Semi-active Seismic Vibration Control Offshore Jacket Platforms

Minaruddin Khan and Diptesh Das

Abstract A semi-active control scheme for the vibration control of offshore steel jacket platforms is developed. Decentralized sliding mode control (SMC) algorithm is adopted for applying the control force to the structure with the help of Magnetorheological (MR) damper for alleviating the earthquake-induced vibrations. SMC method is used due to its robustness against the parametric variations of the structures. The command voltage to the MR dampers is regulated through the clipped-optimal algorithm. A steel jacket platform, available in the literature, is modelled in MATLAB as an example to investigate the dynamic responses under the environmental loads. The earthquakes ground motions, scaled to 0.3 g PGA, considered in the present study are the El Centro (1940), Northridge (1994), San Fernando (1971) and Chichi (1999). Results indicate that sliding mode controller is able to reduce the responses of the offshore jacket platform significantly, subjected to different earthquake loads. It is observed that the positions and the number of MR dampers affect the performance of the controller to a great extend in the offshore jacket platforms. The control algorithm is stable against the variations and uncertainties in structural parameters.

Keywords Offshore jacket platform · Semi-active control · Decentralized sliding mode control · MR damper · Earthquake loads

1 Introduction

Recently offshore platforms play a key factor for the growth of industry, as the platforms are mainly used to extract, drill and store oil and natural gases. The fixed steel jacket platform is generally slender, flexible in nature, and installed in the water at different required depths. The environment surrounding the structures is harsh and hostile and make complexity for the erection and difficulties for employment of control device. There are some major environmental loads act to the structures during

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M. Khan (✉) · D. Das
Department of Civil Engineering, National Institute Technology, Durgapur 713209, India

D. Das
e-mail: diptesh.das@ce.nitdgp.ac.in

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their lifetime, which are nonlinear and dynamic in nature. The vibrations due to the major dynamic forces induced by wave [1–3] and earthquake [4–6] and to some lesser extent current [7] and ice [8] have the substantial affect to the structure and cause large deformation and fatigue damage. Therefore, for the structural productivity, safety and for the smooth and continuous operation, the amplitude of deformation due to the vibrations should be a certain limit. During the last few decades, researchers have been given afford to mitigate the vibrations using different isolator. State-of-the-arts [9] reflect that the general trend for the vibration control system go along from passive to active and towards semi-active and hybrid as because these controller utilized the advantages of both passive active control system.

Literature survey [4, 5, 10–12] show that the passive isolators, mainly, Tuned Liquid Dampers (TLD), Viscous Dampers, Friction Damper Devices (FDD), Tuned Liquid Column-Gas Dampers (TLCGD) and Hydrodynamic Buoyant Mass Dampers are used to attenuate the vibrations of the platforms. Passive controllers have the drawback of their inadaptability to the changes in structural properties and loading conditions. There are many active control schemes [6, 13, 14] has been performed to overcome the shortcomings the passive dampers for the mitigation of the structural vibrations. However, complexity arise for the implementation of active control scheme in the platform due to their sensibility and disruption during power failure. Moreover, modelling error, time-delay and limited frequency bandwidth are the disadvantages for the execution of the active controller.

Semi-active control scheme [15, 16] is an excellent approach for the vibration control as these controllers utilized the benefits of both passive and active control system. The major control algorithms, clipped optimal control algorithm [14], Bang-Bang control algorithm [17], LQG algorithm [30], linear quadratic control algorithm [18] and non-resonance control algorithm [19], are used for implementation of semi-active control schemes. There are lot of assumptions and parameter variations taken under consideration to develop a mathematical model for the water-structure controller and even it is more challenging for random earthquake excitations. Sliding mode control algorithm [20] works more effectively under the complex environment for its implicit robustness and efficiency to cope up with parameter variations and imprecisions. MR damper has considered as a semi-active control device for its excellence fluid properties. In presence of magnetic field, the MR fluid changes its state from fluid to semi solid within millisecond and provides sufficient yield strength to the platform to alleviate the vibrations against external excitations [21]. For controlling large-scale civil structures, decentralized control strategy have better efficiency and robustness as compared to the conventional centralized control approach [22].

The objective of the present work to develop a robust control scheme to work effectively under the adverse environmental condition and capable to reduce structural responses to be a satisfactory level. A semi-active control scheme with MR damper device is proposed to mitigate the vibrations subjected to seismic ground motions, namely, El Centro (1940), Northridge (1994), San Fernando (1971) and Chichi (1999). Decentralized SMC algorithm is developed to supply the control force to the MR dampers due to its inherent robustness with parameter variations and uncertainties. For the supply of the required command voltage to MR dampers, Clipped Optimal algorithm is used. The proposed control scheme fulfill the objective and motivation of the present study in terms response reduction in the deck of the platform. A parametric study on the optimum number and place of installation of MR dampers is carried out to get best results in terms of response reduction of the platform. Results show that control scheme is effective and bear significant contributions toward structural stability and integrity.

2 Theoretical Formulation

Presence of water around the offshore structures make it differences with the conventional civil structures. Therefore, water-structural interaction is also an important factor has to be taken under consideration for the control of the vibrations. The drag force due to the motion of the structures in the water act as dampers and enhance structural stability. The equation of motion of the structures subjected to seismic ground motion, written as [11]

$$\mathrm{M}\ddot{\mathrm{x}}(\mathrm{t}) + \mathbf{C}\dot{\mathrm{x}}(\mathrm{t}) + \mathbf{K}\mathrm{x}(\mathrm{t}) = \mathbf{H}\mathrm{U}(\mathrm{t}) + \eta\ddot{\mathrm{x}}_g(t) + \mathrm{f} \tag{1}$$

$$\text{where,}\quad \mathbf{f} = -\mathbf{K}_{\mathrm{d}}\left(\{\dot{\mathrm{x}}\} + [1]\dot{\mathrm{x}}_{\mathrm{g}}\right)\left|\{\dot{\mathrm{x}}\} + [1]\dot{\mathrm{x}}_{\mathrm{g}}\right| \tag{2}$$

$$\mathbf{M} = \mathbf{M}_{\mathrm{s}} + \mathbf{M}_{\mathrm{a}}, \mathbf{M}_{\mathrm{a}} = \rho(\mathrm{C}_1 - 1)\mathbf{B}, \mathbf{K}_{\mathrm{d}} = \rho\mathrm{C}_{\mathrm{D}}\mathrm{A} \tag{3}$$

In Eq. 1 the term f reflects the effect water-structure interaction, which is considered as the absolute velocity dependent nonlinear dashpots, explain in Eq. 2. $\mathbf{M}_{\mathrm{a}}$ $\mathbf{M}_{\mathrm{s}}$, **C** and **K** are the added mass, the jacket platform mass, damping, and stiffness matrices, respectively; ρ, C_1, C_{D}, **A** and **B** are the sea water density, inertia coefficient, drag coefficient, area and volume matrices; $\ddot{\mathrm{x}}_{\mathrm{g}}$ is earthquake ground motion; **U**(t) is vector to apply control forces; and η is an n-vector denoting the influence of the earthquake excitation. The placement of the dampers are incorporate with the denoting matrix (**H**)**.** The formulation of damping matrix is based on Rayleigh damping concept, which is proportional to mass and stiffness matrix [23].

2.1 Modelling of MR Damper

MR damper has excellence property that in presence of electrical field, the MR fluid change it's state from semi-liquid to solid within millisecond. To describe the dynamic properties of MR Dampers, a numerical Bouc-Wen model is considered. It is highly versatile and simple mechanical model consisting of Bouc-Wen element in parallel with a viscous damper, used for denominating hysteretic behavior of the MR damper. The numerical equations incorporating with Bouc-Wen model to produce force in the MR dampers [21] are given as follows

$$f = c_o\dot{x} + \alpha z \tag{7}$$

$$\dot{z} = -\gamma|\dot{x}|z|\dot{z}|^{n-1} + \beta\dot{x}|\dot{z}| + A_m\dot{x} \tag{8}$$

z is the evolutionary variable important for the hysteretic loop which depends on the response; γ β, n, and A_m are carry their usual meanings. Two parameters α and c_o depends on the control input voltage u as follows:

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \tag{9}$$

$$c_o = c_o(u) = c_{oa} + c_{ob}u \tag{10}$$

The expression of control voltage is given as first-order filter dynamics equation induced in the system as follows:

$$\dot{u} = -\eta(u - v) \tag{11}$$

where, u is required voltage applied to the current driver, and η is the time constant of the first-order filter.

3 Methodology

A four legged, 70 m high steel jacket offshore platform available in literature Mousavi et al. [11] is taken to investigate the efficiency and usefulness of the proposed control scheme in terms of response reductions against seismic induced excitations. The platforms have same properties in the both directions and all the elements are under elastic limit. The density of water is 1000 kg/m^3, the density of steel is 7800 kg/m3, the drag and inertia coefficients are 0.7 and 2, respectively, and the deck mass of the platform is 1000 tons. Lumped mass model of the platform as five degree-of-freedom system mentioned in literature [11], and its mass M and stiffness K matrix are given below

$$K = 10^9 \times \begin{bmatrix} 1 & -0.444 & 0 & 0 & 0 \\ -0.444 & 0.819 & -0.375 & 0 & 0 \\ 0 & -0.375 & 0.661 & -0.286 & 0 \\ 0 & 0 & -0.286 & 0.353 & -0.067 \\ 0 & 0 & 0 & -0.067 & 0.067 \end{bmatrix} (\mathrm{N/m}),\ M = \begin{bmatrix} 157 & 0 & 0 & 0 & 0 \\ 0 & 154 & 0 & 0 & 0 \\ 0 & 0 & 151 & 0 & 0 \\ 0 & 0 & 0 & 137 & 0 \\ 0 & 0 & 0 & 0 & 1087 \end{bmatrix} \times 10^3\ \mathrm{kg}$$

The diagonal elements of the area (A_P) and volume (V_P) matrices of the structural [294, 289, 282, 202, 0] m^2 and [258, 253, 248, 177, 0] m^3, respectively. To formulate the Rayleigh damping matrix, a value of 2% is taken as the damping ratio of all modes in air [23]. MR damper is considered as an isolator in semi-active control system for its excellence properties of fluid. The value of the parameters for 100-ton capacity MR damper is adopted from [21]. The main motive of the sliding mode controller is to enter the structural responses into the sliding surface. The formulation of the sliding mode control algorithm is carried out according to the formulae given in literature [20]. The Clipped-Optimal algorithm proposed by Dyke [21] is used to govern the input voltage delivered to the MR damper. The study is carried out on the base of state space formulation in MATLAB Simulink. The time history responses, mainly, top deck displacement, top deck acceleration, and base shear are the major interest to reduce its amplitudes. The comparative study of controlled and uncontrolled of these responses are carried for the earthquake ground motions (0.3 g peak ground acceleration), namely, El Centro (1940), Northridge (1994), San Fernando (1971) and Chichi (1999) [11]. A parametric study on the optimum number and place of installation of MR dampers is carried out to get best results in terms of response reduction of the platform.

4 Importance Outcomes

To investigate the effectiveness of semi-active control scheme, a steel jacket platform is taken based on assumption that all elements of the structure remain elastic during the external excitation. Control of top deck displacement and acceleration is investigated for different arrangement of 100-ton capacity MR dampers placed in the offshore platform. Following arrangement have been considered to analysis the efficiency of the scheme for structural integrity.

1. Single MR damper placed in the fifth storey.
2. Two MR dampers placed in the four and fifth storeys.
3. Three MR dampers placed in the alternate storeys.
4. Four MR dampers placed in the top four storeys.
5. Five MR dampers placed all storey level.

Time histories responses of top deck displacement, acceleration and RMS value of displacement for both controlled and uncontrolled with different arrangement of MR dampers are shown in Figs. 1, 2 and 3 subjected to El ecntro (1940) ground motion.

Results indicate that positioning five MR dampers towards the storey is the best arrangement to get optimum response reduction. The top deck responses are effectively reduced with the increase of MR dampers. It may be noted that MR dampers are placed on five floors have slight greater reduction of responses other than four dampers are placed towards top four floors but, the position of MR damper near the base of the structure is not a feasible option to install due to requirement of high cost,

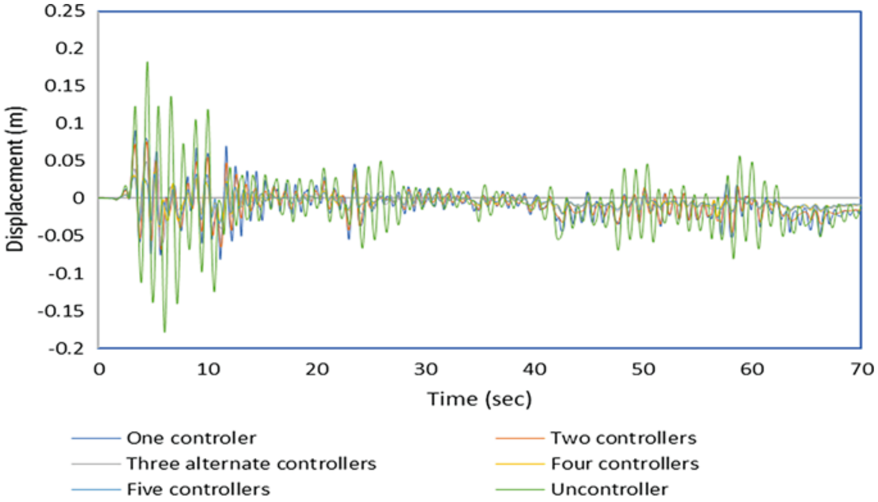

Fig. 1 Variation of top deck displacement with different arrangement of MR dampers subjected to El ecntro (1940)

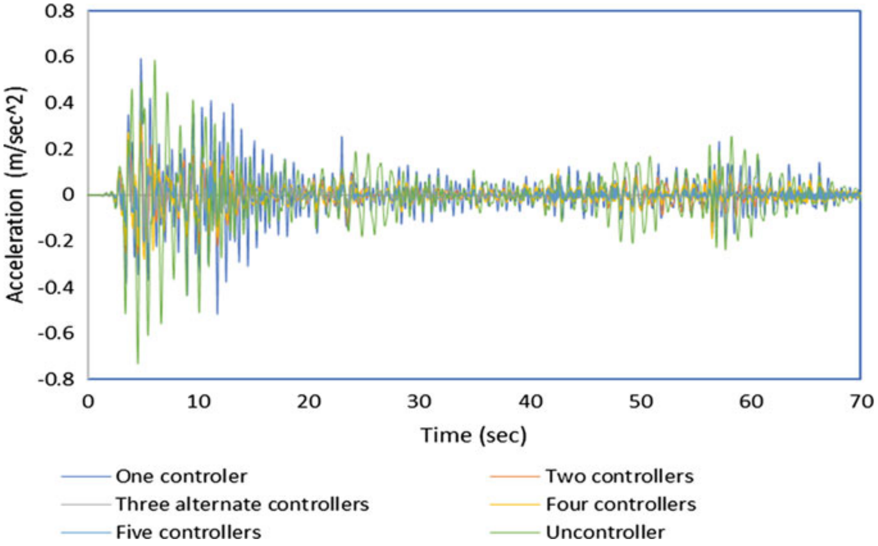

Fig. 2 Variation of top deck acceleration with different arrangement of MR dampers subjected to El ecntro (1940)

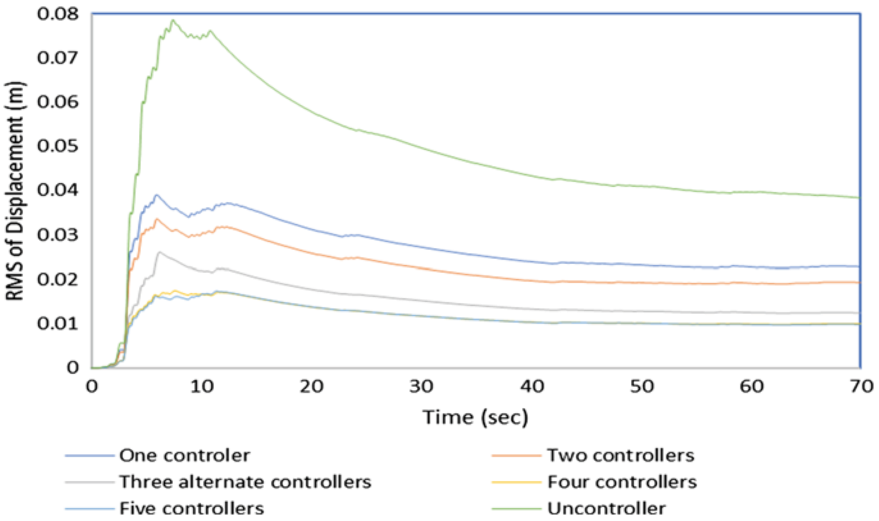

Fig. 3 Variation of top deck RMS value of displacement with different arrangement of MR dampers subjected to El ecntro (1940)

maintenance and operation. Controlled and Uncontrolled responses of displacement, acceleration, velocity and RMS values of displacement, and their corresponding percentage of reduction (%R) for various arrangement of MR dampers against El ecntro (1940) ground motion are shown in Table 1. Therefore, based on the results, four dampers placed on top four floors is taken as an optimum option to study the performance of the scheme against earthquake excitations. Table 2, also reflects similar trend in terms of top deck amplitude reduction for displacement, acceleration, 4th interstory drift and base shear against various earthquake motions. Reduction of base shear bears important for cost optimization; the proposed scheme reduces the base shear (Fig. 4) effectively, which implies less cost involvement for construction. The proposed scheme reduces the inter-storey drift (Fig. 5) and provide stability to some extent.

The effectiveness of the controller does not vary with the sling margin (Fig. 6), therefore, the controller is robust against the parameter uncertainties. As per theory, Sliding surface (S) should be zero but, Fig. 7 shows that response trajectory does not coincide with the sliding surface; this is due to presence of external distribution but the average values of the sliding function tend to be zero. The clipped control algorithm operates as an "on–off" mode, maximum 10 V supplied to the MR damper. The voltage operation, switch between 0 to 10 V to the 100 ton MR Dampers is shown in Fig. 8.

Table 1 Controlled (C) and Uncontrolled (UC) responses (RMS values of displacement) and corresponding percentage of reduction (%R) for El ecntro (1940)

			Displacement (cm)			Acceleration (cm)			Velocity (cm)			RMS displacement (cm)		
	EQ	DOF	UC	C	%R	UC	C	%R	UC	C	%R	UC	C	%R
El Centro31	Alternate	1	2.81	0.95	66.26	26.43	8.46	68.01	2.12	0.43	79.70	1.11	0.33	70.60
		2	5.77	1.78	69.21	50.25	15.48	69.19	4.37	0.87	80.15	2.26	0.62	72.58
		3	8.42	2.30	72.68	64.38	19.66	69.46	6.20	1.16	81.30	3.31	0.82	75.29
		4	10.58	1.97	81.33	82.55	15.60	81.10	7.28	0.95	86.92	3.31	0.73	77.85
		5	18.24	4.88	73.25	58.67	30.58	47.88	8.85	2.66	70.00	7.86	2.61	66.83
	One controller	1	2.81	1.06	62.28	26.43	11.39	56.92	2.12	0.84	60.52	1.11	0.40	64.20
		2	5.77	2.10	63.68	50.25	21.97	56.29	4.37	1.68	61.44	2.26	0.77	65.77
		3	8.42	2.87	65.85	64.38	29.04	54.90	6.20	2.26	63.59	3.31	1.04	68.68
		4	10.58	2.61	75.35	82.55	23.62	71.38	7.28	1.85	74.51	3.31	0.92	72.27
		5	18.24	9.05	50.41	58.67	59.38	-1.21	8.85	4.42	50.12	7.86	3.90	50.41
	Two controllers	1	2.81	0.91	67.53	26.43	9.85	62.74	2.12	0.55	73.94	1.11	0.30	73.39
		2	5.77	1.72	70.17	50.25	12.75	74.63	4.37	0.80	81.77	2.26	0.54	76.26
		3	8.42	2.24	73.33	64.38	14.59	77.33	6.20	0.90	85.52	3.31	0.71	78.55
		4	10.58	1.89	82.18	82.55	21.43	74.04	7.28	0.83	88.65	3.31	0.59	82.14
		5	18.24	7.56	58.55	58.67	30.14	48.63	8.85	3.40	61.61	7.86	1.04	86.72
	Four controllers	1	2.81	0.87	69.13	26.43	15.10	42.86	2.12	0.58	72.66	1.11	0.28	74.77
		2	5.77	1.62	71.99	50.25	18.69	62.82	4.37	1.07	75.55	2.26	0.52	77.10
		3	8.42	2.08	75.25	64.38	24.43	62.06	6.20	1.37	77.83	3.31	0.66	79.94
		4	10.58	1.70	83.93	82.55	25.00	69.71	7.28	1.07	85.26	3.31	0.55	83.51
		5	18.24	3.44	81.14	58.67	32.64	44.38	8.85	3.76	57.57	7.86	1.75	77.80

(continued)

Table 1 (continued)

			Displacement (cm)			Acceleration (cm)			Velocity (cm)			RMS displacement (cm)		
	EQ	DOF	UC	C	%R	UC	C	%R	UC	C	%R	UC	C	%R
	Five controllers	1	2.81	0.80	71.65	26.43	6.50	75.42	2.12	0.39	81.75	1.11	0.26	76.40
		2	5.77	1.48	74.40	50.25	12.55	75.03	4.37	0.64	85.29	2.26	0.49	78.51
		3	8.42	1.95	76.83	64.38	15.75	75.54	6.20	0.82	86.76	3.31	0.65	80.53
		4	10.58	1.62	84.65	82.55	17.88	78.34	7.28	0.61	91.58	3.31	0.54	83.77
		5	18.24	3.30	81.92	58.67	23.16	60.53	8.852	2.71	69.36	7.86	1.74	77.92

Table 2 Controlled (C) and Uncontrolled (UC) amplitude of top deck displacement, acceleration, 4th inter-storey drift and base shear for optimum condition

Forces	Top deck displacement (cm)		Top deck acceleration (cm/s^2)		Base-shear (ton)		Inter storey drift (cm)	
	UC	Semi-active	UC	Semi-active	UC	Semi-active	UC	Semi-active
El ecntro (1940)	18.244	3.440	58.673	32.64	494.88	433.02	2.694	0.474
Chi-Chi (1999)	22.902	6.352	32.187	16.03	305.33	275.35	4.423	1.093
San Fernando (1971)	20.628	4.960	49.813	26.75	495.10	439.02	3.854	0.891
Northridge (1994)	15.643	3.896	57.123	47.18	446.41	439.80	3.155	0.624

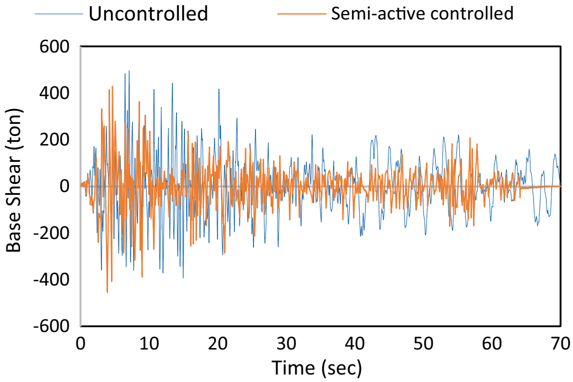

Fig. 4 Time–history variation of base shear subjected to El Centro earthquake

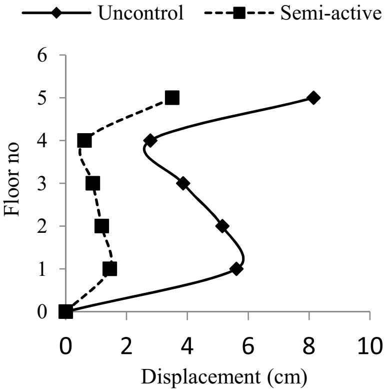

Fig. 5 Variation of maximum amplitude of 4th inter-storey drift subjected to El Centro earthquake (extreme) wave load, and (**c**) irregular (JONSWAP)

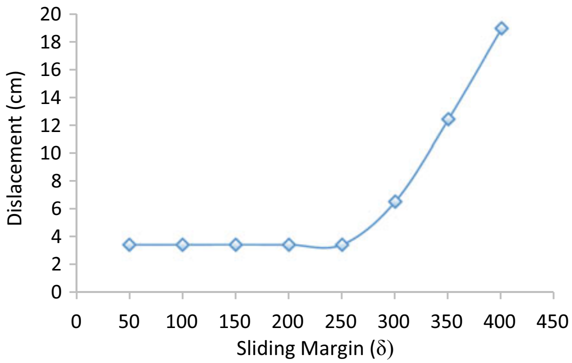

Fig. 6 Variation of top deck displacement with the variation of sliding margin corresponding to El Centro earthquake

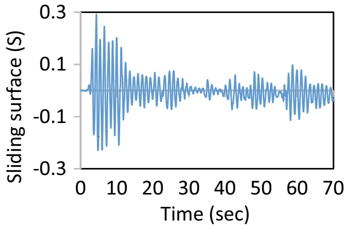

Fig. 7 Variation of sliding surfaces of the controller against El Centro earthquake

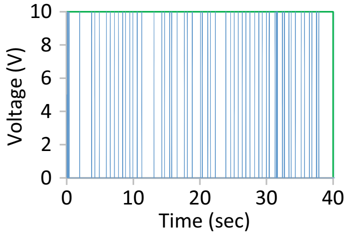

Fig. 8 Variation of command voltage applied to the MR damper subjected to El Centro earthquake

5 Outcomes

There are some certain major conclusions brought out from the present numerical study are enlightened below. The decentralized sliding mode controller using MR damper isolator is capable to reduce the vibrations of the fixed jacket platform against multiple earthquake loads and the number of the MR dampers and its position of installation affect the performance of the controller largely to improve the safety, stability and integrity of the platform. To control structural damage like, cracks and fatigue, displacement reduction is inevitable and for human easement acceleration, reduction is essential. The control scheme is effective to fulfill the bi-objective, acceleration and displacement reduction. The control system is robust against parametric uncertainties and work function is smooth under the harsh and hostile environment and to some extent reduce base shear effectively.

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