DECENTRALIZED SLIDING MODE CONTROL OF OFFSHORE JACKET PLATFORM SUBJECTED TO EARTHQUAKE EXCITATIONS

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Abstract

A semi active control algorithm, using MR dampers, is developed for reduction of responses of offshore jacket platforms induced by earthquake ground motions and the responses are obtained for both nonlinear and linearized drag forces. The MR dampers are placed at different levels of the jacket structure and the coupled structure-damper system is modelled in Simulink. Decentralized Sliding mode controllers are designed to drive the response trajectories into the sliding surfaces and the command voltage to the MR dampers are generated with the help of clipped-optimal control algorithms. The results of the numerical simulations show that the designed semi active sliding mode controller is effective in reducing the structural vibrations caused by earthquake ground motions. As a result of linearization of the drag force, the effectiveness of the controllers is reduced and responses obtained are conservative in nature, i.e., increase in controlled responses are more when linearized drag force is considered. The control system is found to be stable and robust; however, the positions and the number of MR dampers have quite significant impact on the performance of the controller.

Keywords: Clipped optimal control; Magnetorhelogical damper; Sliding mode control; offshore jacket platform; Earthquake

1. Introduction

The offshore structures [1], especially the oil and gas production platforms, play a very important role in the present day world economy. To prevent any structural damage, the vibration of these platforms, under dynamic external loads, should be controlled to a desired level. Studies on vibration control of offshore jacket platforms using passive methods [2] and active control techniques [3-4] have been reported in literature. But a passive control system may be confined by the environmental incongruencies and the large cost, and the limitation of the active control systems are the non availability of precious deck space for housing the control system and high requirement of power and maintenance. Semi active control algorithms have been considered for vibration mitigation of jacket platforms by some researchers [5-7]. Located in hostile ocean environments, the offshore jacket platforms are exposed to external disturbances [8] such as winds and earthquakes, along with self-excited nonlinear wave forces. Eventually these external disturbances lead to large oscillations of the system, thus affecting the operation and comfort of crew on the offshore platforms. Among these, a strong earthquake ground motion can have a disastrous effect and can cause severe damage to these types of structures. Approximately 100 offshore platforms have been installed in seismically active regions of the world's oceans. However, most of the control schemes reported in literature have done more work on wave excitation [6-10], and number of studies where seismic excitations were considered, is confined. Among these researches also, most have used passive control devices [11-16] and limited work has been done using semi active controllers [17-20]. Studies were done on the effect of H_2/LQG algorithm in Sirri jacket seismic vibration control under Kobe earthquake.

It is, however difficult to develop the mathematical model of the structure- controller system accurately in case of real structures, due to the parameter uncertainties involved in the process. This problem is even more critical for offshore jacket platform, considered in the study because it involves the non-linear dynamics of the MR dampers and the interaction between water and structure. A control algorithm, which can accommodate uncertainty and imprecision, compared to all the other algorithms mentioned so far due to its inherent robustness and ability to cope with the parameter uncertainties and imprecision, is the sliding mode control algorithm. To the best of the authors' knowledge, there is no result reported in the published literature on sliding mode control for vibration control of offshore platforms subjected to earthquake excitations.

Developing a semi active control scheme to attenuate the seismic excitations of offshore jacket structure and investigating the influence of linearization of the drag force on the effectiveness of this controller are the motivations of this study. In the present work, numerical simulations of offshore jacket platform, subjected to real earthquake ground motion, is carried out and a semi active sliding mode controller is developed in order to reduce the seismically induced vibrations. MR dampers are stationed at different positions and the command voltage to these dampers is monitored through the Clipped Optimal algorithm.

2. Formulation

2.1Dynamic model of offshore steel jacket platform

The jacket platform is modelled in SimuLink, considering water-structure interaction. The equation of motion for an offshore jacket platform, subjected to seismic excitations, can be written [21],

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=HU(t)+\eta\ddot{x}_g+f \quad (1)$$

$$\text{where, } f = -K_d\left(\{\dot{x}\}+[1]\dot{x}_g\right)\cdot\left|\{\dot{x}\}+[1]\dot{x}_g\right| \quad (2)$$

$$M=M_s+M_a,\ M_a=\rho\ (C_I-1)\ B,\quad K_d=\rho\ C_D A \quad (3)$$

where $\boldsymbol{M}_a$, $\boldsymbol{M}_s$, $\boldsymbol{C}$, $\boldsymbol{K}$ are the added mass, the jacket platform mass, damping, and stiffness matrices, respectively; $\boldsymbol{\rho}$**,** $\boldsymbol{C_I}$**,** $\boldsymbol{C_D}$, $\boldsymbol{A}$ and $\boldsymbol{B}$ are the sea water density, inertia coefficient, drag coefficient, area and volume matrices. The dot operator denotes element-wise multiplication between two vectors. **U(t)** is an r-vector consisting of r control forces; and $\boldsymbol{\eta}$ is an *n-vector* denoting the influence of the earthquake excitation. **H** is a $(n \times r)$ matrix, denoting the location of r controllers. In this case, the effect of the water-structure interaction can be considered as a series of added masses and absolute velocity dependent nonlinear dashpots as shown in [Fig (1)].

2.2. Modelling of MR damper

The design of MR damper is done using Bouc-Wen model [22-23]. The MR Damper model consists of a viscous damper, tied with original Bouc-wen model in series, and a spring, which works in parallel with the whole system.

$$\alpha=\alpha(u)= \alpha_a+ \alpha_b u \quad (4)$$

$$C_1= C_1\ (u) = C_{1a}+ C_{1b}u \quad (5)$$

$$C_0= C_0\ (u) = C_{0a}+ C_{0b}u \quad (6)$$

where,$\mathbf{C_0}$=viscous damping at large velocities; $\mathbf{C_1}$=viscous damping for force roll-off at low velocities. α and η are other parameters that refer to the internal state , and determine its coupling with the force and its evolution. u is given as the output of a first-order filter obtained by

$$\dot{u}=-\eta(u-v) \quad (7)$$

where v is the commanded voltage sent to the current driver. Eqn. 12 is necessary to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper.

2.3 Sliding mode control algorithm

It is a control method [24] which alters the dynamics of a system by application of discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behaviour. The main objective of sliding mode controllers is to design controllers to drive the response trajectory onto the sliding surface (or switching surface), while at the same time, maintaining stable motion on the sliding surface. In the design of the sliding surface, the external excitation is neglected but is taken into account later in the actual controller design.

The design of sliding surface consists of two steps. At first, a sliding surface is designed using an LQR algorithm. The purpose of constructing the sliding surface or switching surface is to restrict the system to the switching surface, thus producing a desired behaviour of the system. The sliding surface 'S' is given by [24]

$$S=PZ=0 \tag{8}$$

The design of the sliding surface S = PZ = 0, consists of obtaining the sliding matrix, $\overline{\mathbf{P}}$, through the minimization of the performance index, $J = \int_0^\infty [Z^T QZ]dt$, constrained by the linear form of state space equation. In the expression of the cost function, Q is a positive semi-definite weighing matrix.

For the existence of a sliding mode on the switching surface, the state velocity vectors should be directed towards the surface, i.e., the system must be stable on the switching surface. Therefore, there must be a Lyapunov function V in the neighbourhood of the switching surface. The purpose of the controller design is to drive the response trajectory onto the sliding surface S= 0.

Using the control law proposed by researchers [16], $U=G-\overline{\delta}\lambda^T$, in which $\overline{\delta}$ is sliding margin matrix and taking it as manual input, we obtain the expression for the control force regulated by both the structural response and the earthquake excitation.

Design and implementation of centralized controllers for large structures like this, generally involve taking into consideration the huge cost, the complexity of dynamic models and the high number of variables .Therefore, to overcome such problems, a decentralized controller has been proposed. In this controller, the control system is decomposed into a number of interconnected subsystems; for each one, a local sub-controller is designed independently using only local subsystem's state information. The obtained decentralized controllers are also reliable in the sense that when some local controllers are out of order, the rest of the system can still be in operation.

A clipped-optimal algorithm is incorporated so that the MR damper is commanded to generate approximately the desired optimal control force f_c.

3. Numerical Simulation

To demonstrate the effectiveness of the sliding mode control algorithm in reducing the vibrations induced by earthquake ground motion, a steel jacket platform is taken from literature [13]. The platform considered is a four leg platform with the same properties in both directions and all the elements are assumed to remain elastic under the earthquake excitation. The density of water is 1000 kg/m^3, density of steel is 7800 kg/m^3, the drag and inertia coefficients are 0.7 and 2, respectively, and the deck mass of the platform is 1000 ton. The platform is modelled [18] as a five degree of freedom system (Fig. 1).

Stiffness and mass proportional damping matrix is considered, according to the Rayleigh damping. A value of 2% is considered as the damping ratio of all modes in air [25]. The jacket platform is modelled in SimuLink, Matlab, (references) taking in consideration the water-structure interaction. The structure is subjected to the San Fernando 1971 earthquake ground excitation scaled to a PGA of

0.3g and time history analysis are carried out.. The effectiveness of the sliding mode controller is studied by comparing the uncontrolled and controlled responses of the platform.

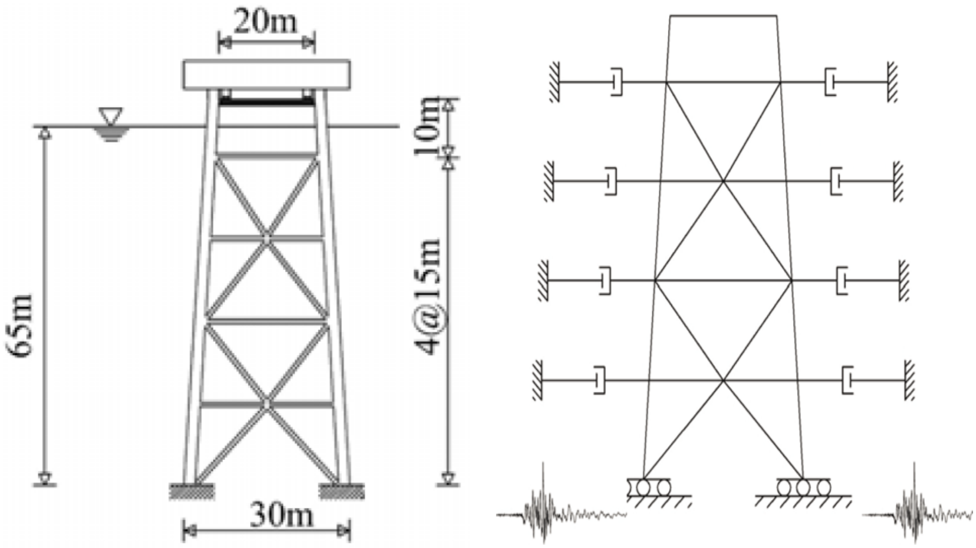


Fig. 1(a) – Steel jacket platform & (b) – Water structure interaction of the steel jacket platform

The nonlinear equation of motion of the jacket platform subjected to earthquake excitation Eqn. (1) is quite often converted into a linear one for simplification. This is achieved by linearizing the non-linear term in the expression of the drag force. The effect of this linearization, in terms of the response of the structure and the performance of the controller, has been studied. The linearization [26] procedure is as mentioned below. The non-linear drag force in Eqn. (2) is linearized in the following way.

$$\left|\{\dot{x}\}+[1]\dot{x}_g\right| \cong \sqrt{\frac{8}{\pi}}\sigma_{\dot{r}\dot{r}} \tag{9}$$

where $\sigma_{\dot{r}\dot{r}}$ denotes the standard deviation of structural velocity relative to water particles.

Using the linearization, the equation of an offshore structure can be rewritten as

$$M\ddot{x}(t)+C_0\dot{x}(t)+Kx(t)=G\dot{x}_g+\eta\ddot{x}_g+HU(t) \tag{10a}$$

where,

$$C_0 = C + K_a \tag{10b}$$

$$G=-K_a[1] \tag{10c}$$

$$Ka=\sqrt{\frac{8}{\pi}}\sigma_{\dot{r}\dot{r}}K_d \tag{10d}$$

As is evident Eqn. 20(a), one component of the drag force, arising due to water-structure interaction, acts like absolute-velocity dependent nonlinear dashpots (Fig. 14), thus reducing the structural response. The other part gets added to the external seismic excitation. Apart from the analysis of the structure with the linearized drag force, the behaviour of the jacket platform is also investigated without the drag force.

The MR dampers are installed at the different levels of the offshore jacket platform. The operation of each damper is governed by designed sliding mode algorithm, and a sliding surface is generated for each damper. For full-state feedback, the LQR method is used for the design of the sliding surface with a diagonal weighting matrix Q, as follows:

$$Q = \text{diag}(10,100,100,100,100000,1,1,1,1,1) \quad (11)$$

The Performance Index J minimized by solving the Riccati equation.

4. Results & Discussions

4.1 Effect of number and position of MR dampers

To show the performance of the SMC, a steel jacket platform, having five degree of freedom,is taken from literature [18] as shown in Fig. (2). All elements of this structure are assumed to remain elastic under the action of the earthquake ground motion considered. In order to investigate the effect of the number of MR dampers and their different arrangements on the performance of the controller, the following cases have been considered:

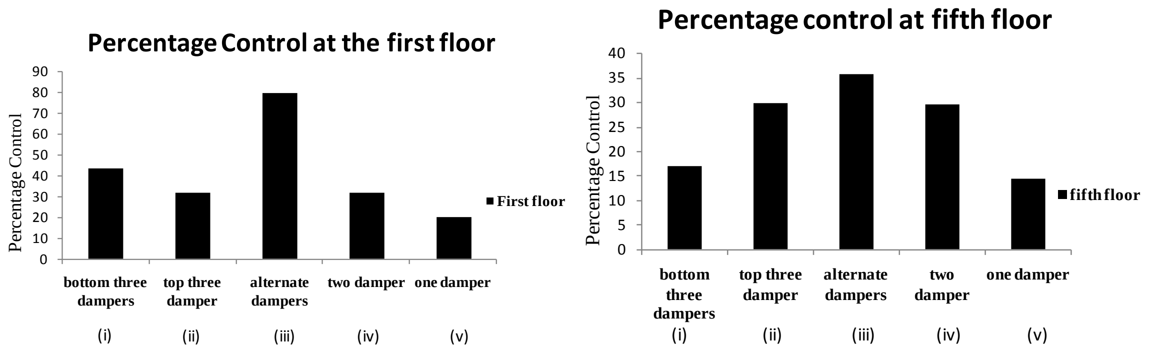
i. Three MR dampers placed in the bottom three storeys,

ii. Three MR dampers positioned in the top three storeys,

iii. Three MR dampers placed in the alternate storeys,

iv. Two MR dampers installed in the fourth and fifth storeys, and

v. A Single MR damper installed in the fifth storey.



(a) (b)

Fig. 2 –Percentage control of displacements at (a) fifth floor and (b) first floor of the offshore jacket structure subjected to San Fernando earthquake ground motion.

It is observed that the reduction of responses depend on the placement and the number of MR dampers. From Fig 2(a) and Fig 2(b), positioning of the MR dampers in the alternate storeys could have been concluded to be the best option, based upon the percentage control of the storey responses. However, positioning the MR dampers near the base of the jacket structure, located at the ocean bed, also results in greater reduction of responses. But, from the point of view of installation, operation, maintenance and cost, these positions are not very much practically feasible options. The percentage control for cases (iii) and (iv) in the fifth storey differs by about 6%.This difference is comparatively very less, when cost and difficulties of placement of dampers in the bottom storeys are incurred. So, the placement of MR dampers in the top two stories of the jacket structure (case iv) can be considered to be an optimum solution. All the results discussed henceforth, are obtained by placing the MR dampers in the top two stories of the jacket platform.

4.2 Performance evaluation of controller

A performance evaluation of the controller is done by comparison of response reduction for passive and semi active controllers in Fig. (3). In the first case a passive controlling device, by applying a constant 0V to the MR damper. The percentage reductions of responses for the passive and semi active cases are

6.7 % and 26.9 % for displacement, 4.0% and 23.8% for velocity and 2.6% and 17% for acceleration. Thus, the semi active control algorithm enhances the performance of the controller over the passive case by 20.2%, 19.8% and 14.4%, respectively, for three response quantities.

Fig. (4) shows the comparison of the uncontrolled and controlled time histories of the acceleration and RMS displacement, velocity and acceleration of the fifth floor of the jacket structure under the same earthquake excitation. From the table, one can see that the sliding mode control scheme can effectively reduce the responses of the offshore structure under the earthquake ground motion considered.

The reduction in response quantities by the is more in case of the displacements, ranging from 30-75%.The acceleration and RMS displacement control values are in the ranges of 10- 50 % and 15-65%, respectively. With the present position of the MR dampers in top two storeys, it is seen that the maximum control of responses take place in the middle storeys, i.e., in the 2nd and 5th storeys

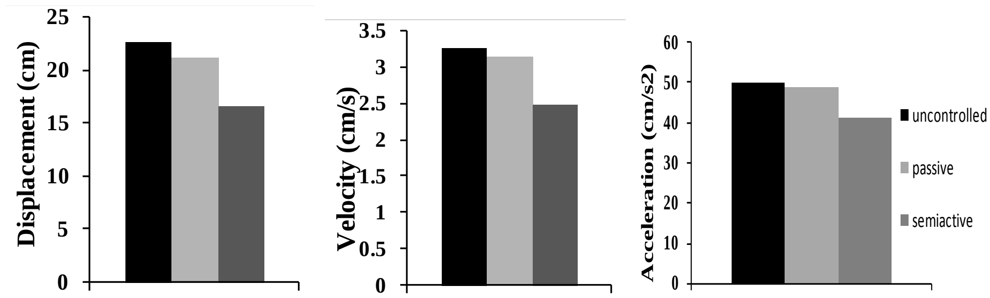
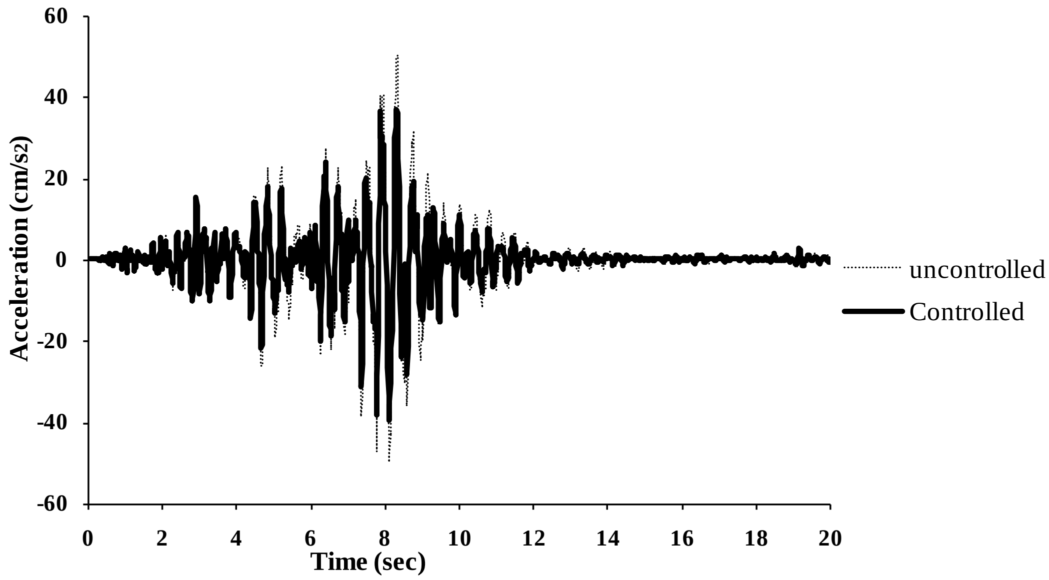
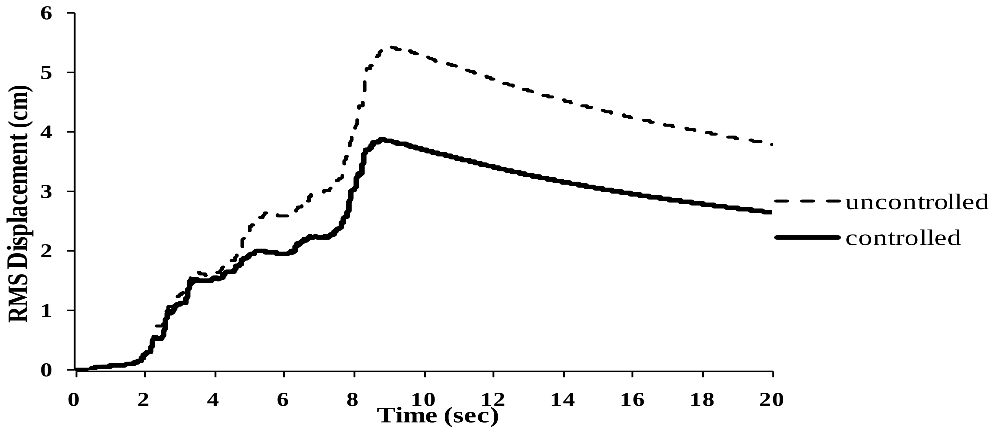


Fig. 3 – Peak displacement, velocity and acceleration of the top storey for uncontrolled, passive controlled and the semi active controlled cases



(a)



(b)

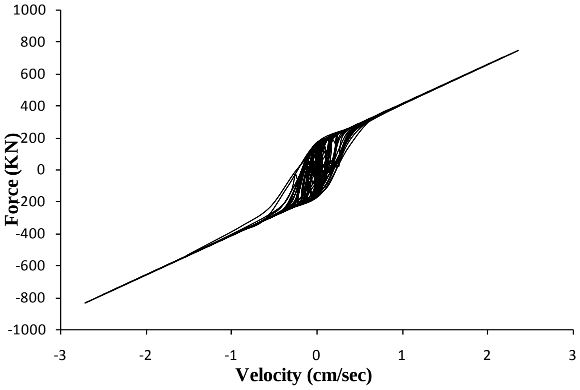
Fig. 4 – Top floor responses of the jacket platform under San Fernando earthquake excitation: (a) absolute acceleration and (b) RMS displacement

Table 1– Response quantities and the corresponding percentage control of jacket structure subjected to San Fernando ground motion

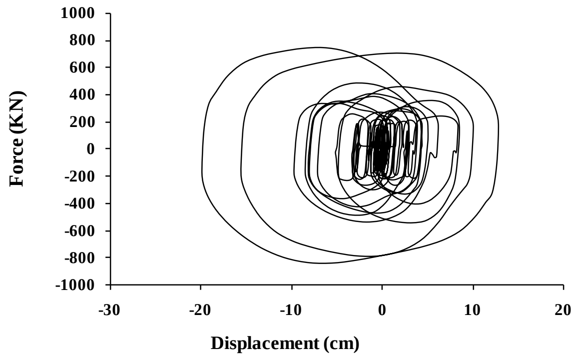
Jacket Storeys	Displacement (cm)		Percentage Reduction	Acceleration (cm/s^2)		Percentage Reduction	RMS Displacement (cm)		Percentage Reduction
	UC	C		UC	C		UC	C	
Fifth	23.4	16.5	31.4	50.6	41.3	18.4	5.4	4.1	25.6
Fourth	24	11.4	52.5	29	22.3	24.5	11.2	4.1	64.7

4.3 MR Dampers

The time history of the command voltage applied to the MR damper at the fifth floor, regulated by the clipped optimal algorithm. A maximum of 10 V is applied to the 20 ton MR damper. The algorithm operates in an ‘on-off’ mode, with the voltage switching between 0V and 10V. Fig. 5 shows the response plot of fifth storey MR damper. It can be observed that the imposed cycles trace a suitable path and dissipates noticeable amount of energy induced by the earthquake ground motion, and significantly reduce the share of structural elements in energy absorption.



(a)



(b)

Fig. 5 – Controlled responses for the fifth storey MR damper : (a) force versus velocity and (b) force versus displacement.

4.4. Stability

The variations of the sliding surface S(t) for the fifth floor controller is illustrated in Fig. (6). It can be seen that the sliding functions S(t) are not equal to 0, but the average values of the sliding functions S(t) tend to zero. Theoretically, even though the sliding function should be zero, i.e., S(t) = 0. However, due to the external disturbances (seismic excitation), there always exist deviations in the sliding function from the sliding surface and the sliding mode controller effectively reduces these deviations by driving the trajectory towards the sliding surface.

In Fig. 8, the phase planes for the top storey of the jacket structure, controlled by the SMC, are shown. From the resultant motion on the sliding surface, or the phase plane trajectory plots, it is observed that each of the trajectories slides towards its respective sliding surface at S=0 or the equilibrium point and hence, it can be concluded that the closed-loop system is stable. During the reaching phase the system response is sensitive to seismic excitations.

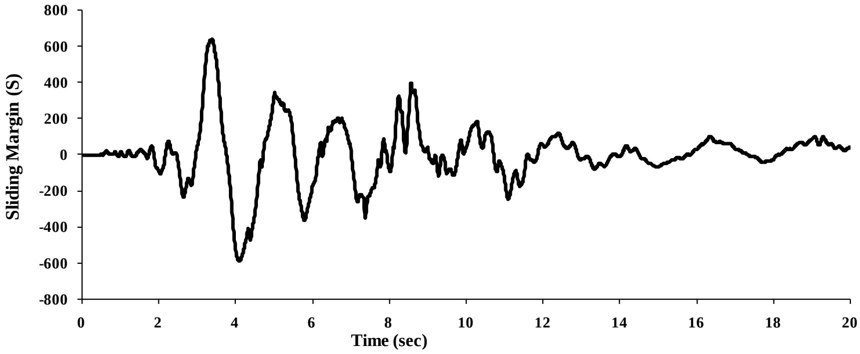
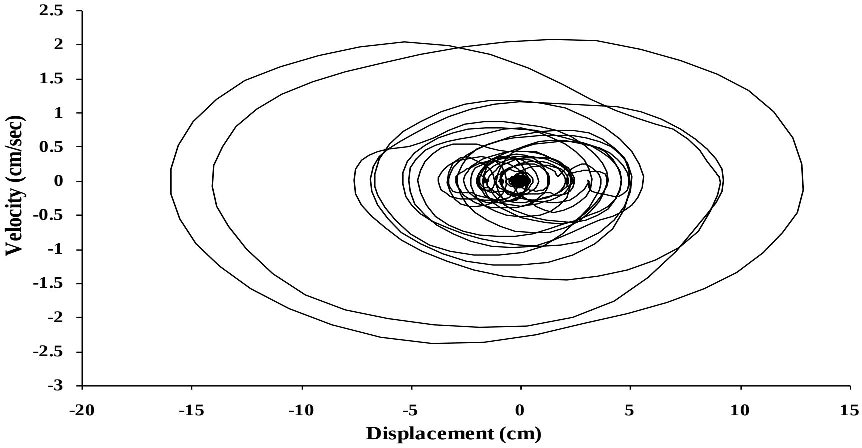


Fig 6: Variation of the sliding surfaces for the sliding mode controllers of fifth storey.



(a)

Fig. 7 – Phase plane plots (controlled displacement versus velocity) of fifth floor

4.5 Effect of linearization of drag force

It is evident from Fig. 11 that there is an increase in response when the structure is analyzed without the drag force and also when the drag force is linearized, as compared to that of nonlinear drag force. The removal of drag force has the same impact on the structure as that of removal of dampers from the structure, thus increasing the response of the structure. The figures show that, out of the two cases, the increase in response is more for the linearized case.

The response quantities shown in Tables 1 & 2 are compared and it can be concluded that both the controlled and uncontrolled absolute maximum values of all these response quantities, namely, displacement, velocity, acceleration and rms displacement, at each storey level increase when the structure is analyzed using linearized drag force. However, in most of the cases, this increase due to linearization is more for the controlled responses of the jacket platform. The linearization technique gives very conservative results, i.e., increase in controlled responses are more when linearized drag force is considered. The overestimation was being considered maximum for displacement and velocity and minimum for acceleration. As a result of this, when the performance of the controller, considering nonlinear drag and considering linearized drag, are compared, the results indicate decrease in effectiveness of controllers (in terms of percentage control) in the linearized case for almost all the responses. The performance of the controller shows maximum deterioration for displacement and velocity (even almost 100% decreases in some cases) and minimum deterioration for acceleration.

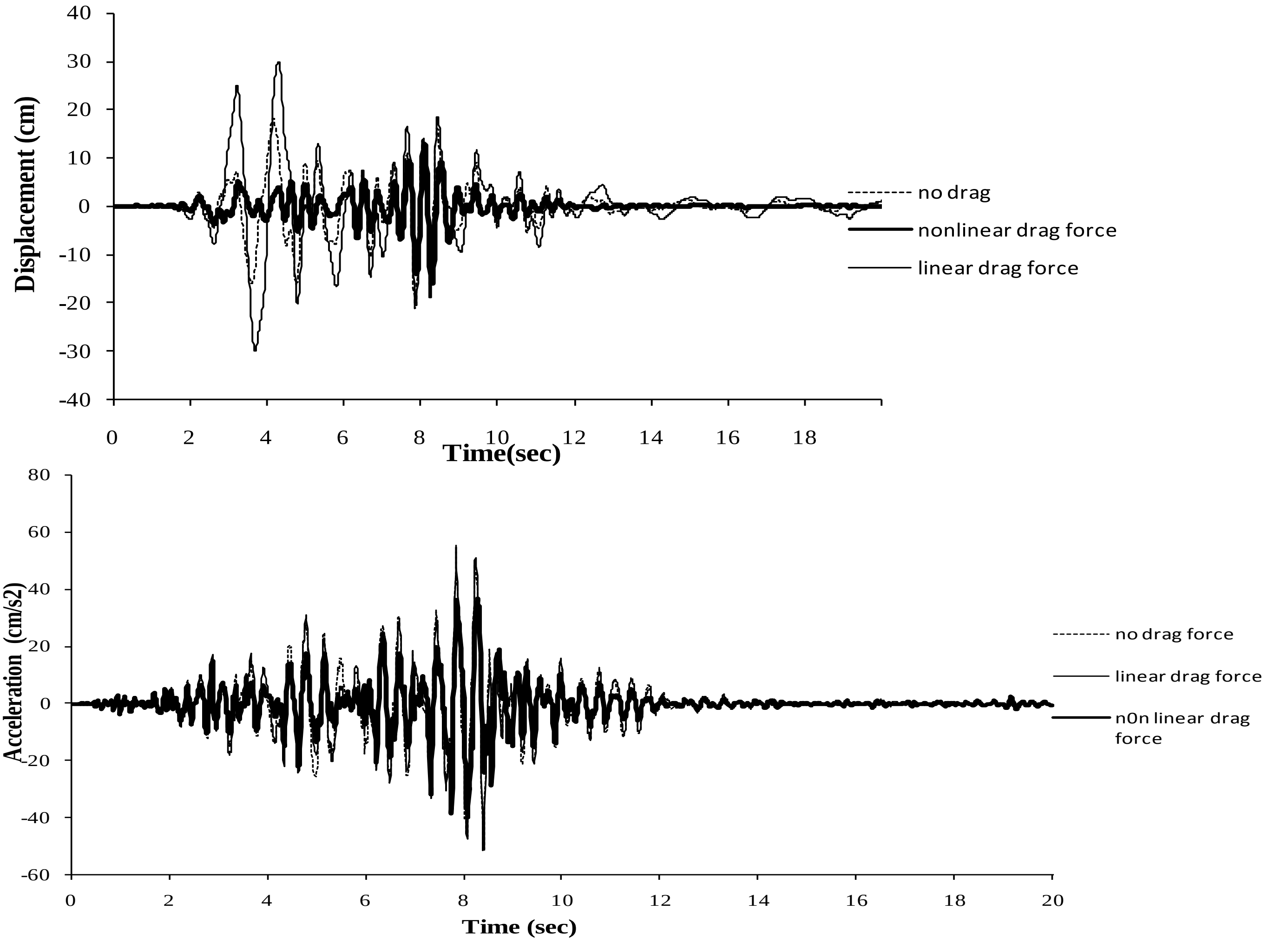


Fig. 9 – Effect of drag force on the control of fifth floor responses: (a) displacement and (b) acceleration.

Table 2– Absolute maximum values of response quantities and percentage control at different storeys with linearized drag force.

Jacket Storeys	Displacement (cm)		Percentage Reduction	Acceleration (cm/s^2)		Percentage Reduction	RMS Displacement (cm)		Percentage Reduction
	UC	C		UC	C		UC	C	
Fifth	41.3	29.9	27.53	63.2	54.7	13.4	16.9	12.2	28.1
Fourth	209	89.1	57.34	50.8	37.7	25.7	80.7	32.3	59.9

4. Conclusions

A sliding mode control algorithm is designed to mitigate the seismically induced vibrations in an offshore jacket platform. The effectiveness of the controller is studied by carrying out numerical simulation of a platform taken from literature [14] and the responses are obtained for both nonlinear and linearized drag forces. MR dampers are used and the command voltages to the dampers are regulated through clipped optimal algorithm. The major conclusions of the present study are summarized below:
1. The sliding mode controller using MR dampers is able to effectively reduce the responses of the seismically excited offshore jacket platform.
2. The number of MR dampers and their placements has significant effect on the performance of the controller in terms of the percentage reduction of responses. In the present study, the placement of MR dampers in the top two stories of the jacket structure can be considered to be an optimum solution
3. Theoretically, even though the sliding function should be zero, it can be seen that the sliding functions S (t) are not equal to 0, but the average values of the sliding functions S (t) tend to zero. Due to the external disturbances (seismic excitation), there always exist the deviations in the sliding function from the sliding surface and the sliding mode controller effectively reduces these deviations by driving the trajectory towards the sliding surface.
4. From the resultant motion on the sliding surface, or the phase plane trajectory plots, it is observed that each of the trajectories slides towards its respective sliding surface at S=0 or the equilibrium point and hence, it can be concluded that the closed-loop system is stable. During the reaching phase, however, period, the system response is sensitive to seismic excitations.
5. Imposed hysteric cycles trace a suitable path and dissipates noticeable amount of energy induced by the earthquake ground motion, and significantly reduce the share of structural elements in energy absorption significantly.
6. The effect of nonlinear drag and linearized drag forces in the efficiency of the controller are compared. The results indicate decrease in effectiveness of controllers (in terms of percentage control) due to linearization for almost all the responses.
7. The performance of the controller shows maximum deterioration for displacement and velocity (even almost 100% decreases in some cases) and minimum deterioration for acceleration. This is because of the increase in controlled displacement & velocity values, as mentioned before, due to drag force linearization is more than the corresponding increase in case of the uncontrolled values.
8. As far as the controlled responses are concerned, the linearization technique gives conservative results i.e., controlled responses are more when linearized drag force is considered. The overestimation is maximum for displacement and velocity and, minimum for acceleration.

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