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DYNAMIC ANALYSIS OF A TENSION LEG PLATFORM UNDER EXTREME WAVES

Srinivasan Chandrasekaran[1] and Yuvraj Koshti[2]

[1]Coresponding author, Deepartment of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, INDIA, Email: drsekaran@iitm.ac.in

[2]Research Scholar, Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, INDIA, Email: yuvraj.koshti@gmail.com

Abstract:

Recent observations of the sea state that result in the undesirable events confirm the presence of extreme waves like freak waves, which is capable of causing irreparable damages to offshore installations and (or) create inoperable conditions to the crew on board. Knowledge on the extreme wave environment and the related wave-structure interaction are required for safer design of deep-water offshore structures. In the current study, typical long crested extreme waves namely: i) New Year wave at offshore Norway; and ii) Freak wave at North Sea are simulated using the combined wave model. Dynamic response of the Tension Leg Platforms (TLP) under these extreme waves is carried out for different wave approach angles. Based on the analytical studies carried out, it is seen that the TLPs are sensitive to the wave directionality when encountered by such extreme waves; ringing type response is developed in TLPs which could result in tether pull out.

Keywords: Tension Leg Platform; Extreme waves; Wave directionality; Long crest sea waves; Dynamic response.

1. Introduction

During the recent past, growing attention is paid to the response of the offshore structures under the extreme environmental conditions caused by the large waves. Increasing number of the reported extreme waves with large wave height, crest height, wave steepness and the group pattern suggest the reconsideration of the design codes (Zanqiang 2011). However, only rare observations of such freak waves are reported in the literature (see, for example, on 1st January, 1995, an extreme wave hit the Draupner Platform located on North sea, offshore Norway). Extreme waves are recorded in the North Sea, about 100 miles east of the Shetland Islands. Significant wave height of the sea surface elevation is about 5.65 m while the maximum wave height is reported as 18.04 m with a crest height of 13.90 m above the mean water level. The Dynamic response of the compliant offshore structures like TLPs under such extreme waves draws special attention since they shall excite TLPs even in their stiff degree-of-freedom like heave (Chandrasekaran et al. 2011; Chandrasekaran and Bhattacharyya 2012). Analysis of deep-water compliant structures shall include the hull-tether coupling as such interaction shall influence the dynamic response significantly (Joseph et al. 2009).

Freak waves, alternatively called as rogue waves or giant waves are characterized by the presence of a single, steep crest. These waves are capable of causing severe damage to the offshore structures and ships (Dysthe et al. 2008). A review of different mechanisms of the formation of the freak waves identifies several factors that are responsible for their occurrence. They are namely: i) wave-wave interaction; ii) wave-current interaction; iii) bathymetry; iv) wind effect; v) self-focusing instabilities; and vi) the directional effects (Kharif and Pelinovsky 2003). Earlier studies reported that the freak waves with high crest of 18.5 m have been a major cause of the severe accidents over the past two decades, which includes the loss of many super-tankers and container ships. Liu (2007) attempted to simulate the freak waves in the laboratory scale using a realistic wave spectrum with a random phase angle approach. He highlighted a serious limitation of the said simulation that such rare events would occur once in approximately 3000 waves according to a Rayleigh wave height distribution. Hence, the experimental studies are not encouraging for the freak wave laboratory cases. Further, model studies pose serious limitations to the experimental investigations of floating/compliant structures due to the limitations in the scale factor; in determining the marine forces due to the wave action, gravity and inertia forces that govern

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the behaviour need to be appropriately considered in the study (Kannah and Natarajan 2006). Alternatively, a spatial and temporal-focused wave group is widely used to generate the extreme waves in the laboratory. Kriebel (2000) proposed an efficient procedure for the numerical simulation of the freak waves by embedding an extreme transient wave within a random sea. The energy percentage is limited to be within the combined wave model. Zhao (2009) summarized the wave focusing models for the generation of such freak waves. He recommended two combinations namely: i) extreme wave model with the random wave model; and ii) extreme wave model with the regular wave model. Motivated by the earlier studies conducted, different researchers used various numerical techniques to generate freak waves. For example, Zanqiang (2011) simulated the nonlinear freak waves by a modified phase modulation method while Clauss (2003) analyzed the dynamic response of a semisubmersible under rogue waves. Various researchers reported the dynamic response behaviour of offshore complaint structures under such extreme waves. For example, Chandrasekaran et al. (2011) simulated the springing and ringing response of TLPs in extreme waves. The combined extreme wave model, as suggested by Kriebel (2000) was used in the study. Based on the critical review of literature stated above, extreme waves are simulated in the present study using the combined extreme wave model as recommended by Kriebel (2000). Dynamic response behaviour of TLPs is investigated for the different wave approach angles of these extreme waves.

2. Mathematical Formulation

a. Extreme wave model

Extreme waves can excite TLPs at their natural frequencies can result in undesirable responses in stiff degree-of-freedom like heave (Chandrasekaran et al. 2011). Kriebel (2000) suggested a combined wave model to simulate the freak wave using JOHNSWAP spectrum which is given by:

$$S(\omega) = \alpha g^2 \omega^5 exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right]\gamma^{exp\left[-\frac{(\omega-\omega_0)^2}{2\sigma^2\omega_0^2}\right]} \tag{1}$$

where γ is the peakness parameter (= 3.30), α is constant (= 0.0081), and σ is shape parameter which is given by the following equation.

$$\sigma = \sigma_a = 0.07 \quad \text{for } \omega < \omega_0 \tag{2a}$$

$$\sigma = \sigma_b = 0.09 \quad \text{for } \omega > \omega_0 \tag{2b}$$

Wave energy present in the spectrum is split at each frequency so that some percentage (P_R) is used to generate the random sea while the remaining (P_T) is used to generate the transient wave. The composition used in the study is given by:

$$\eta(x,t) = \sum_{i=1}^{N} A_{Ri} cos(k_i x - \omega_i t + \varepsilon_i) + \sum_{i=1}^{N} A_{Ti} cos\big(k_i(x - x_0) - \omega_i(t - t_0)\big) \tag{3}$$

$$A_{Ri} = \sqrt{2P_R S(\omega)\Delta\omega} \tag{4}$$

$$A_{Ti} = \sqrt{2P_T S(\omega)\Delta\omega} \tag{5}$$

where, a_i is the amplitude of wave components at i^{th} frequency ω_i, k_i is the wave number, and ε_i is the phase of the wave components, which is a random number in the interval $[0,2\pi]$, N is the number of wave components, x_0 and t_0 represent the focus point and time of the extreme transient wave, respectively.

b. Hydrodynamic forces on TLP

Modified Morison equation, accounting for the relative motion between the platform and the waves is given by:

$$F(t) = \frac{\pi {D_c}^2}{4}\rho C_m \ddot{u} + \frac{1}{2}\varrho C_d D_c(\dot{u} - \dot{x})|\dot{u} - \dot{x}| \pm \frac{\pi {D_c}^2}{4}\rho(C_m - 1)\ddot{x} \tag{6}$$

where, $\dot{x}$, $\ddot{x}$ are horizontal structural velocity and acceleration, $\dot{u}$, $\ddot{u}$ are horizontal water particle velocity and acceleration, C_d, C_m are hydrodynamic drag and inertia coefficients and D_c is diameter of pontoons, respectively. Dynamic tether tension variation is computed from the variable component of the buoyancy caused by the fluctuating sea surface elevation with passage of waves.

c. Equation of motion

Equation of motion, describing the dynamic equilibrium between the inertia, damping, restoring and exciting forces is given by:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \tag{7}$$

where, [M] is the mass matrix, [C] is the damping matrix, [K] is the stiffness matrix of TLP, {F(t)} is the force vector, $\{x, \dot{x}, \ddot{x}\}$ are displacement, velocity and acceleration of the platform respectively.

d. Mass matrix

The structural mass is assumed to be lumped at each degree-of-freedom. Hence it is diagonal in nature and remains constant. The added mass term, M_a due to the water surrounding the structural members is considered up to the MSL. The fluctuating component of the added mass, due to the variable submergence of the structure is considered in the force vector.

$$[M] = \begin{bmatrix} M_{11}+M_{a11} & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & M_{33}+M_{a33} & 0 & 0 & 0 \\ 0 & M_{a42} & 0 & M_{44} & 0 & 0 \\ M_{a51} & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \tag{8}$$

where, $M_{11} = M_{22} = M_{33}$ = total mass of the structure, $M_{44} = Mr_x^2$ is mass moment of inertia about the *x* axis, $M_{55} = Mr_y^2$ is mass moment of inertia about the *y* axis, $M_{66} = Mr_z^2$ is mass moment of inertia about the *z* axis and r_x, r_y and r_z are radius of gyration about the *x*, *y* and *z* axis respectively. M_{a11},and M_{a33} are added mass terms in surge and heave degrees-of-freedom, M_{a42}, M_{a51} are the added mass moment of inertia in the roll and pitch degrees-of-freedom due to the hydrodynamic forces in sway and surge directions, respectively. Presence of the off diagonal terms in the mass matrix indicate the contribution of the added mass due to the hydrodynamic loading in the activate degrees-of-freedom.

e. Stiffness matrix

Coefficients of the stiffness matrix, K_{ij} are derived from the first principles (see, for example, Jain, 1997; Chandrasekaran and Jain, 2002a,b). The same is used in the current study. These coefficients comprise of the nonlinear terms due to cosine, sine, square root and square terms of the structural displacements. Furthermore, the tether tension variations, resulting from the TLP motion also make the stiffness matrix response dependent. Off-diagonal terms of the stiffness matrix reflect the coupling effects between the various degrees-of-freedom. Change in the buoyancy that is caused by the set-down effect influences the tether tension. This subsequently updates the stiffness coefficients at every time step. The coefficients of the stiffness matrix are updated by the new values that are based on the structural response of TLP as well.

$$[K] = \begin{bmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & 0 \\ K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} \\ 0 & K_{42} & 0 & K_{44} & 0 & 0 \\ K_{51} & 0 & 0 & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{66} \end{bmatrix} \tag{9}$$

f. Damping matrix

Rayleigh damping is considered in the present study. Damping matrix [C], as proportional to the mass and stiffness matrices, is given below (Chopra 2003):

$$[C] = a_0[M] + a_1[K] \tag{10}$$

where, a_0 and a_1 are respectively the mass and stiffness proportional damping constants. They are determined for the critical damping of 5% at two different frequencies (ω_1 and ω_2); damping coefficients are as given below:

$$a_1 = 2\omega_1\omega_2\xi/(\omega_1 + \omega_2) \tag{11a}$$

$$a_0 = 2\xi/(\omega_1 + \omega_2) \tag{11b}$$

Table 1 shows the geometric properties and Table 2 shows the natural frequencies of the TLP considered for the study. For surge and heave frequencies considered, Rayleigh constants are obtained as 0.0061 and 0.0441 respectively. Equation of motion, having the time dependent components is subsequently solved by the Newmarks' average acceleration method.

Table 1: Geometric properties of the TLP used in the study

Description	**Property**
Weight (kN)	351600
F_B (kN)	521600
T_0 (kN)	170000
Tether length *l* (m)	568
Water depth (m)	600
CG (m)	28.44
AE/*l* (kN/m)	84000
Plan dimension (m)	70
D_c (m)	17
r_x, r_y, r_z (m)	35.10

Table 2: Natural periods of the TLP

Degrees-of-freedom	**Natural period (s)**	**Natural period (Hz)**
Surge	100	0.01
Sway	100	0.01
Heave	3.10	0.3
Roll	2.02	0.49
Pitch	2.02	0.49
Yaw	85	0.011

g. Extreme waves

In the current study, two extreme waves namely: a) New Year wave; and b) Extreme wave at North Sea are simulated using the combined freak wave model suggested by Kriebel (2000). New Year Wave, shown in Fig. 1(a) was recorded at the Draupner E platform in the central North Sea at 15:20 on the 1st January 1995. It is seen from the figure that the freak wave was formed approximately at 264.5 s in the recorded time series. Significant wave height of the surface elevation time series is 11.92 m while the maximum wave height is 25.60m with a crest height of 18.50m above the mean water level. Fig. 1(b) shows the simulated time series of the freak wave at 264.5 s used in the present study. The simulated series has a significant wave height of 12.1 m. Height of the freak wave is 27 m with a crest height of 18 m.

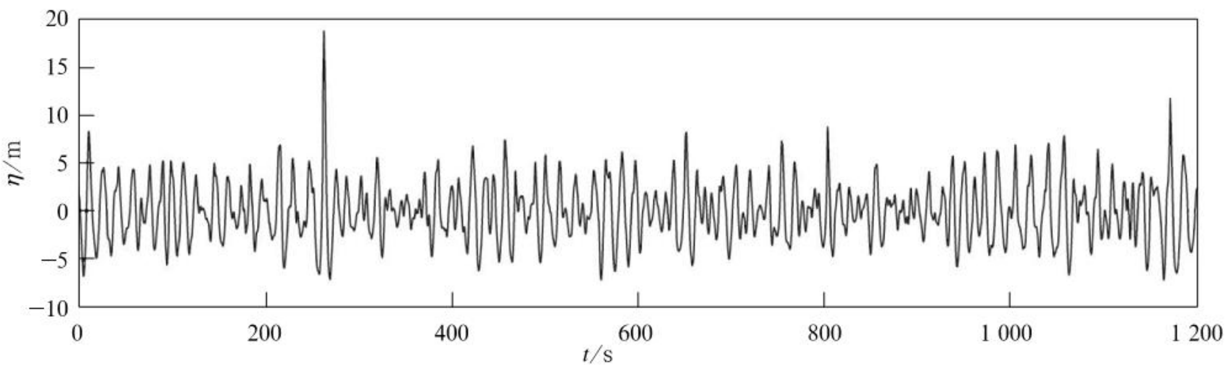

Fig. 1(a): Recorded time series of the New Year Wave at Draupner E platform.

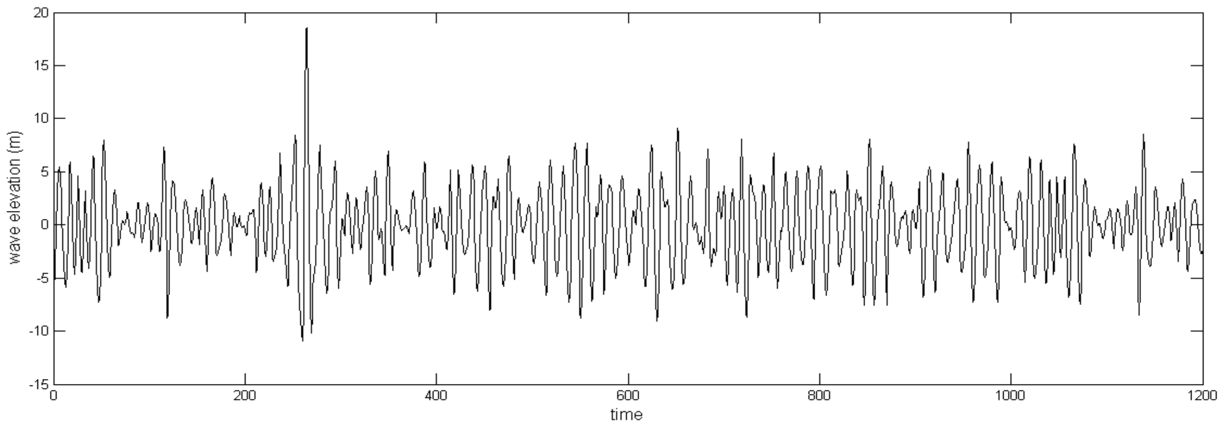

Fig. 1(b): Simulated time series of the New Year freak wave.

The second wave considered in the study is an extreme freak wave event, as shown in Fig. 2(a). This wave was recorded in the North Sea about 100 miles east of the Shetland Islands. The significant wave height of the surface elevation time series was 5.65 m while the maximum wave height was 18.04 m with a crest height of 13.90 m above the mean water level. Fig. 2(b) shows the simulated time series of the North Sea freak wave, used in the present study. Simulated series show that the freak wave is generated at 730s with a significant wave height of 6.02 m. Height of the simulated freak wave is 19.01 m and the crest height is 14.5 m above the mean water level, which is used in the current study.

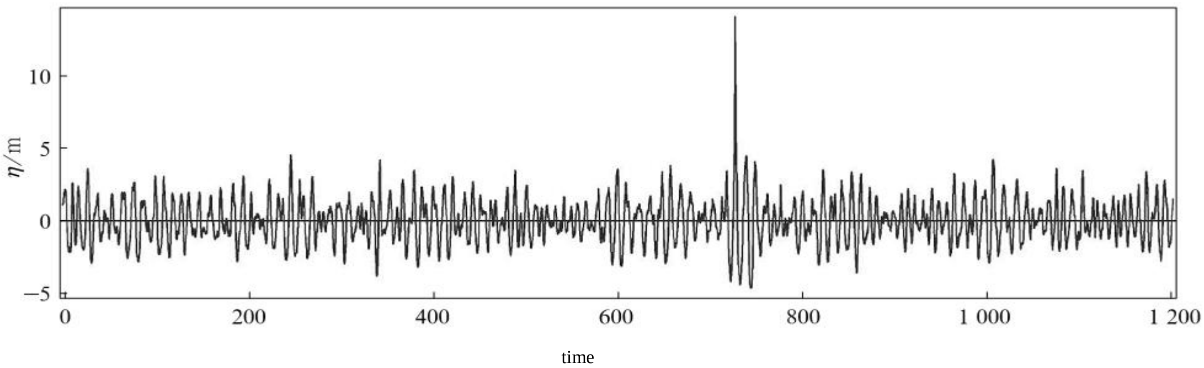

Fig. 2(a): Recorded time series of the North Sea freak wave.

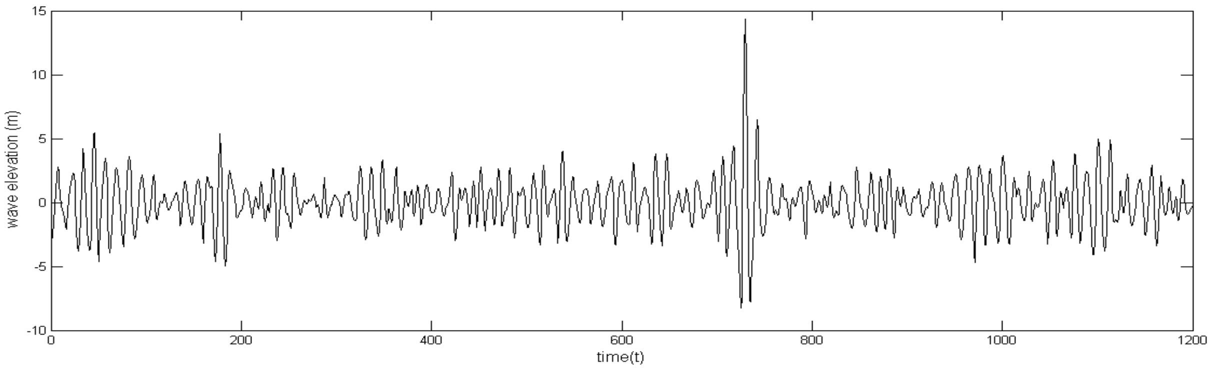

Fig. 2(b): Simulated time series of the North Sea freak wave.

It is seen from the figures that both the simulated extreme waves closely match the recorded time histories of their respective extreme waves, at two different site locations chosen for the study.

3. Results and discussions

Fig. 3 shows the TLP model considered in the study. It consists of four columns of diameter Dc. The cylindrical pontoons of diameter D are connected to the vertical cylinders at the bottom. The platform is anchored to the sea bed by the taut moored tethers those are attached at each corner. Analytical studies are carried out in order to examine the dynamic response of TLP to both the simulated extreme waves.

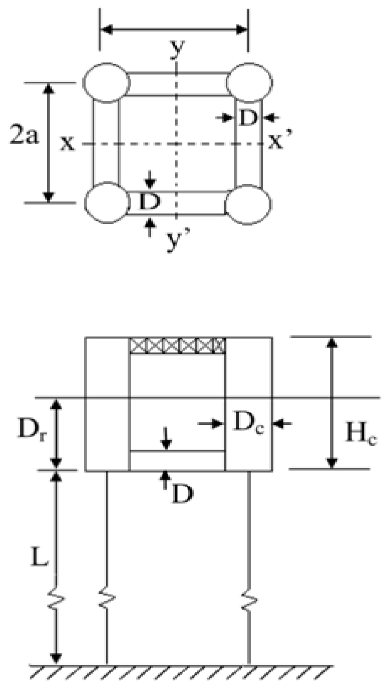

Fig. 3: Schematic plan and elevation of the TLP model.

Figs. 4(a) and 4(b) show the responses of TLP for the simulated North Sea freak wave and the New Year wave for zero degree wave approach angle, respectively. It is seen from the figures that the response is primarily triggered in the pitch degree-of-freedom for a wide range of the time period similar to that of a ringing response; a similar pattern is observed in the heave degree-of-freedom as well.

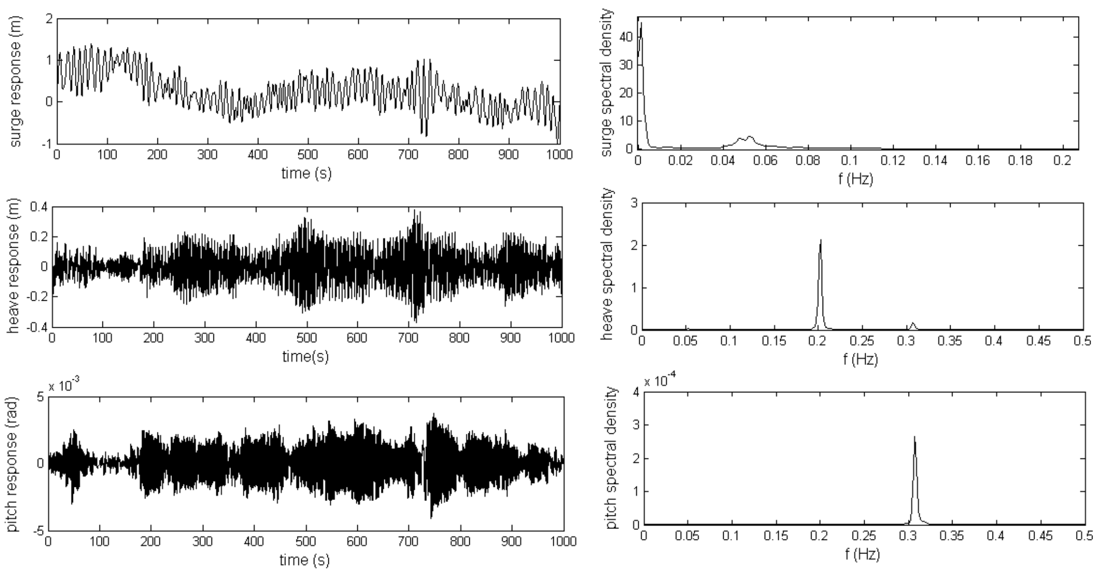

Fig. 4(a): Responses of the TLP for the simulated North Sea freak wave (α = 0°).

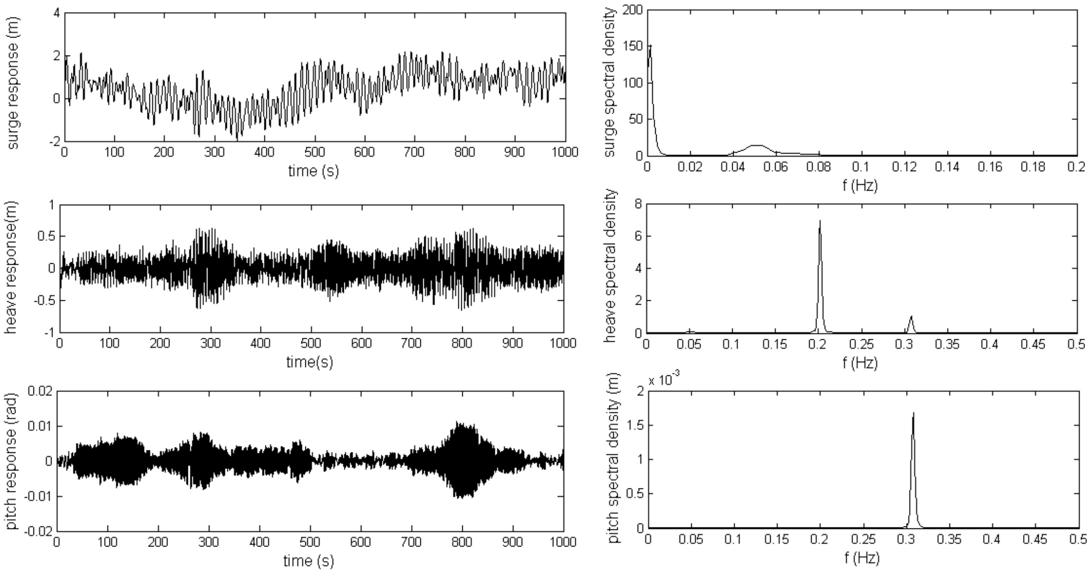

Fig. 4(b): Responses of the TLP for the simulated New Year wave (α = 0°).

By comparing the responses under both the simulated extreme wave events, it is seen that the response under the North Sea wave, in all active degrees-of-freedom is lesser than that of the New Year wave. Responses of the TLP under the simulated extreme waves under different wave approach angles are also studied. Figs. 5(a) and 5(b) show responses of the TLP under the North Sea freak wave and the New Year wave for 45^0 wave approach angle, respectively. It is seen from the figures that the surge and sway responses at 45^0 are similar for both the waves, indicating the symmetry of the platform. The frequency plots shown in the figures indicate the peaks at 0.22 Hz in the heave response and 0.33Hz in the pitch response. These are found closer to their respective natural frequencies of the platform. It is important to note that the platform is excited in the stiff degree-of-freedom like heave. In the absence of such extreme waves, such alarming heave response would be absent. The second peak appearing at 0.3 Hz in the heave response indicates a strong coupling of heave and pitch degrees-of-freedom.

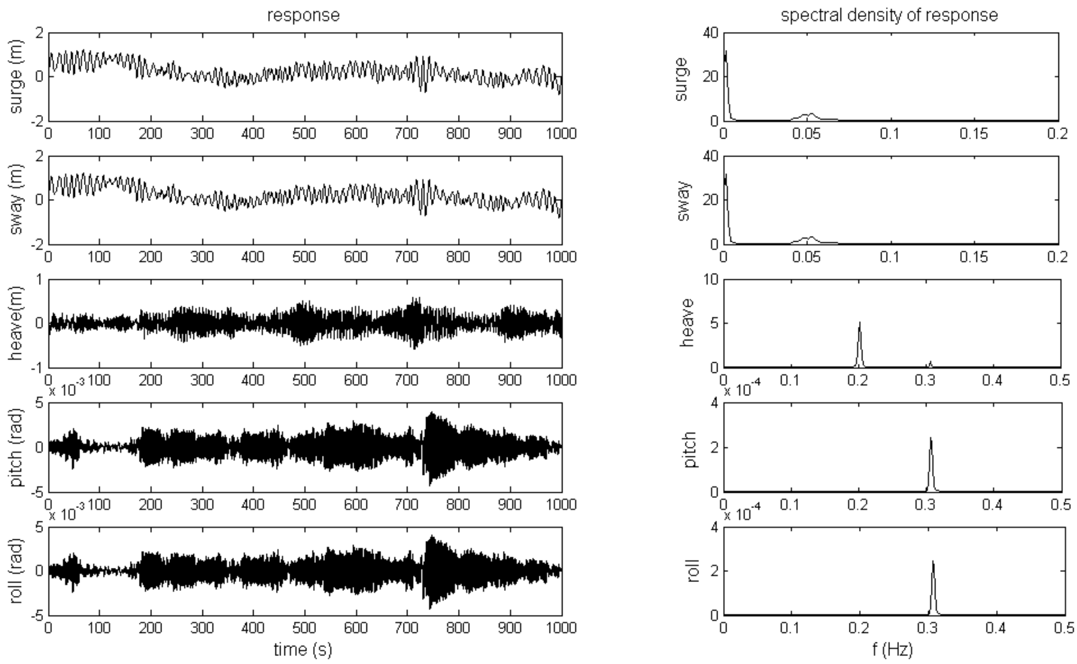

Fig. 5(a): Response of the TLP under the simulated North Sea freak wave (α = 45°).

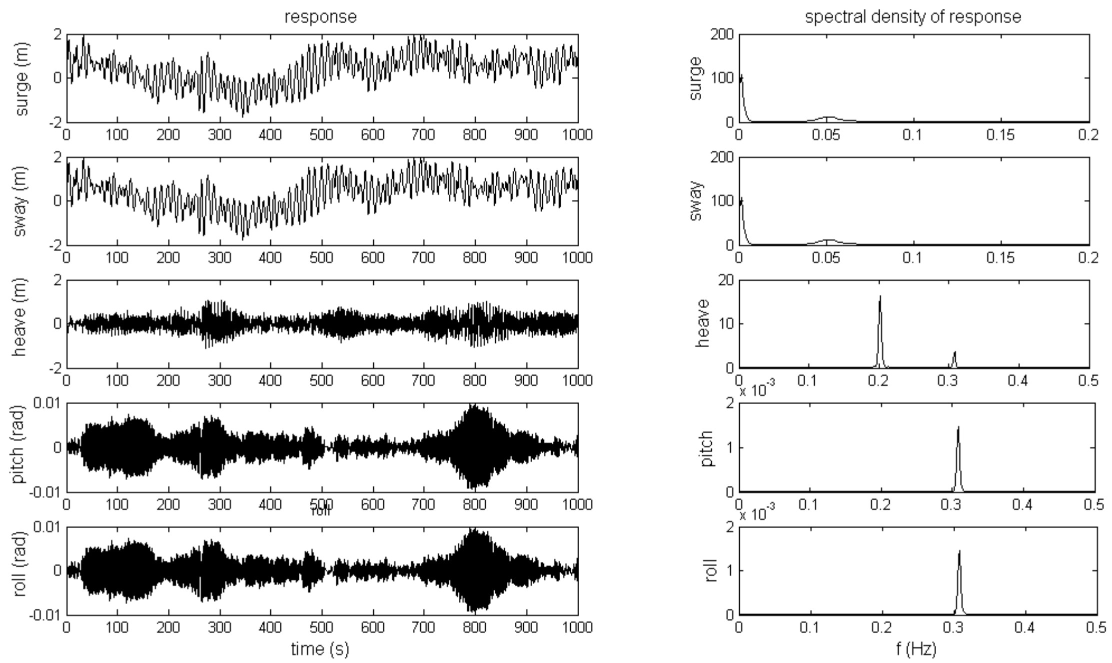

Fig. 5(b): Response of the TLP under the simulated New Year wave (α = 45°).

Fig. 6 is showing the phase plots of the responses. The elliptical nature of the phase plots ensures that the platform is stable and the response is periodic in nature.

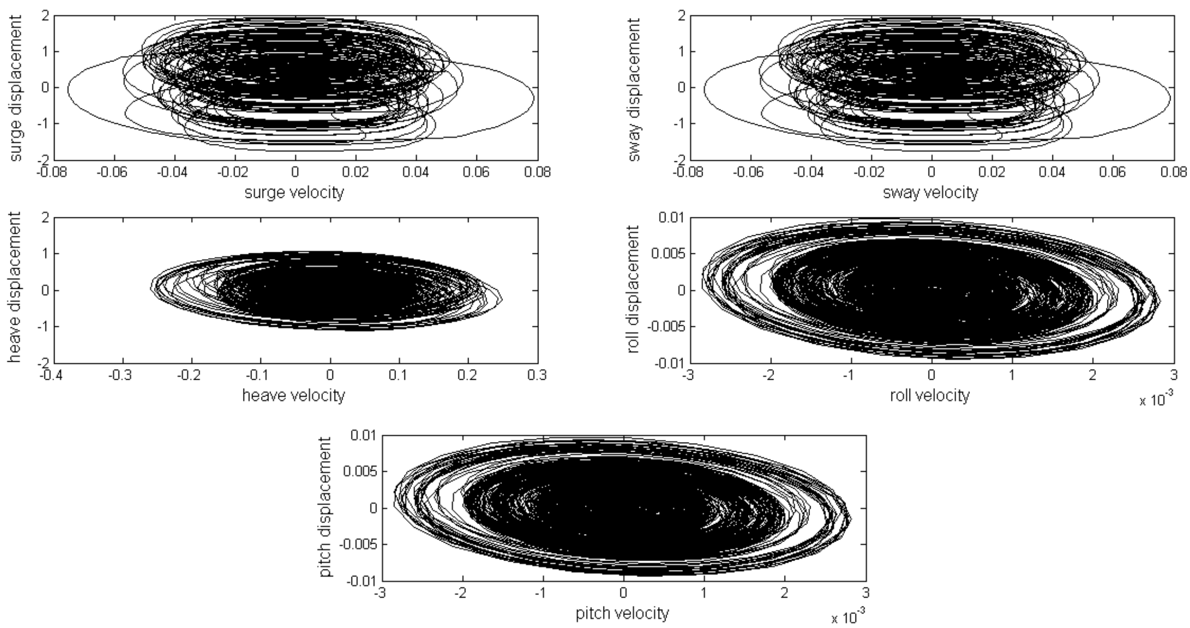

Fig. 6: Phase plots of the response of the TLP under simulated New Year wave (α = 45°).

Figs. 7(a) and 7(b) show the variations of the maximum response in the surge and sway degree-of-freedom with the different wave approach angles for the two simulated extreme wave events, respectively. It can be seen from the figures that the maximum surge response occurs at 0^0 while that of the maximum sway response occurs at 90^0. This indicates the symmetric nature of the platform geometry. The responses in various degrees-of-freedom under different wave approach angles are influenced by the tether tension variations in the fore and the rear group of tethers. Spatial differences caused by the wave periods on the members result in such variations. This is in addition to the system nonlinearities that are implicitly present in the system. Hence, there is a marginal difference in the responses between the corresponding pairs of values (for example, 40^0 and 50^0 etc).

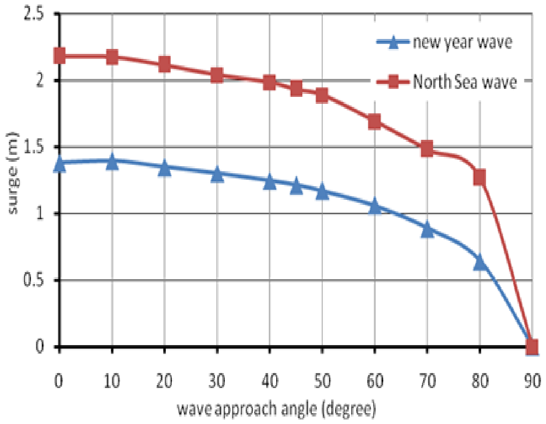

Fig. 7(a): Variation of the maximum response in surge degree-of-freedom

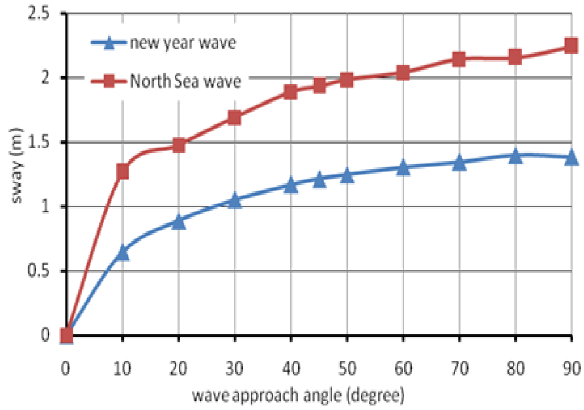

Fig. 7(b): Variation of the maximum response in sway degree-of-freedom

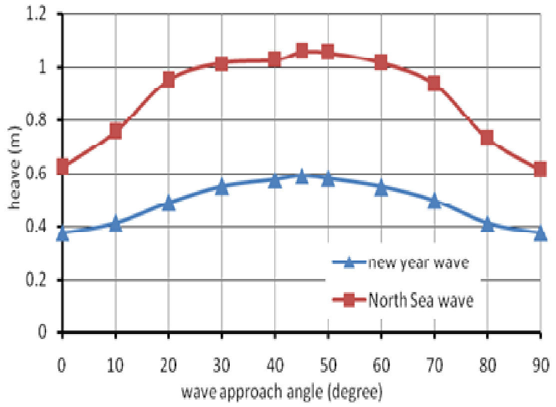

Fig. 7(c): Variation of the maximum response in heave degree-of-freedom

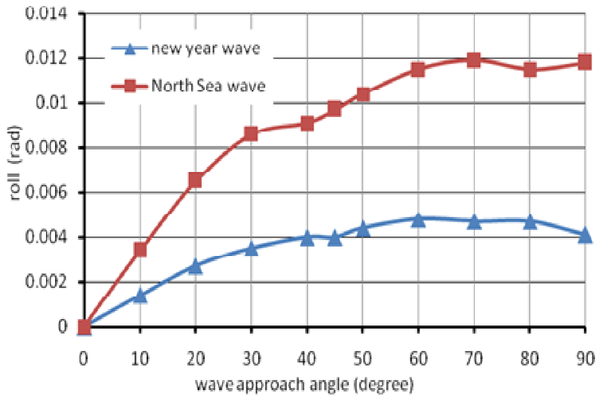

Fig. 7(d): Variation of the maximum response in roll degree-of-freedom

Fig. 7(c) shows the variation of maximum heave response with different wave approach angle with the maximum value occurring at 45^0. Figs. 7(d) and 7(e) show the variation of maximum response in roll and pitch degree-of-freedom with different wave approach angles. It is seen from the figures that the roll response is found to be maximum at 70^0 while that of the pitch response is at 20^0.

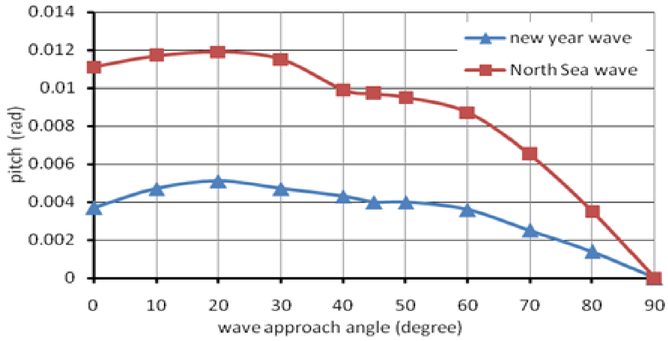

Fig. 7(e): Variation of the maximum response in pitch degree-of-freedom.

4. Conclusions

Recent observations of the sea states confirm occurrence of the freak waves. The recorded events of the New Year wave and the North Sea freak wave are examples of such kind of waves. For their effects omitted in the design of deep-water compliant platforms like TLPs, damage to the platform could be serious. This shall also pose threat to their survival in such extreme sea states. The current study simulated such extreme waves and validated their formulation with that of the recorded ones in the North Sea. It is seen from the analytical studies that the dynamic response of TLPs is sensitive to such waves in the heave and pitch degrees-of-freedom at a frequency closer to the natural heave frequency. Although the phase plots ascertained stability of the platform with long periods, heave excitation is significant under such extreme wave events. This is critical in the design point of view. TLPs are also seen to be sensitive to the wave directionality effects when encountered by such extreme waves. Ringing type responses are developed, which could result in tether pull out.

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