International Journal of Civil Engineering (IJCE)
ISSN(P): 2278-9987; ISSN(E): 2278-9995
Vol. 3, Issue 1, Jan 2014, 7-16
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International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

DYNAMIC CHARACTERISTICS OF OFFSHORE TENSION LEG PLATFORMS UNDER HYDRODYNAMIC FORCES

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ABSTRACT

Tension leg platforms (TLP) are used for deep water oil exploration. Their behavior are highly nonlinear due to large structural displacements and fluid motion-structure interaction. Therefore the nonlinear dynamic characteristics of TLP under hydrodynamic forces is necessary for determining the maximum deformations and stresses. In this paper, numerical studies are conducted to compare the coupled responses of the triangular TLP with that of the square TLP. A numerical study using modified Morison equation was carried out in the time domain to investigate the influence of nonlinearities due to hydrodynamic forces and the coupling effect between surge, sway, heave, roll, pitch and yaw degrees of freedom on the dynamic behavior of TLP's. The stiffness of the TLP was derived from a combination of hydrostatic restoring forces and restoring forces due to cables and the nonlinear equations of motion were solved utilizing Newmark's beta integration scheme. The effect of wave characteristics such as wave period and wave height on the response of TLP's was evaluated. Only uni-directional waves in the surge direction was considered in the analysis.

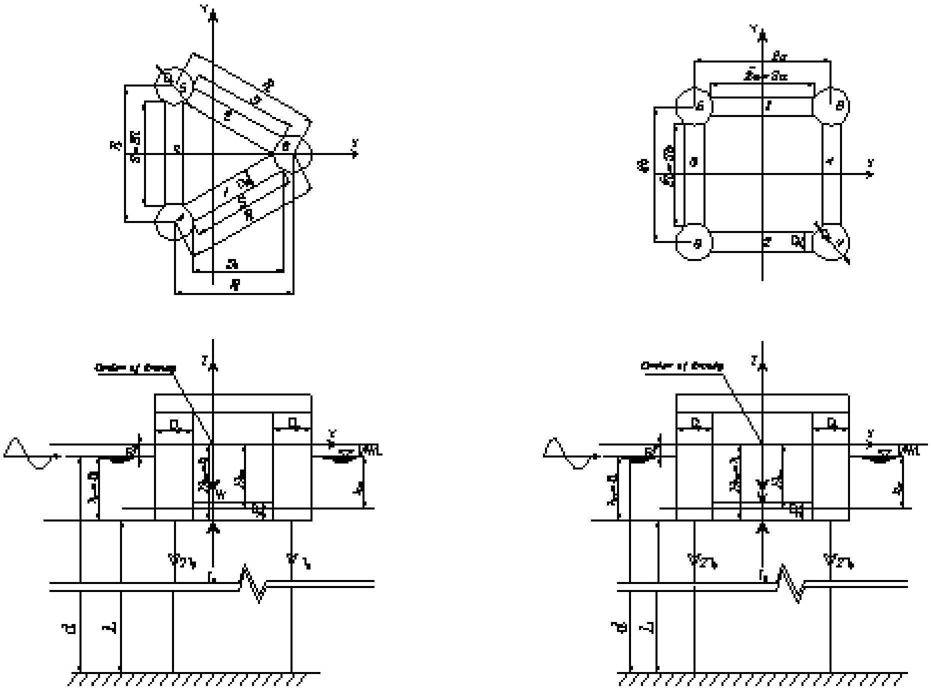
KEYWORDS: Compliant Structures, Coupling Effect, Hydrodynamic Wave Forces

INTRODUCTION

The TLP can be modeled as a rigid body with six degrees of freedom (refer to Figure 1), which can be conveniently divided into two categories, those controlled by the stiffness of tethers, and those controlled by the buoyancy. The former category includes motion in the vertical plane and consists of heave, roll and pitch; whereas the latter comprises the horizontal motions of surge, sway and yaw .The natural periods of motion in the horizontal plane are high, whereas in the vertical plane the periods are low. Generally, the surge and sway motions are predominantly high for head seas due to the combined actions of wind, waves and currents. However, due to coupling among various degrees of freedom and relatively low damping of hydrodynamic origin in the vertical plane motion, a complete analysis of a six degree-of-freedom system subjected to wind, waves and currents is desirable. Moreover**,** the structural flexibility in the horizontal motions causes nonlinearity in the structural stiffness matrix because of large deformations.

A number of studies have been conducted on the dynamic behavior of TLP's under both regular and random. Bhattachatya et al. (2004) investigated coupled dynamic behavior of a mini TLP giving special attention to hull-tether coupling. Ketabdari and Ardakani (2005) developed a computer program to evaluate the dynamic response of sea-star TLP to regular wave forces considering coupling between different degrees of freedom. Low (2009) presented a formulation for the linearization of the tendon restoring forces of a TLP. Chandrasekaran et al. (2007a) conducted dynamic analysis of triangular TLP models at different water depths under the combined action of regular waves and an impulse load affecting the TLP column. Chandrasekaran et al. (2007b) focused on the response analysis of triangular tension leg platform (TLP) for different wave approach angles and studied its influence on the coupled dynamic response of triangular TLPs. Kurian et al. (2008) developed a numerical study on the dynamic response of square TLPs subjected to regular and random waves. Kurian et al. (2008) developed a numerical study on determining the dynamic responses of square and triangular

TLPs subjected to random waves. They found that the responses of triangular TLPs are much higher than those of square TLP. Abou-Rayan et.al, (2012), have investigated the dynamic response of a square TLP under hydrodynamic forces in the surge direction considering all degrees of freedom of the system. They developed a numerical dynamic model for the TLP where Morison's Equation with water particle kinematics using Airy's linear wave theory was used. They accurately modeled the TLP system considering added mass coefficients and nonlinearity in the system together with the coupling between various degrees of freedom. Recently, Abou-Rayan et.al, (2013), have studied the dynamic response of a triangular TLP in deep waters.



(a) **(b)**

Figure 1: (a) The Triangular TLP (Plan and Elevation), and (b) The Square TLP (Plan and Elevation)

In this paper, numerical studies are conducted to compare the coupled responses of the triangular TLP with that of the square one (shown in Figure 1). To investigate the influence of nonlinearities due to hydrodynamic forces and the coupling effect between surge, sway, heave, roll, pitch and yaw degrees of freedom on the dynamic behavior of TLP's, a numerical scheme was carried out using Morison's Equation with water particle kinematics, Airy's linear wave theory. Only uni-directional waves in the surge direction was considered in the analysis.

EQUATION OF MOTION

The equation of motion is coupled and nonlinear and can be written as

$$[M]\{x^{\bullet\bullet}(t+\Delta t)\}+[C]\{x^{\bullet}(t+\Delta t)\}+[K]\{x(t+\Delta t)\}=\{F\ (t+\Delta t)\} \qquad (1)$$

Where, $\{x\}$ is the structural displacement vector, $\{\dot{x}\}$ is the structural velocity vector, $\{\ddot{x}\}$ is the structural acceleration vector; $[M]$ is the structure mass matrix; $[C]$ is the structure damping matrix; $[K]$ is the structure stiffness matrix; and $\{F\ (t)\}$ is the hydrodynamic force vector. The mathematical model derived in this study assumes that the platform and the tethers are treated as a single system and the analysis is carried out for the six degrees of freedom under different environmental loads where wave forces are estimated at the instantaneous equilibrium position of the platform utilizing Morison's equation and using Airy's linear wave theory. Wave force coefficients, Cd and Cm, are the same for the pontoons and the columns and are independent of frequencies as well as constant over the water depth. To achieve the response variation a time domain analysis is carried out. The Newmark's beta time integration procedure is used in a step wise manner.

For more detailed about the derivation of the equation of motion components for both configurations, the reader is referred to Abou-Rayan et.al, (2012, 2013).

RESULTS AND DISCUSSIONS

A numerical scheme was developed using MATLAB software where solution based on Newmark's beta method was obtained. Numerical studies are carried out to compare the coupled responses of both square and triangular TLP's under regular. Coupling of various degrees-of-freedom was taken into consideration by considering the off-diagonal terms in stiffness matrix [K]. Wave forces were taken to be acting in the direction of surge degree-of-freedom. The hydrodynamic data and the geometric properties considered are given in Tables 1-2. To ensure that the comparison is numerically justified, the geometric properties are taken in such a way that the radius of gyration and the total mass are equal for both configurations.

Table 3 shows the coupled natural time periods of both structures. It is observed that TLPs have very long period of vibration associated with motions in the horizontal plane (say 60 to 100 seconds). Since typical wave spectral peaks are between 6 to 15 seconds, resonant response in these degrees of freedom is unlikely to occur.

Surge Response

The time histories of the surge responses for both TLPs configurations are shown in Figure 2. It is clear that, the transient state for the triangular configuration takes almost double the time to reach the stationary state than that of the square one.

For short wave period, T= 6 sec, the maximum positive values of the square TLP responses are higher by about 30% more than that of the triangular TLP. But, for wave period, T= 8 sec, the maximum positive values for the square TLP responses are higher than that of the triangular TLP by about 15%. For longer wave periods (10, 12, and 15 sec), the differences between the responses for both configurations are decreasing to about 5% with the responses of the square one are still higher than those of the triangular one. As a general observation for both configurations responses, is that a long wave period causes a lesser positive surge response offset than those for the cases of short wave period (i.e., the shorter the wave the higher the response offset). In all cases, the surge response seems to have periodic oscillations with period one as seen from figure 5.

Finally, it is seen that the coupled surge response of the square TLP is higher than that of the triangular TLP (compare the amplitude of the response spectrum for both cases in Figure 5).

Heave Response

The time histories of the heave responses for both TLPs configurations are shown in Figure 3. As expected, the response in the heave direction has very small values compared to that of the surge direction. This is attributed to the relatively high stiffness of the tethers in this direction together with the fact that the excitation is indirect in this case. In this case, the response of the triangular TLP is higher than that of the square one (relatively, since both responses are very small compare to the surge one) by about 25%. This inversed trend, than that of the surge response, could be attributed to the geometric configuration itself.

To get an insight into this behavior, the response spectra for wave height of 8.0 m and wave period of 8sec. was obtained and the results are shown in Figure 5. It is clear that we have a period one response for the case of the square configuration with a period tripling response for the triangular one.

Pitch Response

The time histories of the pitch responses for both TLPs configurations are shown in Figure 4. Again as expected, the response in the pitch degree of freedom has very small values compared to that of the surge direction. In general the Triangular configuration has much more higher responses than those of the square one. This could be attributed to the fact that, the pontoons, which are neither perpendicular nor parallel to the unidirectional wave (inclined in plan), attracts forces in the surge direction that results in the moment about the sway axis. Thus, the square TLP response would be less than that of the triangular TLP. For both configuration the response is period tripling (see Figure 5).

Lastly, to gain a conceptual view of the stability and periodicity of the dynamic behavior of the structure, the phase plane and the corresponding response spectrum for wave periods of 8 sec and 8 m. height are plotted in Figure 5. It is observed that the steady state behavior of the structure is periodic and stable. Also, we have a period tripling cases for the pitch response of the square configuration and the heave and pitch responses of the triangular configuration.

CONCLUSIONS

The present study compares the dynamic responses of a square TLP configuration with that of triangular configuration under hydrodynamic forces in the surge direction considering all degrees of freedom of the system. A numerical dynamic model for both TLPs was written where Morison's equation with water particle kinematics using Airy's linear wave theory was used. Results for the time histories for the affected degrees of freedom, phase plane, and response spectrum for both configurations have been presented. Based on the results shown in this paper, the following conclusions can be drawn:

- The triangular configuration exhibits a lower response in the surge degree of freedom than that of the square one.
- The triangular TLP attracts more forces in the pitch degree of freedom with responses about 10 times more than that for square TLP. This could be attributed to the fact that, the pontoons, which are neither perpendicular nor parallel to the unidirectional wave (inclined in plan), attracts forces in the surge direction that results in the moment about the sway axis (pitch degree of freedom).
- The phase plane and the response spectrum show that the steady state behavior of the structure is periodic and stable.

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APPENDICES

Table 1: Water Properties

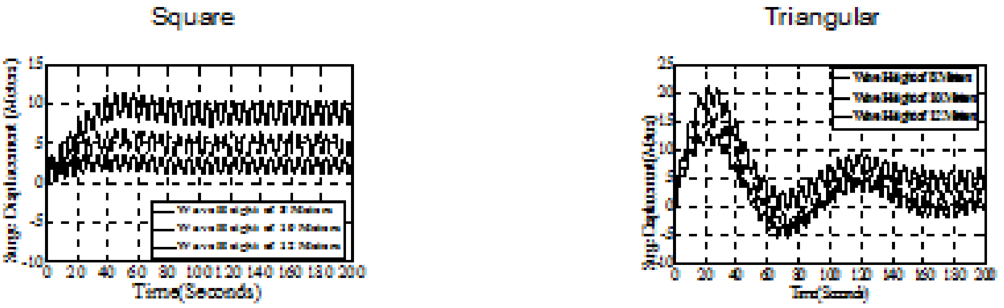
Gravity Acceleration (m/sec^2)	**Water Weight Density (kN/m^3)**	**Inertia Coefficient, C_m**	**Drag Coefficient, C_d**	**Current Velocity (m/sec),U_c**	**Wave Period (sec), T_w**	**Wave Height (m), H_w**	**Water Depth (m),d**
9.81	10.06	2	1	0	6, 8, 10, 12.5, and 15	8, 10 and 12	600

Table 2: Geometric Properties TLP

Platform Properties	**Square TLP**	**Triangular TLP**
Platform weight (KN),W	280000	280000
Platform length (m)	2a = 66.22	PL = 66.22
Platform width (m)	2b = 66.22	-----
Platform radius of gyration in x-directions (m), r_x	32.1	32.1
Platform radius of gyration in y-directions (m), r_y	32.1	32.1
Platform radius of gyration in z-directions (m), r_z	33	33
Tether total force (KN),T	160000	160000
Diameter of columns (m), D_c	18.06	20
Center of gravity above the sea level (m), H_C	6.03	6.03
Tether stiffness (KN/m),γ	80000	80000
Tether length (m), L	569	569
Diameter of pontoon (m), D_P	9.03	11
Draft(m),D_r	13	31
Damping ratio, ζ	5%	5%

Table 3: Calculated Natural Structural Periods

Analysis Case	DOF					
	Surge	Sway	Heave	Roll	Pitch	Yaw
Square	97.099	97.099	2.218	3.126	3.126	86.047
Triangular	97.245	97.245	2.491	3.377	3.389	62.969



(a) wave period =6 sec

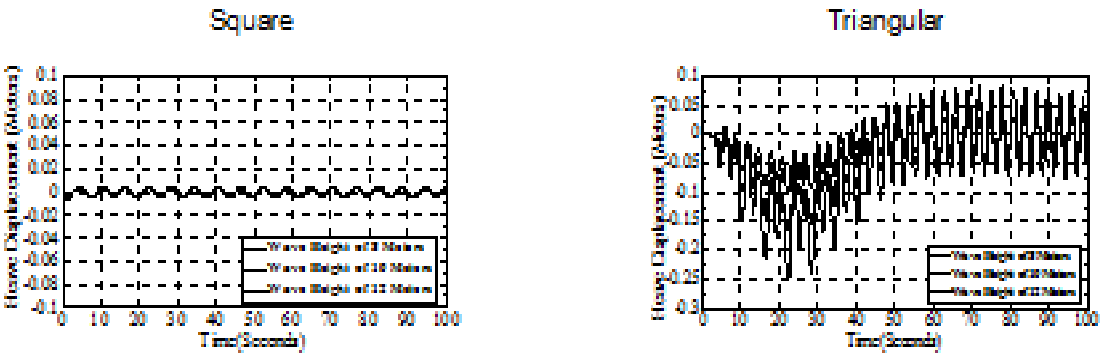
(b) wave period = 8 sec

(c) wave period = 10 sec

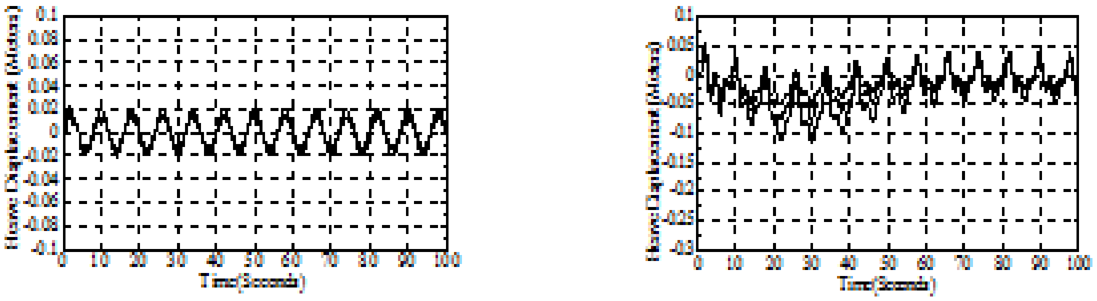
(d)wave period = 12.5 sec

(e) wave period = 15 sec

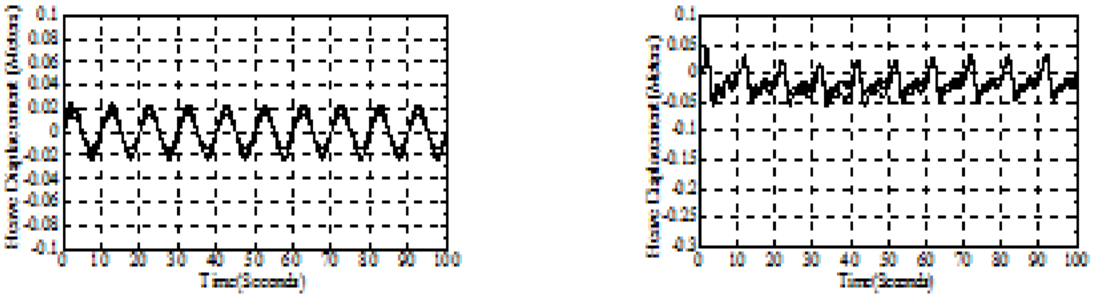
Figure 2: Surge Response of Coupled System



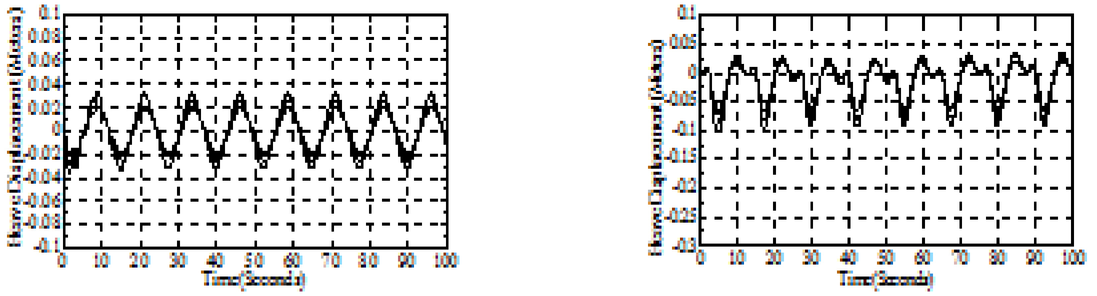
(a) wave period =6sec



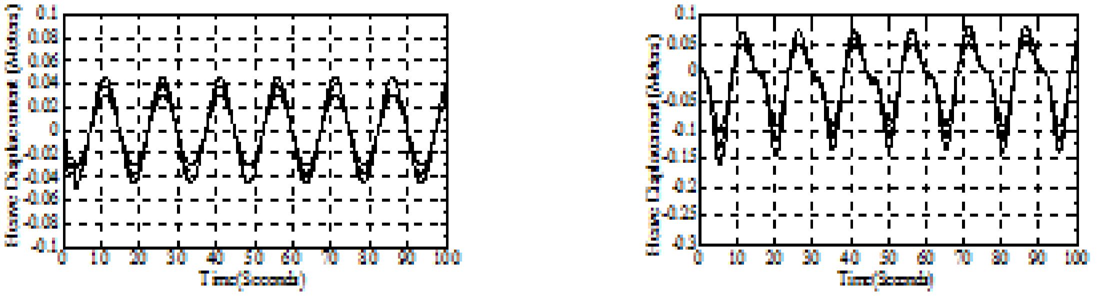
(b) wave period = 8 sec



(c) wave period = 10 sec

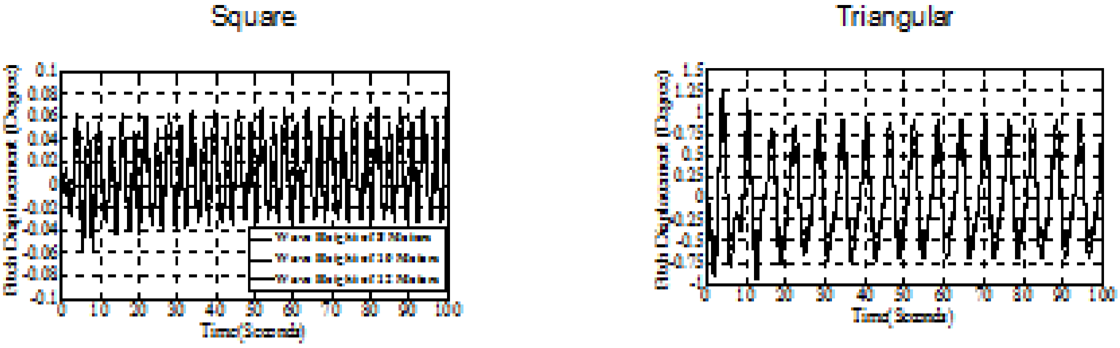


(d) wave period = 12.5sec

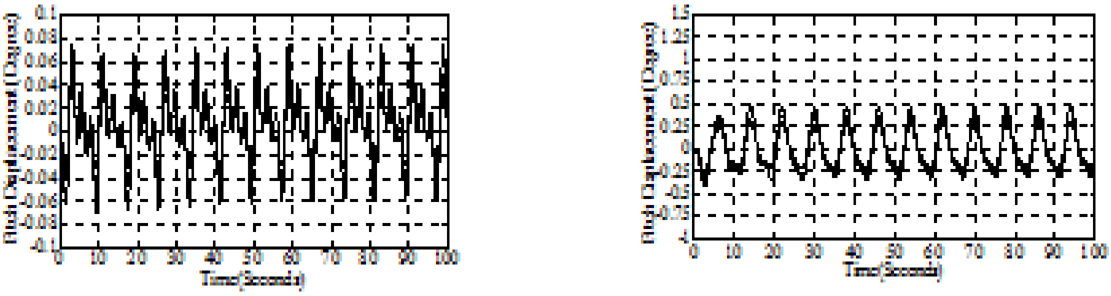


(e) wave period =15sec

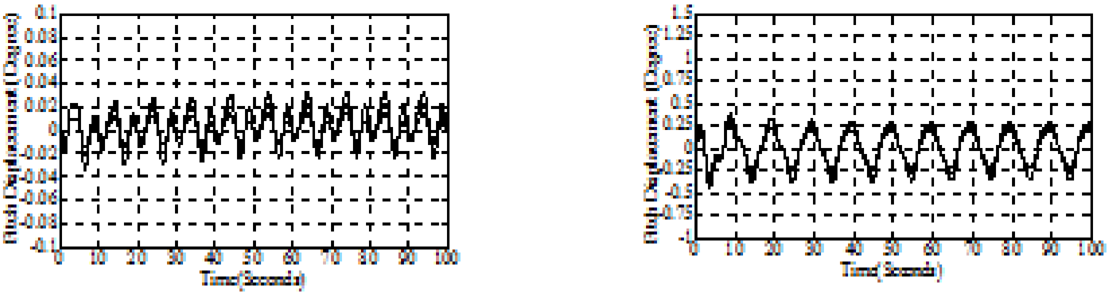
Figure 3: Heave Response of Coupled System



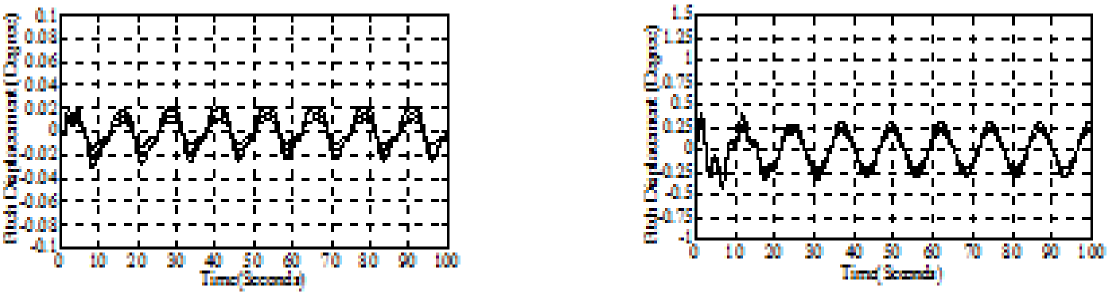
(a) wave period =6sec



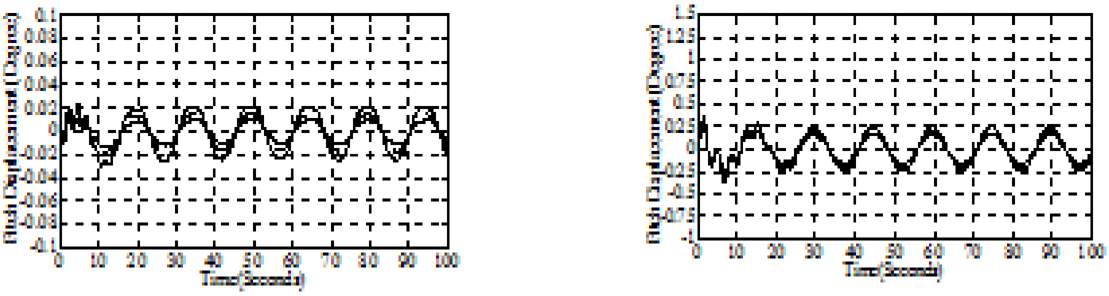
(b) wave period = 8 sec



(c) wave period = 10 sec



(d) wave period = 12.5sec



(e) wave period =15sec

Figure 4: Pitch Response of Coupled System

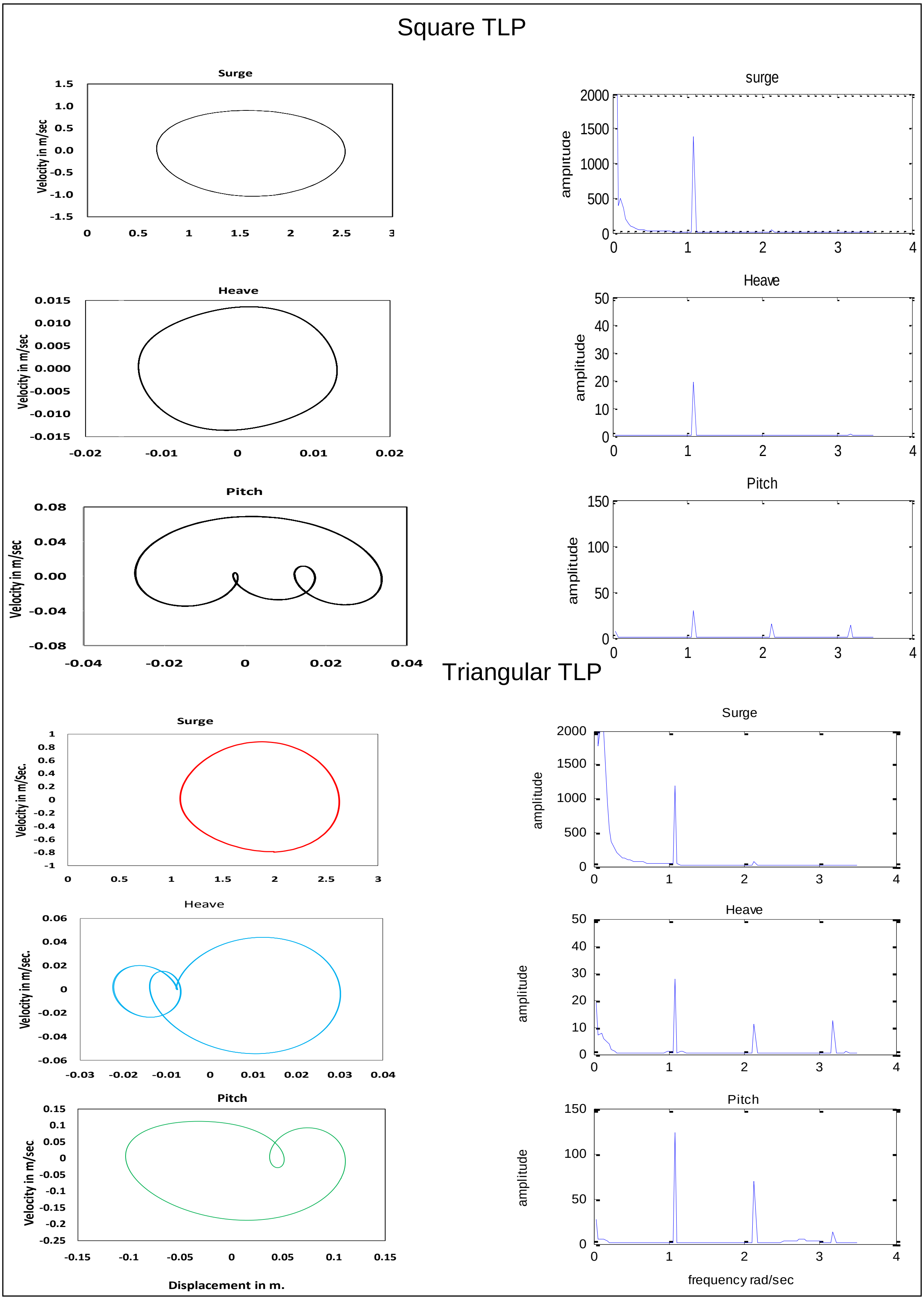


Figure 5: Phase Plane and Response Spectrum for Wave Period=8 sec. and Wave Height=8m