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Published in:
IWWWFB26

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Response of a TLP floating wind turbine subjected to combined wind and wave loading

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1 INTRODUCTION

In this paper, a tension leg platform solution for a floating offshore wind turbine is investigated. A representative location has been chosen to define the environmental loading conditions. The proposed configuration has been subjected to combined wind and wave loading giving rise to the coupled response. The initial study has been done for a two dimensional configuration and two dimensional waves. The effect of wind loading is modelled by means of a simplified constant thrust and a varying aerodynamic thrust from unsteady Blade Element Momentum theory. Wind and wave loads are coupled through a simplified method. The two dimensional responses provide insight into the platform motion and wind turbine behaviour, which gives further motivation for extending the model to 3D and further coupling with an advanced aero-elastic code.

2 CONFIGURATION

2.1 Two dimensional simplified configuration

A two dimensional schematic of the selected TLP configuration is shown in Figure 1. The NREL 5 MW numerical wind turbine has been chosen [1]. In the present simplified study, the platform together with tower and nacelle has been modelled as lumped masses, connected through a spring and damper, whereas, the blades are modelled as distributed masses with first three mode shapes. Rotor thrust and torque from the wind have been modelled.

2.2 Environmental conditions

For the present study, the North Sea in the coastal part of Norway has been chosen. Water depth in this location is of magnitude 200 m. Representative parameters for the wind and wave climate are shown in Table 1. The force coefficients have been listed in Table 2 [2].

Table 1: North Sea Wave and Wind Climate

Parameter	Value
Significant wave height	7 m
Peak period	10 s
Water depth	200 m
Wind conditions	
Annual average wind speed	8-10 m/s

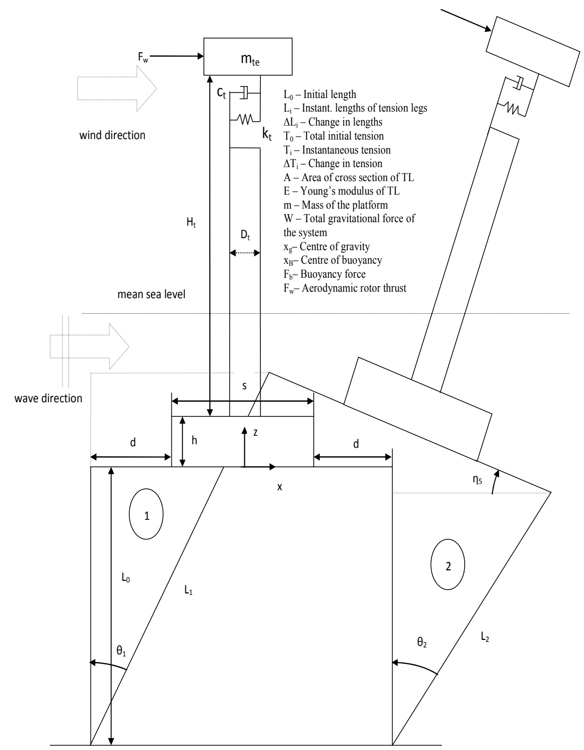

Figure 1: TLP configuration – schematic

Table 2: Force coefficients

Parameter	Value
Added mass and drag coefficients in surge	1.0, 1.0
Added mass and drag coefficients in heave	0.64, 2.0

3 FORMULATION

3.1 Two dimensional TLP – Assumptions

The assumptions followed for the simplified configuration are given below.
In 2D, the platform six degrees of freedom boil down to three degrees of freedom, viz. surge, heave and pitch, which are coupled to each other. The tendons are assumed to be linear elastic with an axial stiffness much higher than the bending stiffness. The tower bending flexibility has been included using an equivalent spring and damper. Linear Airy wave theory has been considered for the waves. Morison's equation has been used for computing the hydrodynamic forces.

3.2 Equations of motion

The equations of motion for the coupled three degrees of freedom are:

$$m_1\ddot{\eta}_{1f} = F_1 + k_t\eta_{1t} + c_t\dot{\eta}_{1t} - T_1\left(\frac{\eta_1 + \tilde{d}(1 - cos\eta_5)}{L_1}\right) - T_2\left(\frac{\eta_1 - \tilde{d}(1 - cos\eta_5)}{L_2}\right) \quad (1)$$

$$\mathrm{m_t}\ddot{\eta}_{1t} = \mathrm{F_w} - \mathrm{k_t}\eta_{1t} - \mathrm{c_t}\dot{\eta}_{1t} - \mathrm{m_t}\ddot{\eta}_{1f} \quad (2)$$

$$m_3\ddot{\eta}_3 = F_3 + T_0 - \rho g\frac{\pi}{4}D_t^2\eta_3 - T_1\left(\frac{L_0 + \eta_3 + \tilde{d}sin\eta_5}{L_1}\right) - T_2\left(\frac{L_0 + \eta_3 - \tilde{d}sin\eta_5}{L_2}\right) \quad (3)$$

$$\begin{aligned} J_5\ddot{\eta}_5 = {} & F_5 + Wx_g - F_b x_B + F_w(H_t + h)\cos\eta_5 + T_2\left(\frac{L_0 + \eta_3 - \tilde{d}\sin\eta_5}{L_2}\right)\tilde{d}\cos\eta_5 \\ & + T_2\left(\frac{\eta_1 - \tilde{d}(1 - \cos\eta_5)}{L_2}\right)\tilde{d}\sin\eta_5 - T_1\left(\frac{L_0 + \eta_3 + \tilde{d}\sin\eta_5}{L_1}\right)\tilde{d}\cos\eta_5 \\ & - T_1\left(\frac{\eta_1 + \tilde{d}(1 - \cos\eta_5)}{L_1}\right)\tilde{d}\sin\eta_5 \end{aligned} \quad (4)$$

Where, $\tilde{d}$ = s/2+d, η_1, η_3 and η_5 represent surge, heave and pitch displacements respectively, $(\dot{\ })$ and $(\ddot{\ })$ represent first and second derivatives with respect to time.

3.3 Wave loading

Linear regular and irregular waves have been considered for the wave climate mentioned in Table 1. The wave kinematics has been Delta stretched from 25 m below mean sea level. The wave induced forces are formulated as follows:

In the surge direction,

$$dF_1 = C_m\rho A(\dot{u} - \ddot{\eta}_1)dz + \rho A\dot{u}dz + C_D\frac{1}{2}\rho s|u - \dot{\eta}_1|(u - \dot{\eta}_1)\,dz \quad (5)$$

In the heave direction,

$$F_3 = \frac{\pi}{4}s^2(p_b - p_t) + \frac{\pi}{8}s^2\rho C_{Dz}|w - \dot{\eta}_3|(w - \dot{\eta}_3) + \frac{4}{3}\pi\left(\frac{s}{2}\right)^3\rho C_{mz}(\dot{w} - \ddot{\eta}_3) \quad (6)$$

In the pitch direction,

$$dF_5 = C_m\rho A(\dot{u} - \ddot{\eta}_1)zdz + \rho A\dot{u}zdz + C_D\frac{1}{2}\rho s|u - \dot{\eta}_1|(u - \dot{\eta}_1)\,zdz \quad (7)$$

The z coordinate with respect to the platform is shown in Figure 1. In the case of irregular waves, the wave spectrum has been constructed based on the JONSWAP spectrum with peak enhancement factor 3.3.

3.4 Wind loading

The aerodynamic loading has been computed using unsteady Blade Element Momentum (BEM) theory, with inclusion of wind shear, tower shadow, dynamic stall, dynamic wake and yaw [3]. Four load cases have been considered, viz. 1) a simplified deterministic constant thrust force, 2) time series thrust from BEM without wind shear, 3) time series thrust from BEM with wind shear and 4) time series thrust from BEM using a spatially coherent turbulent wind spectrum based on [4]. The time series and frequency domain wind spectrum for coherent turbulence are shown in Figure 3. In Figure 3, the frequency domain y-axis has been chosen as fS(f). A further goal (not reported here) is to include the case of spatially varying turbulence. In all of the load cases, the rotor thrust is ramped to the real value within a time span of 50 s, in order to avoid the unrealistic initial responses (see eg: [5]).

3.5 Coupling

The real aim for the numerical model is a full dynamic coupling of the rotor, tower and floater motions subjected to simultaneous wind and wave loads. As a first crude step, we here report on an incomplete coupling, where the BEM model is first run with a fixed tower base. Next, the forces at the tower base are applied within the hydrodynamic model for the platform. Hereby a response of the platform from simultaneous wind and wave loads is obtained.

In this incomplete approach, however, the influence from the wave-induced rotor motion on the aerodynamic loads is missing.

4 RESULTS AND DISCUSSION

The time series and frequency response plots for irregular wave forcing for different load cases of aerodynamic loading are shown in Figures 4, 5, 6 and 7 respectively.

4.1 Surge response (η_1)

The time series shows a positive mean, which was expected because of the presence of rotor thrust. The surge response is higher in the case of first load case (Fig. 4) compared to the BEM generated aerodynamic thrust cases (Figs. 5, 6 and7). This is because the fluctuating aerodynamic thrust has a smaller mean compared to the simplified thrust, which will give rise to higher response for the simplified thrust case. The predominant peak is at the peak wave frequency and we can also see the peaks corresponding to surge and tower natural frequencies.

4.2 Heave response (η_3)

The time series shows a negative mean, which was expected because of the set-down effect of the system. The predominant peak is at the peak wave frequency and we can also see other peaks corresponding to surge, heave and tower natural frequencies. The presence of the surge frequency is a consequence of the set-down effect. Since the surge response has a positive mean because of the presence of rotor thrust, we will not see a peak corresponding to double the surge frequency, instead we can see the surge frequency as it is as a consequence of set down effect. The response is larger for first load case (Fig. 4) compared to the other load cases. The explanation is the same as that of the surge case.

4.3 Pitch response (η_5)

The time series shows a positive mean, which was expected because of the presence of rotor thrust. The predominant peak is at the pitch natural frequency. Smaller peaks at the peak wave and tower natural frequencies occur. Only in the case of simplified rotor thrust (load case 1), we can see the presence of a peak at the surge natural frequency. The mean pitch response for BEM aerodynamic loading are smaller compared to simplified thrust loading and the explanation is the same as that of surge.
An interesting phenomenon in the case of pitch response is that although the amplitudes are smaller, we can see the pitch response grows over time, dies out after some time and again grows with an approximate time interval of 150 s. This modulation could be because of the neighbourhood of the pitch (0.33 Hz) and heave (0.3375 Hz) natural frequencies, which means when both of the frequencies are in phase, we get a maximum response, whereas when they are out of phase the response is minimum. Additionally, the pitch response is slowly increasing in time. This indicates a possible resonant response to the forcing. This has been confirmed by incorporating an artificial pitch damping and observing the response, which doesn't have the pitch natural frequency peak and the response dies out to a steady value. In order to show the complete pitch response, the x-axis for the time domain pitch response has been chosen from 400 s to 1000 s.

5 CONCLUSIONS AND FUTURE WORK

The 2D dynamics of a TLP offshore wind turbine configuration has been investigated in terms of four load cases of combined wave and wind forcing. The present design has been found to be stable in the prescribed environmental conditions except for a resonance effect for the pitch response. Further incorporating appropriate pitch damping from the spokes or arms of the floater might influence the computed response. Further work is to extend the model to three dimensions and coupling with an advanced aero-elastic code. Full coupling of the three dimensional wave load procedure with unsteady BEM model will provide results on the completely integrated system response.
As a final step, an effective stochastic procedure, the First Order Reliability Method (FORM), will be applied to derive extreme values and fatigue estimates for the total system [5]. This will enable the evaluation of the feasibility of different configurations.

ACKNOWLEDGEMENT

This research was carried out as part of the Statkraft Ocean Energy Research Programme, sponsored by Statkraft (www.statkraft.no). This support is gratefully acknowledged.

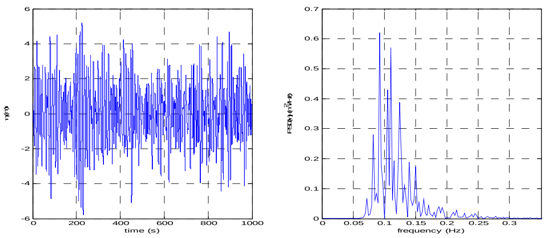

Figure 2: Wave input

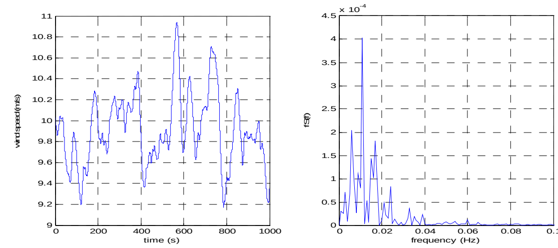

Figure 3: Wind input for Load Case 4

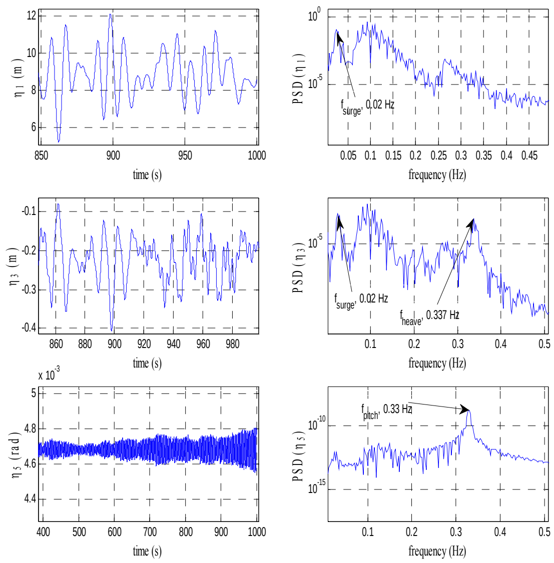

Figure 4: Response of Load Case 1

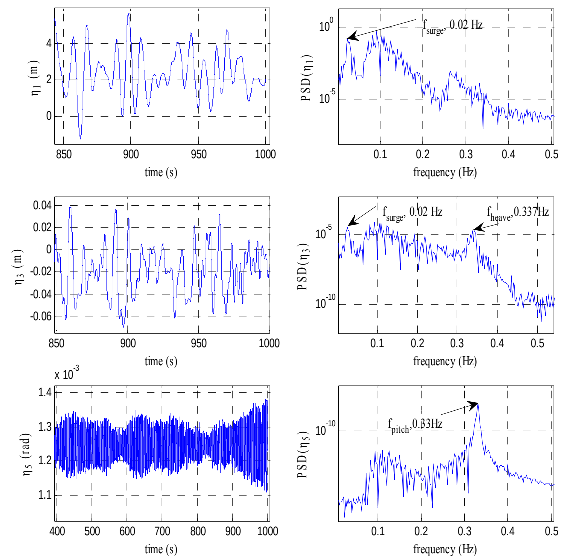

Figure 5: Response of Load Case 2

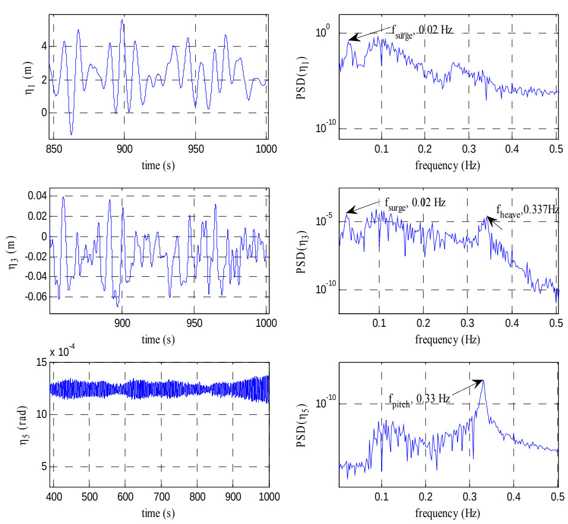

Figure 6: Response of Load Case 3

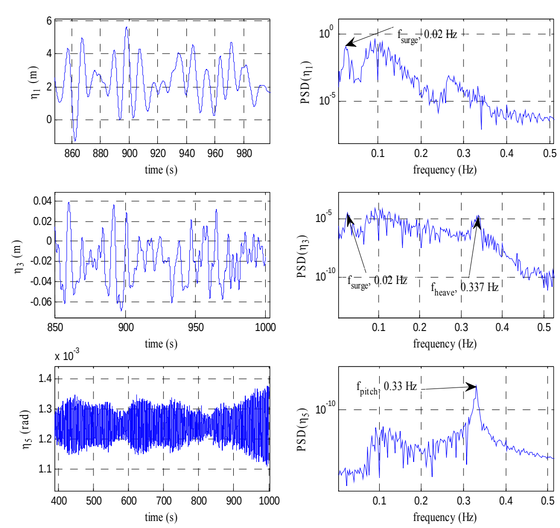

Figure 7: Response of Load Case 4

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