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DYNAMIC ANALYSES OF A TENSION LEG PLATFORM (TLP) UNDER VERY ROUGH SEA-STATE

DINAMIČKA ANALIZA PREDNAPREGNUTE NOŽNE PLATFORME (TLP) U VRLO TEŠKIM USLOVIMA NA MORU

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- offshore engineering
- structural dynamics
- Pierson-Moskowitz (PM) spectrum
- offshore platforms
- Tension Leg Platform (TLP)

Abstract

In order to minimize the risk as well as cost in offshore deep-water activities, the development of several floating offshore platforms has taken place. Being the most widely employed platform for deep-water operations, the performance of a Tension Leg Platform (TLP) is remarkable in terms of its motion under the influence of waves. Dynamic analysis has a key role in the evaluation process of the performance of these platforms in offshore environment. This study focuses on the dynamic numerical analysis of the International Ship and Offshore Structures Congress (ISSC) TLP platform in irregular waves under very rough sea-state using Pierson-Moskowitz (PM) spectrum. The impact of coupling between 2 degrees of freedom (DOF) of TLP motion, surge, and heave, is a significant problem with regard to its structural response. Hence, the motion of the TLP in these two DOF is considered. The TLP's natural periods are computed and validated. From engineering design and response analysis perspective, the study will be useful for offshore engineers to acquire deeper insights into the structural response of TLP.

Ključne reči
- ofšor inženjering
- dinamika konstrukcija
- Pirson-Moskovic (PM) spektar
- ofšor platforme
- prednapregnuta nožna platforma (TLP)

Izvod

Da bi se smanjio rizik, kao i troškovi na ofšor aktivnostima u dubokim vodama, razvijeno je nekoliko plutajućih ofšor platformi. Budući da je najrasprostranjenija platforma za operacije u velikim dubinama, performanse prednapregnute nožne platforme (TLP) su izvanredne u pogledu njenog kretanja pod uticajem talasa. Dinamička analiza ima ključnu ulogu u procesu procene performansi ovih platformi u ofšor okruženju. Ova studija je usredsređena na dinamičku numeričku analizu TLP platforme Međunarodnog kongresa brodskih i ofšor konstrukcija (ISSC) u uslovima nepravilnih talasa pod vrlo teškim uslovima na moru, koristeći Pirson-Moskovic (PM) spektar. Uticaj sprege dva stepena slobode (DOF) kretanja, udara i odizanja TLP-a je značajan problem s obzirom na njegov strukturni odziv. Dakle, kretanje TLP-a u ova dva DOF se razmatra u predstavljenom radu. Sopstveni periodi TLP-a se izračunavaju i potvrđuju. Iz perspektive inženjerskog projektovanja i analize odziva, ovo istraživanje će biti korisno za ofšor inženjere radi sticanja šireg uvida u strukturni odziv TLP-a.

INTRODUCTION

Hydrocarbon resources play a very significant role in the development of human society. The growth in energy demand is closely associated with the progress in the world economy, which is established on these natural resources. This demand growth has further increased the dependency on oil and gas. In order to handle the energy needs, the industry is forced to explore deeper water in search of hydrocarbon resources, /1, 2/. Fixed platforms and compliant platforms are the two main categories of offshore platforms. Weight of the fixed platforms holds them in their place while reaching out to the seabed. In the case of compliant platforms, mooring systems confine them at their position. TLP is often regarded as a hybrid platform. It behaves as a compliant structure when horizontal DOF are taken into consideration. However, when it comes to vertical DOF the platform is stiff and behaves as a fixed structure, /3/. The buoyancy of this moored floating structure significantly exceeds its own weight. This makes it different from the rest of column-stabilized moored platforms. Taut moorings are necessary to connect the structure on top to seabed foundation and to ensure its vertical equilibrium. Figure 1 illustrates a typical TLP configuration.

The TLP's mooring system is composed of several tensioned tethers or tendons, which establish the connection between the seabed foundation and the platform hull. In this way, the motion of the platform along horizontal plane is permitted while its motion along vertical plane is restricted. The tethers are maintained in tension by way of excess buoyancy of the surface platform. They help maintaining much lower levels of heave, pitch, and roll responses in comparison with surge, sway, and yaw responses. Figure 2 highlights the various DOF of platform motion. The TLP's natural periods in various DOF and that of the dominant waves are indicated in Table 1, /4/. The TLP does not get excited at its natural frequencies by the forces at the dominant wave frequencies, /5/.

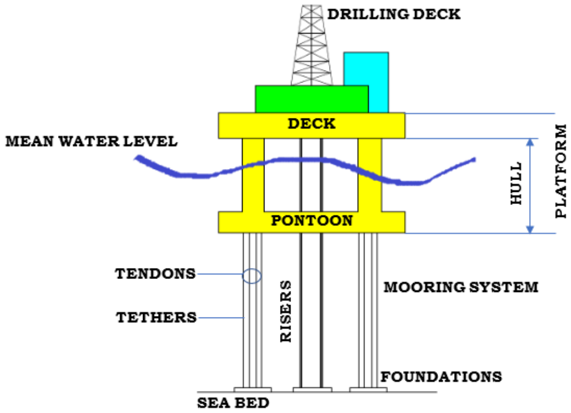

Figure 1. Schematic diagram of a TLP (modified from /6/).

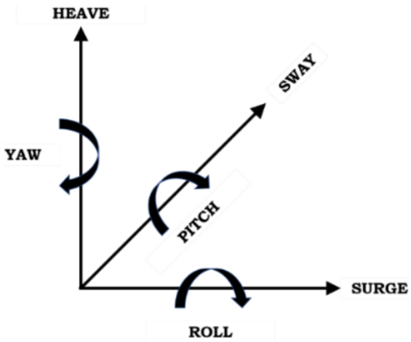

Figure 2. DOF in TLP motion (modified from /7/).

Table 1. Natural periods of TLP in various DOF and that of the dominant waves, /4/.

Component	Natural periods (s)
Dominant waves	6-18
Heave, pitch and roll DOF	2-4
Surge, sway, and yaw DOF	80-120

The hull of the TLP has a dead weight, about two-third of the buoyancy. The tendon mooring system is a significant element associated with the platform, /8/. Its absence can cause instability of the platform hull. The installation of TLP in deep-water settings is accomplished by increasing the length of the tethers. As compared to other offshore structures, a remarkable cost reduction is achieved due to this method. In order to generate tension in the tethers, the process of ballasting the structure, where the mooring connection is established, is succeeded by the process of deballasting. The compliant nature of this platform ensures that the incoming wave load results in less impact on the structure. This makes it a best fit for operating under very rough sea-state. The TLP's natural frequencies in the translational and rotational DOF is away from the frequencies of the wave as a matter of which the possibilities of resonance condition are averted. The easiness in dismantling, transporting, and installing a TLP adds up to its several advantages. Unlike other fixed platforms, TLP is safer for operation in zones that are seismically active. The convenience in monitoring the tether and risers happens due to its state of being restrained in the vertical DOF. The present study focuses on the numerical modelling of tension leg platform under very rough sea-state and carrying out the dynamic analysis to obtain the structural response and tether tension variation for a given sea-state condition.

MASS MATRIX, STIFFNESS MATRIX, AND HEAVE AND SURGE NATURAL PERIODS OF A TLP

The mass matrix of a TLP is represented in Eq.(1), /9/. The mass of the structure is lumped at the corresponding DOF in the derivation. The water that environs the submerged regions of columns and pontoons contributes to the term defined as added mass. This is represented as Ma. The structure's total mass is defined by terms M_{11}, M_{22} and M_{33}. The mass moment of inertia about the different axes x, y and z are defined by terms M_{44}, M_{55} and M_{66}, respectively. In the surge and heave DOF, the added mass terms are represented as Ma_{11} and Ma_{33}, respectively. Ma_{42} and Ma_{51} are the corresponding terms used to represent added mass moment of inertia associated with the roll and pitch DOF.

$$[\mathrm{M}]=\begin{bmatrix} M_{11}+M_{a11} & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{33}+M_{a33} & 0 & 0 & 0 \\ 0 & M_{a42} & 0 & M_{44} & 0 & 0 \\ M_{a51} & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}. \quad (1)$$

Equation 2 represents the stiffness matrix of a TLP. The first principles form the basis to derive the coefficients of stiffness matrix for the TLP, /10/. It is worth noting that a strong coupling exists between the heave and other DOF.

$$[\mathrm{K}]=\begin{bmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & 0 \\ K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} \\ 0 & K_{42} & 0 & K_{44} & 0 & 0 \\ K_{51} & 0 & 0 & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{66} \end{bmatrix}. \quad (2)$$

Here the mass and the added mass of the platform are represented by terms M and Ma, respectively. The motion and position of the TLP are described on the basis of a coordinate system in such a way that the geometric centre of the platform hull's bottom plane corresponds with its origin. Surge, sway, heave, roll, pitch, and yaw constitute the 6 DOF.

PARTICULARS OF ISSC TLP

Water depths more than 1000 ft (305 m) are categorized into deep-water settings, while water depths more than 5000 ft (1524 m) are categorized into ultra-deep-water settings /11/. The platform performs in deep-water settings combined with severe environment. TLP has been chosen for the presented study owing to its lessened dynamic response in deep-water conditions. The International Ship and Offshore Structures Congress (ISSC) TLP model is considered for this analysis. The geometry of the model (Fig. 3) comprises of 4 vertical cylindrical columns and horizontal pontoons. A group of tendons are attached at the end of each corner. The particulars of the platform are specified in Table 2. This TLP has been extensively utilized by several researchers and organisations for research activities, /12, 13/. Seventeen different organisations participated to provide load and response data corresponding to the platform, /14/.

Table 2. Key features of ISSC TLP, /13/.

Parameters	Dimensions
Diameter and spacing between centres of the column	86.25 m and 16.88 m
Pontoon height and width	7.50 m and 10.50 m
Draft at MWL	35.00 m
Displacement	5.346×10^5 kN
Platform weight	40.5×10^7 N
Total pretension in the tether	1.373×10^5 kN
Metacentric heights (longitudinal and transverse)	6.0 m each
Mass moment of inertia (roll)	82.37×10^9 kgm^2
Mass moment of inertia (pitch)	82.37×10^9 kgm^2
Mass moment of inertia (yaw)	98.07×10^9 kgm^2
Vertical position of COG above keel	38.0 m
Mooring tether`s length	415.0 m
Combined tethers' vertical stiffness (*EA/L*)	0.813×10^6 kN/m
Roll and pitch effective stiffness (EI_x/L and EI_y/L)	1.501×10^9 kNm/rad

ANSYS® AQWA is employed to perform the numerical analysis of the platform. Design Modeller is used to model the platform, as shown in Fig. 4, with specified dimensions in Table 2. The fluid wave loading is simulated on the basis of radiation theory, or 3D diffraction theory. While performing dynamic simulation in time domain, predictor-corrector scheme is used to integrate the acceleration for simulating the motion of the floating body in real time. The entire platform mass along with the deck is lumped at its centre of gravity. 3-point Gaussian integration scheme is employed to compute the hydrodynamic forces. Tethers with axial stiffness are modelled using cable elements. The stretching of tether elements is carried out to obtain the initial tension. 3D panel method is used to mesh the numerical model. The meshed model is shown in Fig. 5.

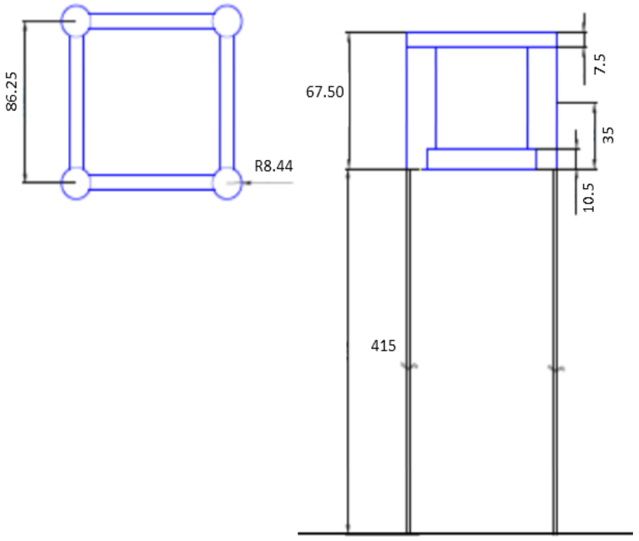

Figure 3. Configuration of the TLP model (modified from /12/, dimensions are in m).

$$\left[\mathrm{M}+\mathrm{M}_a\right]\ddot{x}(t)+\left[\mathrm{C}\right]\dot{x}(t)+\left[\mathrm{K}\right]x(t)=F(t)\,. \qquad (3)$$

For solving Eq.(3), convolution integration technique is employed. M, M_a, [C] and [K] are respective representations of structural mass matrix, added mass matrix, damping matrix, and stiffness matrix. $F(t)$, $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ are the respective representations of force, displacement, velocity, and acceleration vectors.

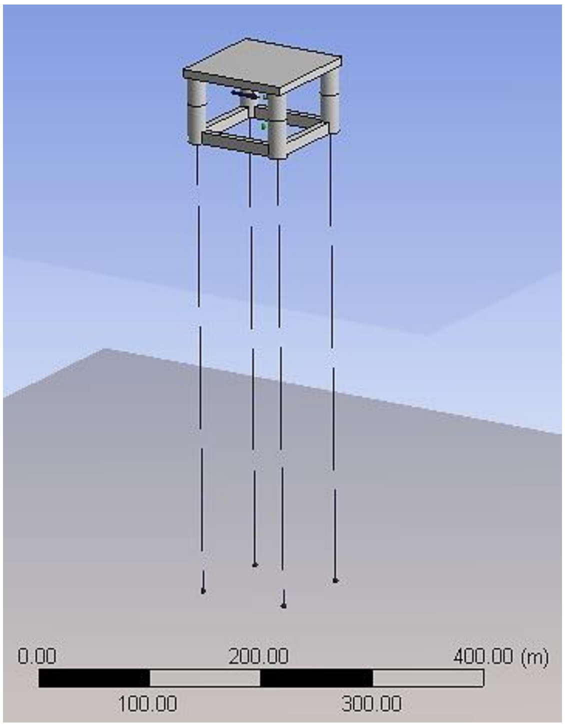

Figure 4. ISSC TLP modelled in ANSYS® AQWA module.

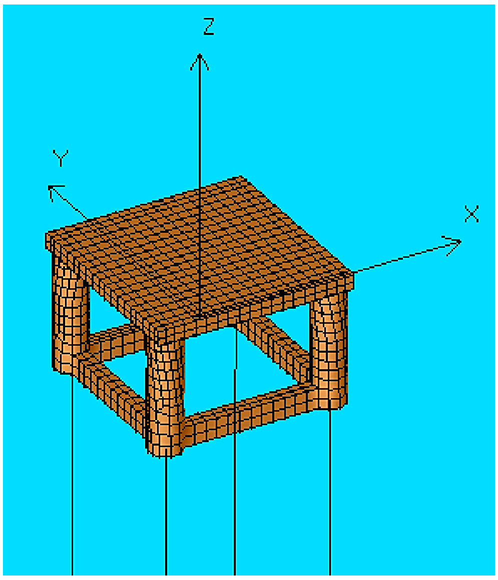

Figure 5. Meshed numerical model of ISSC TLP with 4 sets of tethers.

The natural periods in all the DOF of the platform are obtained from decay tests. During the decay tests, an external perturbation force is provided at each DOF to analyse the vibration responses of the platform. These tests are carried out numerically. For an external perturbation force of 10 MN at heave DOF, the respective decay test responses are presented in Fig. 6. The heave natural period is estimated from the figures and is found to be 1.83 s. The natural periods corresponding to the surge and heave DOF and their validation results are mentioned in Table 3.

Table 3. Natural period of ISSC TLP obtained from free decay test.

DOF	Natural period (s)	Frequency (rad/s)	Natural period (rad/s), /12/
heave	1.83	3.43	3.14

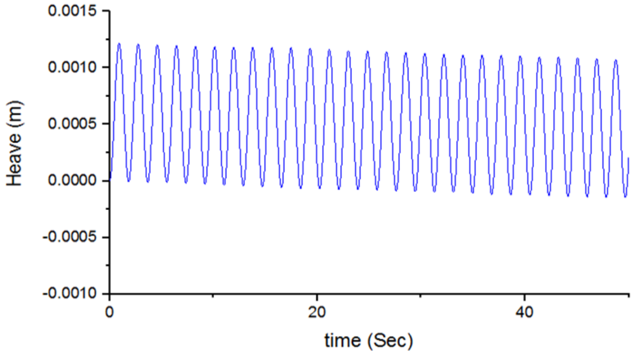

Figure 6. Decay test response obtained in heave DOF.

DYNAMIC RESPONSE OF THE TLP IN IRREGULAR WAVE CONDITIONS

Sea-state is generally defined as the state of the free surface on a large water body at any place and time. It is defined by significant wave height (H_s) and spectral zero crossing period (T_z). Various sea-states are defined in Table 4. The dynamic response analysis of the ISSC TLP in irregular wave conditions under very rough sea-state is carried out using PM spectrum in ANSYS® AQWA. The environmental parameters used for the analysis are shown in Table 5.

Table 4. Description of sea-states, /15/.

WMO sea-state code	Wave height (m)	Characteristics
0	0	calm (glassy)
1	0 – 0.1	calm (rippled)
2	0.1 – 0.5	smooth (wavelets)
3	0.5 – 1.25	slight
4	1.25 – 2.5	moderate
5	2.5 – 4	rough
6	4 – 6	very rough
7	6 – 9	high
8	9 – 14	very high
9	Over 14	phenomenal

Table 5. Environmental parameters used for the analysis.

Parameters	Values
Significant wave height (H_s)	5 m
Spectral zero crossing period (T_z)	7 s

Using a unidirectional wave and PM spectrum, dynamic analysis is carried out on the numerical model in the time-domain for 3000 seconds. This spectrum is chosen owing to its suitability for open sea conditions with two parameters that have been established over a large fetch with moderate winds. The spectrum can be represented using Eq.(4),

$$S^{+}(\omega)=\frac{1}{2\pi}\frac{H_s^2}{4\pi T_z^2}\left(\frac{2\pi}{\omega}\right)^2\exp\left(-\frac{1}{\pi T_z^4}\left(\frac{2\pi}{\omega}\right)^4\right), \quad (4)$$

where: H_s; T_z; and ω represent significant wave height, zero crossing period, and frequency, respectively.

RESULTS AND DISCUSSION

The response of the platform in all six DOF is obtained after subjecting the platform to the environmental parameters mentioned in Table 5. The platform response for surge DOF is shown in Fig. 7. It is observed to surge -2.5 to 2.5 m about the mean position. The platform response for sway DOF is given in Fig. 8. It is observed to sway -0.035 to 0.035 m about the mean position. The platform response for heave DOF is shown in Fig. 9. It is observed to heave -0.015 to 0.008 m about the mean position. The heave response is very marginal as the pre-tension imposed on the tethers constrains the motion of the platform.

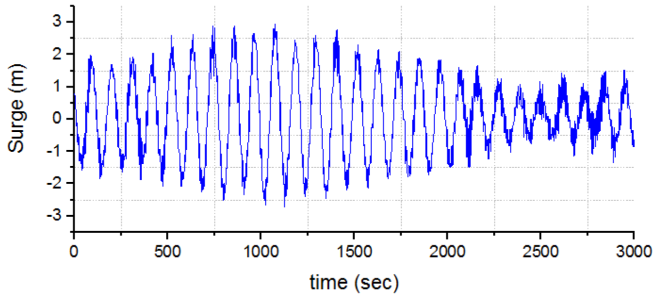

Figure 7. Response for surge motion of TLP (H_s = 5 m, T_z = 7 s).

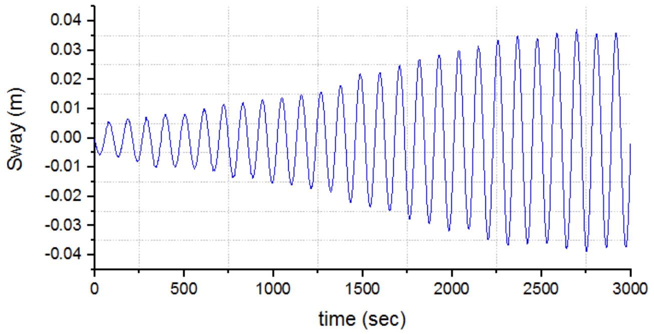

Figure 8. Response for sway motion of TLP (H_s = 5 m, T_z = 7 s).

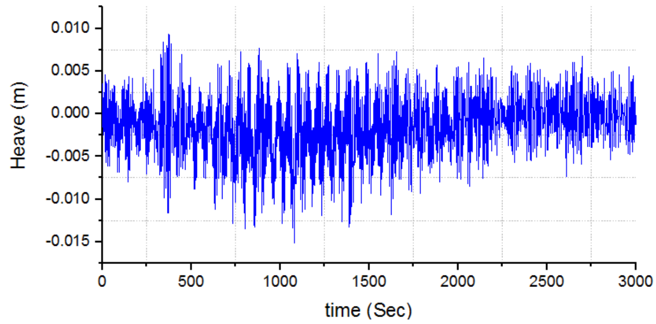

Figure 9. Response for heave motion of TLP (H_s = 5 m, T_z = 7 s).

The platform response for roll DOF is given in Fig. 10. It is observed to roll -0.0007° to 0.00055° about the mean position. Platform response for pitch DOF is shown in Fig. 11. It is observed to pitch -0.03° to 0.03° about the mean position. Lesser is the response in the roll and pitch DOF as the design of TLP constrains motion in rotational degree of freedom. The platform response for yaw DOF is given in Fig. 12. It is observed to yaw -0.035° to 0.035° about the mean position. The variation in tether tension in all the four legs of the TLP is shown in Fig. 13. Tension values vary from 27 to 37 MN. It is observed that the response of the platform in heave DOF is lesser than its response in surge DOF. This is an indication of the stiffness of the platform in heave DOF, which is very much essential for offshore structures performing in deep-water settings.

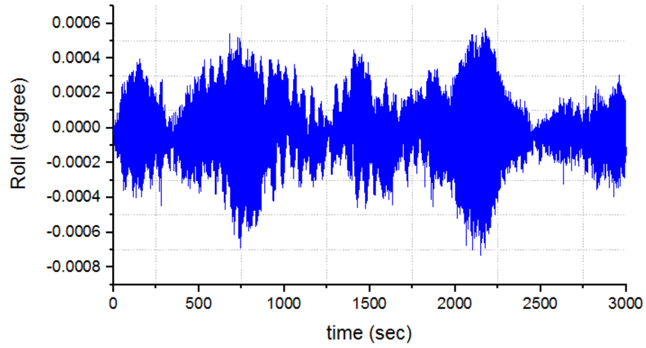

Figure 10. Response for roll motion of TLP (H_s = 5 m, T_z = 7 s).

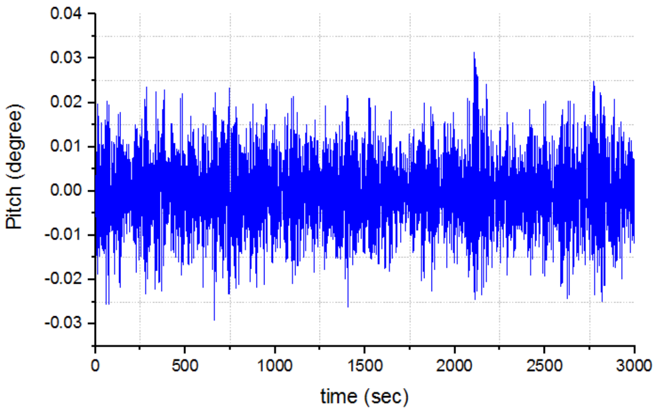

Figure 11. Response for pitch motion of TLP (H_s = 5 m, T_z = 7 s).

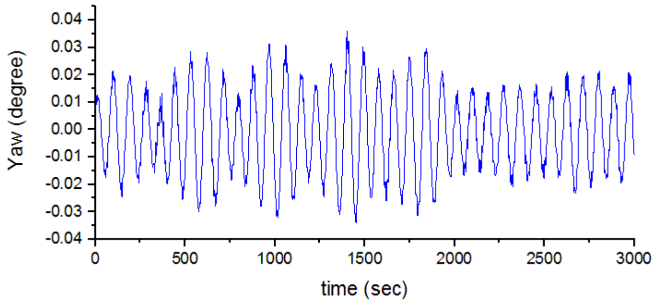

Figure 12. Response for yaw motion of TLP (H_s = 5 m, T_z = 7 s).

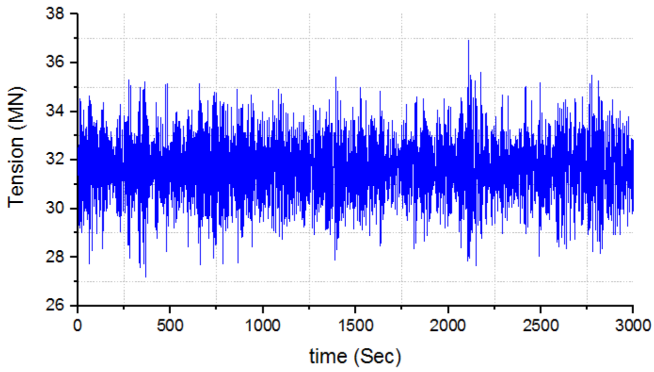

Figure 13. Variation of tether tension in legs of TLP (H_s = 5 m, T_z = 7 s).

Power Spectral Density (PSD) is the measure of power content of the time signal with respect to frequency. It is beneficial to conduct response analysis using PSD because the energy of the time signal is represented at each frequency. Hence it is widely employed in the field of offshore technology for dynamic analysis /16/. The PSD corresponding to surge response of the TLP is given in Fig. 14. A peak can be observed in the plot at 0.057 rad/sec, which is found to be the surge natural frequency of the TLP. The PSD corresponding to heave response of the TLP is shown in Fig. 15. A peak can be seen in the plot at 3.43 rad/s, which is observed to be the heave natural frequency of the TLP, while at the surge natural frequency of 0.057 rad/sec, another peak can be observed in the plot. This is indicative of a strong coupling between the surge and heave DOF for a TLP. The wave natural frequency of 0.897 rad/s is also indicated in the same plot. This shows that the platform's natural periods are away from the wave's natural period. The PSD of tether tension is shown in Fig. 16. A significant peak can be observed in the plot at the heave natural frequency of the platform. The coupling between surge and heave DOF can be detected when the structural response of the platform is taken into consideration.

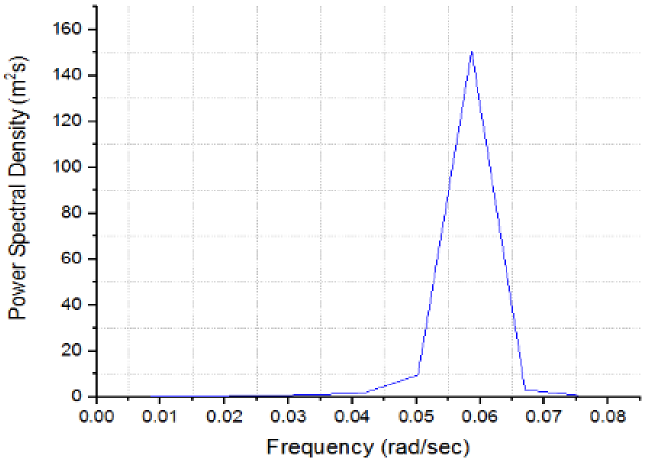

Figure 14. PSD for surge DOF of the TLP.

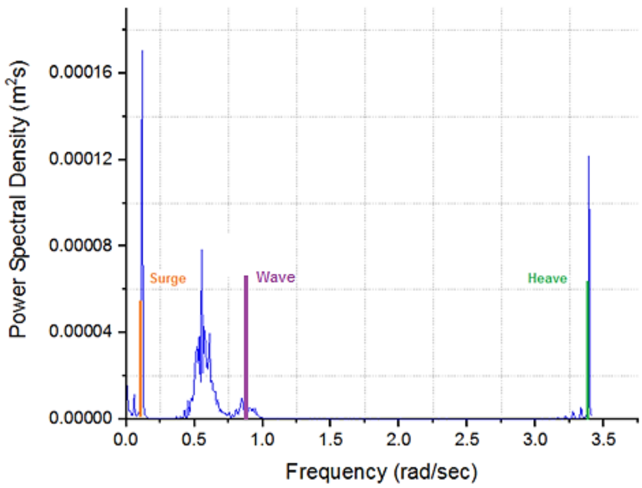

Figure 15. PSD for heave DOF of the TLP.

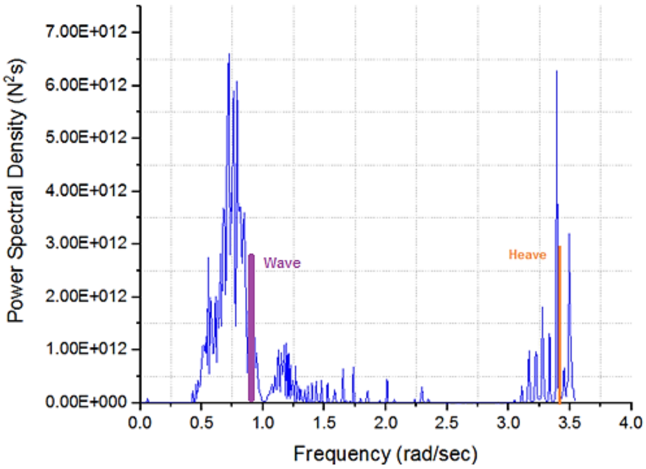

Figure 16. PSD for tether tension observed in the legs of the TLP.

CONCLUSIONS

The study presents the dynamic analysis of ISSC TLP in deep-water settings for irregular waves under very rough sea-state conditions. The relevant points observed from this analysis are highlighted below:

– the response of the platform in heave DOF is found to be lesser than its response in surge DOF. This indicates the stiffness of the platform in heave DOF, which is very much essential for offshore structures performing in deep-water settings;
– while considering the structural response of the platform, the coupling between surge and heave DOF is another key observation of the presented study;
– the natural periods of the platform in surge and heave DOF are obtained from free decay tests. These values are validated using the available literature;
– the natural periods of surge and heave DOF lie away from the natural period of the wave, indicating that the possibilities of resonance are avoided. Such a feature is achieved through the form of the platform.

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