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Dynamic Behaviour of Tension Leg Platform under Impulsive Loading

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ABSTRACT

In the literature on dynamics of tension leg platforms (TLPs), the effect of frequently occurring environmental forces, such as those arising due to wave, wind, current, tide, etc. has given the due consideration. However, less probable forces, such as that arising due to collision of ship with iceberg or any huge sea creature, etc., have not been considered in the study. Such small duration impact forces, usually termed as impulsive forces, may take four possible shapes: (i) rectangular, (ii) sinusoidal, (iii) triangular, and (iv) half-triangular. In the present study, response of TLP has been obtained for all these four shaped impulsive forces. The result of the analyses shows that there is a dramatic change in surge, heave, and yaw responses of TLP due to such forces. In addition, a comparative study to find the most influencing impulsive force out of these four has also been conducted.

Keywords: Dynamic analysis, tension leg platform, offshore structures, impulse, impulsive loading

NOMENCLATURE

a_n	Acceleration of structure
ρ_w	Mass density of water
$[C]$	Damping matrix
C_D	Drag coefficient
C_M	Inertia coefficient
D	Diameter of cylinder
$\{F\}$	Force vector due to environmental and impulsive forces
H	Sea wave height
$[K]$	Nonlinear coupled stiffness matrix
$[M]$	Mass matrix
T	Sea wave period
$\dot{U}_n$	Water particle velocity
$\ddot{U}_n$	Water particle acceleration
V_c	Current velocity
V_n	Velocity of structure
$\{Z\}$	Instantaneous TLP response

1. INTRODUCTION

A tension leg platform (TLP) is a moored floating compliant structure whose buoyancy is more than its weight. The supporting structure of TLP consists

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of a hull, tethers, and templates. The hull is a buoyant structure with deck at its top. The pontoons and columns provide sufficient buoyancy to maintain the deck above the sea waves during all sea states. The hull is anchored to the sea bed through tethers and fixed in place with templates (Fig. 1).

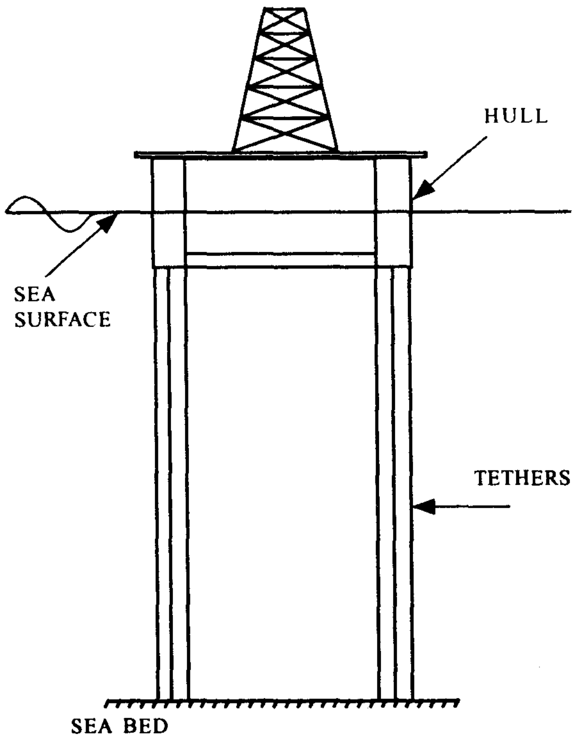

Figure 1. Tension leg platform

Though in the last decade, a good number of research papers have appeared in literature, these papers cover different aspects of dynamic analysis of TLP. Kareem and Li[1] presented a frequency domain analysis procedure to evaluate wind-excited surge response of a TLP in the presence of waves and water currents. Vickery[2] examined the combined effect of wind and wave loads on the response of the TLP. He compared theoretical results with experimental findings and observed a good agreement between these. Ahmad[3] carried out stochastic dynamic analysis of TLP in time domain under long-crested random sea, considering six degrees-of-freedom (DOFs). Lee and Pei-Wen[4] investigated the dynamic behaviour of TLP having a net cage system when subjected to incident waves and flow drags.

Literature review reveals that the response behaviour of TLP under frequently occurring environmental forces, such as those arising due to wave, wind, water current, tide, etc., has been given due consideration. However, less probable forces, such as those arising due to collision of ship with iceberg or any huge sea creature, etc., have not been considered in the study. Such small duration impact forces, usually termed as impulsive forces, may take four possible shapes: (i) rectangular, (ii) sinusoidal, (iii) triangular, and (iv) half-triangular. In the present study, response of TLP has been obtained for all these shaped impulsive forces. Result of the analyses shows that there is a dramatic change in surge, heave, and yaw responses of TLP due to such forces. In addition, a comparative study to find the most influencing impulsive force out of these four impulsive forces has also been conducted. Some parametric studies have also been included.

2. MATHEMATICAL FORMULATION

2.1 Equation of Motion

For the dynamic analysis of TLP under environmental and impulsive forces, it is assumed that the TLP is a rigid body and it has six DOFs *viz*., surge, sway, heave, pitch, roll, and yaw. With this major assumption, the following equations of motion have been derived which represent the dynamic equilibrium in inertia, damping, restoring, and exciting forces:

$$[M]\{\ddot{Z}\}+[C]\{\dot{Z}\}+[K]\{Z\}=\{F\} \tag{1}$$

where $\{Z\}$ is instantaneous TLP response corresponding to surge, sway, heave, roll, pitch, and yaw motions.

2.2 Estimation of Wave & Current-induced Forces

The wave and current-induced normal force, F_n on TLP columns and pontoons have been estimated using the following modified Morison's[5] equation.

$$F_n = \rho_w C_M \frac{\pi D^2}{4}\left[a_n - \ddot{U}_n\right] + \rho_w \frac{\pi D^2}{4}\ddot{U}_n + \frac{1}{2}\rho_w C_D D\left|V_n - \dot{U}_n + V_c\right|\left(V_n - \dot{U}_n + V_c\right) \tag{2}$$

In the present study, water particle velocity and acceleration have been obtained using Airy's theory which gives accurate results in deep-water conditions[6].

2.3 Impulsive Forces

In the sea environment, there is a possibility of impact or impulsive forces on TLP hull due to collision of ship with iceberg or any huge sea creature, etc. In literature, four shapes of impulsive forces are usually reported. These are rectangular, sinusoidal, triangular, and half-triangular (Table 1).

Table 1. TLP response under impulsive forces

Type of impulse (with wave)	Peak response			
	Surge (m)	Heave (m)	Tether tension (N)	Yaw (rad)
No impulse	18.00	0.364	1.21×10^{8}	4.86×10^{-7}
Rectangular	25.40	1.410	3.81×10^{8}	6.78×10^{-1}
Sinusoidal	21.93	0.883	2.05×10^{8}	4.93×10^{-1}
Triangular	20.87	0.764	1.70×10^{8}	4.16×10^{-1}
Half-triangular	19.65	0.636	1.21×10^{8}	3.42×10^{-1}

The response analysis of TLP under the impact of these impulsive forces has been carried out under the following assumptions:

- Both the body and the object that imparts impulsive forces to TLP columns are rigid
- Impulsive forces are acting at the point where resultant of wave forces act
- The impulsive force acts on column number 1 as shown in Fig. 2
- Duration of all the impulsive forces are 0.6 s and these act on the structure at the time of 200 s
- Peak magnitude of the impulsive forces is 5×10^{8} N

3. NUMERICAL STUDY

For the numerical study, one requires physical characteristics of the TLP together with hydrodynamic and aerodynamic properties of the surrounding environment. These physical characteristics and properties are shown in Table 2.

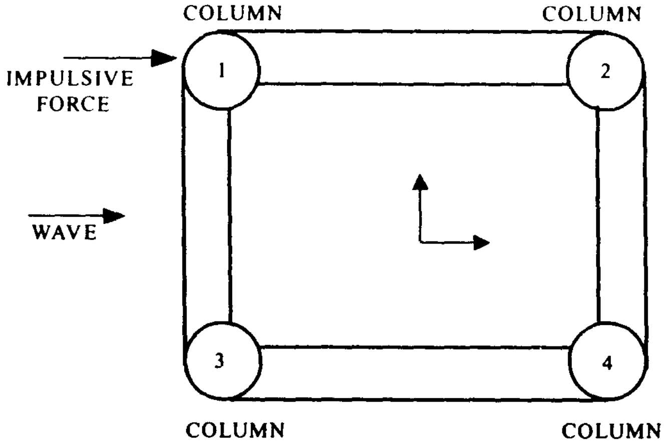

Figure 2. Impulsive force acting on column 1

Table 2. Geometrical and mechanical characteristics[7] of TLP under study

Parameters	Characteristics
Tether diameter (m)	0.40
Axial stiffness (t/m)	5806
Weight of tether (tons)	5257
Radii of gyration (R_x, R_y, R_z) (m)	29.15, 29.15, and 32.15
Breadth of TLP hull (m)	72.5
Diameter of corner columns (m)	14.2
Diameter of the pontoon (m)	11.2
Length of hull (m)	44.1
CG above SWL (m)	9.25
Mass of platform (kg)	2.095×10^{7}
Total tether pretension (N)	1.245×10^{8}
Centre-to-centre spacing (m)	58.3
Current velocity near sea surface and at sea bed (m/s)	1.40, 0.15
Buoyancy (N)	3.34×10^{8}
Water depth (m)	500.0
Draft (m)	26.6
Modulus of elasticity of steel (N/m^2)	2.095×10^{11}
Sea drag coefficient, C_D	0.8
Sea inertia coefficient, C_M	1.8

Table 3. Simulated sea states[a]

Sea state	Wave height (m)	Wave period (s)	Probability of occurrence
S1	17.15	13.26	0.00000037
S2	15.65	12.66	0.00000238
S3	14.15	12.04	0.00001437
S4	12.65	11.39	0.00007980
S5	11.15	10.69	0.00040572
S6	9.65	9.94	0.00187129
S7	8.15	9.14	0.00773824
S8	6.65	8.26	0.02822122
S9	5.15	7.26	0.08851105
S10	3.65	6.12	0.22831162
S11	2.15	4.69	0.43542358
S12	0.65	2.58	0.20942036

A TLP in its design life is subjected to infinite number of sea states represented by various wave heights and wave periods. However, for convenience, twelve representative sea states, described in terms of wave heights and wave periods have been considered. In the present study, these representative 12 sea states are taken from Siddiqui and Ahmad[7] and presented in Table 3. For these twelve sea states, a nonlinear dynamic analysis has been carried out in time domain and responses obtained are analysed.

4. RESULTS & DISCUSSION

Table 4 presents RMS responses of surge, sway, heave, pitch, roll, yaw, and tether tension for 12 sea states (S1 to S12). The table shows that as one moves towards less severe sea state (i.e., from S1 to S12), all the responses are decreasing. This trend is expected. A comparison of tether tension between the sea states S1 and S12 shows that the difference is about 31 per cent wrt sea state S1. This indicates that difference in tether tension for a least-probable sea state and most-probable sea state is considerable. However, for surge and heave responses, differences are about 98 per cent and 100 per cent, respectively. This shows that though the surge and heave responses are the major causes of an increase or decrease in tether tension, their combined influence over the tether tension is considerably less. The table also shows that sway, roll, and yaw responses are almost insignificant, but pitch response is significant at least for the higher sea states.

Table 4. Response of TLP for 12 sea states

Sea state	Root mean square (RMS)						
	Surge (m)	Sway (m)	Heave (m)	Pitch (rad)	Roll (rad)	Yaw (rad)	Tether tension (N)
S1	11.12	5.03×10^{-6}	1.50×10^{-1}	1.74×10^{-1}	5.38×10^{-2}	4.86×10^{-7}	4.62×10^{7}
S2	10.61	4.30×10^{-6}	1.35×10^{-1}	1.65×10^{-1}	5.14×10^{-2}	6.03×10^{-7}	4.51×10^{7}
S3	10.01	3.55×10^{-6}	1.19×10^{-1}	1.54×10^{-1}	4.87×10^{-2}	3.68×10^{-7}	4.39×10^{7}
S4	9.31	2.77×10^{-6}	1.02×10^{-1}	1.39×10^{-1}	4.55×10^{-2}	3.44×10^{-7}	4.25×10^{7}
S5	8.45	1.99×10^{-6}	8.41×10^{-2}	1.19×10^{-1}	4.18×10^{-2}	3.19×10^{-7}	4.09×10^{7}
S6	7.38	1.28×10^{-6}	6.39×10^{-2}	9.27×10^{-2}	3.74×10^{-2}	3.06×10^{-7}	3.90×10^{7}
S7	6.00	5.68×10^{-7}	4.21×10^{-2}	5.76×10^{-2}	3.22×10^{-2}	1.63×10^{-7}	3.65×10^{7}
S8	4.25	5.34×10^{-7}	2.15×10^{-2}	1.56×10^{-2}	2.59×10^{-2}	1.31×10^{-7}	3.38×10^{7}
S9	2.25	1.91×10^{-7}	9.42×10^{-3}	9.60×10^{-2}	1.83×10^{-2}	1.23×10^{-7}	3.52×10^{7}
S10	1.57	1.61×10^{-7}	4.72×10^{-3}	7.42×10^{-2}	9.76×10^{-3}	7.85×10^{-8}	3.65×10^{7}
S11	1.58	8.36×10^{-8}	3.53×10^{-3}	2.94×10^{-2}	2.22×10^{-3}	3.05×10^{-8}	3.29×10^{7}
S12	0.16	4.74×10^{-12}	3.32×10^{-5}	6.70×10^{-3}	4.89×10^{-7}	2.00×10^{-13}	3.17×10^{7}

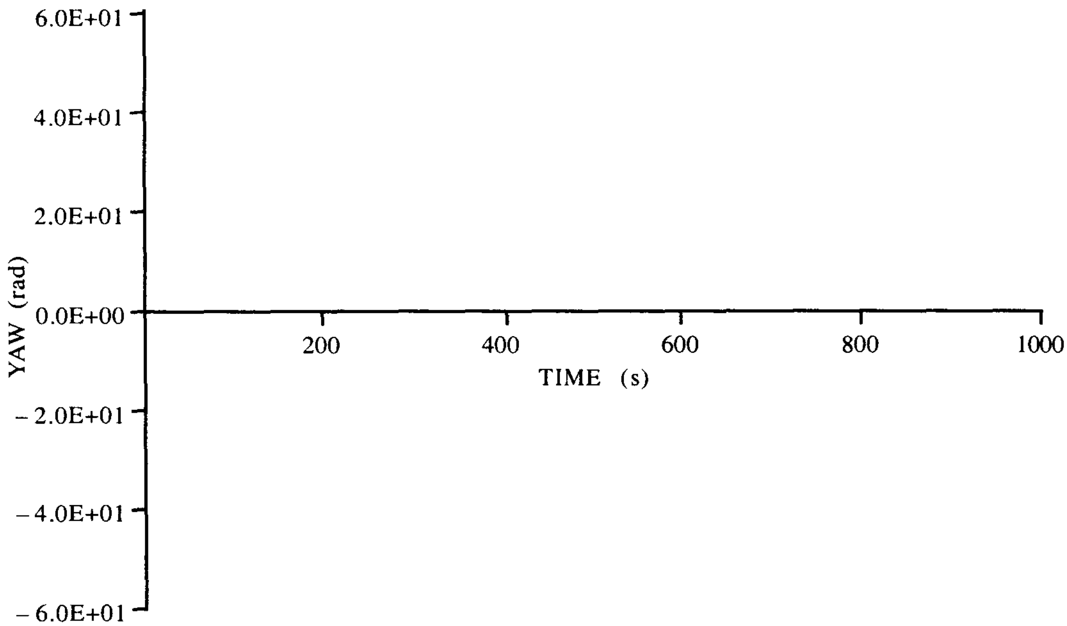

Figure 3. Yaw response of TLP for sea state S6 without impulsive force

Since the impulse force is acting on column 1, it is getting a large lever arm, which provides a large yaw moment to the TLP. It is due to this reason that the yaw response, which was almost zero in the absence of impulsive force, increases substantially at 200 s and then decreases gradually, due to the presence of damping forces (Figs 3 and 4).

Table 1 shows the comparison of peak responses obtained from four different impulses. It was observed that there is a significant variation in almost all the responses. For rectangular impulse, the change in tether tension is maximum and it is about 90 per cent more compared to no impulse, and the changes in responses are found to be minimum for the half-triang ular impulse.

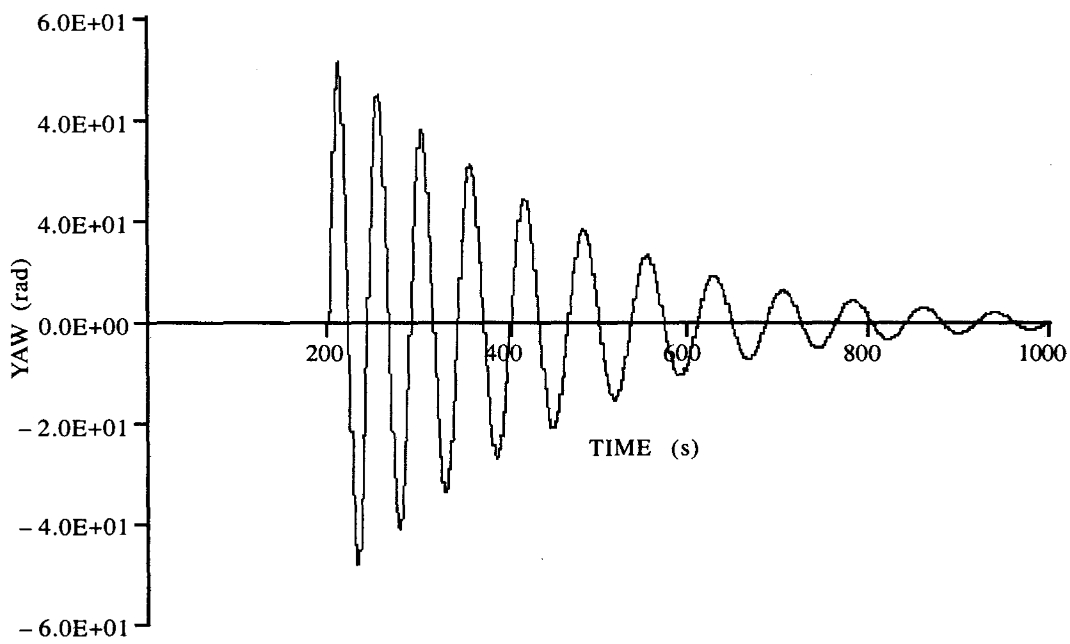

Figure 4. Yaw response of TLP for sea state S6 with sinusoidal impulsive force

5. CONCLUSIONS

In the present study, responses in all the six DOFs are obtained for 12 simulated sea states, for waves coming parallel to the x-direction. It is observed that for all the sea states, surge, heave, and pitch responses are considerable and sway, roll, and yaw responses are insignificant. It is also seen from these responses that the sea state, which has minimum probability of occurrence, gives maximum response and the sea state which has maximum probability of occurrence gives minimum response. Responses obtained under combined wave and impulsive forces showed that impulsive forces dramatically change the responses of the TLP. It is also observed that rectangular shaped impulsive forces are the most severe in comparison to other impulsive forces. The present study thus concludes that such impulsive forces, though less probable, must be considered in the designing of ships, etc., to avoid serious consequences.

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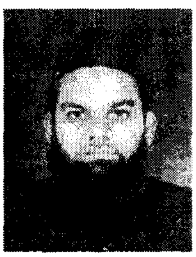
Contributors



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