

Experimental Study on a Tuned-Mass Damper of Offshore for Vibration Reduction

Qiong Wu¹ Xilu Zhao¹ Rencheng Zheng²

¹College of Mechanical Engineering Saitama Institute of Technology, Saitama 369-0293, Japan

²Institute of Industrial Science, the University of Tokyo, Tokyo 153-8505, Japan

Email: wuqiong55@126.com

Abstract. With the development of industry, oceanic oil production is one of the most important energy resources. Normally, offshore platform, located in the hostile environment, is easily subjected to unstable environmental loading, such as wind, wave, ice, and earthquake, and it becomes a critical problem to ensure the stability of offshore platform for safely engineering operations. In recent years, tuned-mass damper (TMD) technology has been adopted to reduce vibrations from wind and earthquake influences. Due to the complexity of earthquake excitations, most of researchers were focused on controlling response of structures under wind loads; however, less attention has been put on controlling earthquake response. Therefore, this study concentrates on the seismic reduction of offshore platform by application of a TMD system, and a comprehensively experimental study was processed to validate its effectiveness exposed to different earthquake. A 4-column offshore platform was built according to the actual size of approximately 1:200 ratios, and a TMD system was prepared for the experiment. By the different performance analyses, experimental results indicated that the proposed TMD system can effectively suppress the earthquake stimulus and keep the stability of offshore platform.

1. Introduction

Offshore platforms are susceptible to vibration induced by the action of waves, which not only affects their structural strength but also has considerable impact on their reliability and safety [1]. In recent years, more and more attention focused on understanding the behaviours of offshore platforms under dynamic loading conditions [2].

In recent decades, vibration control of civil engineering structure using tuned mass damper (TMD), which has been through numerous analytical and experimental verification, is a widely accepted control strategy [3]. Because of the efficiency of TMD systems, they have been used in many structures around the world, such as buildings and bridges [4]. Up to now, TMDs have been installed in many buildings around the world, such as the CN tower at Toronto, the World Finance Center at Shanghai, and the 660-ton TMD for the top of the Taipei Tower at Taiwan that is considered as the largest and most known TMD [5]. Kawano [6] investigated semi-active control devices applied in



jack-up offshore platforms, in which the active control force is determined using a time-domain transient optimal control method. Zhou et al. [7] proposed a semi-active control method utilizing the energy dissipation principle and a bang-bang control based on a linear quadratic regulator optimal control theory. However, offshore platforms are located in ocean environments, which could increase the cost of maintenance of active and semi-active systems and indirectly increase the risk to staff. Therefore, passive vibration control might be the most suitable and feasible strategy for vibration control in offshore platforms.

A passive TMD was studied for the reduction of vibration in flexible structures subjected to long-reduction narrow excitations [8]. The device behaviour is defined by the amount of mass, the frequency at which it is tuned and the damping used. The determination of the optimal values of these parameters according to different objectives (reduce the maximum displacements, story drifts, base shear, etc.) and for different types of excitation (harmonic, white noise, etc.) have been studied by several authors [9]. An analysis of TMD efficiency on single and multiple degrees of freedom structures subjected to near-fault earthquakes was performed by E. Matta [10]. Li et al. [11] proposed using double TMDs, in which the mass damper was optimized for high effectiveness and robustness in reducing undesirable vibrations under the effects of ground acceleration. Yu et al. [12] outlined a robust design optimization framework dedicated to TMDs. A. Bozer et al. [13] proposed a tracking device for the structures with TMD for setting the frequency of TMD according to the structural response. G. Marano et al. [14] studied the robust optimal design criterion of a TMD system under stochastic earthquake load in a probabilistic framework. G. C. Marano et al. [15] dealt with the optimal design of a TMD to reduce undesirable vibrational effects, which were originated in linear structures by seismic excitations.

However, based on our literature review, passive TMD technology has had little application to the control of the response of offshore platforms to an earthquake because of the complexity of the excitation. Many control strategies have been shown effective in the mitigation of structural vibration; however, few studies have examined the response performance of a TMD at the onset of earthquake excitation. In order to reduce the risk of damage to jack-up offshore platforms in harsh marine environments, studies are required to develop efficient and practical vibration-control strategies that can suppress the dynamic response of offshore structures.

This study is involved in comprehensively experimental investigations to extend the understanding of the response performance of TMD systems under two seismic stimuli. The modelling analysis and experimental process was introduced based on a prototype in an experimental setting. After that, the results are interpreted for the amplitude and frequency responses and evaluation indices.

2. Modelling Description

To analyze the effectiveness of a TMD, an actual jack-up offshore platform of the Bohai No. 5, located in the Southern Sea, was referred as the research target. The jack-up offshore platform comprises a rectangular platform resting on four independent operating legs, with a TMD attached beneath the platform. The size of the working platform is $57.5 \times 34.0 \times 5.50$ m, the length and diameter of the operating legs are 78 and 3 m, respectively, and the limit of the operating water depth is 40 m. The 4-column offshore platform was built according to the actual size of approximately 1:200 ratios, and the experimental set-up was fixed in the water tank, the TMD device consists of a frame, a mass, two springs, four wheels, and two tracks, as demonstrated in figure 1.

As presented in figure 2, a systemic model of a jack-up offshore platform with a TMD can be considered as a general structure ($m_1 + m_2$) that includes the main structure of the offshore platform (m_1) and the substructure of the TMD (m_2). Thereby, the dynamic model can be expressed as:

$$m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 - k_2 (x_2 - x_1) = -m_1 \ddot{x}_v, \quad (1)$$

$$m_2 \ddot{x}_2 + k_2 (x_2 - x_1) = -m_2 \ddot{x}_v, \quad (2)$$

where m_1 , c_1 , and k_1 are the mass, damping, and stiffness of the main structure, respectively. m_2 and k_2 are the mass and stiffness of the substructure, respectively. $\ddot{x}_v$ is the acceleration vector of the seismic loads.

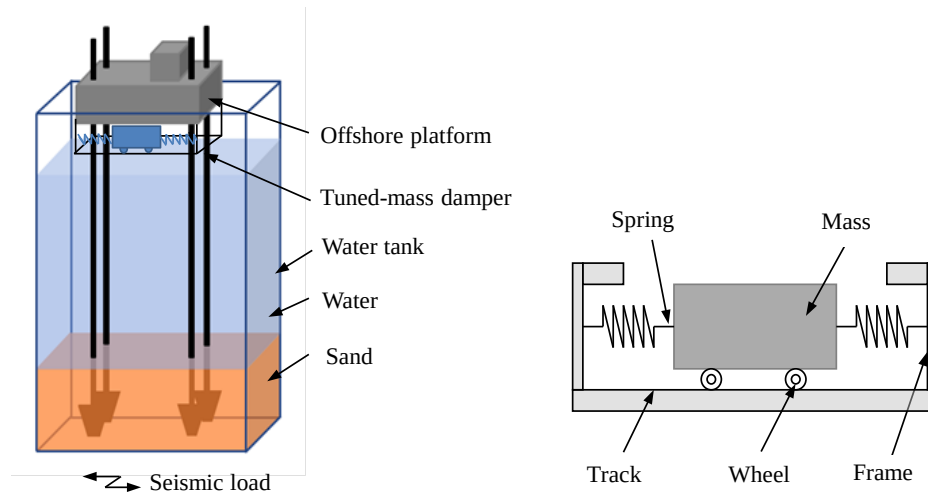


Figure 1. Schematic of a jack-up offshore platform with a tuned-mass damper (TMD).

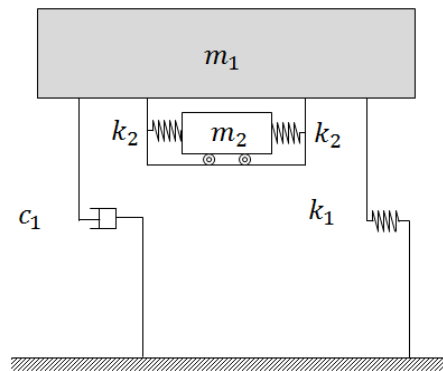


Figure 2. Systemic modelling of a jack-up offshore platform with a tuned-mass damper (TMD).

To resolve Eqs. (1) and (2), the imaginary amplitudes of the main structure and substructure can be expressed as

$$X_1 = |X_1 e^{i\omega t}| = \frac{m_1 \ddot{x}_v (k_2 - m_2 \omega^2)}{\sqrt{c_1^2 \omega^2 (k_2 - m_2 \omega^2)^2 + [(k_1 + k_2 - m_1 \omega^2)(k_2 - m_2 \omega^2) - k_2^2]^2}}, \quad (3)$$

$$X_2 = |X_2 e^{i\omega t}| = \frac{m_2 \ddot{x}_v k_2}{\sqrt{c_1^2 \omega^2 (k_2 - m_2 \omega^2)^2 + [(k_1 + k_2 - m_1 \omega^2)(k_2 - m_2 \omega^2) - k_2^2]^2}}, \quad (4)$$

where ω is the excitation frequency of the seismic loads. From the Eq. (2), the dynamic magnification factor for the main structure can be described as

$$\left| \frac{X_1}{X_{st}} \right| = \sqrt{\frac{(\eta^2 - \lambda^2)^2}{[(\eta^2 - \lambda^2)(1 - \lambda^2) - \mu\eta^2\lambda^2]^2 + [2\xi_1\lambda(\eta^2 - \lambda^2)]^2}}, \quad (5)$$

where $X_{st} = m_1 \ddot{x}_V / k_1$ is the static displacement of the main structure. $\eta = w_2 / w_1$ is the natural frequency ratio. $w_1 = \sqrt{k_1 / m_1}$ and $w_2 = \sqrt{k_2 / m_2}$ are the natural frequencies of the main structure and substructure, respectively. $\lambda = w / w_1$ is the ratio of the excitation and natural frequencies of the main structure, and $\xi_1 = c_1 / (2m_1 w_1)$ is the damping ratio of the main structure.

Based on Eq. (5), the dynamic magnification factor becomes zero while $\eta = \lambda$, which indicates that optimal vibration reduction will be achieved while exposed to the specific excitation frequencies of the seismic loads. The seismic loads involve different frequency components, which can result in the maximum amplitude vibration of the main structure during the range of the resonance frequency. Therefore, when the natural frequency of the TMD is adjusted to the natural frequency of the structure, the TMD will be in a resonant state. Therefore, a large amount of the structural vibration energy can be transferred to the TMD, and thus vibration reduction can be accomplished. By the modelling of the offshore platform with a fixed TMD, the natural frequency can be measured during experimental testing.

3. Evaluation Parameters

A root mean square (RMS) of the displacement or acceleration response can be expressed as

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^n y_i^2}, \quad (6)$$

where y_i is the sampling value of the displacement or acceleration responses. To evaluate effectiveness of the vibration reduction during the entire earthquake period, an evaluation parameter index was proposed:

$$J = \frac{RMS_{ctrl}}{RMS_{unctrl}}, \quad (7)$$

where RMS_{ctrl} and RMS_{unctrl} are the RMS values of the displacement or acceleration responses of the main structure for the entire earthquake period, for the cases with and without the TMD system, respectively. To evaluate the maximum response reduction, a maximum peak value was selected as $y_{\max} = \max\{y_i\}$. Then, a relative ratio of the maximum peak values can be obtained from

$$\beta = \frac{y_{\max-unctrl} - y_{\max-ctrl}}{y_{\max-unctrl}}, \quad (8)$$

where $y_{\max-ctrl}$ and $y_{\max-unctrl}$ are the maximum peak values of the displacement or acceleration response of the main structure with and without the TMD system, respectively.

4. Prototype Experiment

As shown in figure 3, the testing system comprised a personal computer, vibration signal generator, amplifier, shaker, offshore platform system, and fast Fourier transform analyser. In the experiment, the sand height was 80 mm and the water depth was 400 mm. The mass of the offshore platform as the main structure (m_1) was 2.346 kg and the mass of the TMD was 0.591 kg. Through experimental validation, the damping coefficient was determined as 0.012. The offshore platform was placed in a tank that was fixed on the shaker, which simulated the seismic.

Initially, the substructure of the TMD was installed at the bottom of the offshore platform to measure the first natural frequency of the complete structure. The input signal was a 0–8 Hz sweep signal. Then remove the substructure from the offshore platform and to attach it to the shaker. Then, the spring stiffness of the TMD was adjusted to make the first natural frequency of the substructure the same as that of the main structure, the peak frequency response function of both was 2.56 Hz.

Eventually, two types of seismic wave (El-Centro NS and Taft EW) were generated by the signal generator and fed to the shaker to evaluate the effectiveness of the vibration control system. Here, the El-Centro NS was the NS component recorded at the Imperial Valley Irrigation District substation in El Centro, California, USA on May 18, 1940. Its magnitude was 6.9 and the peak acceleration was 341 cm/s^2 . The Taft EW was the EW component recorded at Kern County, California, USA on July 21, 1952. Its magnitude was 7.7 and the peak acceleration value was 175.9 cm/s^2 .

The recording time was 25 s and the sampling frequency was 50 Hz for the two seismic waves. Consequently, the displacement and acceleration of the main structure, and the relative displacement between the main structure and the substructure were recorded.

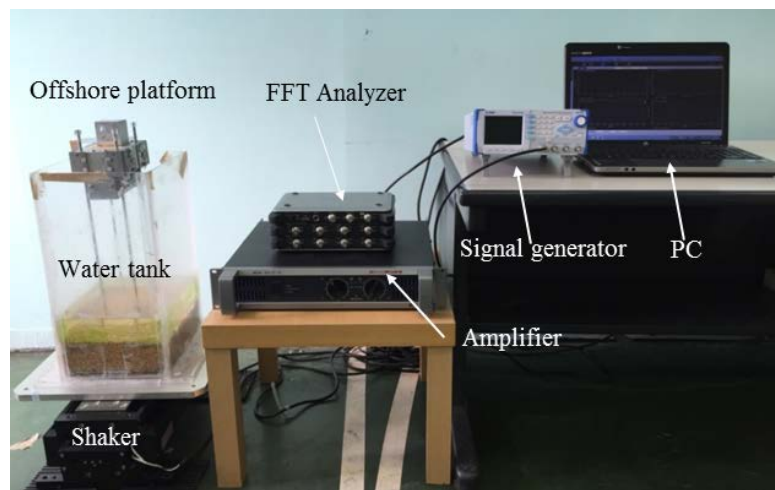


Figure 3. Diagram of the experimental system.

5. Results

5.1. Amplitude Responses

Figures 4 and 5 display the time series of the responses of the main structure with and without the TMD under the excitation of the El Centro NS and Taft EW seismic waves. The experimental results of the displacement response are shown in figure 4, and the experimental results of the acceleration response are shown in figure 5.

As shown in figures 4 and 5 it can be seen that the response of the main structure with TMD is much smaller than that without the TMD during most time duration, except for some low-amplitude locals. These results indicate that the control performance of the TMD is effective as an energy-dissipation device for the reduction of the main structural response. It is particularly important for vibration suppression under excitation by seismic waves that the TMD can effectively reduce the relatively high-amplitude displacements and accelerations.

5.2. Frequency Responses

The corresponding results are presented in figure 6, for the power spectral density (PSD) of displacement of the main structure, and the PSD of acceleration of the main structure are shown in figure 7.

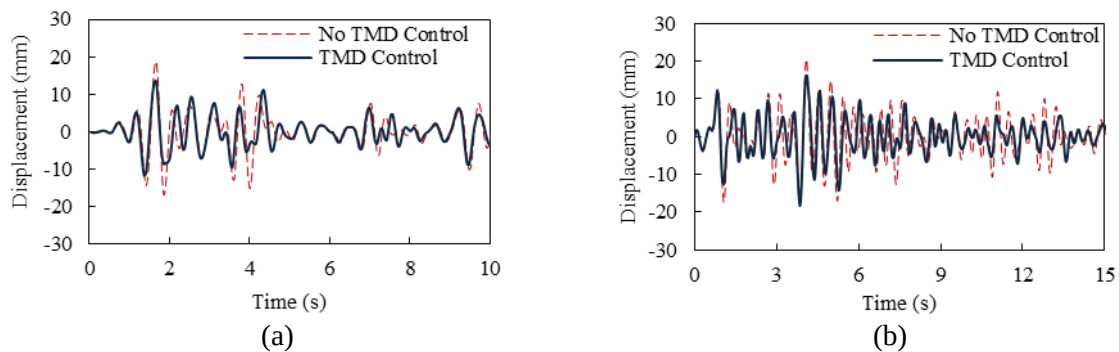


Figure 4. Experimental results of the displacement responses under: (a) the El-Centro NS and (b) the Taft EW seismic waves.

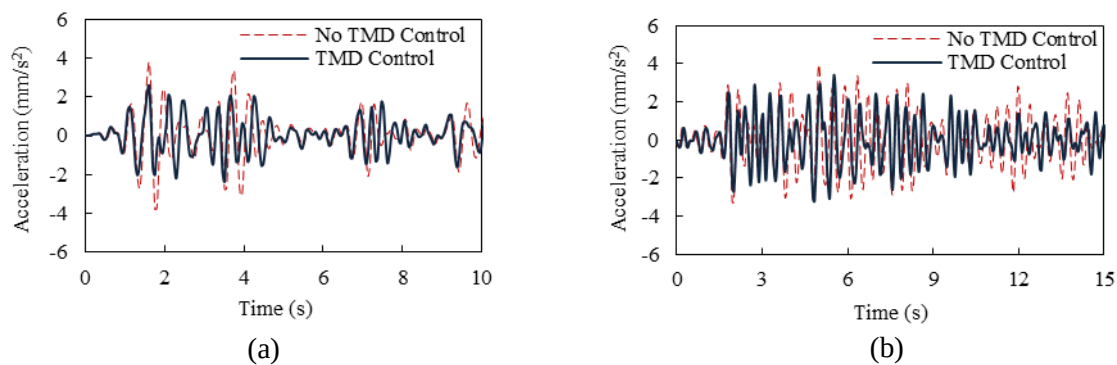


Figure 5. Experimental results of the acceleration responses under: (a) the El-Centro NS and (b) the Taft EW seismic waves.

There is a clear vibration attenuation effect of the TMD control, especially around the 2.56 Hz, because the resonance reaction of the main structure occurred around this frequency domain. Therefore, in the case with TMD control, it is significantly effective in reducing the vibration response of the main structure; in particular, the peak responses were considerably reduced around the 2.56 Hz frequency domain.

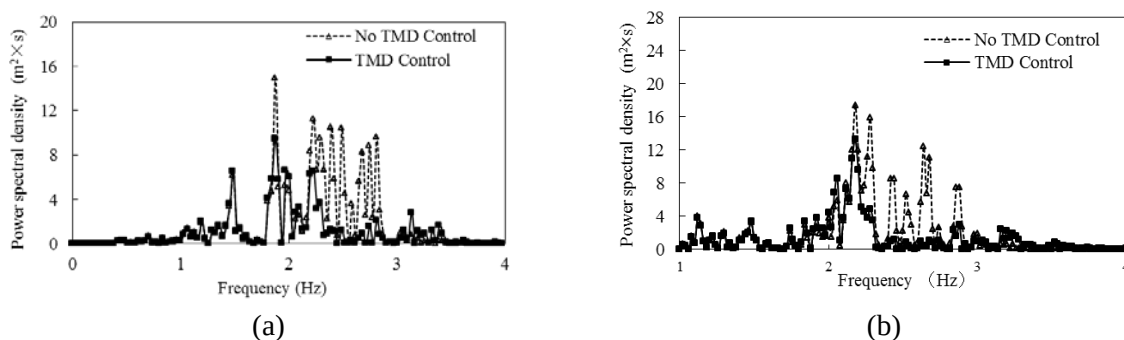


Figure 6. Experimental results of the displacement responses under the El-Centro NS and Taft EW: (a) Power spectral density under the El-Centro NS seismic wave, and (b) Power spectral density of the Taft EW seismic wave.

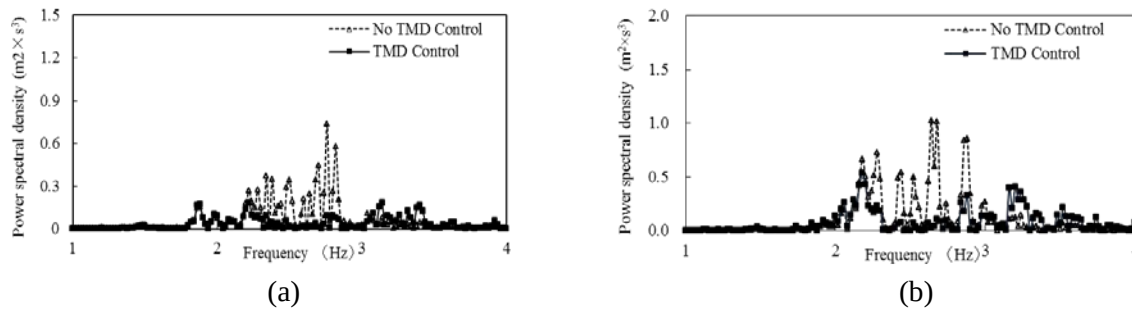


Figure 7. Experimental results of the acceleration responses under the El-Centro NS and Taft EW: (a) power spectral density of the acceleration under El-Centro NS seismic wave, and (b) power spectral density of the acceleration under Taft EW seismic wave.

It is validated that the overall vibration response can be significantly decreased by reducing the first-mode vibration, and the results of the PSD curves can explain why the time series response is effective in vibration reduction. Consequently, a single damper, tuned to the fundamental mode, is adequate for reducing the structural vibration under earthquake excitations. For PSD curves, the TMD device is very effective in reducing the response of main structure in near-resonance conditions, and less efficient for the non-dominant frequency regions.

The investigation of frequency regions, other than the fundamental frequency, revealed that the negative effectiveness do not happen in the non-dominant frequency regions.

5.3. Evaluation Parameters

The control performance was analysed by application of the evaluation parameters of β and J , which are defined in Eqs. (7) and (8), respectively. The β index is the ratio of the RMS values of the displacements or accelerations of the offshore platform between the cases with and without the TMD control. The J index is the relative ratio of the peak values between the cases with and without the TMD control. Figure 8(a) shows the displacement results of evaluation indices, and figure 8(b) shows the acceleration results of evaluation indices.

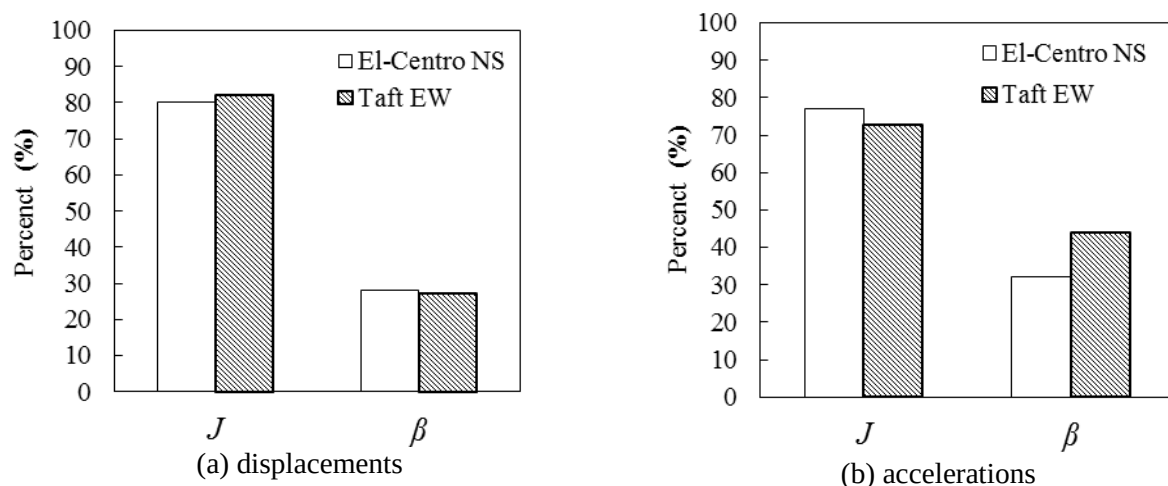


Figure 8. Experimental results of the evaluation parameters under the El-Centro NS and Taft EW: (a) displacement results of the evaluation indices, and (b) acceleration results of the evaluation indices (J : ratio of the RMS values, and β : ratio of the peak values).

As shown in figures 8(a) and (b), the J values for the displacement response are more than 80%, and the β values shows that a reduction of more than 27 % was accomplished for the peak

displacement response by the application of the TMD system, which indicates the TMD can achieve perfect performance for the seismic excitation. For the acceleration response, the J values are more than 70 %, which means the dynamic performance was also improved considerably throughout the entire earthquake period. Similarly, the values β are more than 0.30, which means the peak response was decreased by 30 % by the application of the TMD system.

6. Conclusions

This study is to investigate the effectiveness of a TMD in controlling earthquake response of offshore platform. The mathematical modelling, tuning principle of the dynamic magnification factor, and evaluation indices were described, and then an experimental system was constructed based on a 1:200 scale model of an actual four-column jack-up offshore platform. Specific experiments were performed for the offshore platform both with and without the TMD system under two kinds of seismic loads. The effectiveness of the TMD system was comprehensively investigated by the analyses of the amplitude and frequency responses, as well as evaluation indices.

The amplitude and frequency responses indicated that the displacement, acceleration, and their power spectral density significantly decreased for the offshore platform while the TMD system was applied. Consequently, the RMS ratios reached around 80% for the displacements and around 70% for the acceleration responses, and the vibrating excitations of the offshore platform were improved throughout the entire earthquake period. The relative ratio of the maximum peak values verified that a reduction of 27% was achieved for the maximum peak displacement response, and a reduction of 32% was achieved for the acceleration response. Based on the experimental investigations, this study validated that a passive TMD can constitute a simple but feasible measure for vibration suppression of offshore platforms exposed to earthquake excitations.

7. References

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