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DYNAMIC CHARACTERISTICS OF THREE DIFFERENT TLP'S SUPPORTING 5-MW WIND TURBINES UNDER MULTI-DIRECTIONAL RANDOM AND REGULAR WAVES

ASHRAF M. ABOU-RAYAN[1], NADER N. KHALIL[2] & MOHAMED S. AFIFY[3]

[1]Associate Professor, Department of Civil Engineering, Benha University, Egypt

[2]Assistant Professor, Department of Civil Engineering, Benha University, Egypt

[3]Graduate Student, Department of Civil Engineering, Benha University, Egypt

ABSTRACT

Over recent years the offshore wind turbines are becoming more feasible solution to the energy problem, which is crucial for Egypt. In this article a three floating support structure, tension leg platform types (TLP), for 5-MW wind turbine have been considered. The dynamic behavior of a triangular, square, and pentagon TLP configurations under multi-directional regular and random waves have been investigated. The environmental loads have been considered according to the Egyptian Metrological Authority records in northern Red sea zone. The dynamic analysis were carried out using ANSYS-AQWA a finite element analysis software, FAST a wind turbine dynamic software, and MATLAB software. Investigation results give a better understanding of dynamical behavior and stability of the floating wind turbines. Results include time history, Power Spectrum densities (PSD's), and plan stability for all configurations.

KEYWORDS: Dynamic Response, Offshore Wind Turbines, Tension Leg Platform, Wave Forces

INTRODUCTION

Recently, there has been an enormous increase in the global demand for energy as a result of industrial development and population growth, which lead to the current energy crisis. Offshore floating wind farms in shallow or deep waters are the paramount solution for green cost effective renewable energy. The development of related technology in Europe and USA has made a lot of achievement in that field, but in Egypt it is still in its infancy. It is well known that utilizing wind energy at sea is a good solution, since one can achieve better energy efficiency at sea than on land. A rich wind resource lies untapped off the Gulf of Suez coasts of Egypt. This resource is available 8-80 Km. off the Gulf of Suez coast in water depths mostly greater than 30m. Therefore, the investigation of the dynamic characteristics of wind turbine floating supported structures is very crucial to Egypt. Differently from fixed structures (Jacket type), floating support structures must provide enough buoyancy to sustain the wind turbine weight. Also, it has to provide enough rotational stability to prevent the system from capsizing and acceptable wave response motions in all its six degrees of freedom to prevent the system from large dynamic loads, Simon and Maurizio (2012). The following is a brief review of the current research for the wind turbine on floating support structures.

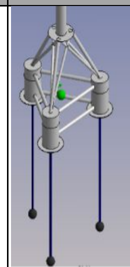
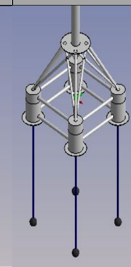
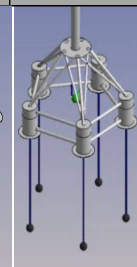
Ramachandran, et al. (2013), have investigated the response amplitude operators (RAO) for floating offshore wind turbines (spar) using two different codes, FAST and WAMIT (a linear frequency-domain tool). They concluded that the WAMIT can be used as a verification tool for modeling of floating wind turbines in FAST, and that the RAO's for a flexible turbine however cannot be estimated using WAMIT. Takeshi, et al. (2007), have developed a FEM code to predict the dynamic response of a floating offshore wind turbine system in the time domain. They found that, the nonlinearity of wave becomes dominant for the water depth less than 100m and the elastic modes might be resonant with the higher order harmonic component of the nonlinear wave, resulting in the increase of the dynamic response of the floating structure. Zhuangle, et al. (2013), have developed a finite element model using AQWA to analyze the small-sized floating foundation of a tri-floater and to make a local optimization on the stress concentration area. Ebrahimi, et al. (2014), have developed a numerical scheme to investigate the dynamic response of a tension leg platform wind turbine(TLPWT) under a parked condition. The obtained data was validated by a scaled-down model fully tested in the marine laboratory. Their results show that the direction of encountering waves is an extremely important factor. Also, wind loads can dampen the oscillation of the model and prevent the impact of large loads on the tethers. Borg, et, al. (2014a, 2014b), have studied the dynamics of a vertical axis wind turbine coupled with three different floating support structures, spar, semi-submersible, and TLP. They have used the FloVAWAT as a design tool with the MATLAB/Simulink environment. Bachynski, E. and Moan, T. (2012), have performed a parametric design on a single-column TLPWT and analyzed it in four different wind-wave conditions. The results indicate that, motions perpendicular to the incoming wind and waves especially in the parked configuration may be critical for TLPWT designs with small displacement. Simon and maurizio (2012) have investigated a preliminary design of a tri-floater 5-MW wind turbine. The pitch motion has been chosen as the critical design driver for the performance and stability of the support. Lei and Bert. (2012), have presented a new method to directly derive the nonlinear equations of motion of a floating wind turbine system using the theorem of conservation of angular momentum and Newton's second law. The results were compared with FAST. Robertson, et al. (2013), gave a summary for conclusions and recommendations for floating offshore wind systems regarding the limitations of FAST as a modeling tool for offshore wind turbines, as well as the scaled-model testing of these systems. Wang, et al. (2013), have investigated the potential advantages of floating vertical axis 5-MW wind turbine (FVAWT) mounted on a semisubmersible support structure. They presented the development of a coupled method for modeling of the dynamics of the system considering the wind inflow, aerodynamics, hydrodynamics, structural dynamics and a generator control.

This investigation addresses the dynamic responses for floating offshore wind turbines specially the tension leg platform types. Three floating support structures configurations are considered; the triangular, the square, and the pentagon support configurations. The environmental forces were taken as wind, regular waves, and random waves in multi-directions (0^0,30^0, 45^0,90^0, 135^0, 180^0), Wind and regular waves properties were taken according to the meteorological data for the red sea (Egyptian Meteorological Authority). Random waves were generated according to Pierson-Moskowitz spectrum, Abou-Rayan, and Husseien (2015). Finite element models were developed for the three configurations using ANSYS-AQWA software (ver.15.0). A 5-MW offshore wind turbine of NREL (National Renewable Energy Laboratory) reference model (Jonkaman et al., 2009) was used. The wind turbine effects on the supporting structures were calculated using FAST program (a comprehensive aero elastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines) where the output from FAST, v.8.0.Were considered as an input for the finite element models. A numerical scheme was written using MATLAB program for computing the PSD's.

DESCRIPTIONS OF THE TLPWT MODELS

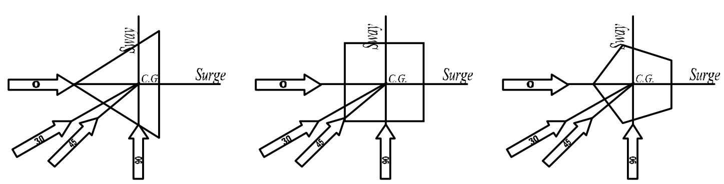
Three configurations were used in this investigation. Configurations properties and the 5-MW wind turbine property are listed in Table 1. The water depth is taken to be constant for all three configurations, which is 80 m. Also, the total tether stiffens is kept constant for all configurations, as shown in table 1.

Table 1: Configurations Properties

Properties of the 5-MW Wind Turbine			Model I	Model II	Model III
Rotor orientation Hub diameter Hub height Max rotor speed Max tip speed Rotor mass Nacelle mass Tower mass		Upwind, 3 blades 126 m, 3m 90 m 12.1 rpm 80 m/s 110,000 Kg 240,000 Kg 347,460 Kg		 s	
Model Shape			**Triangle**	**Square**	**Pentagon**
Length of the side			40m		
Floating system	Main column	No.	3	4	5
		Diameter	10m		
	Connecting beam	No.	6	8	10
		Diameter	2m		
Super structure	Main beam	No.	3	4	5
		Diameter	2m		
	Bracing	No.	6	8	10
		Diameter	1.5m		
Cables		No.	3	4	5
		Stiffness	2658870kn/m/ cable		

ENVIRONMENTAL CONDITIONS

The environmental conditions were taken according to the Egyptian Meteorological Authority (EMA) available data for the red sea northern region. Where, the maximum conditions according to the EMA were as following: a) maximum wave height =4m, maximum wind speed = 9.0 m/sec. In this investigation the regular wave height, wave period, and constant wind velocity were taken to be 5m, 12 sec, and 10.0 m/sec, respectively. For the random wave it was taken also as 5m for wave height and 12 sec. for energy period. It should be noted that, the wind velocity was taken in the direction of the wave. Also, a current load was added as a 10% of the wind load acting linearly in the direction of wind. A regular and random wave forces were considered acting on multi-directions on the three TLPWT configurations with wave heading angles (WHA): *0^o, 30^o,45^o, 90^o, 135^o, and 180^o*, see figure 1.



a) Model I b) Model II c) Model III

Figure 1: Multi-Directional Waves in Degrees

RESULTS AND DISCUSSIONS

FE models with a numerical scheme were developed to obtain the dynamic characteristics for the three models (configurations) mentioned above. Since there are a numerous number of figures, only the essential ones are shown (the response pattern for 180^o WHA is the same for 0^o, also for 45^o WHA has the same pattern as for 135^o for all DOF's) .

Since the heave responses are very small because of cables restrain (heave is a stiff DOF), they are not shown. It should be mentioned that time histories shown are only for a portion of the steady state responses (stationary responses).

Surge Response

Time histories and Power spectrum densities (PSD's) are shown in figures 2, 3, 4and 5 for all three models of TLPWT's for responses under regular waves. From figures 2-a, 3-a, 4-a, and 5-a, it is clear that the maximum responses are for the zero regular waves heading direction for all models. The highest response among the three models is for the triangular one with ~ 2.64 m., whereas for the square and pentagon configurations were less with about 8% and 17%, respectively, see figure 1-a. This is expected because of the structures geometry (mass, added mass, and number of pretensioned cables). Response decreased when the WHA increase (30, 45, and 90 degrees) with about the same response differences as before (8% and 17%). For a 90^o WHA (sway direction), responses die out and but it is not zero for all configurations. This is due to the steady state position, so the force excitation is non-zero. For all cases, it is clear from the PSD that the response has a semi-periodic pattern with a period doubling bifurcation (max peak response is at the wave excitation frequency = 0.523 rad/sec.), see figures 2-b, 3-b and 4-b. Also, surge-pitch couplings were observed for the three models with all WHA's except for WHA=90^o (natural frequency for pitch = 0.33 rad/sec.).

This is logic since pitch responses have zero values at this WHA. The surge-pitch coupling is inversely proportional to the WHA(decreasing the wave heading angle the surge-pitch coupling is more pronounced).It is observed that, increasing the WHA decreases the surge response and giving raise to the sway response to a limit where both are almost equal in amplitude magnitude, which is expected.

Time histories response and Power spectrum densities (PSD's) are shown in figures 6 and 7 (only 0^{o}and 30^o WHA are shown) for all three models of TLPWT's under random waves. All responses have a maximum frequency peak at almost half the excitation frequency. In general, all three models have the same response patterns (i.e. quantitatively) as those due to regular waves. Except that responses in the case of random waves are defiantly chaotic in nature as it is seen from figures. It is obvious the PSD's have multiple frequency responses contributions coming from almost all degrees of freedom.

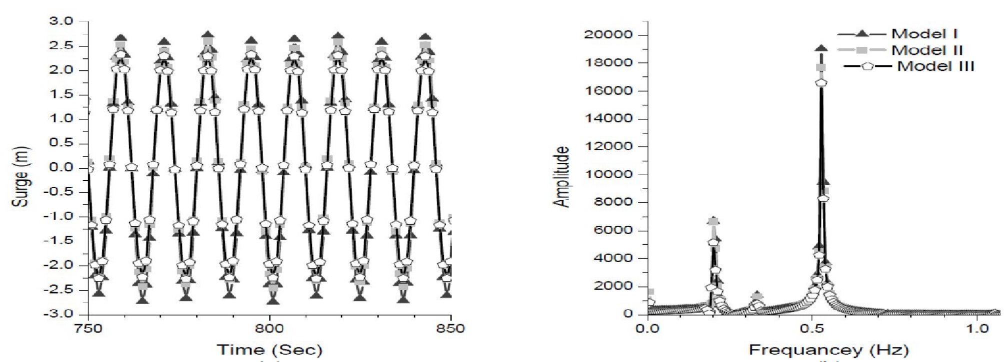


Figure 2: Responses under Regular Waves, WHA=0^0 A) Time History, B) Power Spectrum Density

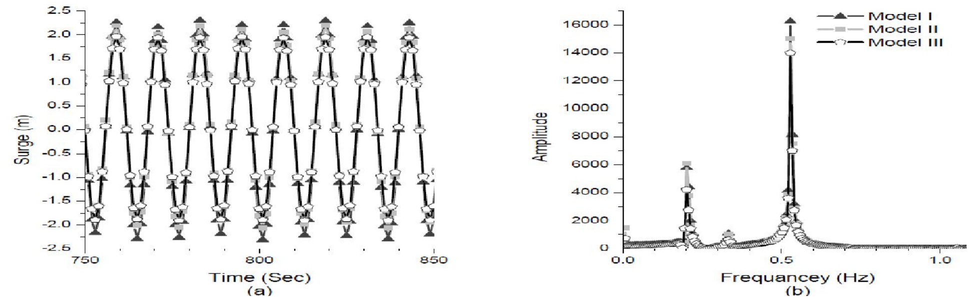


Figure 3: Responses under Regular Waves, WHA=30^0 A) Time History, B) Power Spectrum Density

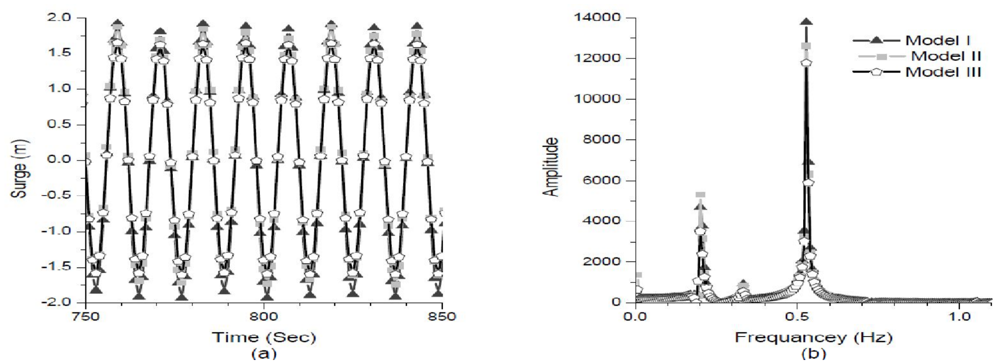


Figure 4: Responses under Regular Waves, WHA=45^0 A) Time History, B) Power Spectrum Density

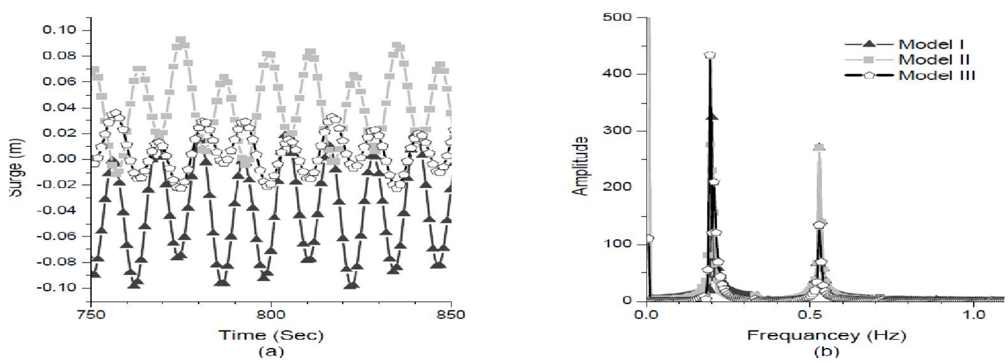


Figure 5: Responses under Regular Waves, WHA=90^0 A) Time History, B) Power Spectrum Density

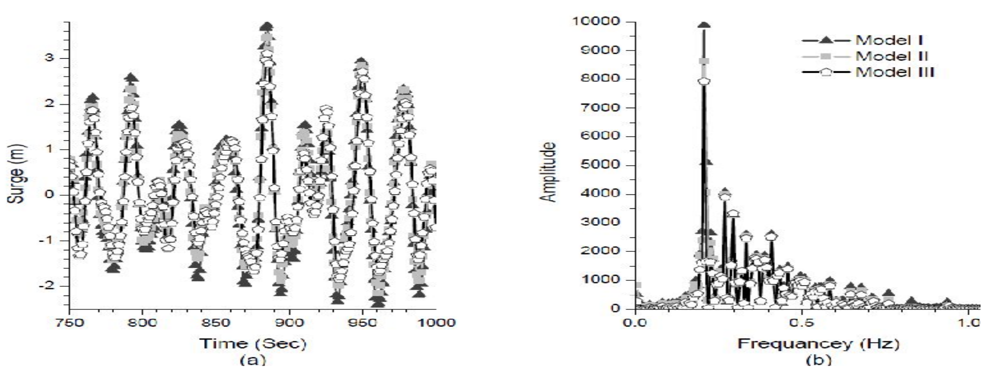


Figure 6: Responses under Random Waves, WHA=0^0 A) Time History, B) Power Spectrum Density

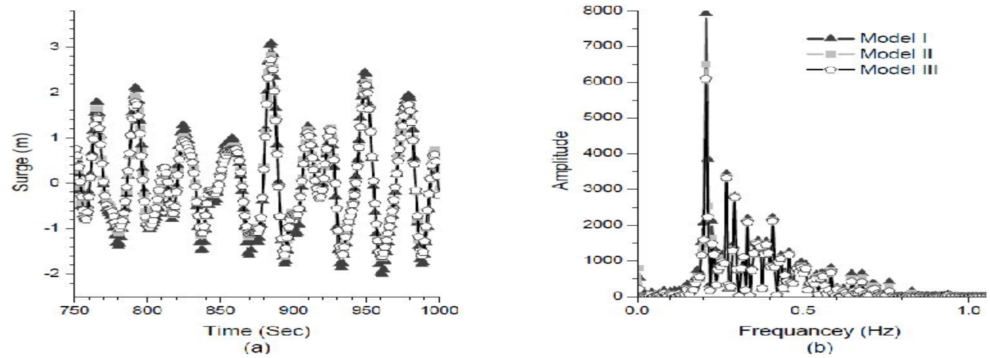


Figure 7: Responses under Random Waves, WHA=300 A) Time History, B) Power Spectrum Density

Sway Response

The same behavior patterns, for regular and random waves, as in the surge response are observed but in a reverse order, see figures 8 and 9 (show responses under regular waves only with WHA 45^{o} and 90^{o}). Increasing the WHA activates the response in the sway direction from almost zero to 2.54m, 2.30m, and 2.17m for the triangular, square, and pentagon configurations, respectively (due to regular waves). There are almost 15% increases in the response amplitude due to random waves than those due regular waves, for all configurations. Comparing figure 2-a, and figure 9-a, it is clear that responses for both surge and sway are equal in magnitude and have the same pattern. Also, comparing figure 5-a and figure 9-ait is clear that the surge response dies out for the case of WHA =90^{o} where the sway one reaches its maximum value contrary to the case of WHA=0^{o}. A sway-roll couplings (natural frequency for roll = 0.33 rad/sec.) are observed, which is directly proportional to the WHA, only with wave headings 30^{o}, 45^{o}, and 90^{o}for all configurations. For 0^{o} WHA, all configurations, the sway responses die out but after relatively long transition time. Again, responses due to random waves excitations take the same pattern as above but with a chaotic nature as shown in time history and PSD, see figure 10.

For plan view of surge-sway instability, figure 11, it seems like that the pentagon configuration is much more stable in moving on the sea surface, also see figure 12. The triangular response under regular waves with WHA=0 ^{o} is almost triple the pentagon one, although both responses are very small.

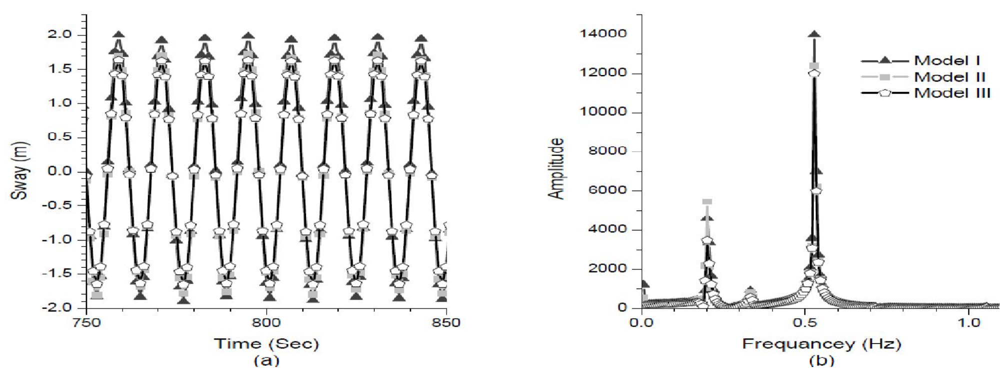


Figure 8: Responses under Regular Waves, WHA=45^{0} A) Time History, B) Power Spectrum Density

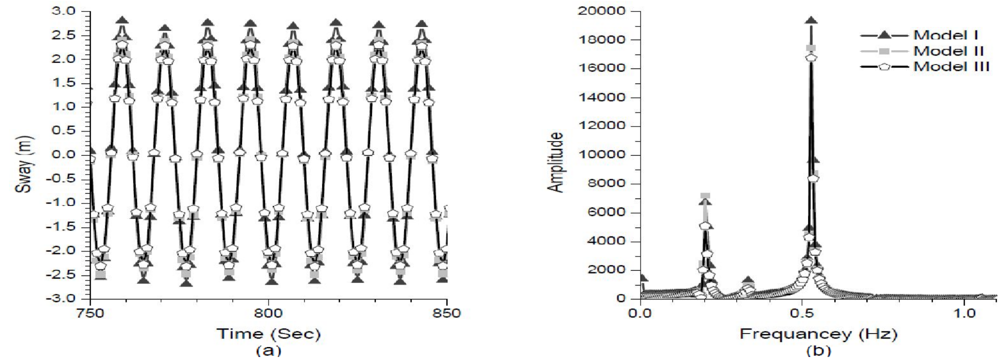


Figure 9: Responses under Regular Waves, WHA=90^0 A) Time History, B) Power Spectrum Density

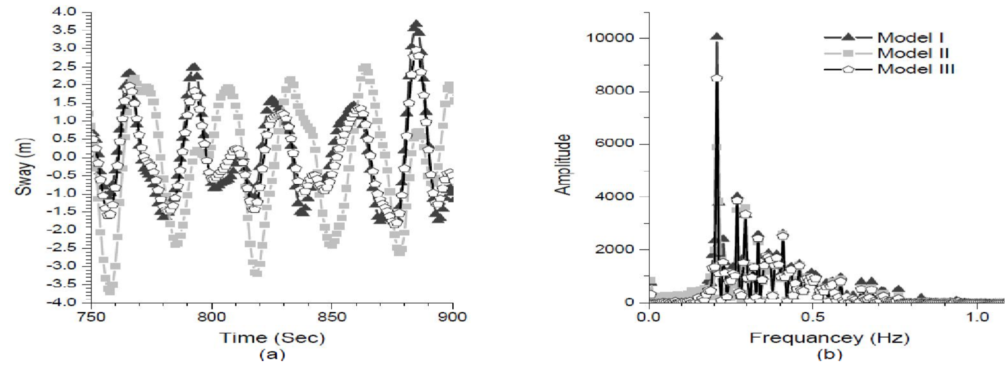


Figure 10: Responses under Random Waves, WHA=90^0 A) Time History, B) Power Spectrum Density

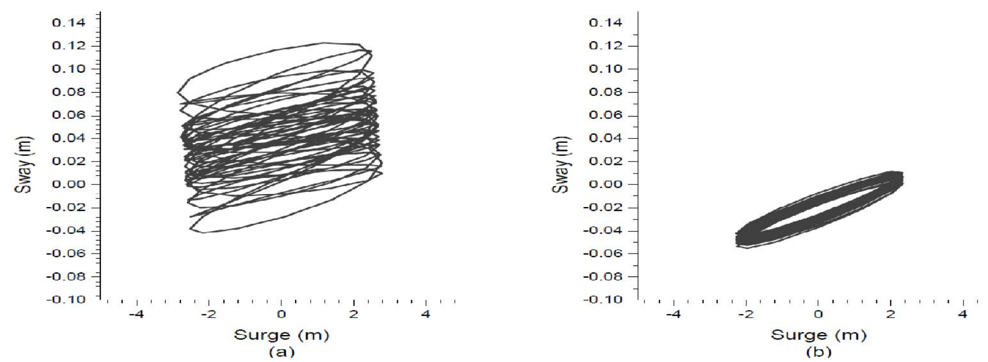


Figure 11: Instability Plane for Surge-Sway (WHA=0^0) A) Model I, B) Model III

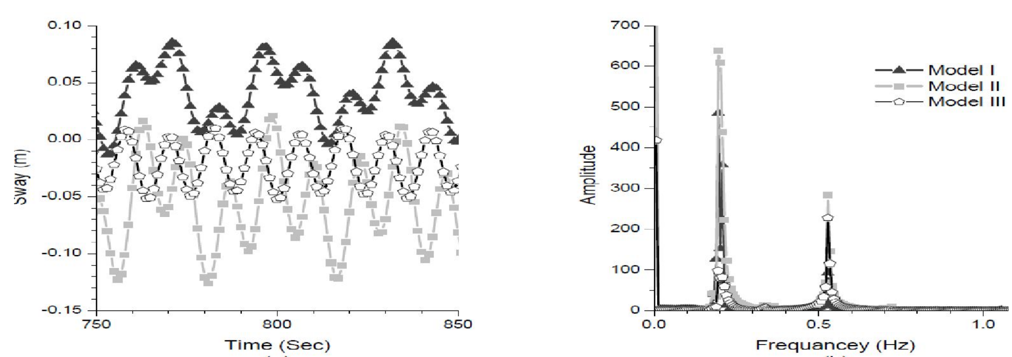


Figure 12: Responses under Regular Waves, WHA=0^0 A) Time History, B) Power Spectrum Density

Roll and Pitch Responses

Roll and pitch responses are affected by the sway and surge responses due to regular and random waves depending on WHA. Although the roll and pitch responses are very small, but an interesting phenomenon, only in case of regular waves, can be observed. Responses are modulated, i.e. responses grow over time and then die out for some time and repeat the same pattern again, see figures 13 and 14. This is called a modulation response and could be attributed to contributions from other degrees of freedom as shown in the PSD. It can be seen from the PSD's, figures 13-b and 14-b that we have a multiple frequencies responses (multiple semi periodic responses) tending to be chaotic under regular waves. For all roll and pitch responses as can be seen from the PSD's there is peak in the almost 1.2 rad/sec. frequency. This could be attributed to contribution from the yaw response, since the yaw natural frequency is 1.2 rad/sec. In the case of random waves, responses are extremely small, it should be mentioned that the PSD has multi frequencies contributions coming from all DOF's. Also, the motion is obviously chaotic one. The modulation phenomenon was not Cleary observed in the case of random waves (figures are not shown for responses under random waves)

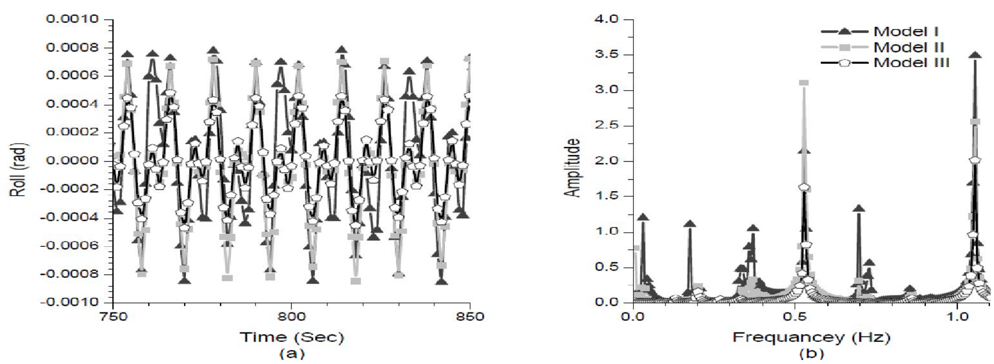


Figure 13: Responses under Regular Waves, WHA=90^0 A) Time History, B) Power Spectrum Density

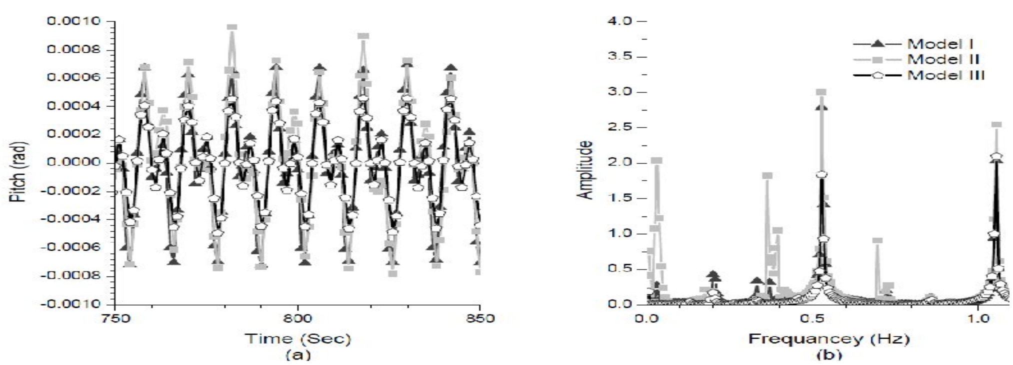


Figure 14: Responses under Regular Waves, WHA=0^0 A) Time History, B) Power Spectrum Density

Yaw Response

For regular and random waves excitations, the highest yaw response was found to be about 0.7, 0.5 rad respectively for the case of triangular configuration with WHA of 90^o, see figures 15 and 16, respectively.

This is because of the orientation of the wave to the geometry of the model, see figure 1. The pentagon configuration has the lowest response in the yaw DOF for all WHA's. This is expected because of the geometry and number of cables. For the triangular configuration the yaw response increases as the WHA increases. Also, the same response patterns under regular waves are observed under random waves. It is observed that the yaw response under regular wave has a period doubling bifurcation, which is not observed under random wave for WHA=90^{o}. In general the maximum yaw responses due to regular or random waves were found in the case of the triangular configuration and the lowest were for pentagon configuration.

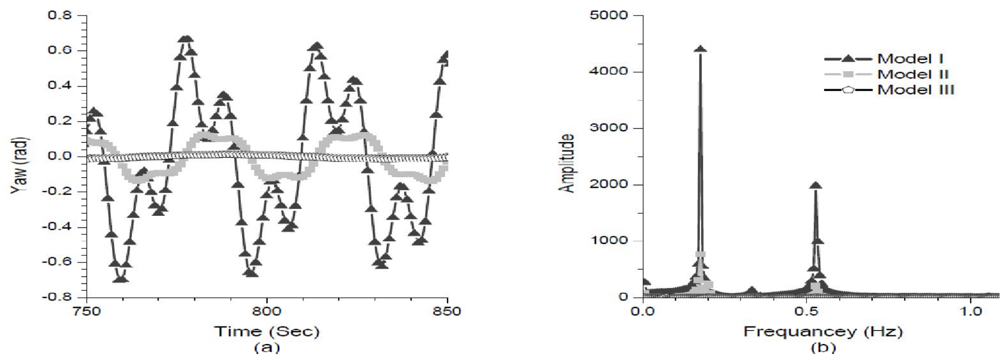


Figure 15: Responses under Regular Waves, WHA=90^{0} A) Time History, B) Power Spectrum Density

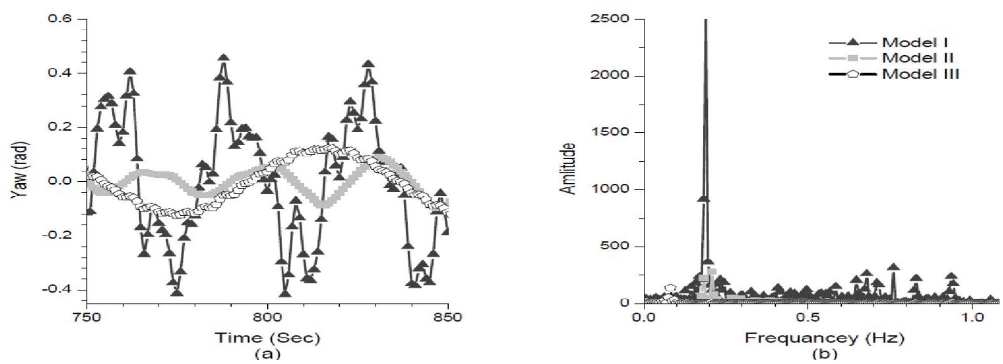


Figure 16: Responses under Random Waves, WHA=90^{0} A) Time History, B) Power Spectrum Density

CONCLUSIONS AND RECOMMENDATIONS

In this paper a proposed pentagon configuration for a TLPWT is proposed and compared with other two configurations, the triangular and square configurations. A finite element models were developed for the three configurations. The NREL 5-MW wind turbine was considered for all configurations. Wave's excitations, regular or random, were considered acting on multi-directions on the three TLPWT configurations. The FAST program by NREL was used to predict the dynamic effect of the 5-MW turbine on the supporting TLP structures considered. A MATLAB scheme was written to manipulate the data from FAST to the finite element program (ANSYS-AQWA) and to calculate the PSD's.

Based on the results and discussions aforementioned, the following conclusions can be drawn:

- The highest and the lowest responses from all configurations and WHA's were for the triangular and pentagon configurations respectively with 0^{o} WHA in the surge direction, wither the waves were regular or random. These responses are expected because of geometry shapes which lead to mass, added mas, and number of pretension cables variances.
- Responses depend significantly on the WHA. For the three TLPWT considered, increasing the WHA

decreasing the surge response and increasing the sway one. In other word, increasing the WHA activates specific degrees of freedom which otherwise are not activated under certain WHA. This is logically acceptable because of the wave direction.

- The magnitude of motion of the rotational degrees of freedom, roll and pitch depend on the WHA, with increasing the WHA roll response increases and pitch response decreases. Since, they are very small (in agreement with Koji, 2012) no major change for wind turbine on land to be mounted on TLP's.
- Yaw responses are higher for the triangular configurations than other ones.
- Surge-pitch and sway-roll coupling were observed.
- Responses under regular waves excitations are periodic ones with period doubling bifurcations being observed, for translation degrees of freedom (surge, Sway, and Yaw) and semi-periodic for rotational degree of freedom (roll, pitch, and yaw).
- Responses under random wave's excitations are chaotic in nature.

In conclusion the pentagon configuration response is more stable and gives the lowest response compare to the triangular and square configurations but on the other hand it is more costly. Finally it's recommended that an experimental investigation should be considered to compare the numerical results with the experimental ones (this recommendation is in progress).

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