Response Control of FPSO Using Multiple Tuned Liquid Dampers

Gurusamy Saravanan, Deepak Kumar and Ruchi Saraswat

Abstract The Floating Production Storage and Off-loading (FPSO) vessels are being used widely in offshore industries. The motion of FPSO subjected extreme sea condition needs to be controlled in order to maintain the station keeping of the vessel. The crude oil containers of an FPSO can be utilized as passive dampers for controlling the response of FPSO. These containers can act as Tuned Liquid Damper (TLD) if the natural frequency of the liquid oscillation in containers is tuned to the natural frequency of FPSO. FPSO container (tank) can be divided into several tanks (Multiple Tuned Liquid Damper, MTLD) with different tank length and liquid depths. The natural frequencies of MTLD can be intelligently distributed over a range around the natural frequency of FPSO or over a band of excitation wave frequencies. Each TLD can be modelled by using an equivalent Tuned Mass Damper (TMD) analogy. The present study attempts to comprehend the response control of FPSO under surge motion only, and the vessel is modelled as a single degree of freedom system subjected to random waves. Both time domain and frequency domain analyses have been carried out to verify the response control. From the present study, it has been found that MTLD for FPSO will be effective if they are tuned to a range of wave excitation frequencies.

Keywords Floating production storage and Off-loading (FPSO) · Tuned liquid damper (TLD) · Tuned mass damper (TMD) · Multiple tuned liquid damper (MTLD) and surge motion

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1 Introduction

Due to increasing demand for oil and gas, industries predominantly depend on ocean resources. For oil extraction and refinery processes, offshore industries rely on fixed structures such as concrete gravity platforms, steel jacket structures, complaint towers; and moored structures, namely spar platforms, tension leg platforms, semi-submersible production systems and FPSOs. In deep water oil fields where sub-sea pipelines are rarely possible, the FPSOs can be utilized for storing and processing the crude oil. Also, they have notable advantages: adaptability for water depth, early deployment in the production unit, self-contained, movable and re-locatable. It is worth to mention that there are 164 operating FPSOs worldwide (as of March 2015). Therefore, it is important to address the issues of safety, efficiency and motion control of FPSO systems under extreme sea state conditions. Wave loads on FPSO cause the interaction between FPSO and liquid in the cargo tanks; the liquid motion in the tanks affects the dynamics of FPSO badly. Excessive surge motion of the vessel could damage the riser system and so the whole production unit gets disrupted. Hence, the surge response control of FPSO is essential to investigate thoroughly. An easy way for structural control is to use passive dampers such as Tuned Mass Dampers (TMDs) and Tuned Liquid Dampers (TLDs) because of their quick installation, cost-effectiveness and minimal maintenance. Passive dampers do not require any external power sources. They impart forces that are developed due to the structural motion. In order to have robust and efficient damping devices, Multiple Tuned Mass Dampers (MTMDs) and Multiple Tuned Liquid Dampers (MTLDs) are preferred rather than single TMD/TLD.

Many researchers have explored the dynamics, efficiency and robustness of MTMD/MTLD. Clark [1] has designed a Multiple Tuned Mass Damper by extending the work of Den Hartog [2] from a single degree of freedom (SDOF) system to multiple degrees of freedom (MDOF) system. Igusa and Xu [3] have examined the effectiveness and robustness of MTMDs with natural frequencies uniformly distributed over a range. They have used the calculus of variations to optimize the design of the MTMDs with a constraint on the total mass. Kareem and Kline [4] have demonstrated the performance of MTMDs with frequencies uniformly and non-uniformly distributed within a specified interval. Moreover, it is observed that MTMDs with non-uniform frequency distribution do not meet any advantages or disadvantages over MTMDs with uniform frequency distribution. Fujino and Sun [5] have investigated extensively the implementation of MTLDs for SDOF systems by using both experimental and theoretical approaches. Lee and Reddy [6] have used cylindrical LTD to suppress the motion of fixed offshore platforms. Jin et al. [7] have done experimental and numerical study on TLDs for controlling earthquake response of jacket offshore platform. Sorkhabi et al. [8] have investigated the use of multiple shallow water tanks in response control of MDOF systems.

In FPSOs, the existing cargo tanks can be modelled as damping devices. Therefore, the present study applies the concept of MTLD for examining the FPSO's surge response control. Based on conventional approach, MTLDs are tuned to the surge natural frequency of FPSO and the responses are obtained. Moreover, in case of deep-sea conditions, we may expect a band of wave frequencies to occur. Hence, an attempt is made to explore the effects on response control if MTLDs are tuned to a range of wave excitation frequencies. In addition, response control is also reviewed if MTLDs are tuned to the natural frequency of FPSO as well as to a range of excitation frequencies.

2 Theory of Tuned Liquid Dampers

Liquid in partially filled containers subjected to dynamic loads undergoes oscillatory motion known as sloshing, and it can be utilized as motion controlling device such as Tuned Liquid Dampers (TLDs). They are used to minimize the horizontal vibration of structures. The fundamental frequency of sloshing is tuned to a natural frequency of structure to suppress the structural vibration. The undesirable vibrational energy will be dissipated due to liquid motion. The frequency of TLD depends on tank length and liquid depth. Based on the ratio of the liquid depth to the tank length in the direction of the motion, the TLDs can be classified into two categories, i.e. shallow water TLDs and deep water TLDs. In the shallow water case, damping originates primarily from the action of wave breaking; whereas in deep water case, baffles and screens are needed to enhance the inherent damping.

If the amplitude of excitation is small, the dynamics of a TLD has similarities with the behaviour of TMD; hence, an easy way to understand the dynamics of rectangular TLDs is based on the equivalent TMD analogy. The equivalent model assumes that tank is rigid; fluid is homogeneous and incompressible; no sources and sinks are present in the liquid domain. The SDOF system with TLD and SDOF system with TMD are shown schematically in Fig. 1a, b. Upon using linear water wave theory, the equivalent mass and stiffness, corresponding to the fundamental mode of sloshing, can be derived as follows (Tait [9]).

The equivalent mass:

$$m_{\mathrm{eq}} = \frac{8\rho b L^2}{\pi^3} \tanh\left(\frac{\pi h}{L}\right) \tag{1}$$

The equivalent stiffness:

$$k_{\mathrm{eq}} = \frac{8\rho b L g}{\pi^2} \tanh^2\left(\frac{\pi h}{L}\right) \tag{2}$$

The fundamental sloshing frequency:

$$\omega_1^2 = \frac{\pi g}{L} \tanh\left(\frac{\pi h}{L}\right) \tag{3}$$

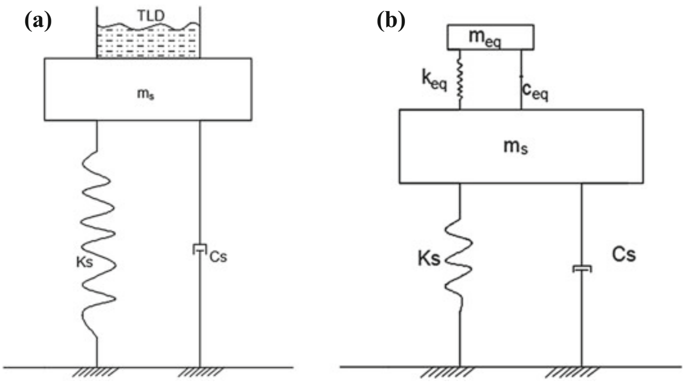

Fig. 1 **a** SDOF system with TLD, **b** SDOF system with TMD

3 Problem Definition

The basic model for investigation is a moored FPSO vessel in deep water. In this study, the existing liquid cargo tanks are utilized to minimize the response of FPSO. The following configurations of FPSO with liquid tanks are considered for study:

Configuration-1: FPSO with empty tanks.

Configuration-2: FPSO with 5-identical rectangular liquid tanks. Natural frequency of each liquid tank is tuned to surge natural frequency of FPSO.

Configuration-3: FPSO with 6-identical rectangular liquid tanks. Natural frequency of each liquid tank is tuned to a wave excitation frequency.

Configuration-4: FPSO with 6-rectangular liquid tanks. Natural frequencies of them are distributed non-uniformly within a range of wave excitation frequencies.

Configuration-5: FPSO with 7-rectangular liquid tanks. Among them, one tank is tuned to natural frequency of FPSO, and frequencies of remaining tanks are distributed non-uniformly within a range of wave excitation frequencies.

The side view of configurations 2 through 5 has been viewed as sketched in Fig. 2a–d. The equivalent model for any configurations 2 through 5 can be viewed as an SDOF system with MTMDs as in Fig. 2e. The diagrams are not drawn in scale.

In order to compare the efficiency of MTLDs in different configurations, the total liquid mass in configuration-2 through configuration-5 is kept as constant. The details of length and liquid depth and natural frequency of tanks accommodated in all configurations are mentioned in Table 1.

3.1 Wave Spectrum

In order to predict linear and nonlinear responses for design of offshore structures, ocean wave spectrum representing particular sea states is an essential factor. For

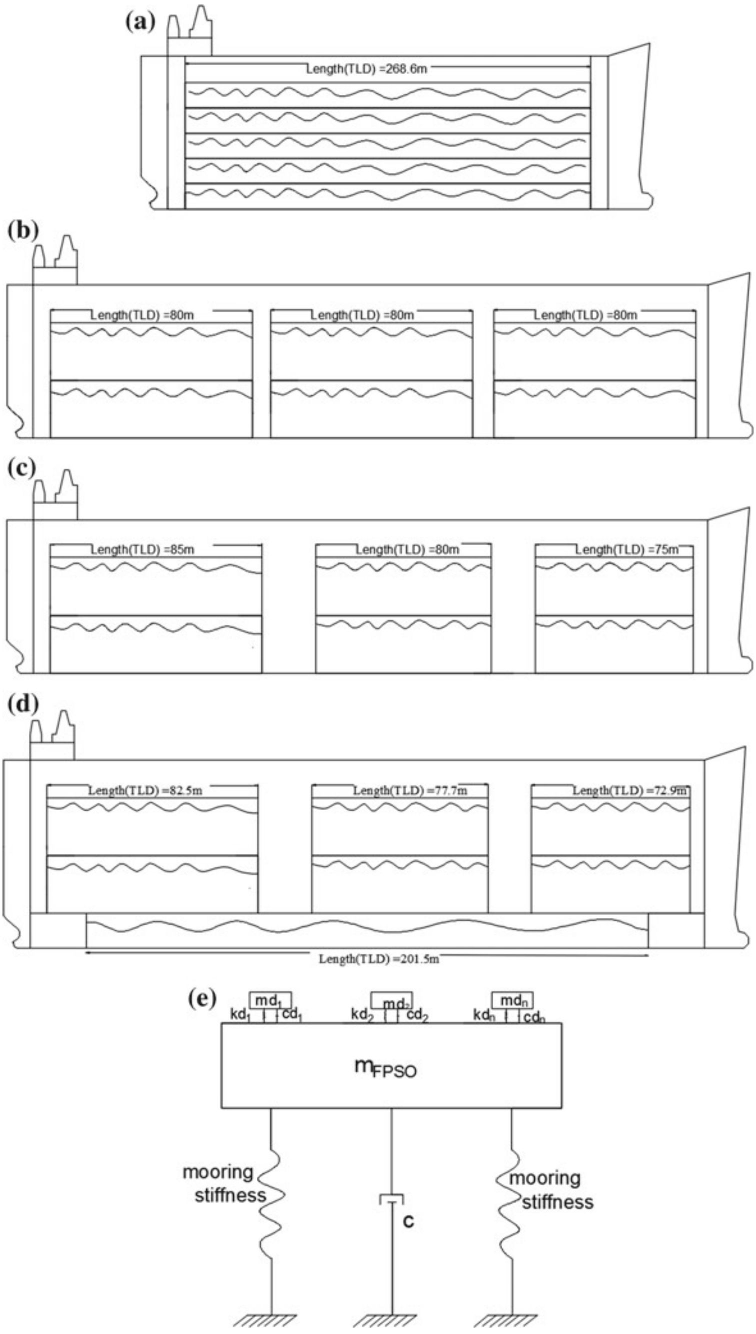

Fig. 2 **a** FPSO with MTLDs: configuration-2, **b** FPSO with MTLDs: configuration-3, **c** FPSO with MTLDs: configuration-4, **d** FPSO with MTLDs: configuration-5, **e** Equivalent model for FPSO with MTLDs

Table 1 Details of different configurations of FPSO with MTLDs

Cases	Number of TLDs	Particulars of TLDs		
		Tank length (m) L_n	Liquid depth (m) h_n	Sloshing frequency (rad/s)
Config-1	0	–	–	
Config-2	5	268.6 m (TLD_n: $n = 1, 2, 3,4, 5$)	2.93	0.06269
Config-3	6	80 m (TLD_n: $n = 1, 2, 3,4, 5,6$)	8.5	0.35216
Config-4	6	85 m (2-identical) TLD_1, TLD_2	8.5	0.33212
		80 m (2-identical) TLD_3, TLD_4	8.5	0.35216
		75 m (2-identical) TLD_5, TLD_6	8.5	0.37473
Config-5	7	201.5 m (TLD_1)	1.65	0.06272
		82.5 m (2-identical) TLD_2, TLD_3	8	0.33227
		77.7 m (2-identical) TLD_4, TLD_5	8	0.35214
		72.9 m (2-identical) TLD_6, TLD_7	8	0.37448

design purposes, one can choose reasonably good wave spectrum which is expected in the ocean sites where the system can be operated safely. In the present study, Pierson–Moskowitz spectrum is used to represent the fully developed sea state with significant wave height, $H_s = 16$ m. The one-sided power spectral density of wave height is given as in Eqs. (4) and (5), and the corresponding plot is shown in Fig. 3.

The modal frequency ω_m exists at 0.3132 rad/s, and the dominant wave frequencies are distributed in the range between 0.28 and 0.38 rad/s.

$$S(\omega) = \frac{8.10}{10^3}\frac{g^2}{\omega^5}\exp(-(5/4)(\omega_m/\omega)^4) \quad (4)$$

$$\omega_m = 0.4\sqrt{g/H_s} \quad (5)$$

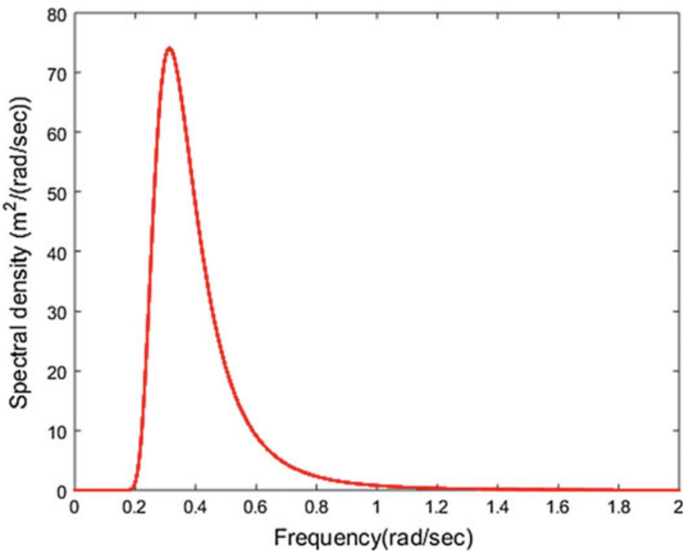

Fig. 3 Wave height spectral density function

3.2 Wave Load on FPSO

The ratio of draft of FPSO to the wavelength is less than 0.2 and so the slender body theory is applicable for FPSO; therefore, Morison's equation is applied to calculate wave loads on FPSO. One can write the horizontal hydrodynamic force on the FPSO as

$$f(t) = \frac{1}{2}\rho C_D BD|\dot{u} - \dot{x}|(\dot{u} - \dot{x}) + \rho C_M BDL\ddot{u} - (C_M - 1)\rho C_M BDL\ddot{x} \tag{6}$$

Here, $\{C_D, C_M\}$ are the drag and inertia coefficients; $\dot{u}$ and $\ddot{u}$ are the ocean water particle velocity and acceleration, respectively; the set $\{x, \dot{x}, \ddot{x}\}$ denotes the displacement, velocity and acceleration of FPSO, respectively; $\{L, B, D\}$ represents the length, maximum beam and Draft of FPSO; ρ denotes the seawater density.

3.3 Mathematical Formulation

The equation of surge motion of FPSO is given as follows:

$$(m + a)\ddot{x} + (2\xi\omega m)\dot{x} + k_1 x + k_2 x^3 + k_5 x^5 = f(t) \tag{7}$$

where $f(t) = \frac{1}{2}\rho C_D BD|\dot{u} - \dot{x}|(\dot{u} - \dot{x}) + \rho C_M BDL\ddot{u} - (C_M - 1)\rho C_M BDL\ddot{x}$.

The equation of motion of TLD$_n$ is given by:

$$m_n\ddot{x}_n + c_{dn}(\dot{x}_n - \dot{x}) + k_{dn}(x_n - x) = 0 \quad \text{for} \;\; n = 1, 2, 3 \ldots \tag{8}$$

Here, $\{m, \xi, \omega\}$ are the mass, damping ratio and surge natural frequency of the FPSO vessel; 'a' is the added mass due to surge motion of FPSO; the set $\{x, \dot{x}, \ddot{x}\}$ denotes the displacement, velocity and acceleration of FPSO, respectively; the set $\{x_n, \dot{x}_n, \ddot{x}_n\}$ denotes the displacement, velocity and acceleration of TLD$_n$ in the FPSO; the set $\{m_{dn}, k_{dn}, c_{dn}, \omega_{dn}\}$ indicates the mass, stiffness, damping constant and natural frequency of the TLD$_n$; k_1, k_2, k_3 are the mooring coefficients obtained by catenary equations; $\dot{u}$ and $\ddot{u}$ are the ocean water particle velocity and acceleration, respectively; let $\{L_n, h_n\}$ denote the length and liquid depth of TLD$_n$. The following can also be noted.

Mass of TLD$_n$:

$$m_{dn} = \frac{8\rho_n b L_n^2}{\pi^3}\tanh\left(\frac{\pi h_n}{L_n}\right) \tag{9}$$

Stiffness of TLD$_n$:

$$k_{dn} = \frac{8\rho_n b L_n g}{\pi^2}\tanh^2\left(\frac{\pi h_n}{L_n}\right) \tag{10}$$

Damping constant of TLD$_n$:

$$c_{dn} = 2\left(\sqrt{\frac{3\mu}{8(1+\mu)}}\right)m_{dn}\omega_{dn}; \quad \mu = \frac{m}{m_{dn}} \tag{11}$$

Natural frequency of TLD$_n$:

$$\omega_{dn} = \sqrt{\frac{\pi g}{L_n}\tanh\left(\frac{\pi h_n}{L_n}\right)} \tag{12}$$

The equation of motion can be written in matrix form compactly:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\} \tag{13}$$

where $[M]$, $[C]$, $[K]$ are mass, damping and stiffness matrices; $\{X\}$, $\{\dot{X}\}$, $\{\ddot{X}\}$ are displacement, velocity and acceleration vectors. For the configuration-2, one can have the following expressions.

$$M = \begin{bmatrix} m+a & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{d1} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{d2} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{d3} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{d4} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{d5} \end{bmatrix}$$

$$C = \begin{bmatrix} c + \sum_{i=1}^{5} c_{di} & -c_{d1} & -c_{d2} & -c_{d3} & -c_{d4} & -c_{d5} \\ -c_{d1} & c_{d1} & 0 & 0 & 0 & 0 \\ -c_{d2} & 0 & c_{d2} & 0 & 0 & 0 \\ -c_{d3} & 0 & 0 & c_{d3} & 0 & 0 \\ -c_{d4} & 0 & 0 & 0 & c_{d4} & 0 \\ -c_{d5} & 0 & 0 & 0 & 0 & c_{d5} \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 + \sum_{i=1}^{5} k_{di} & -k_{d1} & -k_{d2} & -k_{d3} & -k_{d4} & -k_{d5} \\ -k_{d1} & k_{d1} & 0 & 0 & 0 & 0 \\ -k_{d2} & 0 & k_{d2} & 0 & 0 & 0 \\ -k_{d3} & 0 & 0 & k_{d3} & 0 & 0 \\ -k_{d4} & 0 & 0 & 0 & k_{d4} & 0 \\ -k_{d5} & 0 & 0 & 0 & 0 & k_{d5} \end{bmatrix}$$

$$X = \begin{Bmatrix} x \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{Bmatrix} \quad \dot{X} = \begin{Bmatrix} \dot{x} \\ \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{Bmatrix} \quad \ddot{X} = \begin{Bmatrix} \ddot{x} \\ \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \\ \ddot{x}_4 \\ \ddot{x}_5 \end{Bmatrix} \quad F = \begin{Bmatrix} p(t) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

$$p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u} + 2A_1|\dot{x}|\dot{u} - A_1|\dot{x}|\dot{x} - k_2x^3 - k_3x^5 \tag{14}$$

where $A_1 = \frac{1}{2}\rho C_D BD,\ A_2 = \rho C_M BDL,\ a = (C_M - 1)\rho C_M BDL.$

3.4 Parameters of FPSO–MTLD System

Mass (m) = 136,004,663 (Kg)	Damping ratio, $\xi = 0.05$
Length (L) = 312 (m)	$k_1 = 675,490$ (N/m), $k_2 = -110$ (N/m), $k_3 = 10$ (N/m)
Maximum beam (B) = 45 (m)	Surge natural period of FPSO = 100.05 s
Draft (D) = 10 (m)	Density of liquid in TLD, $\rho_n = 850$ kg/m^3
Height (H) = 30 (m)	$C_M = 1.25$, $C_D = 0.7$

4 Solution Techniques

The nonlinear coupled Equations (7) and (8) can be solved in both time and frequency domains. The responses of FPSO are obtained by both ways; the root mean square values of responses are compared.

4.1 Time Domain Analysis

Newmark-beta's time marching algorithm is used to solve the systems (7) and (8).

At every time step, the following procedure is adopted:

1. Solve the linear system initially by considering the excitation force as: $p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u}$.
2. Get the linear responses and update the excitation function $p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u} + 2A_1|\dot{x}|\dot{u} - A_1|\dot{x}|\dot{x} - k_2x^3 - k_3x^5$ using linear responses $x, \dot{x}$.
3. Obtain the system responses using updated $p(t)$.
4. Compare previous responses $\{x, \dot{x}\}_{\text{previous}}$ with the updated responses $\{x, \dot{x}\}_{\text{updated}}$ and check the tolerance of error. If the tolerance is met then store the responses.
5. If not so, again re-update the excitation function $p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u} + 2A_1|\dot{x}|\dot{u} - A_1|\dot{x}|\dot{x} - k_2x^3 - k_3x^5$ by using $\{x, \dot{x}\}_{\text{updated}}$ and get the system responses.
6. Repeat the steps 4 and 5 until convergent of responses.
7. Store the responses for every time step.

4.2 Frequency Domain Analysis

In the frequency domain approach, the nonlinear terms are simplified by stochastic linearization techniques and so the polynomials in the equation of motion (7) can be written as follows:

$$x^3 = \left(\frac{8}{\pi}\sigma_x^2\right)x \quad \text{and} \quad x^5 = \left(\left(\frac{8}{\pi}\right)^2\sigma_x^4\right)x$$

The following steps are used to solve the coupled system (13).

1. Get the Power Spectral Density Function (PSDF) for the excitation $p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u}$.
2. Obtain the frequency response function: $H(\omega) = \left[-\omega^2[M] + i\omega[C] + [K]\right]^{-1}$ for linear part of equation of motion only.
3. Obtain response PSDF (displacement, velocity and acceleration) of linear part of equation.
4. Calculate the RMS values of x and $\dot{x}$. Rewrite the excitation function $p(t) = -A_1|\dot{u}|\dot{u} + A_2\ddot{u} + 2A_1|\dot{x}|\dot{u} - A_1|\dot{x}|\dot{x} - k_2x^3 - k_3x^5$.
5. Using terms $A_1|\dot{x}|\dot{x}$ and $k_2x^3 - k_3x^5$, damping $[C]$ and stiffness $[K]$ matrices are modified.
6. Frequency response function for modified equation is obtained: $\left\{H(\omega) = \left[-\omega^2[M] + i\omega[C] + [K]\right]^{-1}\right\}_{\text{updated}}$.
7. Get the PSDF of updated $p(t)$ in step 4.
8. Obtain the PSDF of displacement, velocity and acceleration using modified response function and modified excitation PSDF.
9. Compare the previous PSDFs (previous iteration) of responses with the updated PSDFs of responses and check the tolerance of error. If the tolerance is met, then store the PSDFs responses.
10. If tolerance error is high, go back to step 4 and continue till convergence is met.

5 Results and Discussions

An FPSO is analysed for its response in surge direction for its response control using its liquid in container as a passive control device (TLD). Several configurations are taken based on TLD tuning. In few configurations, TLDs are tuned to different frequencies to have robustness of response control. Details of different configurations are mentioned previously in text. The techniques used for obtaining the responses are time domain and frequency domain techniques. The time domain simulation is performed up to 3000 s to capture the transient and steady-state response of FPSO. The typical time histories of displacement responses of all configurations are plotted in Figs. 4, 5, 6, 7 and 8. The transient amplitude of configuration-1 is higher than

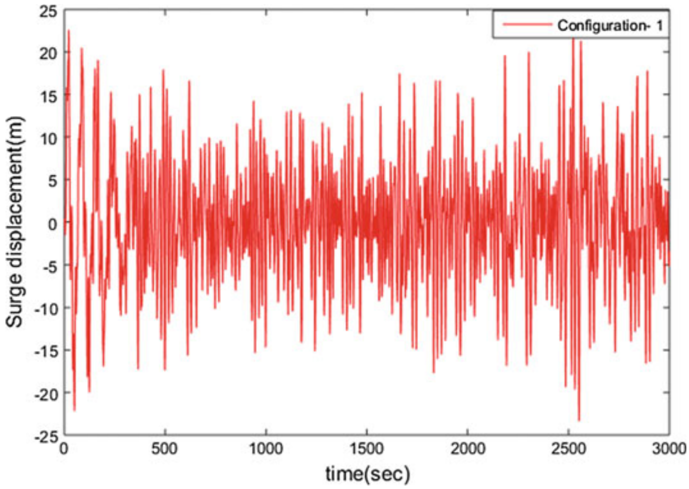

Fig. 4 Time history of displacement response of configuration-1

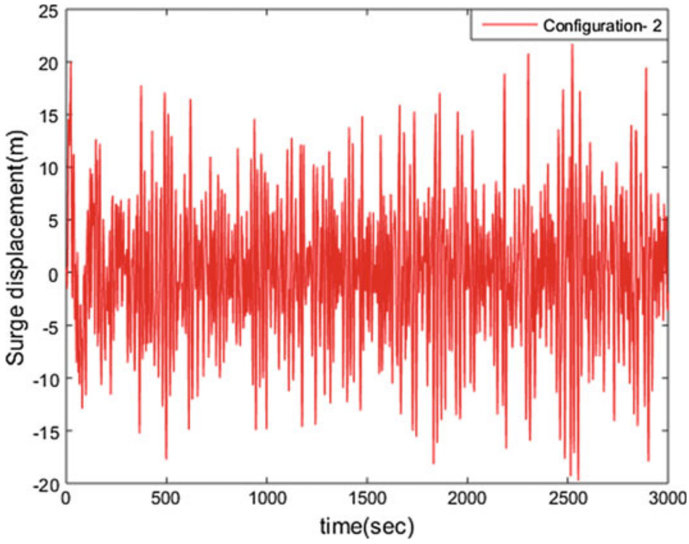

Fig. 5 Time history of displacement response of configuration-2

that of other configurations. This is because FPSO with empty tanks is highly flexible and so it undergoes large excursions. All configurations experience steady state approximately after 500 s, which is five times of the natural period of FPSO. The transient behaviour in configuration-2 differs qualitatively than the configurations 3, 4 and 5.

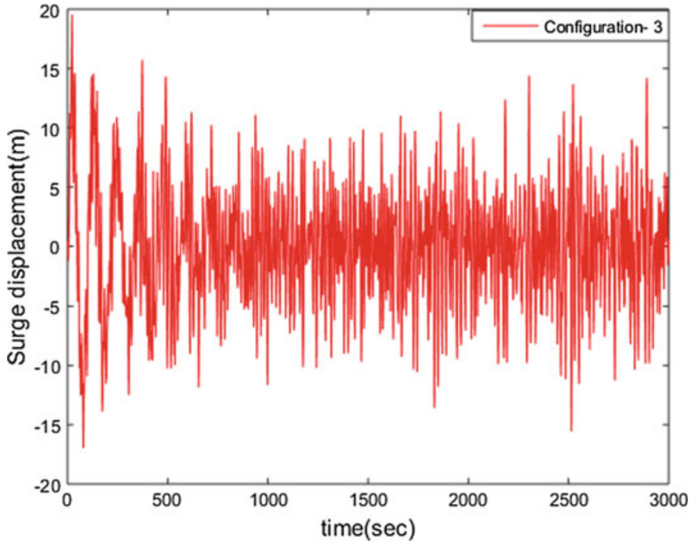

Fig. 6 Time history of displacement response of configuration-3

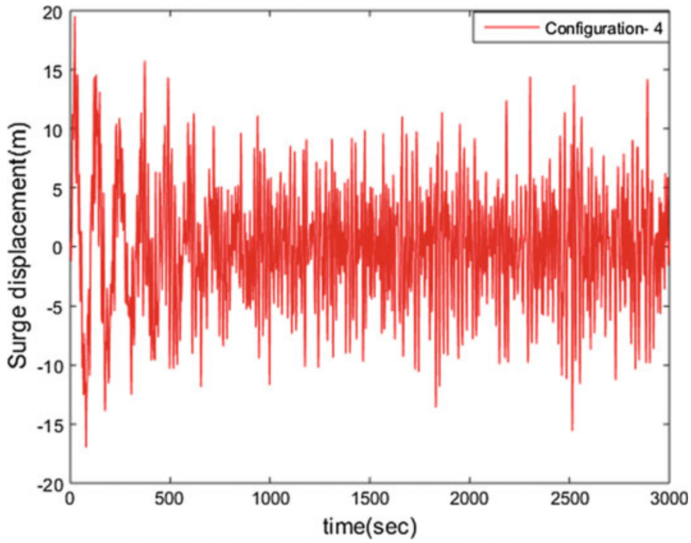

Fig. 7 Time history of displacement response of configuration-4

In Fig. 9, a short span of displacement time history of all configurations (shown in Figs. 4, 5, 6, 7 and 8) is highlighted to distinguish the performance of different configurations in response control. The configuration-2, which contains MTLDs tuned to structural frequency, yields minimal control than other configurations, because each TLD of 268.6 m length has lower sloshing frequency of 0.06269 (rad/s) and

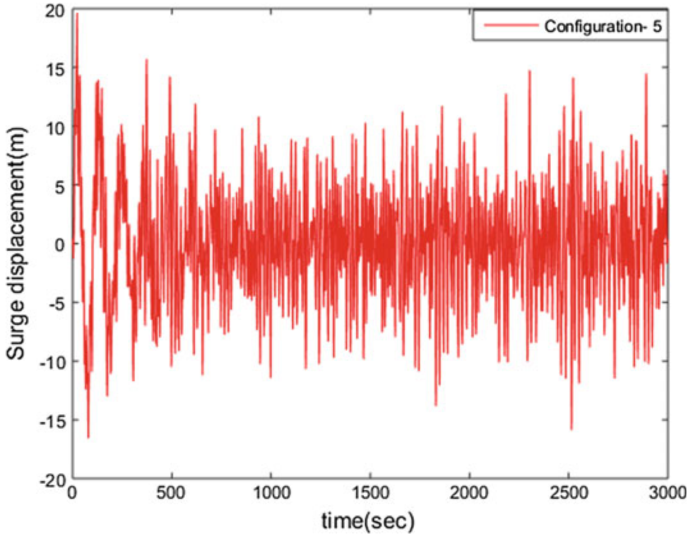

Fig. 8 Time history of displacement response of configuration-5

so they develop less motion to counteract the FPSO motion. In the configuration-3, response reduces significantly; the possible reason is as FPSO is a moored structure, it is expected that the oscillation energy of FPSO is dominant in the excitation frequencies rather than at its own natural frequency. Similar control is noticed in configuration-4 too. Therefore, MTLDs with frequencies tuned to a wave excitation frequency and MTLDs with frequencies tuned to a band of excitation frequencies counteract FPSO motion effectively and so the response diminishes.

Having understood the dynamics of configurations 2, 3 and 4, in configuration-5, a single TLD tuned to the structural frequency and other remaining six TLDs with frequencies distributed over a range of excitation frequencies are used. The response control increases slightly in comparison to other configurations. From the given time history span in Fig. 10, it is visible that configurations 3, 4, 5 display similar trend in displacement response and so performance is almost the same. But configurations 4 and 5 are more robust because of its tuning to wide band of excitation and tuning to FPSO frequency too.

The frequency domain method is also used to justify the response control obtained in time domain analysis. The PSDFs of displacement of all configurations have been plotted in Fig. 11. The peaks of PSDF are present either at the natural frequency of the FPSO and or at the neighbourhood of the excitation frequencies. The RMS value of responses is calculated as the square root of the area under the PSDF curve. The PSDF curve of configuration-1 occupies larger area than other curves. In configuration-2, the peak value of PSDF at the natural frequency of FPSO reduces significantly, since all TLDs tuned to structural frequency and so they contribute in response reduction only at the structural frequency. Also, it is seen that configuration-2 has dominant

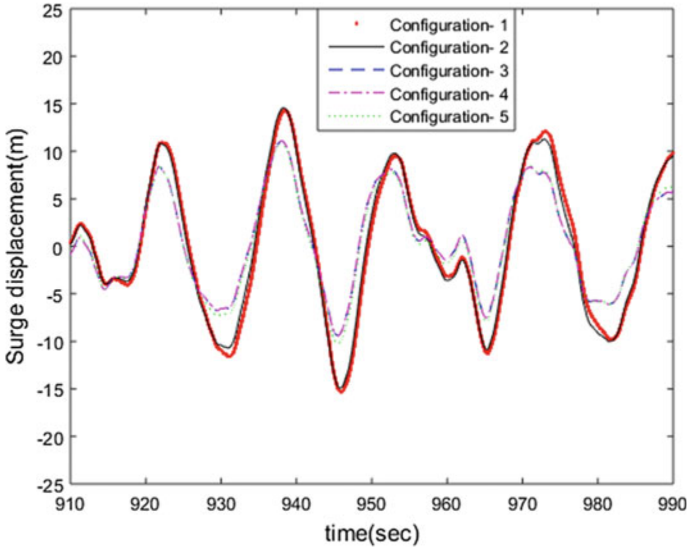

Fig. 9 Comparison of responses of all configurations

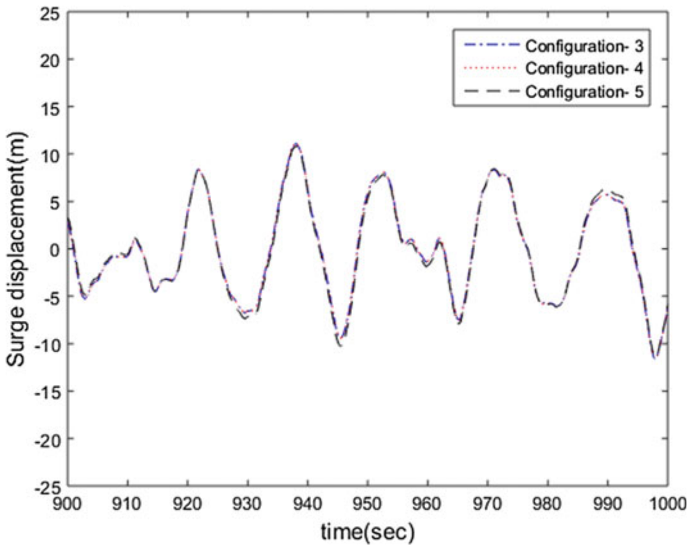

Fig. 10 Comparison of responses of configurations 3, 4 and 5

energy content in the band of excitation frequencies. The PSDF curves of configurations 3 and 4 have higher peak values at the natural frequency of system (FPSO). They have less energy density in the neighbourhood of excitation frequencies; this is because TLDs tuned to wave excitation frequencies damp the energy significantly.

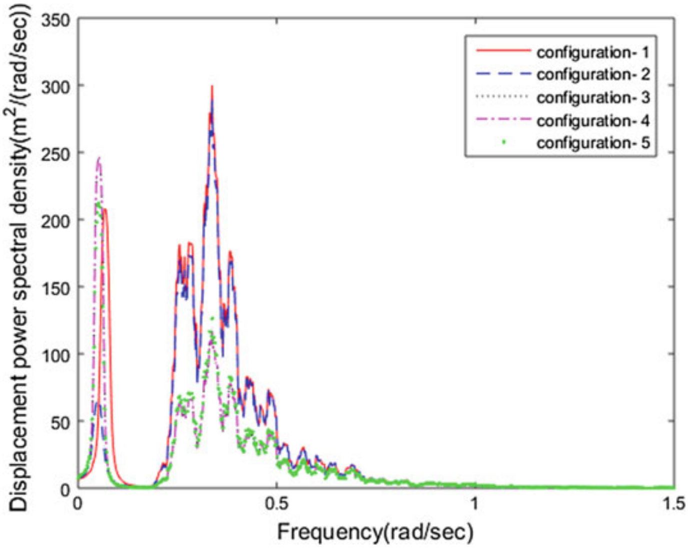

Fig. 11 Comparison of PSDF (time domain) of responses

In configuration-5, one can observe that the peak value of PSDF at the natural frequency of FPSO reduces marginally, because a TLD tuned to the FPSO's frequency contributes a little in response control.

Indeed, one can note that TLD tuned to the natural frequency of FPSO participates in energy reduction at the natural frequency of the system; whereas TLDs tuned to wave excitation frequencies reduce vibrational energy around the wave excitation frequencies. Being FPSO subjected to wave excitation, which has energy concentrated at approximately fixed band of frequencies, its response has large energy content in the region of wave excitation frequencies and so the MTLDs with frequencies tuned to wave frequencies are effective in response control.

The mass ratio for the configurations 2 through 5 is kept as constant so that tuning frequencies are the only responsible factors for control. Since total mass of dampers on FPSO plays a role in response control, one can vary the mass ratio depending on the volume of FPSO and may study the effects of mass ratio on control. However, the present study does not account the variability in mass ratio.

Having non-harmonic displacement time series, root mean square values of responses are obtained to quantify the response control. Table 2 shows the RMS values calculated in both time and frequency domains and percentage control in each configuration. The PSDFs of displacement of the configurations 3, 4 and 5 cover almost the same area, and it is seen from the RMS values in Table 3. The effectiveness of MTLDs on response control is assured by both time and frequency domain results.

From time domain results, the PSDFs of responses are also obtained. This will serve in qualitative comparison of the PSDF plots obtained from both time and fre-

Table 2 RMS values of displacement responses and percentage control

Cases	RMS of displacement		Mass ratio	Percentage control (%)
	Time domain	Frequency domain		
Config-1	7.1034	6.8331	–	–
Config-2	6.4266	6.4328	0.4752	9.528
Config-3	5.007	5.0206	0.4753	29.513
Config-4	5.0111	5.0245	0.4753	29.455
Config-5	4.9964	5.0430	0.4754	29.662

Table 3 RMS values of velocity/acceleration responses

Cases	RMS of velocity		RMS of acceleration	
	Time domain	Frequency domain	Time domain	Frequency domain
Config-1	2.7206	2.7107	3.3232	3.3243
Config-2	2.6733	2.6764	3.3179	3.3199
Config-3	2.0805	2.0859	3.2227	3.2246
Config-4	2.0815	2.0869	3.2228	3.2246
Config-5	2.1159	2.1220	3.2289	3.2308

quency domains. Figure 11 shows the PSDF of displacement response obtained using time domain analysis, and Fig. 12 shows the PSDF of displacement response obtained using frequency domain analysis. In the region of wave excitation frequencies, they have similar spectral shapes and peaks.

The energy transfer between FPSO and TLDs in different configurations can be viewed from Figs. 13, 14, 15 and 16. One can note that Fig. 13 indicates that desired frequencies for which TLDs can be tuned so that response control will be effective. The PSDF of FPSO displays the distribution of energy at natural frequency and at the wave excitation frequencies. FPSO being influenced by wave excitation frequencies, FPSO response has not been restrained effectively by the TLDs tuned to structural natural frequency.

Having reviewed the interaction between TLDs and FPSO in configuration-2, the other configurations are proposed to increase the response control. Figs. 14, 15 and 16 show the energy absorption capacity of MTLDs in configurations 3, 4 and 5, respectively. It is clearly visible that TLD response energy in configurations 3, 4 and 5 are high in the reason of FPSO response energy. So, expected control by configurations 3, 4 and 5 is higher in comparison to configuration-1. Configuration-5 has one additional TLD which is tuned to FPSO natural frequency. This gives little advantage in controlling the response over the configurations 3 and 4.

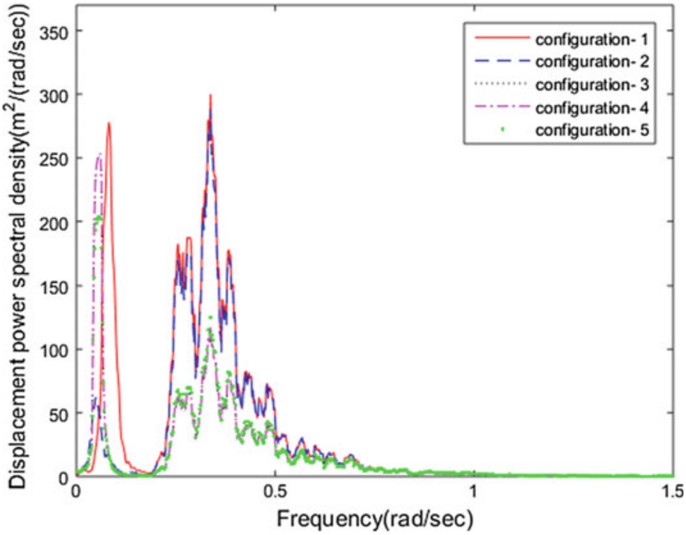

Fig. 12 PSDF (obtained from time domain) of responses

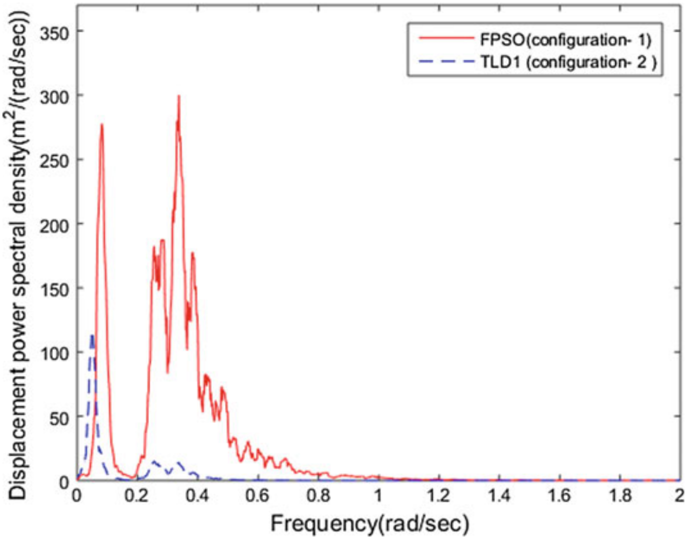

Fig. 13 PSDF of responses of FPSO (config-1) and TLD$_1$ (config-2)

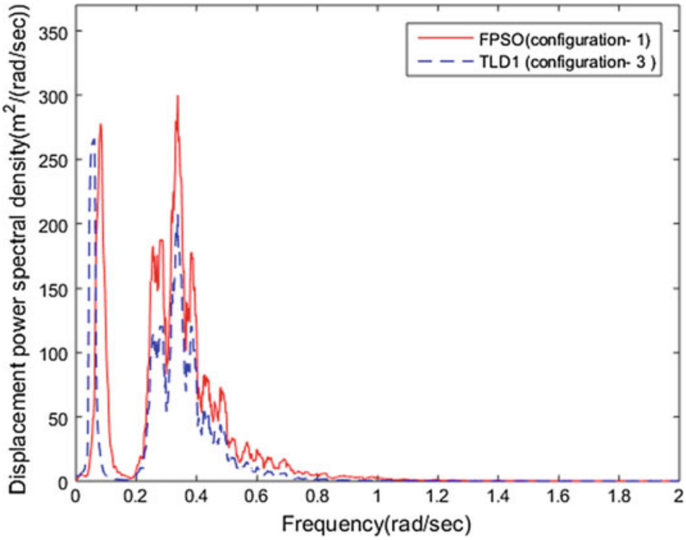

Fig. 14 PSDF of responses of FPSO (config-1) and TLD_1 (config-3)

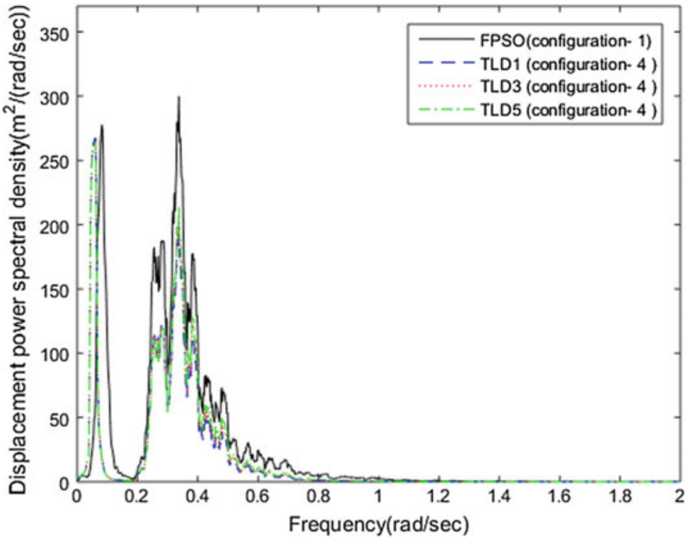

Fig. 15 PSDF of responses of FPSO (config-1) and TLDs (config-4)

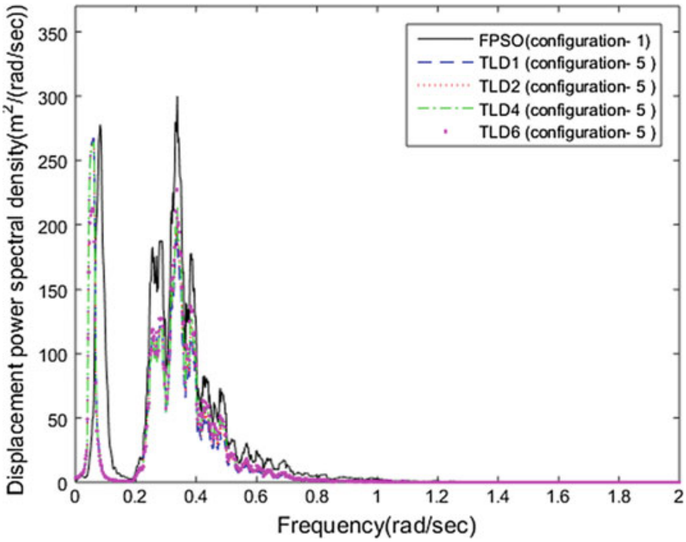

Fig. 16 PSDF of responses of FPSO (config-1) and TLDs (config-5)

6 Conclusions

The present study is intended to analyse the response control of FPSO using the concept of MTLDs. The available cargo containers in FPSO are modelled as liquid dampers. Both time domain and frequency domain methods are employed to prove the efficiency of MTLDs. Being FPSO is a flexible structure, the classical approach, where TLDs are tuned to structural frequency, provides very less control. In order to enhance the response control, TLDs are also tuned to wave excitation frequencies. Based on the analysis, the following salient remarks can be given:

1. MTLDs tuned to structural frequency exhibit about 9.528% response control.
2. A significant control of 29.513% is achieved by MTLDs tuned to a single wave excitation frequency.
3. MTLDs tuned to a range of wave excitation frequencies contribute response control of 29.455%.
4. A maximum control of 29.662% is gained by MTLDs tuned to structural frequency and wave excitation frequencies.
5. The performance of MTLDs tuned to a single excitation frequency, MTLDs tuned to a range of excitation frequencies, MTLDs tuned to structural frequency as well as a range of excitation frequencies does not differ significantly, but robustness of control can increase when TLDs are tuned to band of frequencies.
6. The present study reflects that for flexible structures, passive control devices are effective if they are tuned to wave excitation frequencies.

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