Dynamic Response Control of Offshore Jacket Platforms

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Abstract

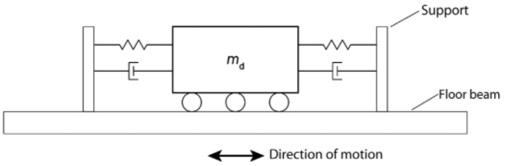
Vibrations in offshore structures have been attributing factors in several major accidents and failures in the marine and offshore industry over the last few decades. Due to various environmental loads, these vibrations can reduce platform productivity, endanger safety, affect serviceability of the structure. The effectiveness of a control technique straightly depends on the performance of the control device. Note that reduction of vibration amplitude of an offshore platform by 15% can extend service life over two times and can result in decreasing expenditure on maintenance and inspection of structures. Therefore, it is of great significance to explore proper ways to reduce different types of vibrations of offshore platforms. Thus, how to mitigate the vibration induced from earthquake loading becomes an important issue. This paper provides an investigation of vibration control methods and their application for offshore jacket platforms. The purpose is to find an effective and economic means to reduce the vibrations of sample jacket platform located in Persian Gulf. In this research, some passive control schemes including dynamic vibration absorbers (such as Tuned Mass Dampers (TMDs) and Tuned Liquid Column Dampers (TLCDs)) utilized in vibration control are studied. Finally, the advantages and disadvantages of these passive control schemes have been discussed.

Keywords: Steel Jacket Type Platform, Passive Control, Tuned Mass Damper (TMD), Tuned Liquid Column Damper (TLCD).

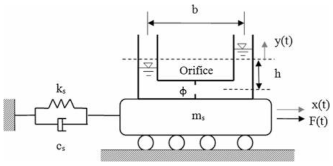
1. INTRODUCTION

Steel jacket type platform is the most common type among the various types of offshore platforms. The offshore platforms located in hostile environment are subjected to more crucial environmental loading such as wind, wave, ice and earthquake. Vibrations not only gradually damage the platform’s structural system but also cause an uncomfortable environment for humans. Therefore, the vibration of the platform becomes an important issue along with the safety requirement, particularly when facilities of recreation and entertainment purposes are installed on the platform system. It is always a challenging task to try to reduce the vibration induced by seismic loading, because of difficulties with monitoring the platform motion accurately and lack of an appropriate mitigation device that can be employed on an offshore structural system. As a result, controlling the dynamic response of platform is an important issue for the development of offshore hydrocarbon. [1].

Four main structural control systems such as passive, active, semi-active and hybrid have been used in a number of structures [2]. Passive control systems can enhance structural damping, stiffness, and strength without employing force devices, complex sensors, and instrumental equipment. The main outcome of using a passive control system is to minimize the oscillation of the system. There are various damping devices such as tuned mass dampers (TMDs), tuned liquid dampers (TLDs), and tuned liquid column dampers (TLCDs). Tuned mass dampers have been implemented in tall buildings, towers and bridges and its effectiveness during earthquakes has been well proved [3]. Due to simplicity and effectiveness of TMDs, they have been popular in the wind industry and there have been a number of studies focusing on wind turbine tower using TMD [4]. Among these, Stewart and Lackner (2014) [4] examined the impact of passive tuned mass dampers considering wind-wave misalignment on offshore wind turbine loads for mono-pile foundations. The results demonstrated that TMDs are efficient in damage reduction of towers, especially in side-side directions. Stewart and Lackner (2013) [5] in another study investigated the effectiveness of TMD systems for four different types of platforms including mono-pile, barge, spar buoy, and tension-leg and they observed tower fatigue damage reductions up to 20% for various TMD configurations. There have also been some investigations on the impact of TMDs on wind turbine blades [6]. The use of active tuned mass dampers for control of in-place vibrations of wind turbine blades was studied by Fitzgerald et al. (2013) [6] and they demonstrated promising results especially for high turbulent loadings. A Tuned Liquid Column Damper (TLCD), which is a vibration decrement device, consists of a rigid U-shaped tube, with an orifice in the middle, filled with a liquid. Vibration decrement in a structure equipped with TLCD occurs through increasing the system damping. The main limitation of these devices is their best performance in a specific frequency ratio. TLCDs provide many advantages, when compared to TMD, such as low cost, no moving mechanical parts, relatively easy installation in new buildings or in retrofitting existing structures, simple maintenance requirements. Indeed, a TLCD may not cause additional cost or weight if a water tank used for water supply and firefighting (earthquake induced fire is not considered) is incorporated into the design of a TLCD [7]. In recent years, there has been an increasing interest in the application of TLCDs to the problem of vibration suppression in civil engineering structures [8]. The damping effect of TLCD on structural vibration control depends on proper tuning and damping value. Matteo et al. (2015) [9] presented that optimal TLCD parameters can be computed taking advantage of the proposed approximated formulation, by which a smooth function, defining the main system variance, can be formulated and easily minimized. It should be noted that any device like TMD or TLCD increase the damping effectively only for lightly damped structures. Therefore, these devices are good options in the case of offshore jacket platforms because it is well-known that these slender structures have relatively low damping as stated in API [10]. Mass damping (TMD, TLD and TLCD) approaches consist of applying a dynamic modification system only in few locations in a structure (usually at the top of the structure). Devices can be placed only in one (e.g., TMD) or multiple locations (e.g., MTMD) [11] but without being allocated in a distributed manner, as described for the dynamic modification system in the previous sections. The schematic diagram showing these devices are provided in Figure 1. The major advantages and disadvantages of each category are summarized in Table 1.



(A)



(B)

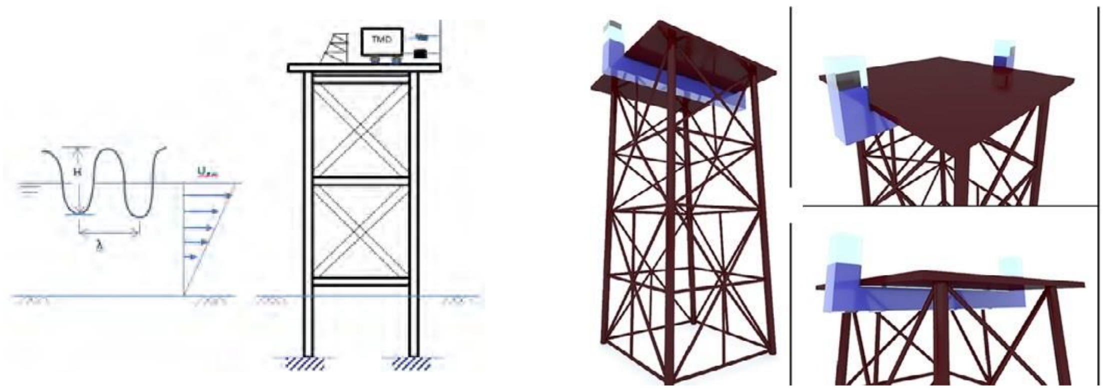
Figure 1. Mass damping approaches simplified schemes: (A) Schematic diagram showing TMD installed on a SDOF[1] system, (B) Schematic diagram showing U-shaped TLCD installed on a SDOF system

Table 1- Advantages and Disadvantages of Mass Dampers

Devices	Advantages	Disadvantages
TMD	• Response to small levels of excitation • Properties can be adjusted in the field • Low maintenance • Cost-effective • Can be designed to add damping to two orthogonal modes of vibration • Effective across all typical tall building periods • Control higher building accelerations than TLCDs	• Large mass and large space required for installation, but smaller than TLCDs of equivalent performance • Effectiveness depending on the maximum mass that can be utilized • Effectiveness depending on the tuning accuracy • Mass, no other functional use
TLCD	• Response to small levels of excitation • Mass can be utilized as water supply/storage/fire fighter • Can be designed to add damping to two orthogonal modes of vibration	• Damping depending on the screens provided • Water can freeze at low temperature • TLCD typically suffers a change in active mass upon tuning • Performance in periods beyond 8 s and/or controlling very high accelerations can be challenging • Possible leakage

[1] Single Degree of Freedom

In Figure 2, the major properties and design principles of each device are reviewed in detail.



(A) **(B)**

Figure 2. Mass damping approaches simplified schemes: (A) Platform Equipped with Tuned Mass Damper, (B) Platform Equipped with Tuned Liquid Column Damper

2. SCOPE OF THE STUDY

The objectives of the current study are to implement the TMD and TLCD separately on top of platform and to evaluate the optimum parameters of the TMD and TLCD and their efficiency when the jacket platform is subjected to seismic excitations. In this paper, the parameter optimization and the numerical calculations are investigated. Den Hartog’s method [12] is used to optimize the parameters of TLCD. Finally, numerical simulation of a sample steel jacket type platform used as benchmark structure at Persian Gulf illustrates the effective vibration control by the proposed devices by using MATLAB package [13].

3. TUNED MASS DAMPER SYSTEM

TMD is a system composed of a mass, spring, and damper (properly tuned) that is attached to a structure to reduce its dynamic response. The original concept was proposed by Frahm (1911) [14] for the ship industry. The main design challenge of this device is to tune its intrinsic frequency to a particular building frequency (usually the fundamental one). Therefore, when the structure is excited with that frequency, the TMD will resonate out of phase with the building and the energy will be dissipated by the damper. Compared to other control devices, TMD involves a relative large mass and displacements. As a consequence, supporting elements are one of the most critical elements in the design process. A TMD is characterized by the following ratios:

- Tuning frequency ratio, γ , as the ratio between the fundamental frequency of the TMD, ω_d , to that of the structure, ω_s .

$$\gamma = \frac{\omega_d}{\omega_s} \tag{1}$$

- Mass ratio, μ, as the ratio between the mass of the TMD, m_d, to that of the structure, m.

$$\mu = \frac{m_d}{m} \tag{2}$$

- Damping ratio, ξ_d

The design goal is to find the optimum TMD parameters γ and ξ_d for a given μ to reduce the building response (e.g., displacement) under different excitation. It is assumed that the main uncontrolled structure is subjected to base excitation and is mitigated by using a tuned mass damper. The equations representing a single-degree-of-freedom (SDOF) system equipped with a tuned mass damper (Figure 3) are [4]:

$$(1+\mu)\ddot{x} + 2\xi_s\omega_s\dot{x} + \omega_s^2 x = -(1+\mu)\ddot{x}_g - \mu\ddot{u} \qquad \text{(Primary system)} \tag{3}$$

$$\ddot{u} + 2\xi_d\omega_d\dot{u} + \omega_d^2 u = -\ddot{x}_g \qquad \text{(TMD system)} \tag{4}$$

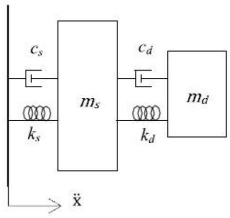


Figure 3. SDOF system with a Tuned Mass Damper (TMD)

where, μ represents the ratio of the TMD mass (m_d) to structural mass (m_s); k_s and c_s are the stiffness and damping coefficient of the structure; k_d and c_d are the stiffness and damping coefficient of the damper; ξ_s is the damping ratio of the structure; ξ_d is the damping ratio of the TMD and γ is the ratio of the frequency of the TMD (ω_d=$\frac{k_d^2}{m_d^2}$) to the frequency of the structure (ω_s=$\frac{k_s^2}{m_s^2}$); x is displacement of the structure; u is the displacement of the TMD, and $\ddot{x}_g$ the ground acceleration.

4. TUNED LIQUID COLUMN DAMPER SYSTEM

Let us consider a U-shaped TLCD installed on a SDOF system. The schematic diagram showing the combined structure-TLCD is provided in Figure 4. The equations of the motion of the structure and the liquid column can be written as [9]:

$$(1+\mu)\ddot{x}+2\xi_s\omega_s\dot{x}+\omega_s^2x=-(1+\mu)\ddot{x}_g-\alpha\mu\ddot{u} \quad \text{(Primary system)} \tag{5}$$

$$\alpha\ddot{x}+\ddot{u}+2\xi_d\omega_d\dot{u}+\omega_d^2u=-\alpha\ddot{x}_g \quad \text{(TLCD system)} \tag{6}$$

All of TLCD parameters in equations 3 and 4 are same as TMD parameters, but $\alpha=\frac{m_h}{m_{TLCD}}$, that, m_h is the horizontal liquid mass of TLCD and m_{TLCD} is total liquid mass and ξ_d is the equivalent damping ratio that has to be chosen minimizing the mean square error made in passing equation (7). Omitting for clarity's sake the time dependence, we have:

$$E\left[\left(c_d\left|\dot{u}\right|\dot{u}-2\xi_d\omega_d\dot{u}\right)^2\right]=\min_{\xi_d} \tag{7}$$

where E[·] means ensemble average and c_d = ξ_d /2L (L = TLCD length). Once the minimum is performed, the expression for the equivalent damping ratio becomes

$$\xi_d=\frac{c}{\omega_d}\sigma_{\dot{u}}\sqrt{\frac{2}{\pi}} \tag{8}$$

where $\sigma_{\dot{u}}$ is the standard deviation of the velocity of the fluid [24]. The use of Eq. (8) for design purposes is not straightforward since the standard deviation of the velocity of the fluid $\sigma_{\dot{u}}$ is still unknown and it implicitly depends on ξ_d, then, in general, an iterative procedure is necessary [9].

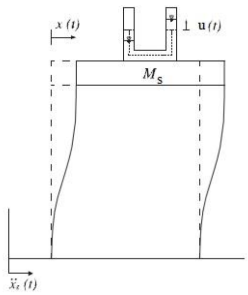


Figure 4. SDOF system with a Tuned Liquid Column Damper (TLCD)

5. DYNAMIC MODEL OF THE JACKET PLATFORM AND THE DAMPER SYSTEMS

5.1. NUMERICAL EXAMPLE

A three-dimensional offshore jacket platform (located in the Persian Gulf) is considered in this regard. A figure of the jacket platform model and the real prototype is shown in Figure 5. The jacket is modeled based on the four-leg prototype structural dimensions with a height of 65.75 m and the water depth of 58.5 m. The weight of the jacket is taken as 5000 tons and the lowest and the highest levels dimensions are considered as 32.8×28.3 and 20.3×14.5 meters, respectively. For the damping matrix Rayleigh's technique is utilized and a value of five percent is taken as the damping ratio. The first three natural period of the jacket platform is gained as 1.99, 1.9 and 1.72 seconds, respectively.

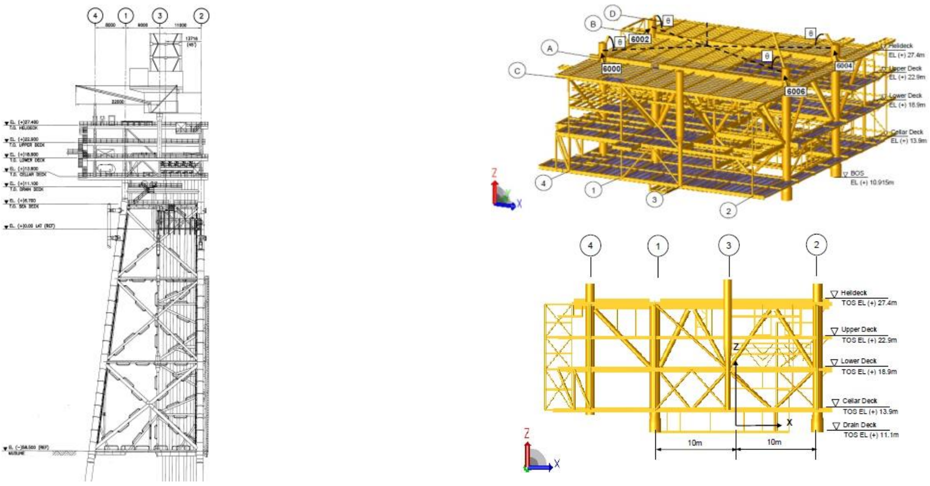


Figure 5. Prototype (A) and FE model (B) of sample jacket platform.

5.2. PLATFORM-TMD

The equation of motion for the whole system including an offshore jacket platform and an TMD system subjected to seismic excitation can be written as following [4]:

$$[\bar{M}]\ddot{x}+[\bar{C}]\dot{x}+[K]x=F_e \qquad \text{(Primary system)} \qquad (9)$$

$$\ddot{u}+2\xi_d\omega_d\dot{u}+\omega_d^2u=-\ddot{x}_g \qquad \text{(TMD system)} \qquad (10)$$

where, F_e is earthquake force, [$\bar{M}$] and [$\bar{C}$] are mass and damping matrices of the jacket system considering added mass and damping which can be given as:

$$[\bar{M}]=[M]+\rho_w(C_M-1)V \qquad (11)$$

$$[\bar{C}]=[C]+0.5\rho_wC_DA\sigma_{vr}\sqrt{\frac{8}{\pi}} \qquad (12)$$

and [K], [M] and [C] are the stiffness, mass and damping matrices of the jacket platform, respectively; V, A, C_D, C_M and ρ_w are displaced volume of the members, projected area of members, drag coefficient, inertia coefficient, and the water mass density, respectively; σ_{vr} is value of the Root Mean Squares (RMS) of relative velocity between water particles and each joints of the structure, respectively. (In this paper C_D=0.7 and C_M=2)

5.3. PLATFORM -TLCD

The equations of motion of TLCD system, developed by Sakai et al. (1989) [15], can be written by:

$$[\bar{M}]\ddot{x}+[\bar{C}]\dot{x}+[K]x=F_e \qquad \text{(Primary system)} \qquad (13)$$

$$\ddot{u} + \frac{1}{2L_d}\delta|\dot{u}|\dot{u} + \omega_d^2 u = -\alpha\ddot{x}_g \qquad \text{(TLCD system)} \qquad (14)$$

where δ is the head loss coefficient.

5.4. Seismic Loading

The platform is investigated under two different ground motion accelerations (Northridge 1994 and Kobe 1995 earthquakes) scaled to PGA=0.06g as extreme level earthquake (ELE) [16].

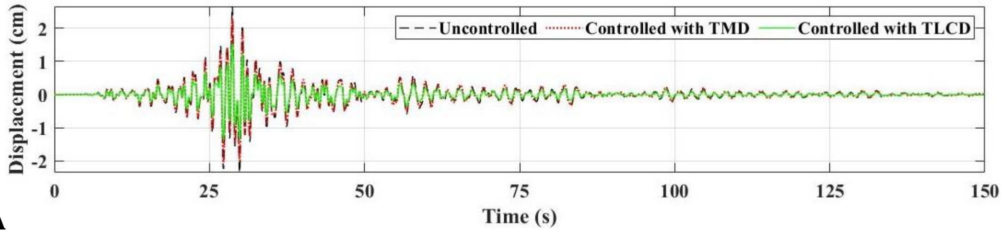
6. Results and Discussion

Vibrational control of an offshore jacket platform is investigated using TMD and TLCD systems under earthquake incidence. Both systems are considered at the top level of a three-dimensional jacket platform in this manuscript. The time history of displacement in the top node of the jacket located at the highest structural level is represented in Figure 5 under seismic loading. The efficiency of the systems is investigated using two near-field ground motion accelerations including Kobe and Northridge earthquakes.

Passive controlling of a system can be implemented using the first natural frequency of the system. In this manuscript, the first main natural frequency of the jacket platform is employed for the damping system parameters calculation. Different head loss coefficient values were taken into account based on the configuration and specification of a system. In this study, the head loss coefficient is calculated by using an equation which is introduced by Mousavi et al. (2013) [17]. The mass ratio of the damper (μ) is taken as 3 percent through a parametric study and the effectiveness of the mass ratio parameter on the performance of the damping system is also investigated within the results. The horizontal length of the damper, B, is considered as 0.8 of the whole damper liquid length (α=0.8). Vertical to horizontal columns cross-section ratio, which is defined as the area ratio, is taken as 2 based on previous studies by Mousavi et al. (2013) [17]. The optimized parameters of the TLCD system are listed in Table 2, which are obtained based on the proposed mass ratio. Both damping systems are located at the top level of the jacket platform.

Table 2- Main optimized parameters of TLCD system

Parameter	Values
Total length of liquid (m)	25
Horizontal length (m)	20.3
Horizontal cross section (m^2)	1.2
Vertical cross section (m^2)	0.3
Area ratio	4
ρ (kg=m^3)	1000



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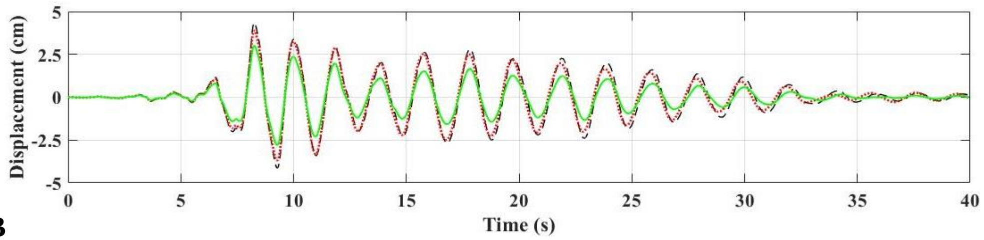

B

Figure 6. Displacement time history under: A) Kobe and B) Northridge earthquakes.

As it is seen in Figure 6, the top node displacement of the jacket platform is decreased using both dampers in which the value of the decrement for the TLCD system is higher with the same value for mass ratio. Although displacements are reduced in most peak points using TLCGD, few higher values are gained in some peaks. As it can be seen in Figure 6A, the peak uncontrolled response of the jacket is 2.7 cm which is reduced to 2.2 and 1.4 cm for TMD and TLCD systems, respectively. In comparison to the uncontrolled values, utilizing both damping systems represents 19 and 37 percent of reduction. Also based on Figure 6B, it can be noted that the structural response is reduced from 4.3 cm to 3.5 cm and 2.6 cm utilizing TMD and TLCD systems, respectively. More details of the displacement time history under earthquake are listed in Table 3.

Table 3- Peak point displacement time history in jacket levels under earthquake excitation.

Level	Peak Points Value (cm)									
	Kobe					Northridge				
	Unc[a]	TMD		TLCD		Unc[a]	TMD		TLCD	
		Value	Diff[b] (%)	Value	Diff[b] (%)		Value	Diff[b] (%)	Value	Diff[b] (%)
Top Level	2.7	2.2	19	1.4	37	4.3	3.5	19	2.6	39

[a] Uncontrolled
[b] Difference

Based on the listed results in Table 3, the whole structural response of the coupled system is reduced in which the most reduction is for the top level using TLCD. The reduction is 19 percent for the top level using TMD and 37 percent considering TLCD, respectively for the Kobe earthquake. The mentioned reduction is 19 and 40 percent for Northridge earthquake respectively.

As it is presented in Figure 7, RMS of the displacement time history of the system equipped without and with TMD and TLCD is shown. The RMS of the displacement is reduced in which the most reduction is for the top level using TLCD. The reduction is 10 percent for the top level using TMD and 26 percent considering TLCD, respectively for the Kobe earthquake. The mentioned reductions are 11 and 23 percent for Northridge earthquake respectively.

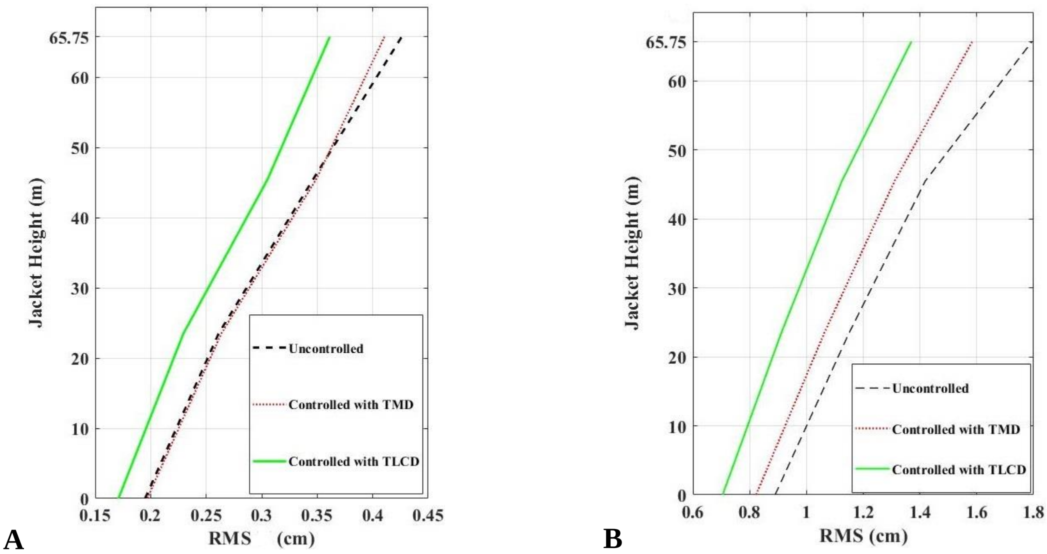

Figure 7. Displacement RMS under: A) Kobe and B) Northridge earthquakes.

7. CONCLUSION

Structural control of an offshore jacket platform is studied under earthquake utilizing TMD and TLCD systems. In the mentioned systems, the damper performs as a TLCD system in lower displacements. The performance of the whole coupled system is studied within different ground motion accelerations. The directions are chosen as the parallel to damper U plane. Based on the results, main parameters in an TMD system are defined as the tuning frequency ratio, mass ratio and the damping ration and for an TLCD system are same as TMD parameters in addition to $\alpha = \frac{m_h}{m_{TLCD}}$ .According to the results, the damper performance as a TLCD system is better than a TMD system for displacements. On the other hand, a TLCD system lowers displacements more. RMS of the system decreases in TLCD system more than TMD system.

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