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Buffered Tuned-Mass Damper for Earthquake Vibration Reduction in Offshore Platform

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Abstract. This paper investigates the buffered tuned-mass damper (TMD) for an offshore structure. The purpose of this paper is to find an effective and economic means to reduce the wave induced vibrations of the offshore platform system. This paper proposes a bufferable TMD, a passive TMD with buffers on both sides, to improve the performance of offshore platforms subjected to large seismic waves. A comprehensive experiment was executed to investigate the dynamic performances of the bufferable TMD, by application of a 1:200-scale offshore platform prototype. It is verified that the bufferable TMD can be effective in absorbing the vibration energy. In conclusion, the experimental results indicate that the response of an offshore platform can be significantly decreased, and the evaluation indices show that the method is effective in reducing overall vibration levels and maximum peak values, with the application of the bufferable damper system.

1. Introduction

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, offshore jacket platform plays an indispensable role in the development and utilization of marine resources [1]. Located in hostile ocean environments, offshore platforms are exposed to external disturbances such as winds and earthquakes, which generally lead to large oscillation of the system [2].

While many efforts have been put in the study of the platform and waves, rare attention is being paid on the vibration mitigation. There are two intractable problems while taking into account the possibility of damage to the offshore platform during a high intensity earthquake. One such problem is that the large earthquake excitation may cause local damage to the vibration absorber; and another problem is that the duration of an earthquake excitation event is generally short.

To solve the problem of stroke between vibration absorber and target structure, several attempts had been made to decrease the stroke, by introducing the idea of impact dampers. An impact damper is a freely moving mass, constrained by stops fixed to a dynamically excited structure to be controlled. Energy is dissipated as heat and noise together with the development of high frequency vibrations in the structure [3]. On the other hand, the impact dampers will produce impulsive loads between the two coupled systems, and will cause a high-level noise during the impact process. In contrast, buffer materials have been incorporated in the impact damper system to reduce impact forces [4]. Chen et al. [5] performed numerical modeling of impact damping with a discrete element method, and it indicated that the collision and friction mechanism might play different or equivalent roles in energy dissipation, under different vibration and particle system parameters. As to the fundamental theory of impact dampers, numerical and experimental studies had been undertaken to test specific applications, check theoretical results, and select parameters of impact damper systems [6–9]. Li [10] and Liu et al. [11] conducted a series of experimental investigations to examine the effect of an impact damper, using equivalent viscous damping model to represent the nonlinearity.

Damping characteristics of an impact damper were also studied to improve the damping capability. Fang and Tang [12] developed an improved analytical model using multiphase flow theory based on the previous work of Wu et al. [13]. Recently, experimental work has studied the effect of controlling friction-driven oscillations using an impact damper, and the effects of mass ratio, coefficient of restitution, and clearance on the performance of an impact damper was verified through the experimental and numerical investigations [14].

For an earthquake excitation in which its duration is substantially shorter, considerable disasters often occurred during the initial period of an earthquake load. The several previous studies [15-17] used the vibration absorber with viscous damping to improve the vibration control effectiveness; however, because the high response performance of the dampers is not considered, the dampers may not have enough reaction time to produce a significant effect in the initial seconds of the earthquake excitation.

This paper involves experimental and analytical investigations that comprehensively extend the understanding of the high response performance and damping characteristics of bufferable TMD systems under two large seismic vibrations. The experimental processes were based on a prototype of an existing offshore jacket platform, and the bufferable, high-response, absorption characteristics were discussed dependent on the results of the amplitude and frequency responses.

2. Methods

2.1. Description

This study makes use of a TMD with a buffer to realize the advantages of both the TMD with and without damper. The TMD device (Figure 1) consists of a frame, a mass, two springs, four wheels, two tracks, and two buffers. The buffers, which adopt buffering materials, can be fixed to the frame by adhesive. The gap between the buffer and mass can be adjusted depending on performance.

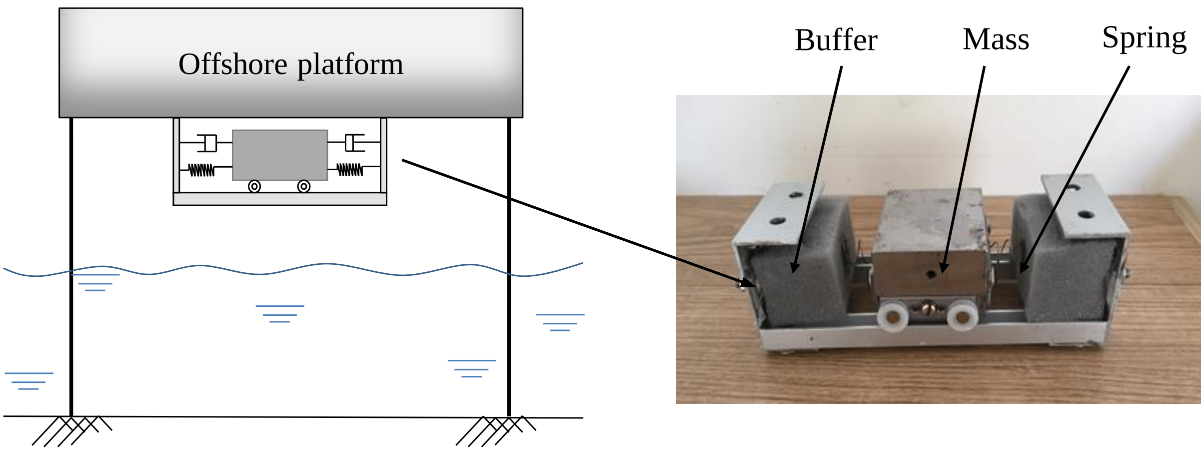

Fig.1. Schematic of a jack-up offshore platform with a bufferable TMD

2.2 Modeling

As presented in Figure 1, a systemic model of a jack-up offshore platform with a bufferable TMD can be considered as a generalized structure consisting of the main structure of the offshore platform and the substructure of the TMD. The buffers are modeled by two linear contact springs and dampers, as k_B and c_B, respectively.

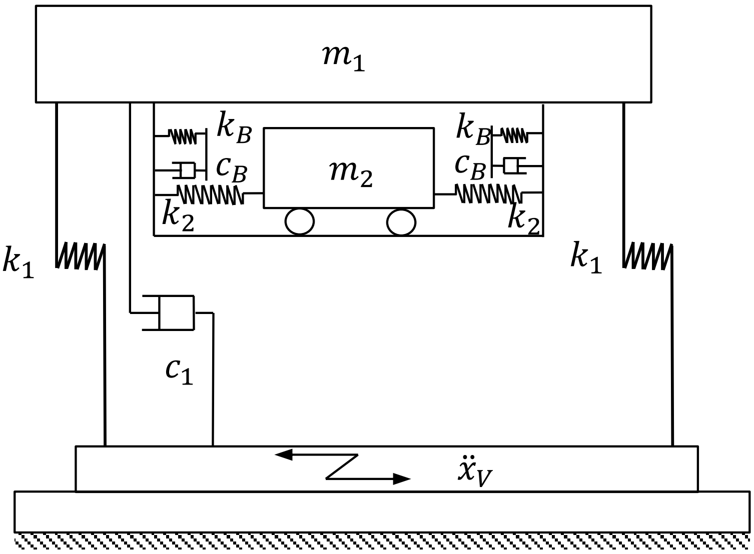

Fig. 2: Systemic model of a jack-up offshore platform with a bufferable TMD.

The motion of the system can be treated as a piecewise linear process. x_1 and x_2 are the displacement of main structure and substructures, respectively. When $|x_2 - x_1| \le d$, the mass can move without collisions with the buffers, where d is the distance between the buffer and mass of the TMD, as shown in Figure 1; therefore, the dynamic model can be expressed by normal forms:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - k_2(x_2 - x_1) = -m_1\ddot{x}_V \ , \tag{1}$$

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

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 on the main structure.

When $|x_2 - x_1| > d$, the mass collides with the left or right buffers; therefore, the dynamic model can be expressed as:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 - c_B(\dot{x}_2 - \dot{x}_1) + k_1x_1 - k_2(x_2 - x_1) - k_B(|x_2 - x_1| - d)\,\mathrm{sgn}(x_2 - x_1) = -m_1\ddot{x}_V \ , \tag{3}$$

$$m_2\ddot{x}_2 + c_B(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) + k_B(|x_2 - x_1| - d)\,\mathrm{sgn}(x_2 - x_1) = -m_2\ddot{x}_V \ , \tag{4}$$

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; k_B and c_B are the stiffness and damping of buffers, respectively; x_1 and x_2 are the displacement of main structure and substructures, respectively; $\ddot{x}_V$ is the acceleration vector of the seismic loads on the main structure.

The central difference method [24] is used for numerically solving the above equations. A time marching scheme for the forward difference method is used, where $x^{(i)} = x\ (t = t_i)$ and the time interval $\Delta t = t_{i+1} - t_i$. The differential acceleration and velocity can be expressed as:

$$\ddot{x}^{(i)} = \frac{x^{(i+1)} - 2x^{(i)} + x^{(i-1)}}{\Delta^2 t}, \quad (5)$$

$$\dot{x}^{(i)} = \frac{x^{(i+1)} - x^{(i-1)}}{2\Delta t}. \quad (6)$$

Eqs. (5) and (6) can be substituted into Eqs. (1) to (4) to calculate the displacement difference. When $|x_2 - x_1| \le d$, the formula can be expressed as:

$$x_1^{(i+1)} = \frac{(2m_1 - k_1\Delta^2 t - k_2\Delta^2 t)x_1^{(i)} + k_2\Delta^2 t x_2^{(i)} + (-m_1 + 0.5c_1\Delta t)x_1^{(i-1)} - m_1\ddot{x}_V\Delta^2 t}{m_1 + 0.5c_1\Delta t}, \quad (7)$$

$$x_2^{(i+1)} = \frac{(2m_2 - k_2\Delta^2 t)x_2^{(i)} + k_2\Delta^2 t x_1^{(i)} - m_2 x_2^{(i-1)} - m_2\ddot{x}_V\Delta^2 t}{m_2}. \quad (8)$$

When $|x_2 - x_1| > d$, for the case of $x_2 > x_1$, the formula can be expressed as:

$$x_1^{(i+1)} = \frac{Ak_{22} - Bk_{12}}{k_{11}k_{22} - k_{21}k_{12}}, \quad (9)$$

$$x_2^{(i+1)} = \frac{Bk_{22} - Ak_{12}}{k_{11}k_{22} - k_{21}k_{12}}, \quad (10)$$

where

$$\begin{aligned} A = &-(2m_1 + k_1\Delta^2 t + k_2\Delta^2 t + k_b\Delta^2 t)x_1^{(i)} - (-k_2\Delta^2 t - k_b\Delta^2 t)x_2^{(i)} - (m_1 - 0.5c_1\Delta t - 0.5c_b\Delta t)x_1^{(i-1)} \\ &- 0.5c_b\Delta t x_2^{(i-1)} - k_b\Delta^2 t \cdot d^2 - m_1\ddot{x}_V{}^2\Delta^2 t \end{aligned}, \quad (11)$$

$$\begin{aligned} B = &-(-k_2\Delta^2 t - k_b\Delta^2 t)x_1^{(i)} - (-2m_2 + k_2\Delta^2 t + k_b\Delta^2 t)x_2^{(i)} - 0.5c_b\Delta t x_1^{(i-1)} - m_2 x_2^{(i-1)} + k_b\Delta^2 t \cdot d \\ &- m_2\ddot{x}_V\Delta^2 t \end{aligned}, \quad (12)$$

$$\begin{aligned} k_{11} &= m_1 + 0.5c_1\Delta t, \\ k_{12} &= -0.5c_b\Delta t, \\ k_{21} &= -0.5c_b\Delta t, \\ k_{22} &= m_2 + 0.5c_b\Delta t. \end{aligned} \quad (13)$$

When $|x_2 - x_1| > d$, for the case of $x_2 < x_1$, the formula can be expressed as:

$$x_1^{(i+1)} = \frac{A'k_{22} - B'k_{12}}{k'_{11}k_{22} - k'_{21}k_{12}}, \quad (14)$$

$$x_2^{(i+1)} = \frac{B'k_{22} - A'k_{12}}{k_{11}k_{22} - k_{21}k_{12}}, \quad (15)$$

where

$$\begin{aligned} A' = &-(2m_1 + k_1\Delta^2 t + k_2\Delta^2 t + k_b\Delta^2 t)x_1^{(i)} - (-k_2\Delta^2 t - k_b\Delta^2 t)x_2^{(i)} - (m_1 - 0.5c_1\Delta t - 0.5c_b\Delta t)x_1^{(i-1)} \\ &- 0.5c_b\Delta t x_2^{(i-1)} + k_b\Delta^2 t \cdot d^2 - m_1\ddot{x}_V{}^2\Delta^2 t \end{aligned}, \quad (16)$$

$$\begin{aligned} B' = &-(-k_2\Delta^2 t - k_b\Delta^2 t)x_1^{(i)} - (-2m_2 + k_2\Delta^2 t + k_b\Delta^2 t)x_2^{(i)} - 0.5c_b\Delta t x_1^{(i-1)} - (m_2 - 0.5c_b\Delta t)x_2^{(i-1)} \\ &- k_b\Delta^2 t \cdot d - m_2\ddot{x}_V\Delta^2 t \end{aligned}. \quad (17)$$

The initial conditions of the offshore platform can be expressed as:

$$x_1^{(0)} = 0,\ \dot{x}_1^{(0)} = 0,\ \ddot{x}_1^{(0)} = 0\,, \tag{18}$$

$$x_2^{(0)} = 0,\ \dot{x}_2^{(0)} = 0,\ \ddot{x}_2^{(0)} = 0\,. \tag{19}$$

Inserting the initial displacements of the second step of $x_1^{(0)}=0$, $x_2^{(0)}=0$, $x_1^{(1)}=0$, and $x_2^{(1)}=0$ into Eqs. (7) and (8), the subsequent differential displacements $x_1^{(2)}$ and $x_2^{(2)}$ can be obtained. By continually increasing the calculation step, the differential displacements of $x_1^{(i+1)}$ and $x_2^{(i+1)}$ can be estimated from $x_1^{(i-1)}$, $x_2^{(i-1)}$, $x_1^{(i)}$, and $x_2^{(i)}$.

Numerical simulation and experimental investigations can constrain displacements of the offshore platform with the bufferable TMD when it is subjected to seismic shaking represented as sinusoidal excitation (Figure 3). The theoretical response is observed to be identical to the experimental response over the entire time period, which suggests that the analytical method can yield estimates of the damper system response under earthquake excitations with an acceptable accuracy.

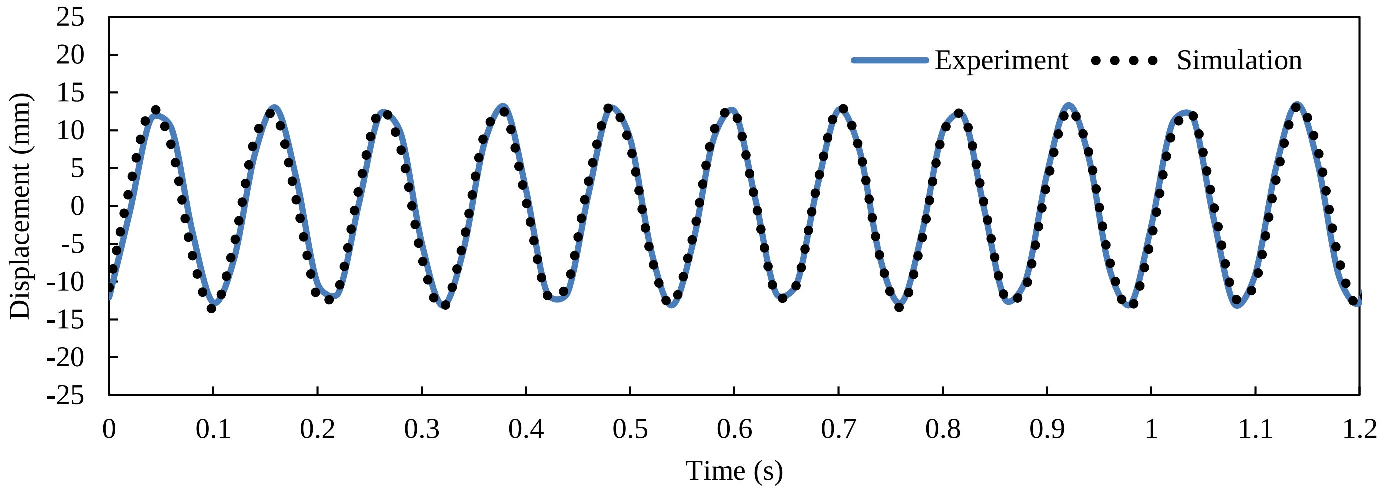

Fig. 3: Displacements of the offshore platform with the bufferable TMD under sinusoidal excitation.

3. Experiment

3.1. Setup

As shown in Figure 4, the testing system comprised a computer, vibration signal generator, amplifier, shaker, offshore platform system, acceleration sensor, laser displacement sensor, and fast Fourier transform analyzer. The Bohai No. 5 offshore jack-up platform, located in the Southern Sea, was used as a research target to analyze the practical effectiveness of a TMD. A 1:200-scale model of the actual four-column platform was constructed. The size of the working platform is 57.5 × 34.0 × 5.50 m, with operating leg lengths of 78 m and diameters of 3 m. The minimum operating water depth is 4 m.

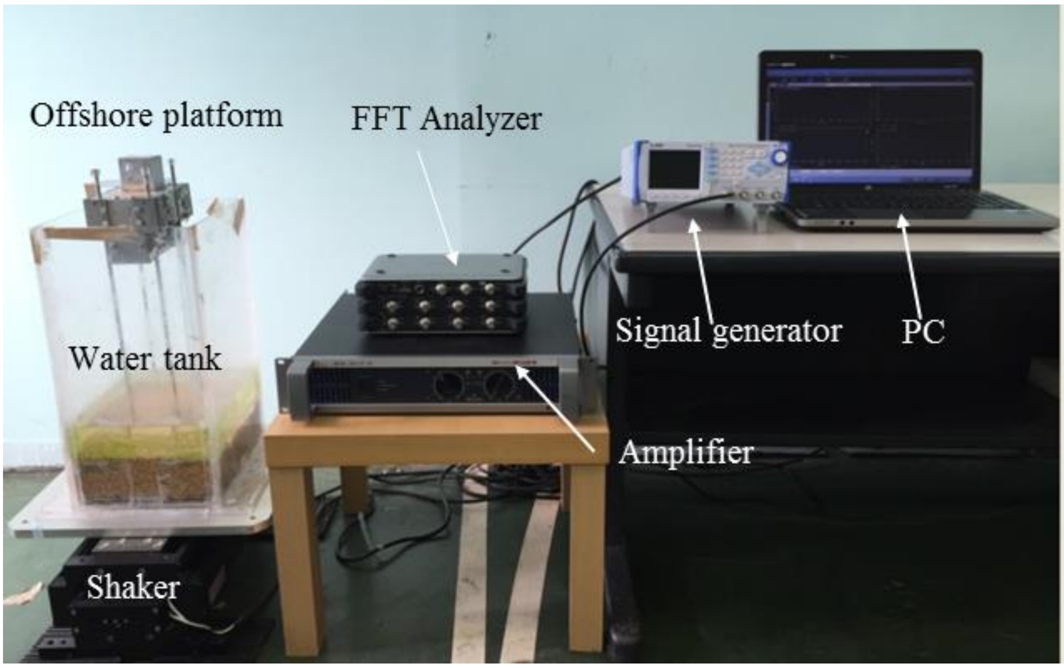

Fig. 4. Diagram of the experimental system

The modeled operating platform was scaled and simplified into a horizontal rectangular metal mass with support columns constructed of hollow tubes. Cylindrical pile shoes were set at the base of each column and the connections between the columns and the operating platform were rigid. The model platform was placed in a tank that was fixed to the shaker apparatus capable of simulating seismic loads. The response of the structure was measured using an accelerometer and a laser vibrometer. In the experiment, the sand height was 80 mm, and the water depth was 400 mm. The mass of the main structure of the model platform (m_1) was 2.346 kg and the mass of the bufferable TMD was 0.591 kg. Through experimental validation, the damping coefficient of the offshore platform was determined to be 0.012, with a buffer damping coefficient of 0.012.

4. Results

4.1 Amplitude Responses

As presented in Fig 5 and Fig.6, the time series of the responses are shown for the main structure with and without the bufferable TMD under the excitations of the Fukujima NS and Taft EW seismic waves. The experimental results show that the peak values of the displacement responses decreased significantly with bufferable TMD control, when compared with those cases without bufferable TMD control. It can be observed that this decreasing tendency was more significant for the acceleration responses. These results indicate that the control performance of the bufferable TMD is effective as an energy-dissipation device for the reduction of the main structural response.

The vibration reduction during the entire earthquake period for the displacement response are more than 65.5%, which indicates that the vibration of the platform was significantly improved during the period of earthquake excitation when the bufferable TMD was used. Moreover, analysis of the peak value reduction values shows that a reduction more than 34.5% was accomplished for the peak displacement response, by applying the bufferable TMD system.

For the acceleration displacement response, the vibration reduction during the entire earthquake period is more than 70%, which means that the dynamic performance was considerably improved throughout the entire period of the earthquake. Over the same time, the peak value reduction is more than 23.8%, which means that the peak response was also decreased by the application of the bufferable TMD system.

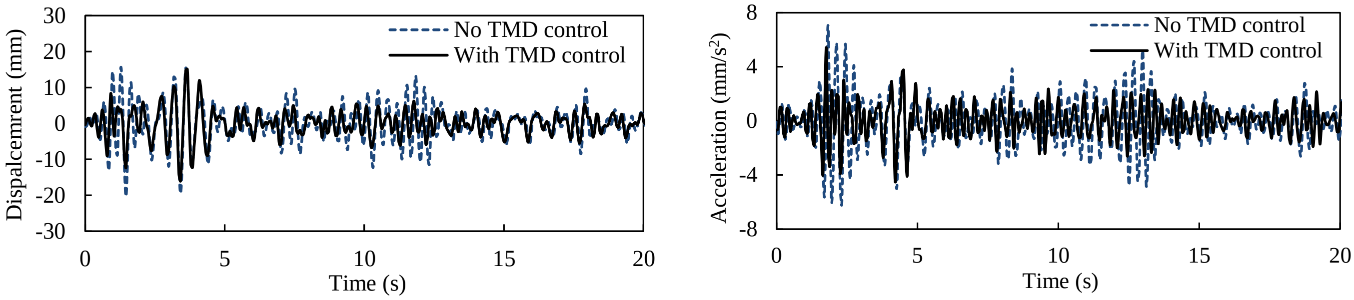

Fig. 5. Experimental results of the amplitude responses under the Fukujima NS seismic waves.

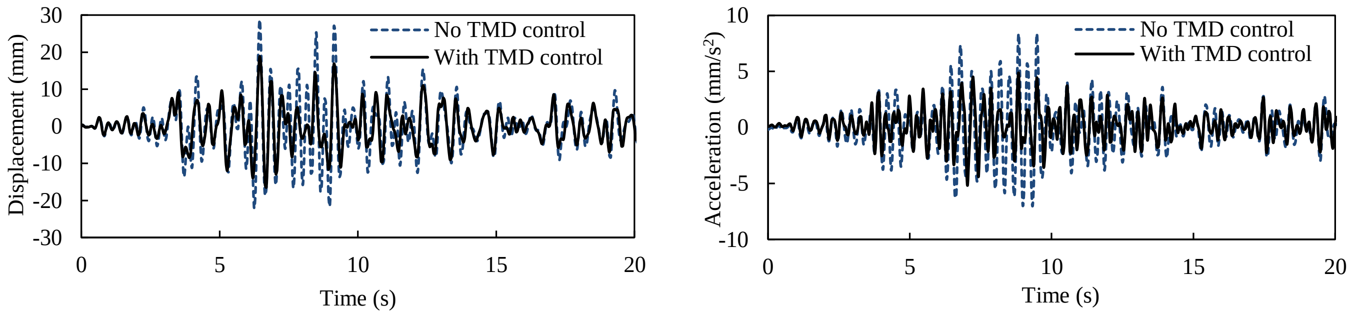

Fig. 6. Experimental results of the amplitude responses under the Taft EW seismic waves.

4.2 Frequency Responses

The power spectral density (PSD) results are presented in Figure 7 and Figure 8 for the displacement and acceleration of the platform with and without the bufferable TMD. The maximum amplitude of the PSD is observed to occur at around 3 Hz for the case without bufferable TMD control; the resonance reaction of the platform is seen to occur around this frequency. This explains why the designed bufferable TMD's frequency was nearly 3 Hz. The overall vibration response can be decreased significantly by reducing first-mode vibrations, and the resulting PSD curves explain why the time series response is effective for vibration reduction. Consequently, a single damper tuned to the fundamental mode is adequate for reducing structural vibrations resulting from earthquake excitations. Investigations of frequency bands above or below the fundamental frequency revealed no negative effects at non-dominant frequencies.

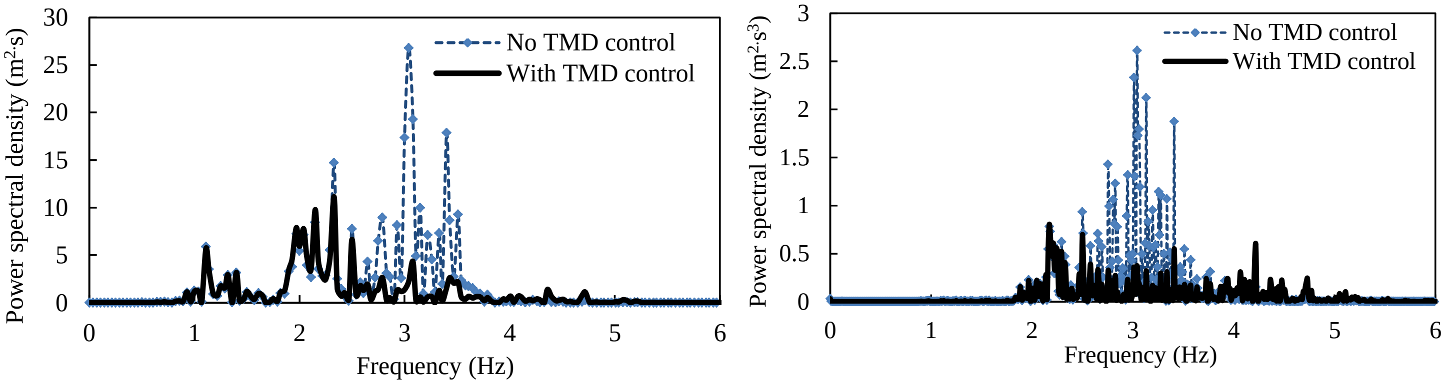

Fig. 7. Experimental results of the frequency responses under the Fukujima NS seismic waves.

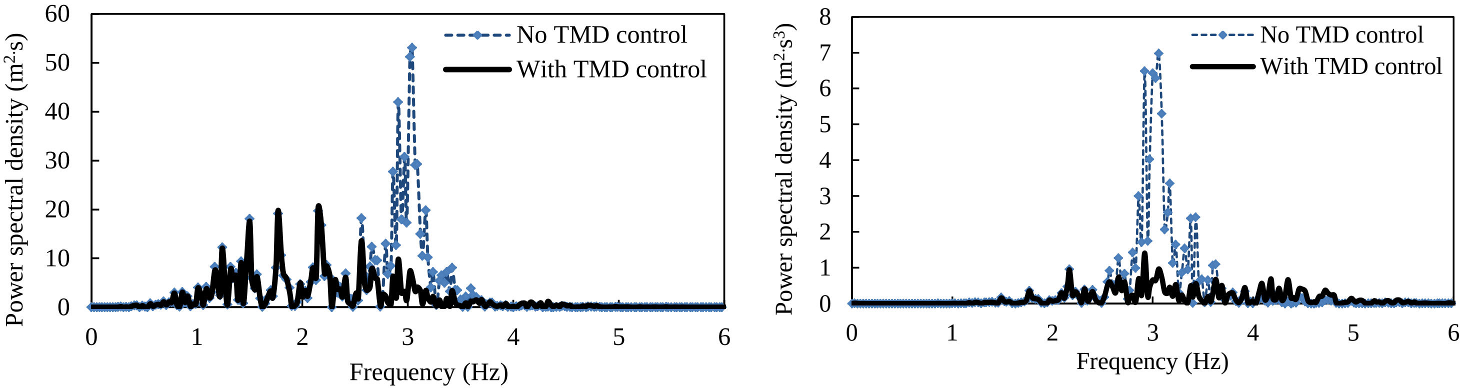

Fig. 8. Experimental results of the frequency responses under the Taft EW seismic waves.

5. Conclusions

This study proposes a bufferable TMD system to mitigate damaging responses of an offshore platform exposed to significant earthquake-sourced seismic waves. Moreover, a comprehensively numerical and experimental investigation has been conducted to examine bufferable high-response absorption processes. The preliminary results indicated that the displacement, acceleration and frequency performances of the offshore platform were significantly improved under two types of earthquake-induced seismic loads.

In conclusion, the experimental investigations verify that the bufferable TMD constitutes a simple but feasible measure against stroke for vibration suppression under large earthquake loads.

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