, sway, and roll responses, the heave, pitch, and yaw responses are very small.

4) In comparison to the pitch, and heave responses, the TLP responses are very small than the Spar model because the effect of the tension leg cables.

5) The experiment model response results are somehow disturbed due to the back wave effect and the small size of the basin.

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