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Semi-active Groundhook Control of Offshore Tension Leg Platforms Using TMD with Optimized Parameters and MR Damper Under Regular waves

Suryasish Patra [1], Diptesh Das [2,*]

[1] Department of Civil Engineering, National Institute of Technology Durgapur, Durgapur, 713209, India
[2] Department of Civil Engineering, National Institute of Technology Durgapur, Durgapur, 713209, India

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Abstract

The motivation and objective of the present study are to propose a semi-active control system for offshore tension leg platforms (TLPs) to mitigate the vibrations induced by regular wave loads. State-of-the-art indicates that not much work is reported on semi-active control of offshore TLPs considering potential nonlinearities for multiple hazards using a control algorithm, which is robust against uncertainties. A displacement based groundhook (DB-GH) control algorithm using tuned mass damper (TMD) and magneto-rheological (MR) damper is employed for the semi-active controller because of its robustness against parametric uncertainties and reliability. Optimized parameters of the semi-active TMD (SATMD) are obtained using constrained nonlinear optimization to achieve the best control performance. The flexibility of the groundhook control lies in its simplicity of implementation, computational efficiency and its demand for only two sensors in order to achieve the calculations of control forces. The scope of the present study is to demonstrate the efficiency of the proposed controller and investigate the effects of different influencing parameters. A TLP, reported in literature, is taken as an illustrative example. The non-linearly coupled dynamic responses of the structure-damper system is analysed and solved in time domain using MATLAB SIMULINK. The results show the SATMD performs quite satisfactorily in reducing the responses of the TLP in different critical conditions.

Keywords: Tension Leg Platform, optimized semi-active Tuned mass damper, MR damper, regular waves.

1. Introduction

Offshore structures constructed on or above the continental shelves and on the adjacent continental slopes take many forms and serve a multitude of purposes: exploration, drilling, production, storage of natural gas and oil. Among different types of offshore structures, the buoyant TLPs have been considered the most promising hydro elastic systems intended for deep water oil exploitation, especially because of its economic viability. However, these platforms are highly susceptible to fatigue damage due to high frequency resonant vibration in hostile environmental conditions [1]. Large displacements under a multiple hazard scenario lead to the extensive structural damage and thus lead to reduction of serviceability to a great extent [2]. A strong random wind motion can have a disastrous effect and can cause severe damage to these type of structures [3]. Therefore, many studies have been made to suppress the vibration of these offshore TLPs to reduce stress levels in tendons and anchorages, minimize fatigue problem thus lead to increase in their structural safety, integrity and production performance. Literature shows that passive vibration absorber such as the tuned mass dampers [4-8], tuned liquid column dampers [9-11], under water tuned liquid column dampers [12], [S-shaped tuned liquid column dampers [13], Fuzzy PDC control scheme [14], T-S fuzzy approach [15] have been used to alleviate the vibration in the TLPs. Among the passive structural control devices, TMDs are the most promising due to their robustness, reliability and computational flexibility. Since the TMDs have their limitations in practical application of compliant offshore structures; due to the complexity of excitation and the harsh environmental conditions inevitable de-tuning of the TMDs occur because of the changes in the operating conditions or the system parameters. Moreover, the de-tuned TMDs can amplify the vibration levels of primary structure excessively, thereby not only rendering the TMDs useless but also causing possible damages to the structure. As an alternative to overcome these drawbacks of conventional passive TMDs, active control schemes, which utilize a controlled force actuator, or hybrid mass dampers (HMDs), which combine a passive and active TMD, have been developed by the researchers [16-19].

*Corresponding author. Tel: +919434788152; E-mail address: diptesh.das@ce.nitdgp.ac.in

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However, active and HMDs still have critical drawbacks such as substantial power requirements, time delay, limited frequency bandwidth and large strokes of the TMDs [20].
Considering these facts, the SATMDs were employed by the researchers because they utilized the reliability of passive systems and the adaptability of active systems with very less power requirement. Limited work, however has been done on the vibration control of structures, subjected to hostile environmental conditions, using SATMDs. Esteki et al. [21] used SATMDs to control a 40-story tall, steel structure with LGR control system to provide the required control command to the SATMDs for seismic applications. C.Sun [22] used semi-active TMD to mitigate the vibration caused by wind, wave and earthquake and desired damping force is derived by short-time Fourier transformation (STFT) based algorithm. Hidaka et al. [23] experimentally designed an efficient Neural network control strategy for a three-story structural model, which is excited by shaking table. Nadathur and Satish [24] worked on semi-active variable stiffness-tuned mass damper (SAIVS-TMD), using Hilbert Transform Instantaneous Frequency control algorithm for suppressing wind induced vibration of a 76-story tall building. Viet et al. [25] discussed mixed groundhook control algorithm to effectively mitigate the harmonic vibration of the unsprung mass. It is very much difficult to develop a mathematical model for the tension leg platforms due to its critical non-linear behaviour and involvement of parametric uncertainties, assumptions and imprecisions. This problem becomes more critical for semi-active control of offshore TLPs with MR dampers as it involve the non-linear dynamics and also the structure-water interaction. These problems, however, need to be tackled wisely in order to design and develop controllers which will effectively perform under such circumstances. The external wave and wind loads make the problem more challenging due to involvement of higher uncertainties and uninterrupted wave induced vibrations. A control algorithm which will effectively perform under these circumstances and makes the development of controller a little bit simpler, is groundhook control algorithm [26], because of its inherent simplicity of implementation, computational efficiency, requirements of only two sensors and robustness to deal with the parametric uncertainties. Validating the effectiveness of the groundhook control scheme, Koo et al. [27] examined the performances of different groundhook control
strategies on a baseline model, demonstrating that the DB-GH controlled SATMD devices can substantially reduce the responses when compared with the passive solutions. So, we have implemented DB-GH control algorithm along with slight modifications in our study in order to improve the control performances. Kang et al. [28] introduced DB-GH control algorithm with SATMD and MR damper to effectively mitigate the responses of a tall building subjected to wind excitations. They also compared the performance of the SATMD with passive TMD and active TMD, and it is reported that SATMD along with DB-GH algorithm performs best among them.
From the review, it is clearly seen that not much work is reported on semi-active control of offshore TLPs for regular waves using TMD and MR damper with DB-GH control algorithm which is robust against uncertainties and imprecisions. With the above background in view, the objective and motivation of our study is to develop an efficient semi-active control scheme for compliant offshore TLPs using the combination of the passive TMD and semi-active MR damper and investigate performance of the controller in mitigating the structural responses under regular wave excitations. For the semi-active MR damper control, the DB-GH control algorithm is used to provide the command current to the MR damper. The above may be stated as the innovative contribution of the paper based on the state-of-the-art. A constrained non-linear optimization technique is carried out to obtain the optimal TMD control parameters in order to achieve the best response reduction of the surge motion of TLP.

2. Structural Model of TLP

The structure-water-wind interaction plays an important role in the dynamic behaviour of the structure and, consequently, in the control of vibration. The TLP as shown in Fig. 1, is considered as a three-dimensional rigid body, with six degrees of freedom, and the whole mass of the body in confined to a point i.e. centre of gravity. The tendons are assumed as elastic springs, and the initial and instantaneous tension in all the tendons are equal. A structural model of a TLP as a buoyant structure is shown in Fig. 2. Since the buoyancy of the TLP exceeds its weight, the vertical equilibrium of the platform requires taut moorings connecting the upper structure to the seabed. The extra buoyancy over the platform weight ensures that the tendons are always in tension. To derive the equation of motion an arbitrary displacement is given in the surge direction as shown in Fig. 2. If x is the arbitrary displacement in surge direction, l_0 is the initial length of each tether, T_0 is the initial pretension in each tether, E represents the modulus of elasticity of tether, due to the displacement, the increase in the initial pretension is given by:

$$\Delta T = AE\left(\frac{\Delta l}{l_0}\right) \therefore\ \Delta T = AE\left(\sqrt{{l_0}^2 + x^2} - l_0\right)/l_0 \qquad (1)$$

Since, $x \ll l_0$, the above equation can be written as $\Delta T = AE\left(l_0 + \frac{1}{2}x^2 - l_0\right)/l_0$ (2)

Therefore, $\Delta T = 0.5AEx^2/l_0$ (3)

Also, since $x \ll l_0$, $\sin\theta = x/\sqrt{{l_0}^2 + x^2} = x/l_0$ (4)

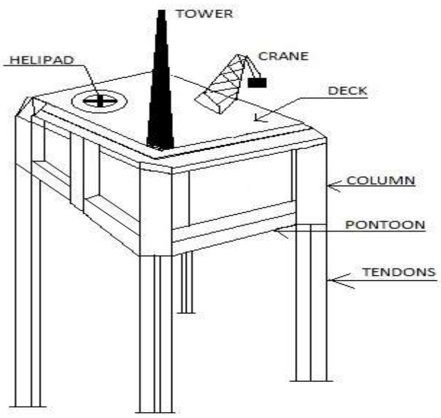


Fig. 1. Tension leg platform

The equation of motion along surge degree of freedom can be written as:

$$M\ddot{x} + C\dot{x} + (nT_0 + n\Delta T)\sin\theta = F_{lateral} \quad (5)$$

Substituting the values of ΔT and $\sin\theta$ from Eq. (3) and Eq. (4) respectively to Eq. (5), the above Eq. (5) can be rewritten as:

$$M\ddot{x} + C\dot{x} + \left(nT_0 + \frac{nAEx^2}{2l_0}\right)\frac{x}{l_0} = F_{lateral} \quad (6a)$$

Here, M, C, $k_1 = \frac{nT_0}{l_0}$ and $k_2 = \frac{nAE}{2l_0^2}$ are the structural mass, damping, linear stiffness parameter and non-linear stiffness parameter respectively, where n is the number of tendons. $F_{lateral}$ is the encountered wave force, along surge direction. To formulate the structural damping, stiffness and mass proportional damping according to Rayleigh damping concept is used. According to this method, it is assumed that the structural damping C is proportional to the structural mass M and the initial structural stiffness k_1 as

$$C = \alpha M + \beta K \quad (7)$$

Where the values of α and β are given by the following relations:

$$\alpha = \frac{2\zeta\omega_1\omega_2}{\omega_1+\omega_2} \quad (8)$$

$$\beta = \frac{2\zeta}{\omega_1+\omega_2} \quad (9)$$

Where ω_1 and ω_2 are the critical frequencies of the first two modes.

2.1. Ground hook control theory

To control the damping force of the MR damper in the SATMD, DB-GH control scheme is adopted because of its simplicity in practical applications. Fig. 3 shows a dynamic system subjected to lateral excitations for which M, K, and C represent the mass, stiffness, and damping of the main system, respectively. When the excitation frequency (ω) becomes close to the system natural frequency (ω_1), it will be in resonance and the main mass will be subjected to large amplitudes of motion (x_1). In order to reduce the vibration level, a secondary mass (m_d), is attached to the main mass through one spring with stiffness coefficients k_d, and one MR damper with variable damping coefficients c_d. The system consisting of m_d, c_d, k_d represent the SATMD. The most comprehensive way to determine the groundhook damping force is to examine the force acting on the main structure under several conditions. The DB-GH control policy is dependent upon the relative velocity and the displacement of the main structure (x_1) with respect to the center-line (C.L.) position. The relative velocity is defined by subtracting the velocity of SATMD from that of main structure, i.e. $v_1 - v_2$. Using these definitions, four cases are identified and damper forces are calculated in accordance that in Table 1.

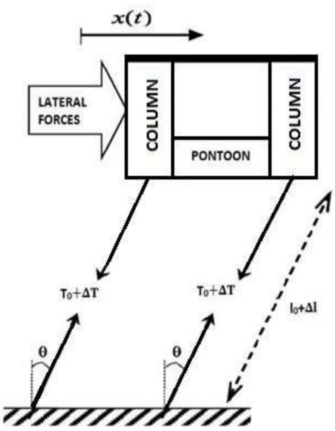


Fig. 2. TLP given an arbitrary displacement.

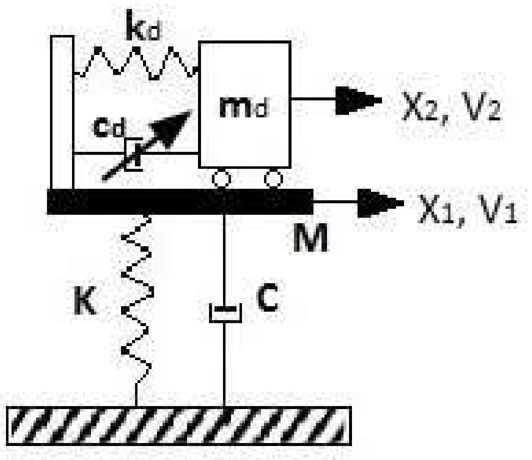


Fig. 3. Configuration of SATMD

Summarizing these four conditions, the DB-GH control policy was derived, as shown in Eq. 10 and 11:

$$\text{If } x_1(v_1 - v_2) \geq 0, \text{ then } c_d = c_{on} \quad (10)$$

$$\text{If } x_1(v_1 - v_2) < 0, \text{ then } c_2 = c_{off} \quad (11)$$

where c_{on} denotes the passive-on damping coefficient, and c_{off} denotes the passive-off damping coefficient.

Table 1: Displacement based ground hook control algorithm

Structure displacement	Relative velocity	Damper status	Desired damping state
$x_1 > 0$	$v_1 - v_2 > 0$	C	On
	$v_1 - v_2 < 0$	T	Off
$x_1 < 0$	$v_1 - v_2 < 0$	T	On
	$v_1 - v_2 > 0$	C	Off

Note: C: compression; T: tension

2.2. *Optimization of SATMD parameters*

The optimal tuning is carried out by using constrained nonlinear minimization which uses the minimization of peak transmissibility as an optimization criterion. Proper tuning of the SATMD parameters are necessary because of the presence of the damping of the primary system and nonlinearity of semi-active control. The goal of the optimization technique is to find the SATMD parameters, such as the on-off damping ratios (ξ_{on} *and* ξ_{off}) and the SATMD's stiffness (k_d), which will generate the best performance of the controller. The optimization technique involves three stages which are as follows:

Stage I: System parameters are defined along with the initial values and the ranges of the simulation parameters.

Stage II: The peak transmissibility is obtained and it is sent to the minimization function, fmincon.m.

Stage III: The minimum value of peak transmissibility is returned along with the corresponding parameters. When a peak transmissibility value is smaller than the previous peak transmissibility value, the optimization routine ends.

Table 2 summarizes the initial values and ranges of simulation parameters used in the present study for optimization. Larger upper limits of on-state damping ratio are taken to give desirable optimization results.

2.3. *Modelling of Magneto-rheological damper.*

The emergent property MR damper is that it consists magnetically polarizable fluid which has excellent capability of changing its state. In the presence of an electromagnetic field, it is reversibly changed from liquid state to semi-solid state with controllable yield strength in milliseconds. The mechanical model proposed by Spencer et al. [29] was used for demonstrating hysteretic behavior of the MR damper. Force produced by the damper in the Spencer's model described as follows:

$$f = c_1\dot{y} + k_1(x - x_0) \quad (12a)$$

$$\dot{y} = \frac{1}{c_0+c_1}[\alpha z + c_0\dot{x} + k_0(x - y)] \quad (12b)$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \quad (12c)$$

Table 2: Simulation parameters for optimization

Control scheme	Parameter	Initial value	Range
Passive	ξ	0.15	$0.1 \le \xi \le 1.5$
	k_d	13340.55	$10000 \le k_2 \le 100000$
DB-GH	ξ_{on}	4.69	$0.1 \le \xi_{on} \le 100$
	ξ_{off}	0.5	$0.01 \le \xi_{off} \le 1.0$
	k_d	10417.3	$10000 \le k_2 \le 100000$

Note: ξ_{on}: on-state damping ratio, ξ_{off}: off-state damping ratio, k_d: SATMD's stiffness

Where:

$$\alpha(i) = 16566i^3 - 87071i^2 + 168326i + 15114 \quad (12d)$$

$$c_0(i) = 437097i^3 - 1545407i^2 + 1641376i + 457741 \quad (12e)$$

$$c_1(i) = -9363108i^3 + 5334183i^2 + 48788640i - 2791630 \quad (12f)$$

Where y is the internal displacement of the MR damper and x is damper displacement in the x-direction.

3. Numerical study

To demonstrate the efficiency and effectiveness of the proposed semi-active control system in reducing the vibrations induced by regular wave loads, a buoyant TLP is taken from the literature [17]. The four-legged platform is tethered to sea bed by 473.4 m long tendons and the platform has same properties along both the directions, and all the elements are assumed to be elastic during external excitations. A two-dimensional analysis is performed, and the spatial variation in wave and wind forces along the width of platform is ignored. The control devices are symmetrically placed over the deck. Therefore, the bi-directional moments and torsional vibrations and their interactions are not within the scope of the present study. The nonlinear stiffness coefficients are derived along surge direction, considering the TLP as a rigid body [30]. The nonlinear effects considered in this analysis are due to stiffness nonlinearity arising from large displacement, variable submergence. To formulate the Rayleigh damping matrix, a value of 5% is taken as the critical damping at two different frequencies (ω_1 *and* ω_2). The values of α and β in Eqs. (8)-(9) are obtained as 0.0441 and 0.0061 respectively.

The responses of the structure are obtained for regular operating and regular extreme waves. Since the TLP is tethered to sea bed in vertical direction, it is only complaint in surge, sway and yaw directions. Moreover, control of the lateral response of the structure is of interest in the present study; control of any secondary system mounted on the deck is not considered. Operating wave with 1-year return period and extreme wave with 100 years return period are taken as regular waves to the study the response of the TLP. The values amplitude and time period required for procreation of regular operating and extreme waves are shown in Table 3.

A single TMD with mass ratio 5% and a MR damper with 20-ton capacity is employed together to form the SATMD which is used in the present study. The MR damper is taken from the literature [32], and the values of the modelling parameters for this device are provided in Table 4.

Table 3: Amplitude and time period values of different sea states [31]

Sea state of wave	Amplitude	Time period
Operating	12 m	11 s
Extreme	18 m	14.4 s

Table 4: Values of parameters adopted for modelling of MR damper

Parameter	Value
A	2679.0 m-1
γ, β	647.46 m-1
k_0	137810 N/m
n	10
k_1	617.31 /m

3.1. Optimization of SATMD parameters

The transmissibility plots for various control schemes as well as the uncontrolled responses are shown in Fig. 7. Transmissibility is defined as the ratio of output displacement of the structure to input excitation, so that the smaller values of transmissibility indicate more vibration reduction. In uncontrolled state when resonance occurs, the transmissibility value is very high, thus signifies the importance of control scheme. Fig. 4 shows that transmissibility of DB-GH control policy is significantly lower than the passive control scheme, which indicates that DB-GH control scheme performs better than the passive control scheme. Fig. 4 also shows the optimal tuning frequency for the SATMD. A tuning frequency ratio is defined as the ratio of the structure natural frequency and the SATMD frequency. The valley of the SATMD model identifies this optimal tuning frequency. The tuning frequency ratio of the DG-GH control scheme is largest among the considered control policies. This means that the natural frequency of the SATMD with the DB-GH control scheme is the lowest compared with the other control policies.

The results of the optimization routine are summarized in Table 5. Note that the tuning frequency ratio of the DB-GH model is 0.62, which is higher than the optimal passive frequency ratio of value 0.58. The lower stiffness value of the SATMD is 12865.5 N/m, confirms this result. From Table 7 we can further observe that maximum percentage reduction of peak transmissibility is 78.29%, which occurs in the case of DB-GH control policy. Note that the DB-GH control model offers the lowest valley because its off-state damping is low.

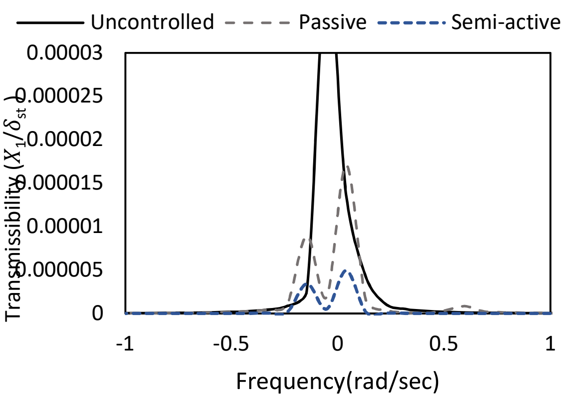


Fig. 4 Optimally tuned transmissibility results

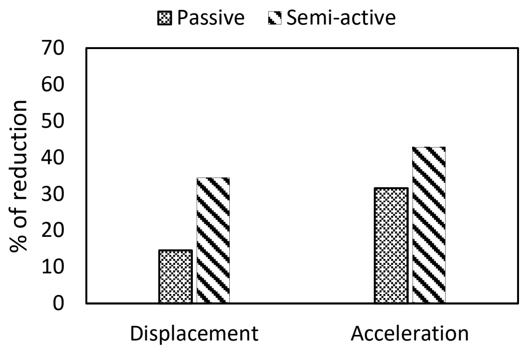
Table 5 Summary of optimal SATMD parameters

Parameters	Passive control	DB-GH control
SATMD stiffness (N/m)	14345.55	12865.5
Tuning frequency ratio	0.58	0.62
On-state damping ratio	1.267	8.632
Off-state damping ratio	N/A	0.879
% reduction of peak transmissibility	56.94	78.29

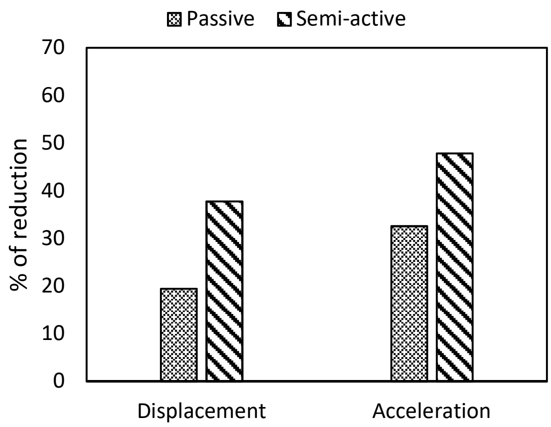
3.2. Performance evaluation of controller

Numerical example for the offshore TLP incorporated with the SATMD system has been carried out in this session. This investigation is focused on the time domain analysis of the platform and the effectiveness of mitigation of responses, when the platform is subjected to regular wave loadings. Percentage reduction of top deck displacement and acceleration have been shown in Figs. 5(a)-5(b), when the platform is subjected to regular wave (operating and extreme) loadings. The figures show that the passive control scheme is effective in minimizing the acceleration of the TLP for all the loading cases; but effective control of displacement is not observed. The drawback of the passive controller, however, is overcome by the semi-active controller in which the adaptability to the changes in structural properties is incorporated by DB-GH control algorithm as discussed later.

Furthermore, in order to enhance the performance of the semi-active control system, one MR damper as variable dampening device is used. The maximum amplitude of top deck displacement, top deck acceleration, which are main responses for interest, for different control schemes are shown in Table 6. The time histories of uncontrolled and controlled response quantities for regular (extreme and operating) wave with passive, and semi-active controllers are shown in Figs. 6-7. The comparative study shows that the performance of the semi-active control system, in terms of response reduction, is significantly better. The response reduction of the top deck displacement and top deck acceleration are 14.56% and 31.67%, respectively, for the passive control system for regular operating wave force. Similarly, the response reductions are 19.41% and 32.54%, respectively, for the regular extreme wave force. In case of semi-active control system, responses reductions are 34.47% and 42.86%, respectively, for regular operating force and 37.76% and 47.86%, respectively, for regular extreme wave. In real life applications, there are many unforeseen factors, which are not possible to be taken into consideration in analytical studies. Due to this reason, depending upon the particular situation, the actual response reductions obtained in reality are expected to be lesser than those predicted by the analytical research. From the tables and figures, it may be concluded that the performance of the SATMD with DB-GH control algorithm is better than that of the passive TMD in terms of reduction of all the responses. In the critical environmental conditions, due to

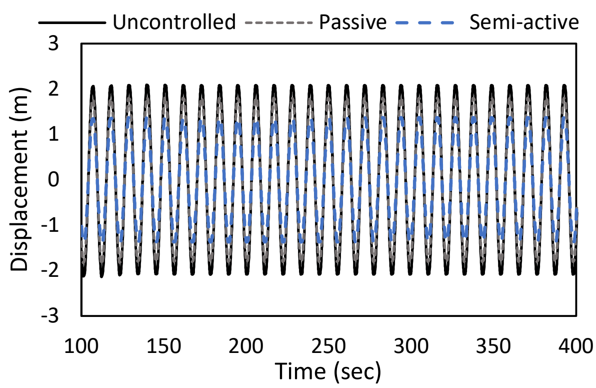


(a)



(b)

Fig. 5 Percentage reduction of the top deck displacement, top deck acceleration for (a) regular operating wave, and (b) regular extreme wave

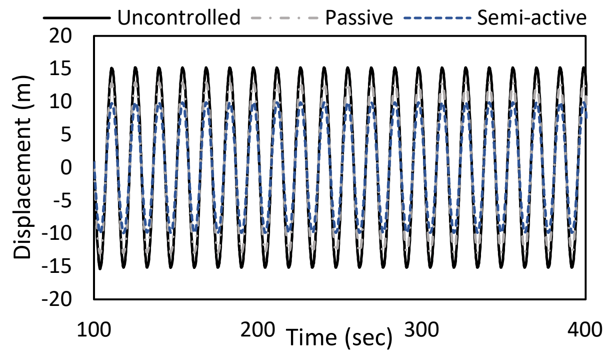


(a)

involvement of nonlinearly coupled stiffness parameters of TLP, the passive control system is incapable to mitigate the responses, because of detuning of TMD but the semi-active control strategy significantly reduces the responses.

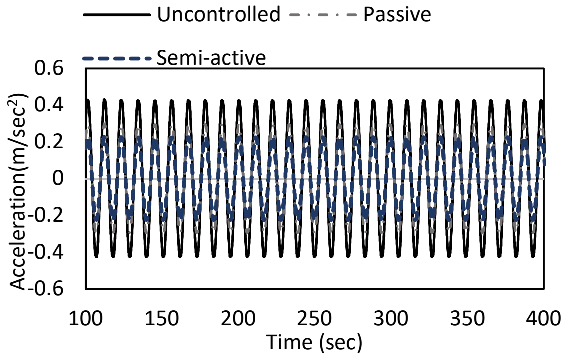
3.2.1. Stability of controller:

Fig. 8 is showing the phase plots of the controlled surge response for regular (extreme) wave. The elliptical nature of the phase plots ensures that the platform is stable and the response is periodic in nature.

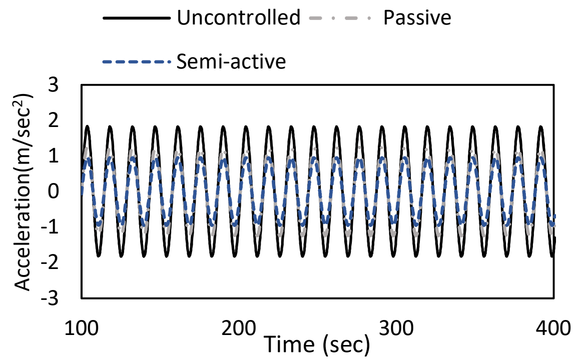


(b)

Fig. 6 Time-history variation of top deck displacement subjected to (a) regular operating, and (b) regular extreme wave load



(a)



(b)

Fig. 7 Time-history variation of top deck acceleration subjected to (a) regular operating, and (b) regular extreme wave load

Table 6: Absolute maximum values deck displacement, deck acceleration, control forces of MR damper subjected to environmental loads

Forces	Displacement (m)			Acceleration (m/sec^2)			F (ton)
	UC	P	SA	UC	P	SA	
Operating	2.06	1.76	1.35	0.42	0.29	0.24	1.69
Extreme	15.15	12.21	9.43	1.73	1.17	0.90	10.25

Note: UC: Uncontrolled; P: Passive control; SA: semi-active control; F: control force of MR damper

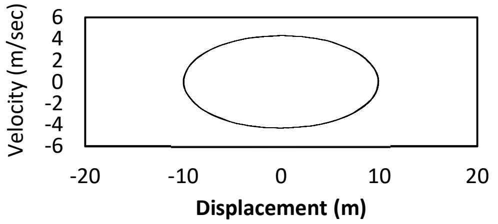


Fig. 8 Phase plots of controlled surge response of the TLP for regular extreme wave load

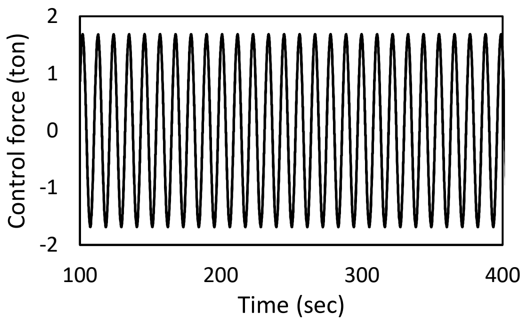


Fig. 9 Time-history variation of control force.

3.2.2. Performance of magneto-rheological damper:

A 20 -ton capacity MR damper is used as the variable dampening device of SATMD, to effectively mitigate the structural vibrations of the TLP and the installation layout is shown in Fig. 3. The forces generated by the MR damper for the semi-active control scheme are shown in Tables 6. The maximum control force generated by MR damper for semi-active control scheme is 10.25 ton when subjected to regular extreme wave. Higher control force is required when the TLP is subjected to the extreme loading condition. Time history analysis of control forces generated by MR damper for regular operating wave are depicted in Fig. 9. A maximum of 2-amp current can be applied to the 20-ton MR damper. The MR damper with DB-GH control algorithm operates in an “on-off” mode, with the current switching between 0-amp to 2-amp.

4. Conclusions

A semi-active control system is proposed for buoyant offshore TLPs to mitigate the vibrations induced by regular wave loads. The DB-GH control algorithm with SATMD as the control device is used as the semi-active controller. For structural safety, displacement mitigation is essential and for the human easement, reduction of acceleration. Proposed semi-active control scheme, effectively reduces the deck displacement, and the acceleration, which are the main responses of interest. However, its performance is observed to be better for regular extreme wave excitations and less for regular operating wave forces. The control forces generated by the MR damper in regular wave loading conditions, are within the capacity of MR damper thus indicates that magnetic saturation of MR damper is never reached. A more elaborate study is required in future to investigate the feasibility of real-life applications including layout, design details, installation and maintenance of SATMD. Further investigations on vibration control also need to be carried out by doing a three-dimensional modelling of the TLP and introducing the bi-directional and torsional vibrations and their interactions which may lead to a new pattern of fatigue failure.

Disclosures

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