Dynamic Analysis of TLP in Intact and Damaged Tendon Conditions

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Abstract

Stability of Tension Leg Platforms (TLP) is sensitive to tendons situations. Therefore, behavior and exact calculation of stiffness matrix of TLP is important for dynamic analysis and investigation of TLP in intact and damaged tendon conditions is necessary to accurate and reliable design of TLP. In this paper deals with dynamic analysis of TLP when tendons are intact and one or three tendons are damaged. Static stability of TLP in damage condition has been studied and static offsets have been estimated, then stiffness of surge, heave and pitch has been derived. Finally, responses of heave and pitch for three load conditions have been predicted.

Keywords: TLP, damage condition, tendon.

Introduction

TLP is floating platform moored to seabed by tendons. This platform is consisted of buoyant hull, deck and mooring system. Buoyant hull sustains deck sufficiently above water level and anchored to seabed by a complex mooring system. Buoyancy of TLP is more than weight. Therefore, it need stiff and strong pre tensioned tendon to support additional buoyancy. Tendons connect hull to seabed by high performance anchors. Tendon mooring system allows platform move compliantly against lateral wave, wind and current loads but keep that unmovable vertically. Therefore, it has high stability and is good alternative for deep seas. Some of installed or proposed TLPs are shown in fig.1. According to the figure, maximum operational depth is 1581m.

Damage condition is an important analysis case that must be taking into account in design process. There is general three damage types can be occurred in various scenarios. General first damage type is flooding of tanks and then sinking of platform that can be occurred due to ship collision. Second damage type is structural damage without any flooding that can be occurred by an explosion or hurricane and third damage type is mooring or tether system failure that can be occurred by a hurricane. The damage types are shown schematically in fig.2 [1].

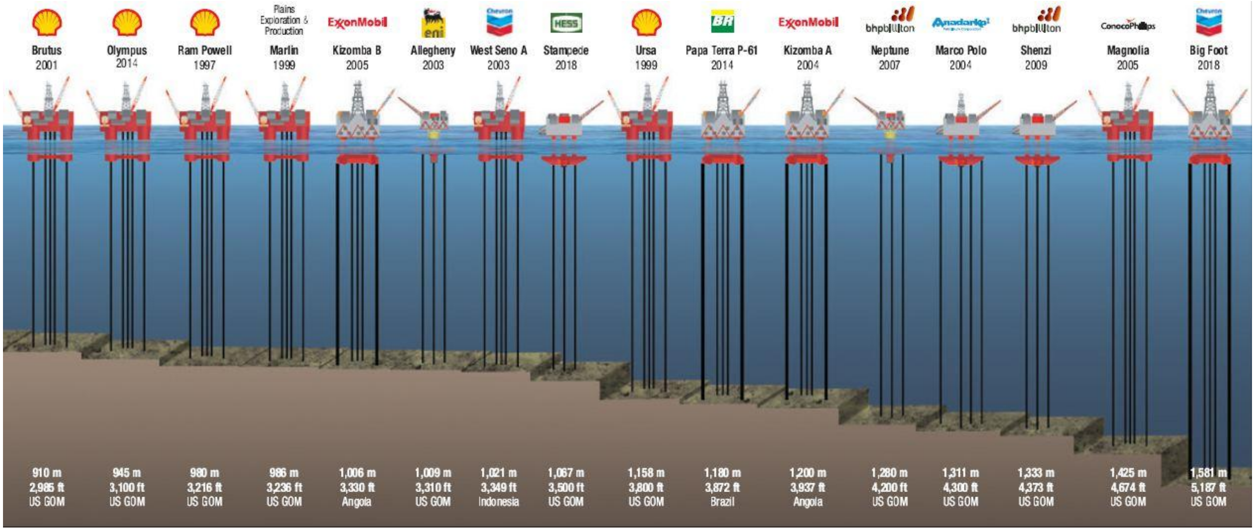
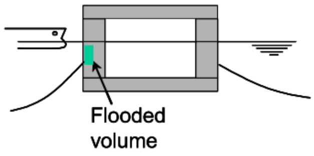


Figure 1: deepest installed or proposed TLP in the world

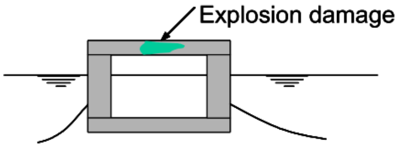
It is important to study TLP behavior in case of damaged tendon. Although tendon disconnection is a rare event in comparison to catenary mooring line failures, considerable population of installed TLP, that lead to considerable installed tendons over the world, make this problem important since tendons subjected to disconnection event become more. TLP is a deep water platform and installed where the ocean environment is harsh with severe waves and strong winds and this problem makes disconnection events more probable .

Reliability of floater must be analyzed both in intact and damaged condition. These analyses help designers to understand degree of reliability in intact and various damage scenarios. Reliability analysis is one of key stages in tendon system design process. Theses analyses can help assess different degree of reliability of tendon system among designs utilizing different numbers of tendons, different types of connectors, and/or end terminations, etc. Also, such analyses can help assess reliability versus system cost.

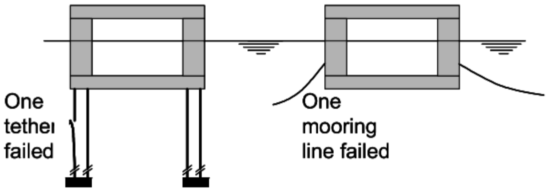
Since TLPs are installed in deep water fields, there are some joints along tendon length to connect smaller elements together. These joints may take several forms of couplings, welded joints and etc. These are subjected to fluctuating and extreme stresses and resulting fatigue or accidental damage.



a) **Capsizing/sinking** due to (progressive) flooding



b) **Structural failure** e.g. due to impact damage,....



c) **Failure of mooring system** due to "premature" failure

Figure 2: different types of damage in floating platforms [1]

Tendon removal must be considered in tendon system design. Tendons may permanently installed or be removable. Stress change must be in an acceptable range if one tendon is removed. A tendon has certain design life that must be match with platform design life. Some factors affect tendon design life such as initial tendon cost, the cost of tendon replacement, tendon in-place inspect ability, and the risks associated with tendon retrieval and reinstallation.

There is several events can make tendon damaged and some real experiences such as TLP tendon failure in storms in Gulf of Mexico affirm them.

Vortex induced cross flow vibrations can damage tendon since natural frequency of tendon is close to excitation frequency of shedding that cause relatively considerable lateral vibrations lead to large stress fluctuations in the tendon. Therefor this phenomenon can cause fatigue damage and finally breaking down even in low cycle vibrations. Bachynski and Moan [2] try to optimize design of a tensioned leg platform wind turbine (TLPWT) to minimize fatigue damage and hence extend fatigue life time. They focus on pitch motion of TLPWT and investigate ratio of standard deviation of leg tension and pretension, standard deviation of pitch motion, base moment and surge motion to assess fatigue behavior of floater.

Gongwei and et al [3] solve nonlinear dynamic equation of motion of tendon subjected to current field and floater motions. Their study contains effect of tendon pretension on VIV behavior of that. A finite element code was developed to model nonlinear tendon. The CFD program FLUENT was used to solve 2D modeling of fluid move around tendon. Tao and Jun [4] investigate hydrodynamic aspects of tendon design such as Mathieu instability, ringing and springing, bottom tension slacking and vortex induced vibrations and then coupled hull/tendon/riser dynamic analysis of TLP. In this study, a FEM approach used to analysis tendons and risers and an experimental study carry out to verify VIV calculations.

Kim and Zhang [5] had a concentrate look on dynamic stability and survivability of a damaged TLP in moderate hurricane condition when one or more tendons are failed. They developed a BE-FEM computer code to model coupled dynamic behavior of hull-tendon-riser in time domain. As shown in their study, snap-like transient effect of tendon disconnection cause significant increase in neighboring tendon tension and may lead to general failure of system because of continuous failure of tendons.

Tabeshpour and et al [6] have a comprehensive interpretation on responses of TLP in random sea according to environmental and structural characteristics. They have a brief review on hydrodynamic loadings based on Morison equation and effective parameters in equations of motions. Nonlinearities in these equations are taken into account and time and frequency domain behavior of particular TLP subjected to irregular wave loading is interpreted comprehensively. Tabeshpour and malayjerdi [7] take a precise look on pitch motion portion in vertical displacement of TLP columns and then tendon tension. They carry both frequency and time domain analyses out and show that pitch motion can affect tendon tension severely in some wave periods. They represent the RAO of heave and pitch of platform and vertical motion of tendon top end and discuss about pitch portion in that.

Senjanović and et al [8] represent a new formulation for stiffness of surge, sway and yaw motions. They develop formulations by both static force equilibrium and energy balance approaches for large and small surge, sway and yaw degrees of freedom. They compare their results by FEM analysis and good agreement seen with those results. Only diagonal elements of stiffness matrix of horizontal plane motions are extracted in this study.

Barranco and et al [9] represent a reliability-based methodology to perform a LRFD criterion for the design of tendon of TLP. The proposed design criterion considers the Ultimate Limit State (ULS) for the tendon sections, expressed in terms of the expected value of the extreme Interaction Ratio, considering long-term storm sea states, and takes into account the dynamic load effects interaction and the statistics of its associated extreme response.

Alberto and et al [10] take a look on TLP tendon tension during LiLi hurricane. It was 2002 and hit several offshore units near track. One of them was a TLP that there is a sufficient measurement of wind, motion and tendon tension from that. Time and frequency analyses performed on tension sensor data and in-service behavior compared with design situation. Other relevant comparisons included natural period and damping estimates.

In this paper deals with dynamic analysis of TLP in intact and damage conditions. Static stability of TLP in damaged tendons condition has been studied and static offsets are estimated due to disconnection of tendons. Stiffness matrix of TLP derives when one or more tendons are disconnected. Then motion equations solved and response of heave and pitch motions obtained for three load conditions.

Vertical irrotational static stability of TLP in damage condition

Stability of TLP for on-site condition, with tendon legs system connected is not governed by a metacentric approach. The stability is typically provided by the pretension and stiffness of the tendon system, rather than by water plan area and moments. lateral load enforce TLP to offsets in x, y and θ_z in order to static stability, after tendon disconnection. It is noted that the most important offsets occur in soft degrees of freedom. Eliminating angular offsets, generally, disconnection of tendon causes draft and buoyancy reduction (ΔB) and tension in rest of tendons (T_a) increase. Due to increase of tension of tendon, elongation in tendon Δz_B occurs. Equations of static stability are as follow [11]:

$$T_a = T_0 + \Delta T \tag{1}$$

$$T_0 = \frac{B-W}{N_t} \tag{2}$$

$$\Delta T = k\,\Delta z_B \tag{3}$$

$$\Delta z_B = \frac{\Delta B}{\rho g A_w} \tag{4}$$

$$(N_t - N_d)T_a = B - \Delta B - W \tag{5}$$

Where T_a will be defined later, T_0 is pretension of tendon in intact condition, ΔT represents the additional tension applied to a tendon related to the additional elongation, $k = EA_t/L$ is axial stiffness of tendon, that A_t is cross section area of tendon, L is length of tendon, A_W is water plane area, N_t is total number of intact tendons, N_d is number of damaged tendons and W is weight of TLP. Equation (5) represents vertical stability of TLP and solving this equation can calculate T_a and ΔB as follow:

$$\Delta B = \frac{B - W - (N_t - N_d)T_0}{\dfrac{(N_t - N_d)k}{\rho g A_w} + 1} \tag{6}$$

Then using equation (1) to (5), T_a is calculated as follows:

$$T_a = T_0 + \frac{B - W - (N_t - N_d)T_0}{(N_t - N_d)k + \rho g A_w} \tag{7}$$

Vertical plan angular Static stability around neutral axis-damage condition

TLP will jump and rotate after tendon disconnection. When transient vibrations finished, TLP rests in static stability condition in calm water. We can assume that TLP is jumped at first and then rotate. Platform jump was studied in previous section and rotation will be discussed in this section.

When a tendon from group no.1 is damaged, the platform will be inclined around neutral axis. Neutral axis is a set of points that not affected by tendon remove inclination and keep their vertical position after that. So, TLP inclination will affect tendon group no.1 and no.3 only.

Considering axial stiffness of tendon, *k*, inclination angle and trim and heel angles can be derived as equation (8):

$$\theta_{inc} = \frac{T_a(6 - N_d)}{6\sqrt{2}(3 - N_d)\,p\,k}, \ \theta_{trim} = \theta_{heel} = \sqrt{2}\,\theta_{inc} \tag{8}$$

Motion Equations of TLP

The equations of motion of TLP in frequency and time domains can be written as follow:

$$\sum_{i=1}^{6}\left[-\omega^2\left\{M_i + A_i(\omega)\right\} + i\omega C_i(\omega) + K_i\right]q_i(\omega)\,\mathrm{e}^{i\omega t} = F_i(\omega) \tag{9}$$

where $[M_i]$, ω, $[A_i(\omega)]$, $[\mathrm{C}_i(\omega)]$, $[K_i]$, $[q_i(\omega)]$, and $[F_i(\omega)]$ are mass matrix, wave frequency, added mass matrix, damping matrix, stiffness matrix, displacement amplitude and wave force for every degree of freedom.

Stiffness matrix of TLP in damage condition

Stiffness matrix of TLP in damaged tendon condition differs with intact tendon condition. The coefficients of matrix of stiffness k_{ij} derive as the reaction in the degree of freedom i due to unit displacement in the degree of freedom j, keeping all other degrees of freedom restrained. When TLP move purely in vertical plan as heave, roll and pitch motions, there is no horizontal component for resulting restoring tensions. Therefore, pure vertical plan motions just affect vertical degrees of freedom, while horizontal plan motions of TLP results in both vertical and horizontal components of restoring tensions. Therefore, horizontal plan motions affect both vertical and horizontal plan degrees of freedom.

It is important to derive stiffness matrix elements when tendon is removed from a group. Some surge motion induced stiffness of TLP in damage condition can be expressed as follow:

$$k_{11}x = (12 - N_d)(T_a + \Delta T_x)\sin\theta_x \tag{10}$$

$$k_{51}x = -(k_{11}\,x)KG - N_d\,(T_a + \Delta T_x)\cos\theta_x\,\frac{p}{2} \tag{11}$$

$$\sin\theta_x = \frac{x}{\sqrt{x^2 + L^2}} \cong \frac{x}{L} \tag{12}$$

$$\cos\theta_x = \frac{L}{\sqrt{x^2 + L^2}} \tag{13}$$

$$\Delta T_x = \frac{A_t E}{2}\left(\frac{x}{L}\right)^2 \tag{14}$$

Where ΔT_x is the change in tension of each remaining tendon and θ_x is the angle between the initial and displaced position of the tendon in surge direction.

Some heave motion induced stiffness for TLP in damage condition can be written as follow:

$$k_{53} = -\frac{N_d A_t E}{L}\,\frac{p}{2} \tag{15}$$

Enforcing TLP to an arbitrary pitch rotation, tension of remaining tendons change and pitch stiffeness of tendon system calculated as follow:

$$k_{55} = \frac{(12 - N_d)\,A_t E}{L}\,\frac{p^2}{4} \tag{16}$$

Figure (3) shows displacement of pitch degree of freedom. ΔT_θ is axial tension change in tendon defined as bellow:

$$\Delta T_\theta = \frac{A_t E}{L}\,\frac{p}{2}\,\theta_5 \tag{17}$$

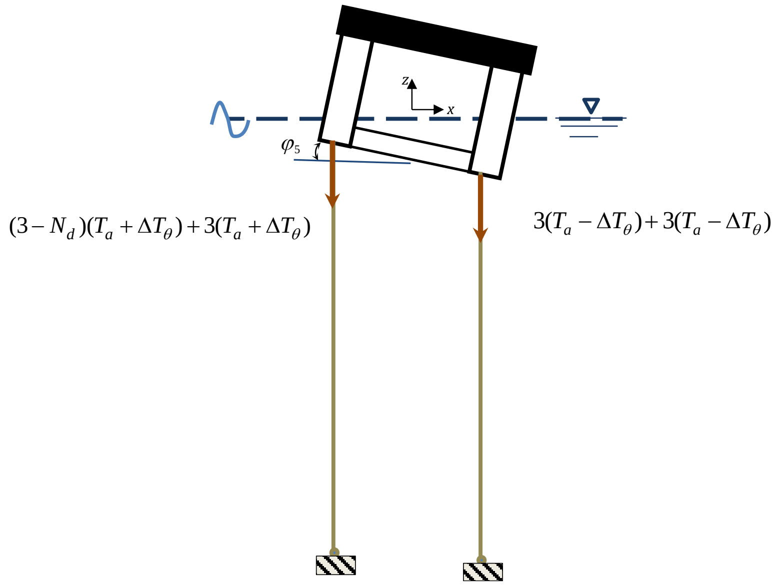


Figure 3: Pitch rotation of TLP in damage condition.

Case study

The research platform is a tension-leg platform named ISSC TLP with specifications given in table (1), [12]:

Table 1: specifications of ISSC TLP in depth of 230 m [12]

Draft	$35m$	External radius of tendon	$0.3m$
Displacement	$54.5\times10^{6}\ kg$	Internal radius of tendon	$0.212m$
Mass	$40.5\times10^{6}\ kg$	Length of tendon	195
Roll motion moment of inertia	$82.37\times10^{9}\ kg.m^{2}$	Pre-tension in tendon	$1.1445E7\ N$
Pitch motion moment of inertia	$82.37\times10^{9}\ kg.m^{2}$	Young's modulus of tendon	$2.1E11\ N/m^{2}$
yaw motion moment of inertia	$98.07\times10^{9}\ kg.m^{2}$	Axial stiffness of tendon	$1.5E8\ N/m$
Center of gravity height	$38m$	Number of tendons under leg	3

Results and discussions

In this section, recently mentioned motion equations are solved and response of heave and pitch motions obtained. In this study lateral excitation that incidents to TLP is regular wave. The characteristics of load cases are presented in table (2) as follow:

Table 2: The characteristics of load cases

Load case number	**Tendon condition**	**Wave approaching (degree)**	**Wave height (m)**	**Wave period (s)**
LC1	intact	0	8	8
LC2	One tendon damaged	0	8	8
LC3	Three tendons damaged	0	8	8

Figure (4) shows schematic view of TLP and wave approach angle.

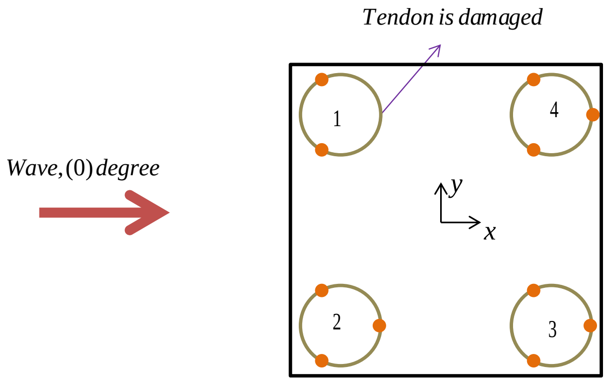


Figure 4: Schematic view of TLP and wave approach angle

Figure (5) presents heave displacement of TLP for load conditions (1, 2 and 3). It can be seen that heave responses for the cases of LC1 and LC2 in transient and steady states are equal. Heave response based on three damaged tendons is more than LC1 and LC2, because according to table (1), ratio of heave stiffness in intact condition to damaged one tendon and three tendons condition are $\left((k_{33})_{\text{intact}}/(k_{33})_{\text{damaged one tendon}}=1.09\right)$ and $\left((k_{33})_{\text{intact}}/(k_{33})_{\text{damaged three tendons}}=1.5\right)$. Therefore natural period of heave response in damage condition increases.

Pitch response of TLP for LC1, LC2 and LC3 is shown in Figure (6). The difference between the results from three load conditions is found in transient and steady states of pitch response. Pitch response of TLP when one tendon is damaged (LC2) is slightly more than the intact tendons condition (LC1). Pitch response for LC3 is significantly more than LC1 and LC2, because pitch stiffness when three tendons are damaged significantly is decreased. From equation (15), it is seen that there is stiffness of coupling pitch with heave due to disconnection of tendons and when tendons are intact tensions of tendons are equal and there is not stiffness but this stiffness is negative, therefore cause pitch response increases.

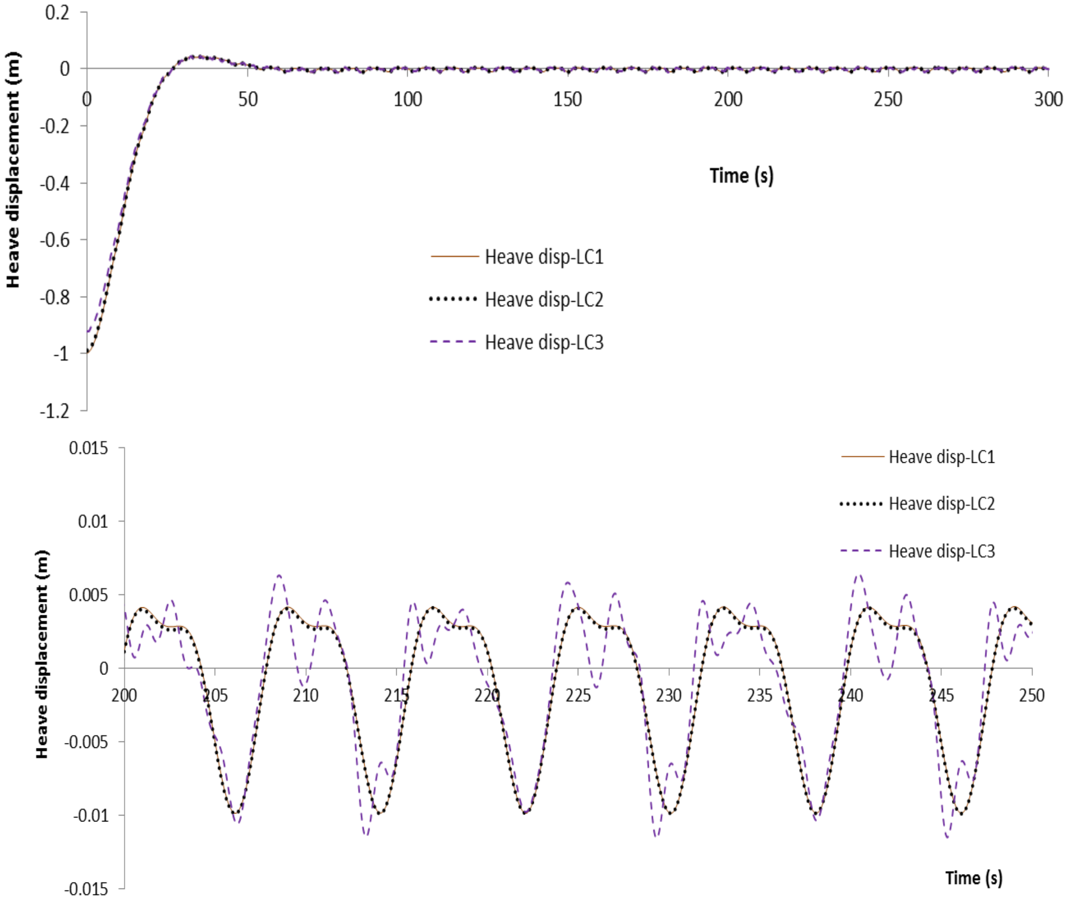


Figure 5: Heave displacement of TLP for LC1, LC2 and LC3.

Summary and conclusion

In this study, dynamic analysis of TLP investigates when tendons are intact and damaged. From the mathematical section and numerical results, the following points was obtained as follow:

1. Change in tendon tension after tendon removal in calm water (static condition) is a result of composite angular and linear vertical transitional offset of TLP.
2. Stiffness matrix of TLP in damaged tendons condition differs with intact condition. Stiffness of heave and pitch of TLP in damage condition significantly decreases. There is no coupling between pitch and heave in intact condition but it can be seen in damage condition.
3. Heave and pitch responses of TLP for LC1 and LC2 are similar but when all tendons of column (1) are damaged, these responses increase.

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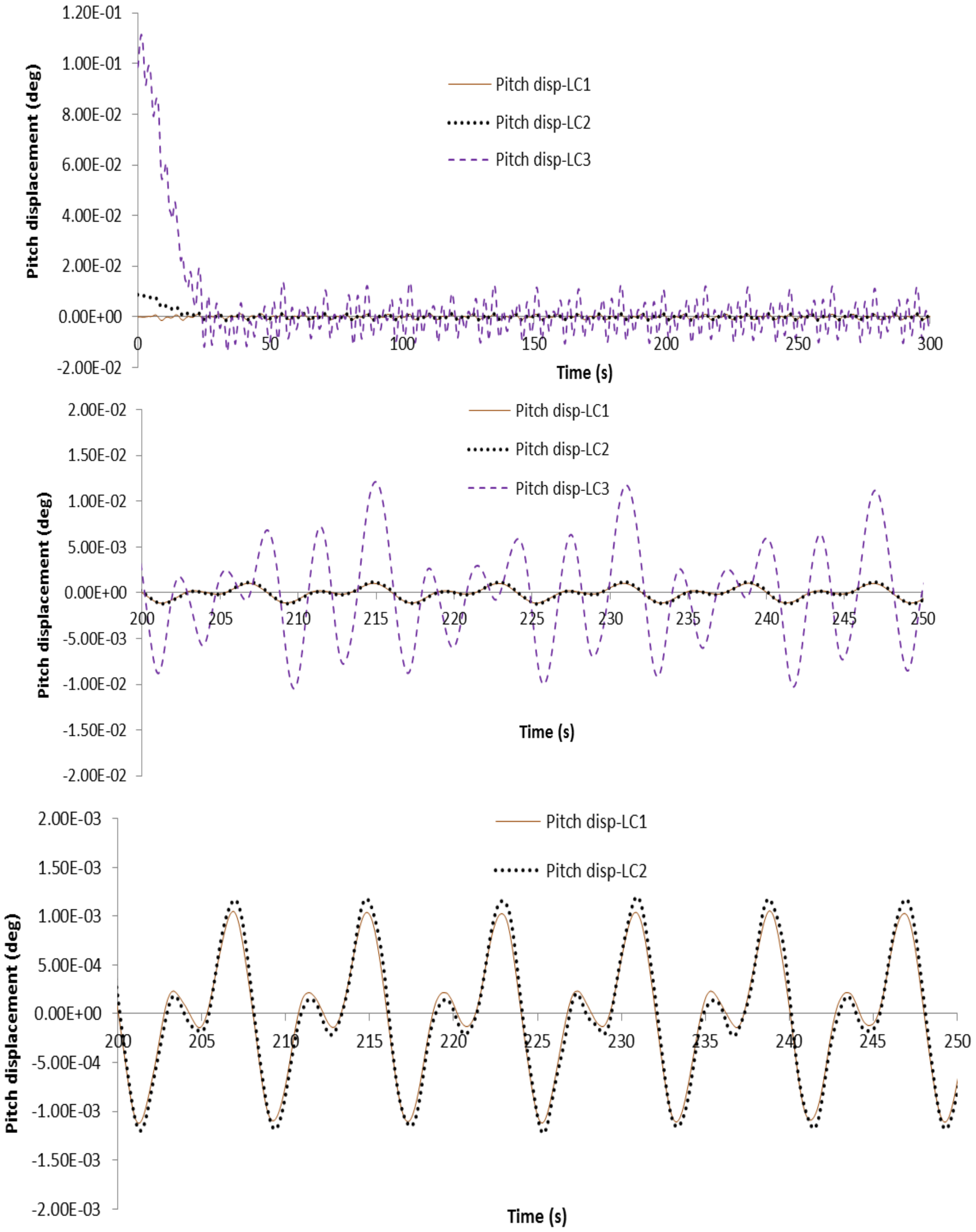

Figure 6: Pitch displacement of TLP for LC1, LC2 and LC3.