Multiple Tuned Mass Dampers for Vibration Control of Offshore Platform against Natural Loadings

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ABSTRACT

In present, offshore drilling becomes an important resource for the supply of oil. The offshore platforms have many uses including oil exploration and production, navigation, ship loading and unloading, and to support bridges and causeways. However, vibration problems caused by severe environmental loads such as ice, wave, wind and seismic loads pose risks to the functionality of the platform facilities and worker’s comfort. This may lead to piping failures, poor equipment reliability, and safety concerns. Therefore, vibration control of offshore platform is very essential for the assurance of structural safety, equipment functionality and human comfort.

In this study, an optimal MTMD system is proposed to mitigate excessive vibration of a three-dimensional offshore platform under ice and earthquake loadings. The MTMD system is designed to control the first few dominant coupled modes. The optimum placement and system parameters of MTMD are determined based on the controlled modal properties. Numerical simulation results showed that the proposed MTMD system is able to reduce both displacement and acceleration responses of the offshore platform effectively. An optimum design procedure for the MTMD system is also proposed to determine their optimal locations, moving directions and system parameters.

1. INTRODUCTION

Offshore platforms are subjected to different environmental loads during their service life time, such as wave, wind, ice and earthquake. Particularly, seismic and ice load should be taken into account comprehensively due to their severity and
randomness. Therefore, it is necessary to ensure that the platform does not fail or collapse during ice hit and seismic excitation and alleviate the damage conditions to a minimum. For example, a popular offshore platform, named JZ20-2, was built in the Bohai gulf of the east China sea where is an earthquake-prone area. Usually, in the higher latitudes like Bohai gulf, ice load was considered as the design control loading based on long time estimation. Severe vibration induced by continuous crushing of ice will jeopardize structural safety and influence the security and comfort of workers. Furthermore, the degradation of structural resistance induced by the excessive and large amplitude of vibration may lead to fatal disasters. In 1969, a new platform was collapsed due to the repeated hit of large ice loads which the average ice thickness of flat ice was about 60 cm, and the biggest thickness was above 1 m. Since the differences of geographic locations and the hydrological effects, different sea areas have different characteristics of ice loads. In China, Liaodong bay is one of the important oil regions in the Bohai oil field where is located at the unique sea-ice covered waters. Fast ice, also called land-fast ice, is a sea ice that is fastened to coastline, to the sea floor along grounded icebergs. On the other hand, floating ice is the main ice feature in the open sea. In addition, the ice conditions behave intense dynamic features due to waves and currents under large tidal variations in Bohai gulf. According to large amount of field observation, it was found that the sea ice is variant in different areas based on the classification of ice engineering sub-areas in Bohai gulf (Li et al., 2004). The JZ20-2 platform investigated in this study was located at the fourth area as shown in Fig. 1.

![Fig. 1 Ice engineering sub-areas in Bohai gulf of east China sea.](image.png)

The JZ20-2 is a four-legged jacket platform consisting of jacket, jacket cap, pillar, helideck, pedestal crane and breasting dolphin at different elevations as shown in Fig. 2. It can be categorized into two main components, i.e. substructure and superstructure. The superstructure is supported on a deck which is fixed on the substructure. Moreover, the superstructure is composed of helideck, living and utility module. The helideck is located at the top of platform at EL. +24.8 m. The living module is at the upper deck at
EL. +17 m. The utility module is located at the lower deck at EL. +13 m. The upper deck is mainly used for living quarter and drilling rig, while, the lower deck is served for storage areas and system of drilling mud circulation.

In recent, the application of energy dissipation devices for vibration control of civil engineering structures against natural and man-induced excitations has received much research interest from researchers and practicing engineers to assure structure safety and human comfort. Among those devices, tuned mass damper (TMD) is one of the most popular devices due to its little interference as incorporated into existing structures. Since the early of 1970s, a large number of TMDs have been successfully installed in high-rise buildings, slender towers, long-span highway and pedestrian bridges to reduce vibrations.

In recent years, the authors have developed optimal design methodology for multiple TMD (MTMD) system and verified its control performance through extensive analytical studies and large-scale shaking table tests (Lin et al, 2009, 2010, 2012). In this study, the optimal MTMD system is applied to mitigate excessive vibration of the JZ20-2 offshore platform, modelled by the ABAQUS computer program, under ice and earthquake loadings. The MTMD system is designed to control the first few dominant coupled modes. The optimum placement and system parameters of MTMD are determined based on the controlled modal properties. Numerical simulation results showed that the proposed MTMD system is able to reduce both displacement and acceleration responses of the offshore platform effectively. An optimum design procedure for the MTMD system is also proposed to determine their optimal locations, moving directions and system parameters.
2. DYNAMIC EQUATIONS OF MOTION OF PLATFORM-MTMD SYSTEMS

The dynamic equations of motion of a general $n$-DOF offshore platform structure equipped with a MTMD system consisting of $p$ units located at the $m$-DOF under external loadings $F(t)$ and earthquake excitation $\ddot{x}_g(t)$ can be expressed as

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = BF(t) + M_f\ddot{r}_g(t)$$

in which

$$M = \begin{bmatrix} M_p & 0 \\ M_p & M_s \end{bmatrix}, \quad C = \begin{bmatrix} C_p & C_{ps} \\ 0^T & C_s \end{bmatrix}, \quad K = \begin{bmatrix} K_p & K_{ps} \\ 0^T & K_s \end{bmatrix}, \quad M_f = \begin{bmatrix} M_p & 0 \\ 0^T & M_s \end{bmatrix}$$

are $(n+p) \times (n+p)$ mass, damping and stiffness matrices of the entire structure-MTMD system, respectively. $M_p$, $C_p$, and $K_p$ are $n \times n$ mass, damping and stiffness matrices of the controlled offshore platform structure. $M_s = \text{diag}[m_i]$, $C_s = \text{diag}[c_i]$, $K_s = \text{diag}[k_i]$ are $p \times p$ diagonal matrices, and $M_{ps} = M_p u$, $C_{ps} = (C_p u)^T$, $K_{ps} = -(K_p u)^T$. $m_i$, $c_i$, and $k_i$ are mass, damping and stiffness coefficients of the $i$th unit of MTMD ($k = 1, 2, \ldots, p$). $u = [0 \ 0 \ \ldots \ 1^{(i)} \ \ldots \ 0]_p$, where 0 and 1 are $p \times 1$ vectors with each element equal to 0 and 1, respectively. The superscript $(i)$ indicates the position of vector 1 in matrix $u$. $\chi(t) = [\chi_p^T(t) \ \chi_s^T(t)]^T$ is the displacement vector. $\chi_p(t)$ and $\chi_s(t)$ denote the vector of displacement of platform structure relative to the ground and the vector of MTMD’s displacement relative to the $i$th DOF (called stroke), respectively. $B$ denotes the $(n+p) \times l$ location matrix for the $l$ external loadings $F(t)$. $r$ is a $(n+p) \times 1$ influence vector with each element equal to -1. $\ddot{x}_g(t)$ represents the base acceleration in $x$-direction.

Let $\Phi$ be the $n \times n$ mode shape matrix of the platform structure and $\eta(t)$ be the $n \times 1$ modal displacement vector. By substituting $\chi_p(t) = \Phi \eta(t)$ into Eq. (1) and pre-multiplying two sides of the structure part by $\Phi^T$ to transform the system coordinates from physical domain to modal domain, the modal equations of motion of the platform structure combined with the MTMD system under earthquake excitation become

$$\begin{bmatrix} M_p^* & 0 \\ M_p^* & M_s^* \end{bmatrix} \ddot{\eta}(t) + \begin{bmatrix} C_p^* & C_{ps}^* \\ 0^T & C_s^* \end{bmatrix} \dot{\eta}(t) + \begin{bmatrix} K_p^* & K_{ps}^* \\ 0^T & K_s^* \end{bmatrix} \eta(t) = \begin{bmatrix} \Gamma_p & \Gamma_s \end{bmatrix} \ddot{x}_g(t)$$

where $M_p^*$ and $M_s^*$ are $n \times n$ and $p \times p$ unity matrices, respectively, and
\[
C_p^* = \text{diag}(2\xi_j \omega_j) \quad K_p^* = \text{diag}(\omega_j^2)
\]
\[
C_s^* = \text{diag}(2\xi_{sk} \omega_{sk}) \quad K_s^* = \text{diag}(\omega_{sk}^2) \quad M_{sp}^* = u\Phi
\]
\[
C_{ps}^* = \begin{bmatrix}
2\xi_{s1} \omega_{s1} \mu_{s1,j} & 2\xi_{s2} \omega_{s2} \mu_{s1,j} & \ldots & 2\xi_{sp} \omega_{sp} \mu_{s1,j} \\
2\xi_{s1} \omega_{s1} \mu_{s2,j} & 2\xi_{s2} \omega_{s2} \mu_{s2,j} & \ldots & 2\xi_{sp} \omega_{sp} \mu_{s2,j} \\
\vdots & \vdots & \ddots & \vdots \\
2\xi_{s1} \omega_{s1} \mu_{sk,j} & 2\xi_{s2} \omega_{s2} \mu_{sk,j} & \ldots & 2\xi_{sp} \omega_{sp} \mu_{sk,j}
\end{bmatrix} = -\Phi^T_{(i)} \mu_s C_s^*
\]
\[
K_{ps}^* = \begin{bmatrix}
\omega_{s1}^2 & \omega_{s2}^2 & \ldots & \omega_{sp}^2 \\
\omega_{s1}^2 \mu_{s1,j} & \omega_{s2}^2 \mu_{s1,j} & \ldots & \omega_{sp}^2 \mu_{s1,j} \\
\vdots & \vdots & \ddots & \vdots \\
\omega_{s1}^2 \mu_{sk,j} & \omega_{s2}^2 \mu_{sk,j} & \ldots & \omega_{sp}^2 \mu_{sk,j}
\end{bmatrix} = -\Phi^T_{(i)} \mu_s K_s^*
\]
\[
\Gamma_p = \frac{\Phi^T M_p \Gamma}{\Phi^T M_p \Phi} \quad \Gamma_s = -1 \quad M_p^* = \Phi^T M_p \Phi = \text{diag}(m_j^*)
\]

where \(\xi_j\) and \(\omega_j\) are the \(j\)th modal damping ratio and modal frequency of the platform structure; \(\xi_{sk}\) and \(\omega_{sk}\) are damping ratio and natural frequency of the \(k\)th TMD, respectively; \(\Phi_{(i)}\) is the \(i\)th row of \(\Phi\) representing the mode-shape value at \(i\)th DOF in each mode; \(\mu_s = \{\mu_{s1,j}, \mu_{s2,j}, \ldots, \mu_{sk,j}, \ldots, \mu_{sp,j}\}\) where \(\mu_{sk,j} = m_{sk} / m_j^*\) is mass ratio of the \(k\)th TMD to \(j\)th modal mass of the structure; \(m_j^* = \sum_{l=1}^n (\phi_{lj} m_l) = \phi_{lj} m_j\) is generalized modal mass of the structure; \(\phi_{lj}\) is the \(l\)th value of the \(j\)th mode shape; and \(\Gamma_p\) is the modal participation vector with its \(j\)th value \(\Gamma_{p,j} = (\sum_{l=1}^n \phi_{lj} m_l) / m_j^*\). It is observed that the dynamic responses of platform structure and MTMD system can be solved from Eq. (2) if the modal parameters of the platform structure and MTMD system are obtained by finite element modeling or system identification techniques.

### 2.1 TRANSFER FUNCTIONS OF STRUCTURE AND MTMD

In Eq. (2), consider the \(j\)th mode of the structure only and take Fourier transform on both sides. The \(j\)th modal displacement vector of structure and the stroke vector of MTMD can be represented in frequency domain, in terms of transfer functions, as
\[
\begin{bmatrix}
\eta_j(\omega) \\
v_{x}(\omega)
\end{bmatrix}
= A^{-1}
\begin{bmatrix}
\Gamma_{p_j} \\
\Gamma_s
\end{bmatrix}
\ddot{X}_g(\omega)
= \begin{bmatrix}
H_{pp_j}(\omega) & H_{ps}(\omega) \\
H_{sp}(\omega) & H_{ss}(\omega)
\end{bmatrix}
\begin{bmatrix}
\Gamma_{p_j} \\
\Gamma_s
\end{bmatrix}
\ddot{X}_g(\omega)
\]

In detail,
\[
\begin{bmatrix}
\eta_j(\omega) \\
v_{x}(\omega)
\end{bmatrix}
= \begin{bmatrix}
A_j & C_j & \ldots & C_k & \ldots & C_p \\
D_1 & B_1 & 0 & \ldots & 0 & \ldots & 0 \\
D_2 & 0 & B_2 & \ldots & 0 & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
D_k & 0 & B_k & \ldots & 0 & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
D_p & 0 & 0 & \ldots & 0 & \ldots & B_p
\end{bmatrix}^{-1}
\begin{bmatrix}
\Gamma_{p_j} \\
\Gamma_s
\end{bmatrix}
\ddot{X}_g(\omega)
\]

where
\[
A_j = -\omega^2 + i\omega(2\xi_j\omega_j) + \omega_j^2 \\
B_k = -\omega^2 + i\omega(2\xi_k\omega_k) + \omega_k^2 \\
C_{ki} = \phi_{kj}\mu_{s_k,j}[-i\omega(2\xi_k\omega_k) - \omega_k^2] \\
D_k = -\omega^2 \phi_{kj}
\]

i = 1, 2, ..., n, k = 1, 2, ..., p

The inverse of matrix in Eq. (4) can be solved either numerically or analytically and Eq. (4) can be rewritten as

\[
\begin{bmatrix}
\eta_j(\omega) \\
v_{s1}(\omega)
\end{bmatrix}
= \begin{bmatrix}
H_{1,1} & H_{1,2} & H_{1,3} & \ldots & H_{1,k} & \ldots & H_{1,p+1} \\
H_{2,1} & H_{2,2} & H_{2,3} & \ldots & H_{2,k} & \ldots & H_{2,p+1} \\
H_{3,1} & H_{3,2} & H_{3,3} & \ldots & H_{3,k} & \ldots & H_{3,p+1} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
H_{k,1} & H_{k,2} & H_{k,3} & \ldots & H_{k,k} & \ldots & H_{k,p+1} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
H_{p+1,1} & H_{p+1,2} & H_{p+1,3} & \ldots & H_{p+1,k} & \ldots & H_{p+1,p+1}
\end{bmatrix}
\begin{bmatrix}
\Gamma_{p_j} \\
\Gamma_s
\end{bmatrix}
\ddot{X}_g(\omega)
\]

Then, the jth modal displacement of structure and the kth TMD’s stroke of the MTMD system can be expressed as

\[
\eta_j(\omega) = H_{j1}(\omega)\Gamma_{p_j} + \sum_{i=1}^{p} H_{j,i+1}(\omega)\Gamma_i \ddot{X}_s(\omega) = H_{\eta_j}\ddot{X}_s(\omega)
\]

\[
v_{s1}(\omega) = [H_{k1}(\omega)\Gamma_{p_j} + \sum_{i=1}^{p} H_{k,i+1}(\omega)\Gamma_i )\ddot{X}_s(\omega) = H_{v_{s1}}\ddot{X}_s(\omega)
\]
It is noted that $\eta_j(\omega)$ represents the modified jth modal displacement of the structure with the existence of MTMD system. The reduction of $\eta_j(\omega)$ indicates the control effectiveness of the MTMD system.

2.2 OPTIMAL DESIGN OF MTMD SYSTEM

From Eqs. (5) and (6), it has been found that to reduce the jth modal response, the kth TMD is best located at the DOF where the jth mode shape value is the largest and moves in the direction which the jth mode participates most. In addition, from Eq. (5), the MTMD’s control effectiveness can be evaluated by the performance index, $R_j$, defined as

$$R_j = \frac{E[\eta_j^2]_{\text{MTMD}}}{E[\eta_j^2]_{\text{w/o MTMD}}}$$

representing the ratio of mean square displacement response of the jth structural mode with MTMD to that without MTMD. $R_j$ is a function of the jth modal damping ratio, $\xi_j$, the jth mode shape value at jth DOF of the structure, $\phi_j$, the mass ratio of the kth MTMD unit mass to the jth modal effective mass of the structure, $\mu_{n,j}$, damping ratio of the kth MTMD unit, $\xi_k$, and frequency ratio of the kth MTMD unit to the jth modal frequency of the structure, $r_{jk} (= \omega_j / \omega_k)$, where $k = 1, 2, \ldots, p$. With the prior knowledge of structural modal parameters, $\omega_j$, $\xi_j$, and $\phi_j$ and the consideration of low cost and easy construction, identical stiffness coefficient, $k_s$, and damping coefficient, $c_s$, for each MTMD unit are proposed. They have been derived and expressed as

$$k_s = \frac{m_{st}}{\sum_{k=1}^{p} \frac{1}{\omega_j^2 r_{jk}^2}}$$
$$c_s = \frac{2 \xi_k}{r_{jk} \omega_j} k_s$$
$$m_s = \frac{k_s}{r_{jk}^2 \omega_j^2}$$

(8a, 8b, 8c)

where $m_{st} = \sum_{k=1}^{p} m_k$ is the total mass of all MTMD units. Based on Eqs. (8a)-(8c), the damping ratio of each MTMD unit, $\xi_k, \xi_2, \ldots, \xi_p$, can be expressed as $\xi_k = \xi_{s0} r_{jk}$ where $\xi_{s0}$ is a constant. Moreover, with a given MTMD mass ratio, $\mu_{n,j} = \phi_j m_{st}/m_j^*$, the modal mass ratio of the kth MTMD unit can be calculated by

$$\mu_{n,j} = \frac{1/ r_{jk}^2}{\sum_{l=1}^{p} 1/ r_{jl}^2}$$

(9)
where $m_j^*$ is the generalized $j$th modal mass of the structure. Without any restriction on the frequency distribution of MTMD units, the optimization of MTMD system with identical stiffness and damping coefficients involves $(p + 1)$ independent parameters, i.e., $r_{f_1}, r_{f_2}, \ldots, r_{f_p}$ and $\xi_{s_k}$. Theoretically, with given $\omega_j$, $\xi_j$, and $\phi_j$, the optimal MTMD's parameters, $(r_{f_1})_{opt}$, $(r_{f_2})_{opt}$, ..., $(r_{f_p})_{opt}$, and $(\xi_{s_k})_{opt}$, can be obtained by solving the following system of equations which are established by differentiating $R_j$ with respect to the $(p+1)$ parameters and equating to zero, respectively, to minimize $R_j$.

$$
\frac{\partial R_j}{\partial r_{f_1}} = 0, \quad \frac{\partial R_j}{\partial r_{f_2}} = 0, \quad \ldots, \quad \frac{\partial R_j}{\partial r_{f_p}} = 0, \quad \frac{\partial R_j}{\partial \xi_{s_k}} = 0
$$

(10)

Then, the optimal stiffness coefficient, $(k_{s_k})_{opt}$, damping coefficient, $(c_{s_k})_{opt}$, and mass for the $k$th MTMD unit, $(m_{s_k})_{opt}$, can be obtained (Lin and Wang, 2012). The optimization process can be performed by numerical searching techniques which are available in mathematical software packages, such as MATLAB.

3. OPTIMAL MTMD SYSTEM FOR THE JZ20-2 PLATFORM

The JZ20-2 platform shown in Fig. 2 was considered as the target structure to design its optimal MTMD system to reduce excessive vibrations at the helideck and upper deck due to extreme ice loads and earthquake excitations. The foundation of the platform is composed of four jacket pipes and driven into the seabed through the piles. It is mainly made of steel with density of 7.85 kg/m$^3$, Young's modulus of 2.06×10$^5$ Mpa, and Poisson’s ratio of 0.3. According to design drawings and details, the commercial finite element program ABAQUS (V14) was employed to model the structure and calculate its modal parameters. The steel beams are modeled with element B31. The mass is simulated as isotropic mass and the total mass of the platform is 1131.257 metric ton (t). Table 1 shows the first five modal frequencies, effective masses, and damping ratios, which were observed from the field. It is seen that the first three modes dominate the lateral (z direction) and longitudinal (x direction) responses with accumulated effective modal mass ratio up to 80% and 70%, respectively. Their corresponding mode shapes are illustrated in Fig. 3. Therefore, a MTMD system is designed to control the first three modes with 5 units (p=5) for each mode. Their optimum locations are shown in Fig. 4.
Table 1: Modal frequencies, modal masses and modal damping ratios of the first five modes

<table>
<thead>
<tr>
<th>Controlled mode</th>
<th>Modal frequency (Hz)</th>
<th>Modal mass (ton)</th>
<th>Modal damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Mode (Lateral)</td>
<td>0.89</td>
<td>171.986 (16%)</td>
<td>3.743</td>
</tr>
<tr>
<td>2nd Mode (Longitudinal)</td>
<td>1.08</td>
<td>769.915 (70%)</td>
<td>3.469</td>
</tr>
<tr>
<td>3rd Mode (Lateral)</td>
<td>1.49</td>
<td>662.239 (64%)</td>
<td>3.303</td>
</tr>
<tr>
<td>4th Mode (Longitudinal)</td>
<td>1.66</td>
<td>75.133 (6.8%)</td>
<td>3.322</td>
</tr>
<tr>
<td>5th Mode (Lateral)</td>
<td>2.14</td>
<td>5.16 (0.5%)</td>
<td>3.352</td>
</tr>
</tbody>
</table>

Fig. 3 (a) 1st (Lateral), (b) 2nd (Longitudinal) and (c) 3rd (Lateral) mode shapes

Fig. 4 Locations of MTMD system to control the 1st, 2nd and 3rd modes
3.1 OPTIMAL MTMD SYSTEM PARAMETERS

According to the design procedure mentioned in section 2.2, the optimal system parameters of three groups of MTMD system to control the 1st, 2nd, and 3rd modes are determined. Considering the available space and local member capacity, a total mass ratio of 1% to the platform mass is used to control two horizontal (lateral and longitudinal) responses, respectively, to increase the controlled modal damping ratios above 5%. The mass is distributed to each mode based on the modal effective mass ratio in each direction. Hence, the mass ratios to control the 1st, 2nd, and 3rd mode are \( \mu_1 = 0.2\% \), \( \mu_2 = 1\% \), and \( \mu_3 = 0.8\% \), respectively. Table 2 lists the system parameters of the three MTMD groups. Each MTMD’s unit has different mass, but identical stiffness coefficient and damping coefficient to reduce construction error and cost. It can be calculated that the equivalent damping ratios of the first three modes are increased to 6.53%, 6.73%, and 5.6% through the application of the MTMD systems.

Table 2 MTMD parameters for controlling 1\(^{\text{st}}\), 2\(^{\text{nd}}\) and 3\(^{\text{rd}}\) mode

<table>
<thead>
<tr>
<th>TMD No.</th>
<th>Node</th>
<th>Mass (t)</th>
<th>Stiffness (KN/m)</th>
<th>Frequency (Hz)</th>
<th>Damping (KN-s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>161</td>
<td>0.44</td>
<td></td>
<td></td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>169</td>
<td>0.50</td>
<td></td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>0.40</td>
<td></td>
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<td>4</td>
<td>181</td>
<td>0.35</td>
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<td></td>
<td>1.04</td>
</tr>
<tr>
<td>5</td>
<td>113</td>
<td>0.57</td>
<td></td>
<td></td>
<td>0.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TMD No.</th>
<th>Node</th>
<th>Mass (t)</th>
<th>Stiffness (KN/m)</th>
<th>Frequency (Hz)</th>
<th>Damping (KN-s/m)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>109</td>
<td>1.70</td>
<td></td>
<td></td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>107</td>
<td>1.94</td>
<td></td>
<td></td>
<td>1.21</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>2.21</td>
<td></td>
<td></td>
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<td>0.98</td>
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</table>

<table>
<thead>
<tr>
<th>TMD No.</th>
<th>Node</th>
<th>Mass (t)</th>
<th>Stiffness (KN/m)</th>
<th>Frequency (Hz)</th>
<th>Damping (KN-s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>2.20</td>
<td></td>
<td></td>
<td>1.38</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>1.79</td>
<td></td>
<td></td>
<td>1.53</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>1.47</td>
<td></td>
<td></td>
<td>1.69</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1.97</td>
<td></td>
<td></td>
<td>1.46</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>1.62</td>
<td></td>
<td></td>
<td>1.61</td>
</tr>
</tbody>
</table>

Table. 2 MTMD parameters for controlling 1\(^{\text{st}}\), 2\(^{\text{nd}}\) and 3\(^{\text{rd}}\) mode
4. CONTROL PERFORMANCE OF MTMD SYSTEMS

A swept-sine signal with frequency bandwidth of 0.1-20 Hz, magnitude of $5 \times 10^5$ KN, sampling time of 0.02 second, and total duration of 40 seconds is used to simulate the ice loading and base excitation to examine the dynamic behavior of the JZ20-2 platform with and without MTMD systems. Its time history and Fourier amplitude spectrum are shown in Fig. 5. The control performance of the proposed MTMD system is evaluated through the reduction of acceleration responses at helideck and upper deck of the platform under two types of ice loadings and earthquake excitation.

Figs. 6 and 7 show the acceleration transfer functions at mid-point of helideck and upper deck due to ice loading applied at four legs in lateral (z) and longitudinal (x) directions, respectively. Since the MTMD systems are designed to control the first and third mode for the lateral direction and the second mode for the longitudinal direction. It is seen that the modal amplitude of the controlled modes is significantly suppressed at the helideck and upper deck. The same observations from Figs. 8 and 9 are made for the cases due to base acceleration excitation. Thus, it can be anticipated that the dynamic responses at both decks can be reduced as well.
Fig. 6 Acceleration transfer functions at center of helideck (left) and upper deck (right) due to ice loading applied at four legs in lateral (z) direction.

Fig. 7 Acceleration transfer functions at center of helideck (left) and upper deck (right) due to ice loading applied at four legs in longitudinal (x) direction.

Fig. 8 Acceleration transfer functions at center of helideck (left) and upper deck (right) due to base acceleration in lateral (z) direction.

Fig. 9 Acceleration transfer functions at center of helideck (left) and upper deck (right) due to base acceleration in longitudinal (x) direction.
4.1. DYNAMIC RESPONSES DUE TO ICE LOADINGS

Bohai gulf is one of the sea areas with serious ice condition in China. Since last century. Ice condition to a large scale has happened seven times in this area. In this study, an actual ice, called bending ice, load with return period of 50 years is assumed to excite at four legs at EL. 4 m above sea level along both lateral and longitudinal directions. For the JZ-20-2 platform, it is observed from Fig. 3 that the helideck and upper deck show higher modal deformation in two horizontal directions. In addition, crew members may be evoked discomfort due to excessive acceleration vibration at two decks during ice or seismic excitations. In view of this, the mitigation of vibration responses at center of both decks is very important and considered for the demonstration of control performance of MTMD system.

The time history of actual bending ice loading and its corresponding Fourier amplitude spectrum are shown in Fig. 10. It is seen that its dominant frequency contents are below 2.0 Hz. The acceleration responses at the center of two decks of the platform with and without the proposed MTMD systems are illustrated in Figs. 11 and 12. It is seen that two horizontal responses are obviously reduced. The root-mean-square (RMS) responses are reduced near 40% by using the MTMD system with mass ratio of only 1% in each horizontal direction as shown in Table 3.

![Fig. 10 Time history (above) and Fourier amplitude spectrum (below) of bending ice load](image_url)
Fig. 11 Acceleration responses at center of helideck (left) and upper deck (right) due to bending ice loading in lateral direction

Fig. 12 Acceleration responses at center of helideck (left) and upper deck (right) due to bending ice loading in longitudinal direction

Table 3. Control performance of MTMD under bending Ice loading

<table>
<thead>
<tr>
<th>Direction</th>
<th>Location</th>
<th>RMS Acceleration (gal)</th>
<th>Uncontrolled</th>
<th>Controlled</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral (z)</td>
<td>Helideck</td>
<td>42.57</td>
<td>25.83</td>
<td>39.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper deck</td>
<td>52.6</td>
<td>35.55</td>
<td>32.41</td>
<td></td>
</tr>
<tr>
<td>Longitudinal (x)</td>
<td>Helideck</td>
<td>116.87</td>
<td>74.97</td>
<td>35.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper deck</td>
<td>61.44</td>
<td>37.11</td>
<td>39.60</td>
<td></td>
</tr>
</tbody>
</table>

Vibration problem may influence the crew members both physiologically and psychologically when working and living in a vibration environment for long period of time, and even threaten their health. The effects of vibration are largely related to four factors, i.e., acceleration amplitude, frequency, duration, and direction. The serviceability of a platform in terms of crew discomfort can be assessed by using standards on human exposure to vibrations. In this study, three evaluations are made on Bohai Sea platforms, such as comfort degradation, decline of working efficiency and exposure time. The Chinese standard “Reduced Comfort Boundary and Evaluation Criteria for Human Exposure to Whole-body Vibration” (GB/T 13442-92) is used for the evaluation. Table 4 shows the bounds of the RMS acceleration as a function of the time.
of exposure (GB/T 13442 - 92, 1992). These bounds are given for vibration frequencies less than 2 Hz. Level I is comfort degradation limit, II is work efficiency degradation limit, and III is exposure limitation. II is 3.15 times as great as I, and III is 2.0 times greater than II. Therefore, According to the standard of GB/T 13442 - 92, it is found that the proposed MTMD system is effective in increasing the work efficiency and exposure time based on the vibration reduction at upper deck, and sufficient time for evacuation based on that at helideck.

<table>
<thead>
<tr>
<th>Table 4. Critical value of human tolerance on vibration acceleration and duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II</td>
</tr>
<tr>
<td>III</td>
</tr>
</tbody>
</table>

Unit: gal (cm/s²)

4.2. DYNAMIC RESPONSES DUE TO EARTHQUAKE EXCITATION

As investigated in last section, the 1940 El Centro earthquake is assumed to excite at the base (EL. -15.6 m) of the platform along both lateral and longitudinal directions. Its time history and Fourier amplitude spectrum are shown in Fig. 13. It is found that the first five modes of the platform are located within the dominant frequency range (0.5 to 3.0 Hz) of the earthquake. Figs. 14 and 15 show the time history of acceleration responses at center of helideck and upper deck for the platform without and with the proposed MTMD system under earthquake excitation in lateral and longitudinal directions. It is seen that the horizontal responses at two decks are significantly reduced. Table 5 shows the RMS responses are reduced up to 50% indicating the control effectiveness of the proposed MTMD system.

![Acceleration time history of 1940 El Centro earthquake](image-url)
Fig. 13(b) Fourier amplitude spectrum of acceleration of 1940 El Centro earthquake

Fig. 14 Acceleration responses at center of helideck (left) and upper deck (right) due to earthquake excitation in lateral direction

Fig. 15 Acceleration responses at center of helideck (left) and upper deck (right) due to earthquake excitation in longitudinal direction

Table 5. Control performance of MTMD system under earthquake excitation

<table>
<thead>
<tr>
<th>Direction</th>
<th>Location</th>
<th>RMS Acceleration (gal)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Uncontrolled</td>
<td>Controlled</td>
<td>Reduction (%)</td>
</tr>
<tr>
<td>Lateral (z)</td>
<td>Helideck</td>
<td>168.5</td>
<td>93.6</td>
<td>44.5</td>
</tr>
<tr>
<td></td>
<td>Upper deck</td>
<td>251.5</td>
<td>125</td>
<td>50.3</td>
</tr>
<tr>
<td>Longitudinal (x)</td>
<td>Helideck</td>
<td>329</td>
<td>193.2</td>
<td>41.3</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

In this study, an optimal MTMD system is proposed to mitigate excessive acceleration responses of the JZ20-2 offshore platform located at Bohai Gulf of east China sea. Both extreme ice force and earthquake acceleration are assumed to excite at the structure and the base, respectively. The RMS accelerations at helideck and upper deck of the platform are investigated to examine the comfort condition, work efficiency, and exposure time of workers. Three groups of MTMD system with five units each are designed to control the first three modes of the platform structure. A total of 1% mass ratio is used for each control direction to increase all controlled modal damping ratio above 5%. Their optimum locations, moving direction and system parameters are determined based on the minimization of modal displacement response with and with MTMD system. Numerical simulation results showed that the proposed MTMD system is able to reduce acceleration responses significantly at two decks of the JZ20-2 platform to enhance its equipment functionality and human comfort, work efficiency, and safety.

REFERENCES