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Response of Piping System with Semi-active Magnetorheological Damper under Tri-directional Seismic Excitation

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Abstract: Seismic loads on piping system due to earthquakes can cause excessive vibrations, which can lead to serious instability resulting in damage or complete failure of piping system.Vibrations in the piping system can be reduced using passive control, active control, semiactive control and hybrid control. In this paper, semi-active magnetorheological (MR) dampers have been studied to mitigate seismic response and vibration control in piping system used in the process industries, fossil and fissile fuel power plant. The performance of MR dampers using various control algorithms is explored. A study is also conducted on the performance of control due to variation in the command voltage of MR dampers. The effectiveness of the MR dampers in terms of the reduction in responses, namely, displacements, accelerations and base shear of the piping system are compared with uncontrolled and passive controlled responses. This study is carried out under four artificial earthquake motions with increasing amplitudes in all the three directions of motion. The analytical results demonstrate that the MR dampers under particular optimum parameters are very effective and practically implementable for the seismic response mitigation, vibration control and seismic requalification of piping system.

Keywords: Seismic; earthquakes; passive control; active control; semi-active control; control algorithms; MR dampers.

1. Introduction

In the chemical and petrochemical industries, thermal, fossil and fissile power plants, it is necessary that the pipe networks remain functional in the event of design basis strong motion earthquake. Unlike other flexible structures, piping system are made of materials such as carbon steel, stainless steel, copper, cast iron etc. which provide a large amount of system stiffness. However these piping materials provide very little damping to the system, leaving these system especially susceptible to random vibrations. In an attempt to improve the damping in structures, passive, semi-active and active control devices have been employed by Housner et al. (1997) [1]. An active control system requires large external power supplies during a severe seismic event for effectively controlling the

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seismic response. However, the large external power supply may not be guaranteed during strong earthquake due to failure of power systems. The alternative to this is the use of semi-active control systems that require a small external power source for operation and utilize the motion of the piping system to develop the control forces. They potentially offer highly reliable operation and can be viewed as fail-safe systems (Symans and Constantinou ,1999) [2].

Dyke et al. (1996) [3] studied the performance of a clipped optimal control algorithm for MR damper installed in a multi-degree-of-freedom (MDOF) system. Dyke and Spencer (1997) [4] carried out a comparative study of various semi-active control strategies that were applied to MR damper installed in a MDOF structure through numerical simulation. Jansen and Dyke (2000) [5] also studied the performance of recently proposed semi-active algorithms for the use of multiple MR dampers in a MDOF structural model. Yoshida and Dyke (2004) [6] applied semi-active control systems using MR dampers to a non-linear model of a full-scale building to verify its effectiveness in reducing responses when non-linear behavior is considered. Soneji and Jangid (2006) [7] studied the effectiveness of semi-active MR dampers in reducing the seismic response of cable-stayed bridges. Kori and Jangid (2009) [8] studied the performance of various semi-active control algorithms and obtained the optimum input command voltage of MR dampers that were installed in multi-storey building models subjected to real earthquake ground motions.

In the first part of this study, seismic performance of piping system is investigated under effect of variation of maximum command voltage for different locations of MR dampers (vertical, horizontal and both vertical and horizontal) in the piping system subjected to four artificial earthquake motions with increasing amplitudes. In the second part of this study, seismic responses of piping system are investigated by changing the locations of MR dampers in the piping system. The specific objectives of the present study are summarized as to: (i) compare the response of piping system with or without MR dampers, (ii) compare the performance of various semi-active control algorithms applied for MR dampers installed in piping system, (iii) study the effect of variation of maximum command voltage on MR dampers.

2. Modeling of Piping System with MR Damper

The piping system considered for the present study is made of carbon steel (SA106 Gr B) having Young’s modulus of 210 GN/m2 and Poisson’s ratio =0.30. The damping ratio (1.2%) of piping system used in the analysis was obtained from experimental data. In the finite element modal, the two ends which are rigidly fixed are considered as restrained in all degree-of-freedom. The damper locations are highlighted as D1 and D2 effective in Z- and X-direction of the piping system, respectively. Figure 1 shows a schematic diagram of piping system with MR damper and control feedback system. Figure 1 also shows the location of lumped masses.

The following assumptions are made for seismic analysis of a piping system with MR dampers: (1) The straight members in the piping system are modelled as 3D Beam elements and the bends are modelled as 3D Elbows having six degrees-of-freedom at each node. (2) The mass of each member is assumed to be distributed between its two nodes as a point mass. In addition to the mass of the piping system, the externally lumped masses are assumed to be effective in the three translational degrees-of-freedom.

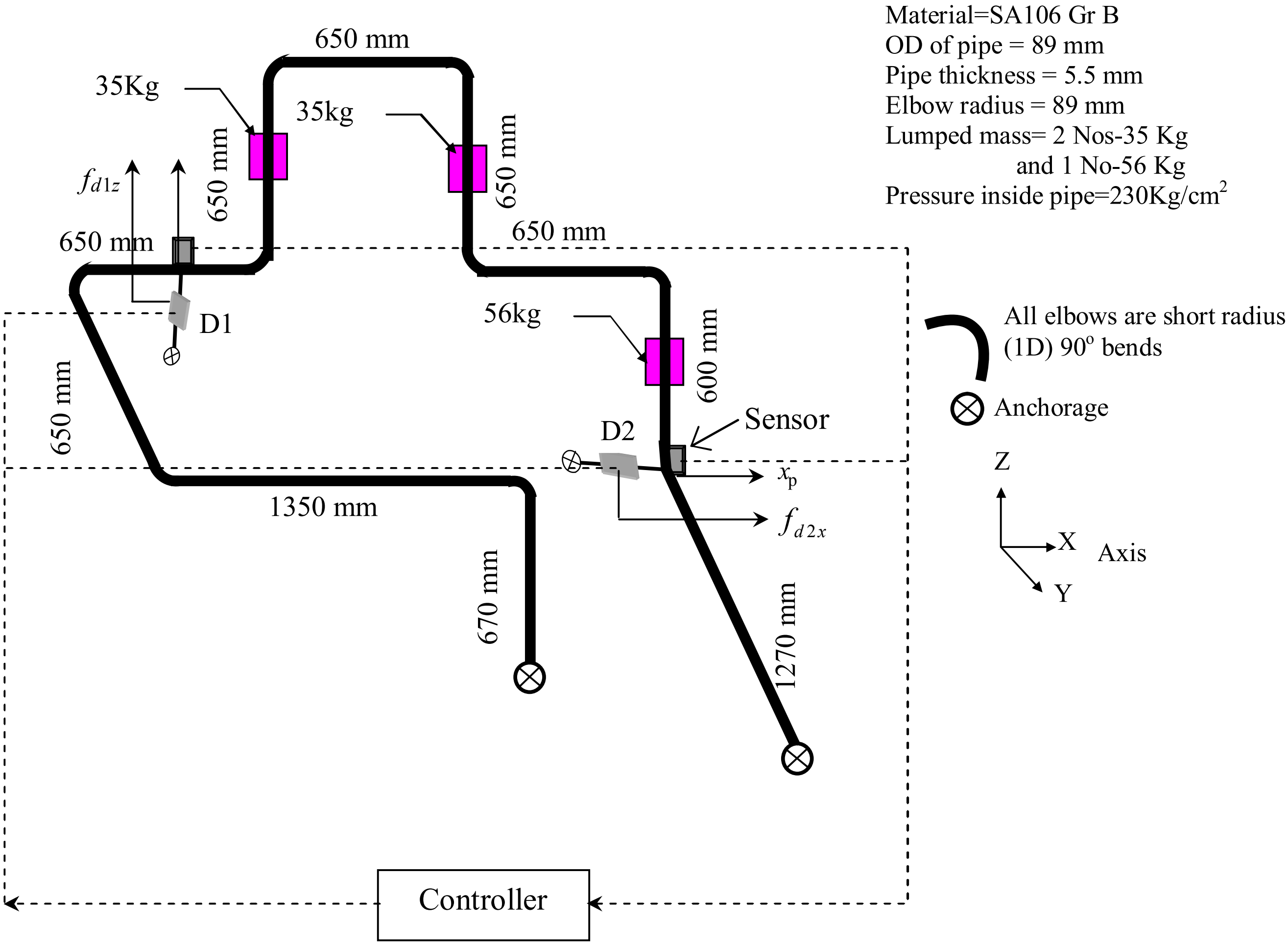
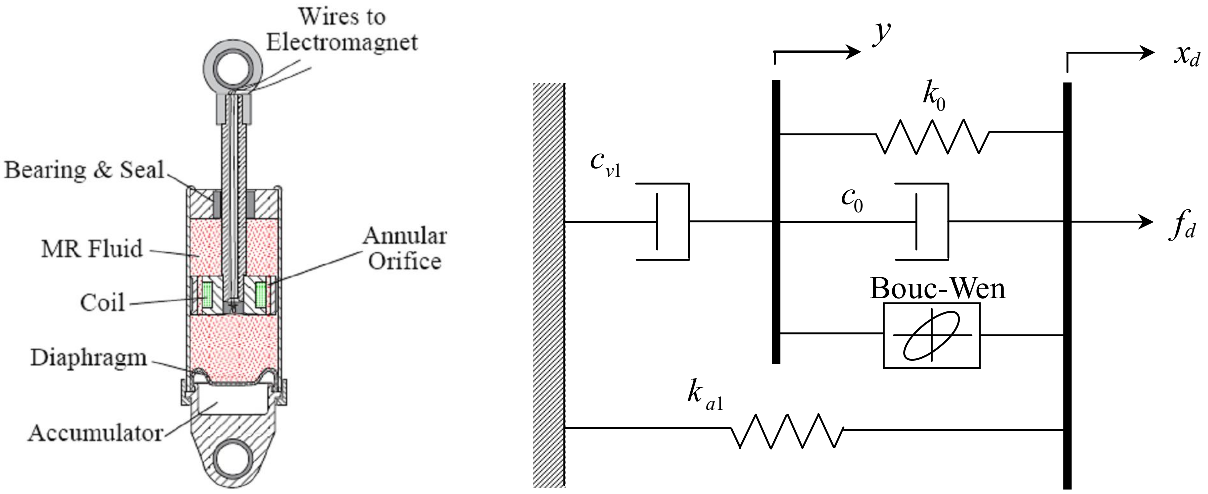


Figure 1. Schematic diagram of piping system with MR dampers and control feedback system

3. Model of MR Damper

A typical MR fluid consists of 20-40 percent by volume of relatively pure 3-10 microns diameter soft iron particles, e.g. carbonyl iron suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water, glycol or silicon. Moreover, MR fluids can operate at temperatures from -40 to 150 ^{O}C. When magnetic field is applied to these fluids particle chains are formed and the fluid becomes semisolid within milliseconds exhibiting plastic behavior similar to that of ER fluids [3]. A schematic diagram of MR damper is shown in Figure 2 (a) [3]. The damper is 21.5 cm long in its extended position and has a ± 2.5 cm stroke. The main cylinder is 3.8 cm in diameter and houses the piston, the magnetic circuit, an accumulator with 50 ml of MR fluid. The magnetic field produced in the device is generated by a small electromagnet in the piston head. The current for the electromagnet is supplied by a linear current driver which generates a current that is proportional to the applied voltage. The peak power required is less than 10 watts. The system, including the damper and the current driver, has a response time of typically less than 10 msec.

The force velocity behavior of MR damper is highly non linear. Hence more accurate dynamic model of MR dampers is necessary. Modeling the control devices is also essential for the adequate prediction of the behavior of the controlled system. Several models have been proposed to describe the behavior of MR dampers. The Bouc-Wen model by Wen [9] that is numerically tractable and has been used extensively for modeling hysteretic system is considered for describing the behaviour of the MR damper. Spencer [10] proposed the modified Bouc-Wen model as shown in Figure 2(b).



(a) Schematic diagram of MR damper (b) Modified Bouc-Wen model.

Figure 2. Schematic and mechanical model of MR damper

The equations governing the force f_d predicted by Modified Bouc-wen model of MR damper are given by

$$f_d = c_{v1}\dot{y} + k_{a1}(x_d - x_0) \tag{1}$$

$$\dot{z} = -\gamma\left|\dot{x}_d - \dot{y}\right| z|z|^{n-1} - \beta(\dot{x}_d - \dot{y})|z|^{n} + A(\dot{x}_d - \dot{y}) \tag{2}$$

$$\dot{y} = \frac{1}{(c_0 + c_{v1})}\left\{\alpha z + c_0\dot{x}_d + k_0(x_d - y)\right\} \tag{3}$$

where c_{v1} is viscous damping at lower velocity in the model to produce the roll-off; k_{a1} is the accumulator stiffness; x_d is the damper displacement; x_0 is the initial displacement of spring; $\dot{x}_d$ is the velocity across the damper; z is an evolutionary variable that accounts for the history dependence of the response; c_0 is viscous damping at larger velocity; k_0 is the stiffness at large velocity; and α, β, γ, n and A are the shape or characteristic parameters of the model.

Parameters α, c_0 and c_{v1} depend on the command voltage v sent to the current driver as follows

$$\alpha = \alpha_a + \alpha_b u,\ c_0 = c_{0a} + c_{0b}u, \text{ and } c_{v1} = c_{1a} + c_{1b}u \tag{4}$$

where u is given as the output of the first-order filter

$$\dot{u} = -\eta(u - v) \tag{5}$$

The parameters considered for 3000 N, MR damper are shown in Table 1 [4]. These parameters have been linearly scaled down to have a maximum capacity of 1500 N [11] with a maximum command voltage of $V_{\max} = 2.25$ V.

Table 1. Parameters for the MR damper model (Dyke et al. 1997)

Parameter	Value	Parameter	Value
c_{oa}	8 N.sec/cm	α_a	100 N.cm^{-1}
c_{ob}	6 N.sec/cm/V	α_b	450 N.cm^{-1}V^{-1}
k_0	50 N/cm	γ	363 cm^{-2}
c_{1a}	290 N.sec/cm	β	363 cm^{-2}
c_{1b}	5 N.sec/cm/V	A	301
k_1	12 N/cm	n	2
x_0	14.3cm	η	190 sec^{-1}

4. Governing Equations of Motion

Consider the piping system equipped with semi-active MR dampers as shown in Figure 2. The equation of motion of piping system with MR dampers are given as

$$M\ddot{x} + C\dot{x} + Kx = \Gamma F - M\Lambda\ddot{x}_g \tag{6}$$

where M is the mass matrix; C is the damping matrix; K is the stiffness matrix; x is the vector of displacements; $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration vectors, respectively; Γ is a matrix of zeros and ones, where one will indicate where the MR damper force is being applied; $F=[f_{d1}, f_{d2}, \ldots .f_{dr}]^T$ is the vector of control force produced by the dampers; Λ is the influence coefficient vector of ones and $\ddot{x}_g$ is the acceleration due to an earthquake. For the uncontrolled case, the force, F produced by the MR damper is zero. The governing equations of motion are solved in the incremental form using Newmark's time-stepping method [12]. The mass matrix has a diagonal form. The stiffness matrix of the piping system with MR damper is constructed separately and then static condensation is carried out to eliminate the rotational degree-of-freedom. With the first two natural frequencies of the piping system known, the damping matrix is obtained by using Rayleigh's method. The time history analysis of piping system with and without MR dampers is performed with input excitation of artificial earthquake motions with increasing amplitudes and designated as TH10, TH20, TH30 and TH40. The specific components of these artificial earthquake motions are indicated in Table 2.Using the sate-space representation, Equation(6) takes the following form

$$\dot{z} = Az + Bu + E\ddot{x}_g \tag{7}$$

$$y = Cz + DF + v \tag{8}$$

where $z=[x\,\dot{x}]^T$ is the state vector; $y=[\ddot{x}\,x]^T$ is the vector of measured outputs and v is the measurement noise vector. The system matrices are defined as in Dyke [13].

$$A=\begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix},\ B=\begin{bmatrix} 0 \\ -M^{-1}\Gamma \end{bmatrix},\ E=-\begin{bmatrix} 0 \\ \Lambda \end{bmatrix} \tag{9}$$

$$C=\begin{bmatrix} -M^{-1}K & -M^{-1}C \\ I & 0 \end{bmatrix},\ D=\begin{bmatrix} -M^{-1}\Gamma \\ 0 \end{bmatrix} \tag{10}$$

Table 2. Peak ground acceleration of various artificial earthquake motions

Artificial earthquake motions	Peak ground acceleration (m/sec^2)			Duration of earthquake
	x- component	y- component	z-component	sec.
TH10	2.38	2.15	1.88	33.50
TH20	4.85	4.15	3.22	33.64
TH30	7.17	6.31	4.91	33.68
TH40	10.01	8.65	6.25	33.89

5. Control Algorithm

The MR damper control systems are typically highly non-linear. One of the main challenges in MR control is the development of an appropriate control algorithm that can take advantage of the features of the control device to produce an effective control system. To evaluate the performance of MR damper piping system two versatile and effective control algorithms, Bang-Bang and Lyapunov control algorithms is selected in the current study.

5.1. Bang-Bang Control Algorithm

This approach requires measurements of the velocities and applied forces at the damper location. In this approach, the Lyapunov function is chosen to represent the total vibratory energy in the structure as in Dyke [4] and the control law is given by

$$v_i = V_{\max} H((-\dot{x}^{\mathrm{T}})\Lambda_i f_{di}) \tag{11}$$

where v_i is the voltage supplied to i^{th} damper; $V_{\max}$ is the maximum command voltage; $H(\cdot)$ is the heaviside step function and Λ_i is the i^{th} column of $\mathbf{\Lambda}$ matrix.

5.2. Lyapunov Stability Theory Control Algorithm

This approach requires the use of a Lyapunov function in Dyke [4] which must be a positive definite function of the states of the system. In the case of a linear system, the matrix P is found using the Lyapunov equation.

$$A^{\mathrm{T}}P + PA = -Q_p \tag{12}$$

For a positive definite matrix Q_p, the control law is given by

$$v_i = V_{\max} H((-z)^T PB_i f_{di}) \tag{13}$$

where B_i is the i^{th} column of matrix B.

6. Numerical Study on MR Damper

The response quantities of interest for the piping system under consideration are the relative displacements (x_p, y_p or z_p), accelerations ($\ddot{x}_p, \ddot{y}_p$ or $\ddot{z}_p$) of the piping system at the damper-piping connections and base shear (V_x, V_y or V_z). The x, y and z in the response quantities refer to the responses in the X-, Y- and Z-directions of the piping system, respectively. The responses are noted for, (i) uncontrolled system (i.e. piping system without MR dampers), (ii) controlled system (i.e. Passive-off, Passive-on, Bang-Bang control algorithm and Lyapunov control algorithm). The relative displacements of the piping system at the damper locations are crucial from design point of view of both, the MR dampers and the piping system. Whereas, the acceleration of the piping system and the base shear are directly proportional to the forces exerted on the piping system.

A parametric study is performed to investigate the effect of variation in command voltage in the range of 0 to 2.25V for piping system with vertical MR damper, horizontal MR damper and both vertical and horizontal

MR dampers. Figure 3 shows the effects of variation in command voltage, against displacement, acceleration, base shear and peak control forces at damper location, D1 of the piping system with both vertical and horizontal MR dampers. The results indicate that the displacement response of the piping system reduces with the increase in command voltage V. However, there exists an optimum value of voltage input for which the peak acceleration and base shear response attains the minimum value. From Figure 3, an optimum value of command voltage can be found as 2.25V when the MR damper is placed at D1 and D2 of piping system for all the responses under the different earthquake motions. Hence it is observed that the command voltage plays an important role in the response of the piping system and also its optimum value varies with different configurations of damper placements

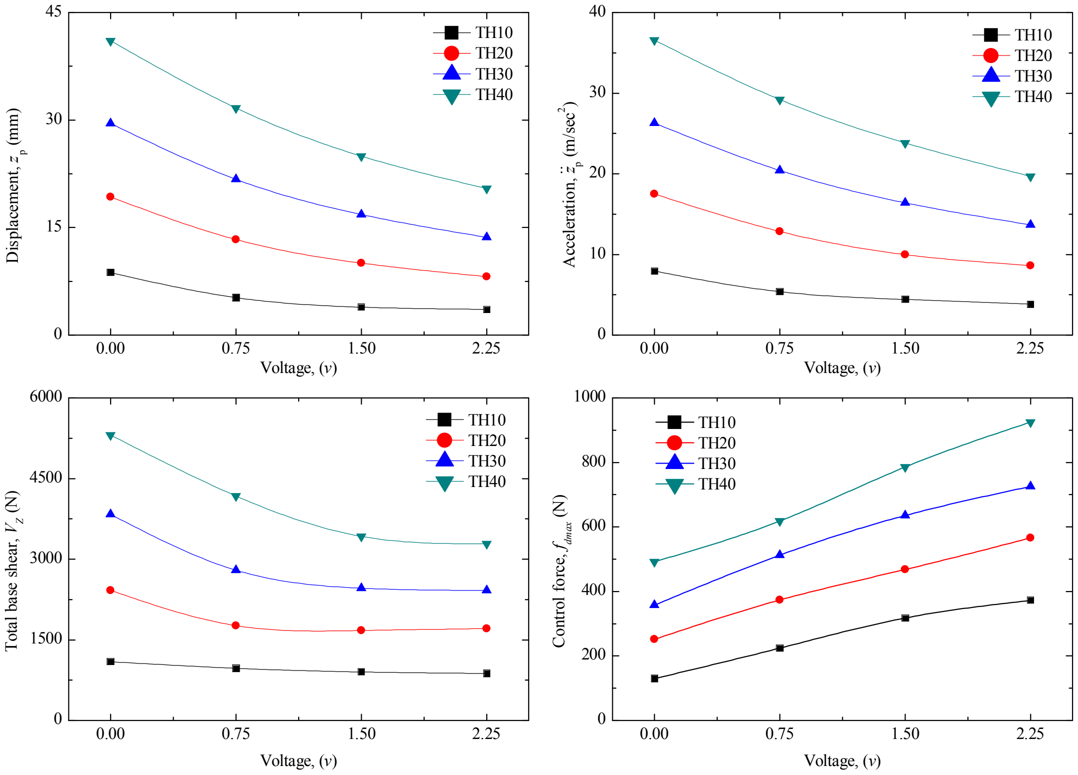


Figure 3. Effects of variation in command voltage at D1 for the piping system with both vertical and horizontal MR damper under various time histories

Table 3. Peak response quantities of piping system with vertical MR damper or horizontal MR damper under artificial earthquake motions

Time History	Control Type	Voltage Input	With Vertical MR damper				With Horizontal MR damper			
			Response at D1		Damper Force at D1	Total Base Shear	Response at D2		Damper Force at D2	Total Base Shear
		V	z_p	$\ddot{z}_p$	f_{d1max}	V_{zp}	x_p	$\ddot{x}_p$	f_{d2max}	V_{xp}
		(Volts)	(mm)	(m/sec^2)	(N)	(N)	(mm)	(m/sec^2)	(N)	(N)
TH10	Uncontrolled	---	18.17	14.13	---	1987	4.27	7.66	---	2335
	Passive-off	0	9.14	8.55	141	1336	3.44	6.10	83	1944
	Passive-on	2.25	2.08	3.79	408	1098	1.88	3.64	407	1233
	Bang-Bang	2.25	2.06	3.77	408	1098	1.88	3.64	407	1234
	Lyapunov	2.25	8.00	10.64	436	1268	3.22	6.89	395	1645
TH20	Uncontrolled	---	37.68	29.64	---	4056	8.86	16.01	---	4796
	Passive-off	0	20.03	18.14	270	2930	7.46	12.18	144	4069
	Passive-on	2.25	8.32	11.87	611	2483	4.95	9.49	528	2731
	Bang-Bang	2.25	8.35	11.85	612	2482	4.96	9.50	528	2733
	Lyapunov	2.25	19.14	12.99	632	2789	7.01	13.56	508	3675
TH30	Uncontrolled	---	56.15	44.81	---	5993	13.39	23.43	---	7197
	Passive-off	0	29.99	27.59	390	4579	11.50	18.63	201	6172
	Passive-on	2.25	14.66	18.48	809	3506	8.02	15.34	641	4545
	Bang-Bang	2.25	14.70	18.46	810	3505	8.04	15.37	640	4553
	Lyapunov	2.25	26.67	29.65	816	4393	10.75	18.83	614	5661
TH40	Uncontrolled	---	72.06	59.81	---	8341	19.83	32.74	---	9865
	Passive-off	0	42.15	38.52	514	6279	16.08	25.22	271	8599
	Passive-on	2.25	22.23	25.91	1048	4702	12.06	21.44	783	6519
	Bang-Bang	2.25	22.30	25.91	1050	4696	12.08	21.55	782	6526
	Lyapunov	2.25	40.21	40.17	1017	6013	15.17	25.49	731	8039

Table 3 summarizes the maximum values of the displacements, accelerations, damper forces and base shear resulting from the piping system with vertical MR damper or horizontal MR damper evaluated under different earthquake motions. Note that in Table 3 the based on Figure 3, optimum values of command voltage, V_{max} is considered as voltage input in the piping system with MR dampers. The peak response quantities for the two passive cases, passive-ON and passive-OFF, which refers to the cases in which the voltage to the MR damper is held at a constant value of maximum V = 2.25V and minimum V = 0V, are also studied. Similarly, Table 4 summarizes the maximum values of the displacements, accelerations, damper forces and base shear resulting from the piping system with both vertical and horizontal MR damper evaluated under different earthquake motions.

Table 4. Peak response quantities of piping system with both vertical and horizontal MR damper under artificial earthquake motions

Time History	Control Type	With both vertical and horizontal MR damper								
		Voltage Input	Response at D1		Damper Force at D1	Response at D2		Damper Force at D2	Total Base Shear	Total Base Shear
		V	z_p	$\ddot{z}_p$	f_{d1max}	x_p	$\ddot{x}_p$	f_{d2max}	V_{zp}	V_{xp}
		(Volts)	(mm)	(m/sec^2)	(N)	(mm)	(m/sec^2)	(N)	(N)	(N)
TH10	Uncontrolled	---	18.17	14.13	---	4.27	7.66	---	1987	2335
	Passive-off	0	8.72	7.93	130	2.80	4.25	140	1091	1438
	Passive-on	2.25	3.59	3.82	373	3.05	3.69	708	873	1169
	Bang-Bang	2.25	3.17	3.31	350	2.74	3.33	681	769	1094
	Lyapunov	2.25	5.93	8.10	423	2.91	6.64	722	1352	1479
TH20	Uncontrolled	---	37.68	29.64	---	8.86	16.01	---	4056	4796
	Passive-off	0	19.29	17.50	253	6.00	9.16	228	2416	2980
	Passive-on	2.25	8.13	8.60	566	5.87	7.86	966	1708	2347
	Bang-Bang	2.25	6.91	7.52	538	5.25	7.20	953	1647	2241
	Lyapunov	2.25	14.17	16.48	700	7.72	13.15	901	2597	3006
TH30	Uncontrolled	---	56.15	44.81	---	13.39	23.43	---	5993	7197
	Passive-off	0	29.54	26.28	358	9.02	13.61	310	3837	4571
	Passive-on	2.25	13.65	13.67	726	8.36	11.46	1115	2422	3774
	Bang-Bang	2.25	11.51	12.51	703	7.47	11.51	1110	2387	3304
	Lyapunov	2.25	24.13	23.26	924	8.40	20.41	1065	3608	4172
TH40	Uncontrolled	---	72.06	59.81	---	19.83	32.74	---	8341	9865
	Passive-off	0	41.05	36.57	492	12.80	18.95	413	5309	6317
	Passive-on	2.25	20.44	19.68	925	11.11	15.49	1276	3290	4704
	Bang-Bang	2.25	17.95	18.31	897	9.98	15.07	1270	3286	4433
	Lyapunov	2.25	34.34	33.42	1051	11.67	30.45	1220	4968	5707

The results from Table 3 for the Bang-Bang control algorithm with identified optimum command voltage under different earthquake motions shows maximum displacement reductions ranging from 69 to 88%, while maximum absolute acceleration reductions ranged from 56 to 73% for piping system with vertical MR damper. The results from Table 3 for the Bang-Bang control algorithm with identified optimum command voltage under different earthquake motions shows maximum displacement reductions ranging from 39 to 56%, while maximum absolute acceleration reductions ranged from 34 to 52% for piping system with horizontal MR damper. The results from Table 4 for the Bang-Bang control algorithm with identified optimum command voltage under artificial different motions shows maximum displacement reductions at D1 ranging from 75 to 82%, while maximum absolute acceleration reductions ranged from 59 to 76% for piping system with both vertical and horizontal MR damper. This implies that MR dampers are effective in reducing the seismic response of the piping system. Figures 4 and 5 compare the time variation of displacements and accelerations at D1, for the uncontrolled and controlled (Passive-off, Passive-on and Bang-Bang) for the piping system with both vertical and horizontal MR dampers under TH20. These results show that considerable reduction in displacements and accelerations for piping system with MR damper as compared to un-controlled and passive-off cases. Figure 6 shows the force-deformation variation loops at D1 of Bang-Bang control algorithm for the piping system with vertical MR damper under the different time histories. It is observed from the hysteresis loops that good amount of energy is absorbed by the MR dampers under all the time histories.

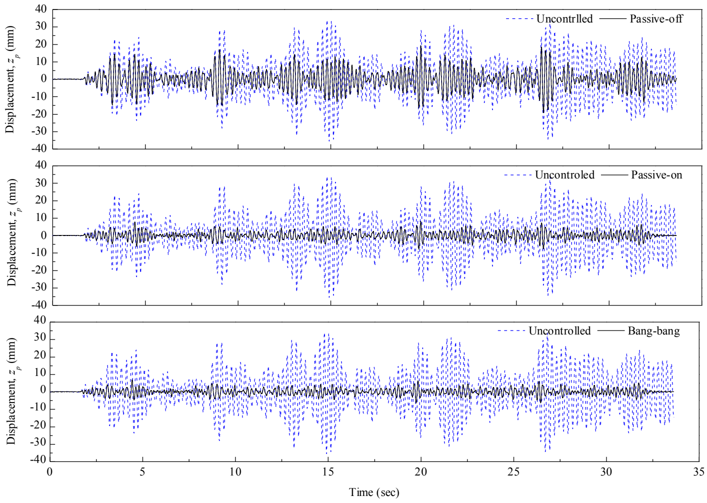


Figure 4. Variation of displacement with time at D1 of Uncontrolled, Passive-OFF, Passive-ON and Bang-Bang control algorithm for the piping system with both vertical and horizontal MR damper under time history, TH20

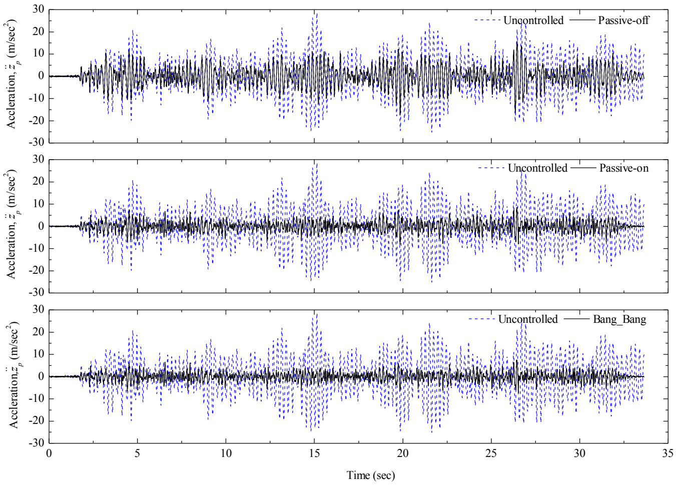


Figure 5. Variation of acceleration with time at D1 of Uncontrolled, Passive-OFF, Passive-ON and Bang- Bang control algorithm for the piping system with both vertical and horizontal MR damper under time history, TH20

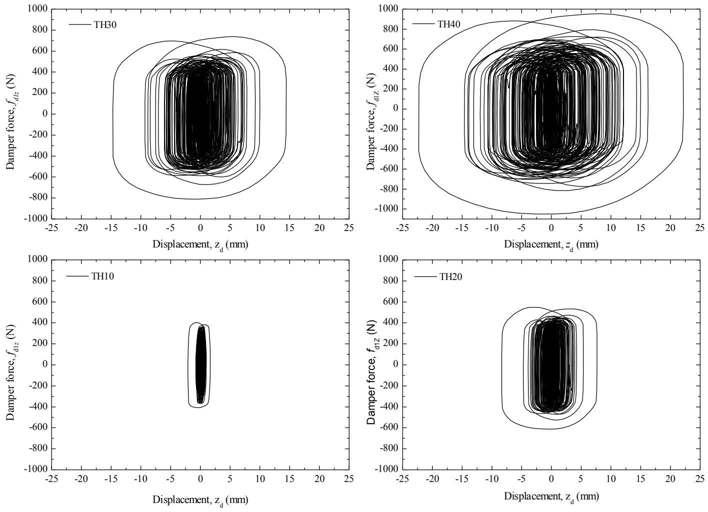


Figure 6. Force-deformation variations at D1 of Bang-Bang control algorithm for the piping system with vertical MR damper under different time histories

Figure 7 shows the force-velocity variation at D1 of Bang-Bang control algorithm for the piping system with vertical MR damper under the different time histories. Further, Figures 8 shows the comparison of corresponding Fast Fourier Transform (FFT) amplitude spectra at D1 of uncontrolled, passive-of, passive-on, Bang-Bang control algorithm and Lyapunov control algorithm for the piping system with both vertical and horizontal MR damper under TH20. These results show that there is considerable reduction in FFT amplitudes for piping system with MR damper as compared to uncontrolled and passive-off cases. The over-all results of these studies indicate that MR dampers shall be beneficial in reducing the seismic response of piping system and may prevent or significantly reduce the damage during a seismic event.

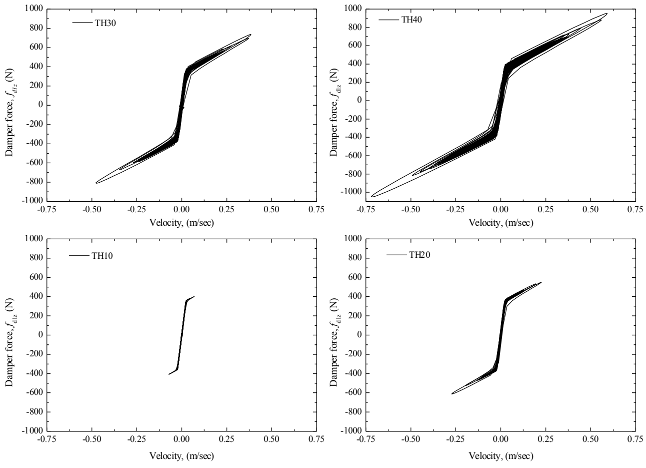


Figure 7. Force-velocity variations at D1 of Bang-Bang control algorithm for the piping system with vertical MR damper under different time histories

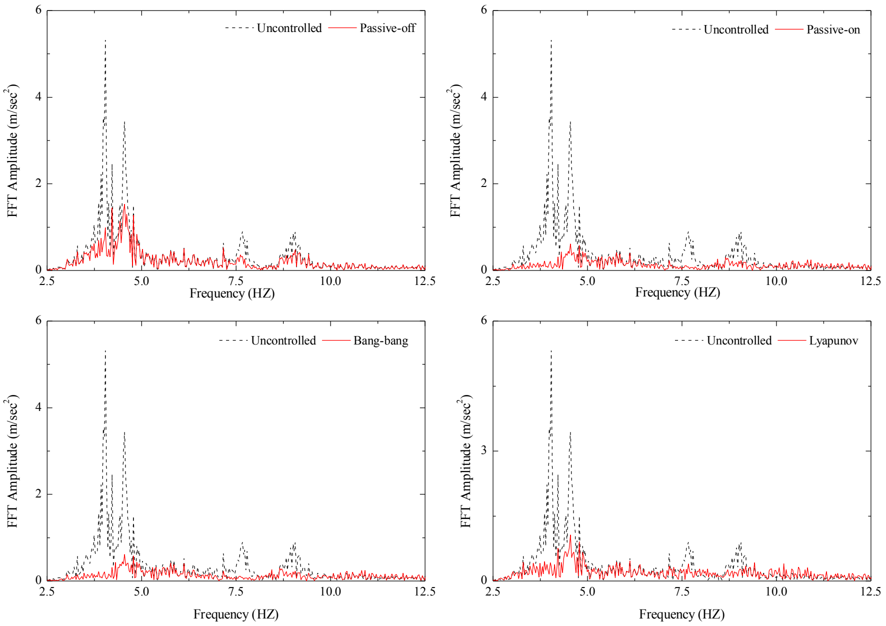


Figure 8. FFT spectra of acceleration at D1 of Uncontrolled, Passive-OFF, Passive-ON, Bang-Bang and Lyapunov control algorithm for the piping system with both vertical and horizontal MR damper under time history, TH20

7. Conclusions

The effectiveness and performance of various control algorithms for semi-active MR dampers in piping system subjected to different earthquake motions have been investigated and presented. The parametric study was conducted to observe the influence of variation of input command voltage in the range of 0 to 2.25V with different configurations of the MR damper deployment positions in the piping system. All control algorithms while using optimum voltage parameter demonstrated their effectiveness in reducing the piping system response. From the numerical investigation for the piping system with MR dampers as a protective controlling system, the following conclusions are drawn:

a) Numerical studies show that the MR dampers are very effective in reducing the seismic response of piping system. Hence, the problem of earthquake response mitigation, vibration control and seismic requalification of the piping system in industrial installations and utilities like nuclear power plants can be conveniently solved by the use of MR dampers.

b) From the parametric study, the peak displacements, accelerations and base shear are reduced with increase in the input command voltage of MR dampers. However, there exists an optimum value of the voltage input depending upon the damper locations.

c) There is considerable reduction in FFT amplitudes for the piping system with MR damper as compared to uncontrolled and passive-off cases.

d) Hysteresis loops indicate, good amount of energy is absorbed by the MR dampers.

e) The control algorithms considered for the MR damper, namely, the Bang-Bang and the Lyapunov imparts reduction in structural responses. But comparatively, Bang-Bang control algorithm performed better than Lyapunov control algorithm.

f) The larger the maximum command voltage, the better the overall performance of the piping system is observed with all the control algorithms for MR dampers.

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