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Effect of feedback on PID controlled active structures under earthquake excitations

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Abstract. In this paper, different feedback control strategies are presented for active seismic control using proportional–integral–derivative (PID) type controllers. The parameters of PID controller are found by using an numerical algorithm considering time delay, maximum allowed control force and time domain analyses of shear buildings under different earthquake excitations. The numerical algorithm scans combinations of different controller parameters such as proportional gain (K_p), integral time (T_i) and derivative time (T_d) in order to minimize a defined response of the structure. The controllers for displacement, velocity and acceleration feedback control strategies are tuned for structures with active control at the first story and all stories. The performance and robustness of different feedback controls on time and frequency responses of structures are evaluated. All feedback controls are generally robust for the changing properties of the structure, but acceleration feedback control is the best one for efficiency and stability of control system.

Keywords: structural control; PID controller; feedback control; earthquake excitation

1. Introduction

Structural control strategies have various types, such as active, passive, hybrid and semi-active systems. Passive systems play a great role for reducing undesirable vibrations with their mechanical component. By using high technology materials, the importance of passive systems in structural control became more popular than before, especially for retrofitting of existing structures. Passive control systems such as base isolation systems, passive tuned mass dampers, diagonal steel braces, friction dampers and viscoelastic dampers have been widely used for the seismic protection and retrofit applications.

Optimization of the passive devices is needed for the best performance of the system and several approaches have been proposed for base isolation systems (Suresh *et al.* 2010 and Ozbulut and Hurlebaus 2011), tuned mass dampers (Sadek *et al.* 1997, Hadi and Arfiadi 1998, Bekdas and Nigdeli 2011 and Nigdeli and Bekdas 2013), diagonal steel braces (Aydın and Boduroglu 2008) and dampers (Takewaki 2000, Aydın *et al.* 2007, Takewaki 2009, Amini and Ghaderi 2013 and Murakami *et al.* 2013). When structures subjected to unstable excitations like earthquakes, passive systems may be insufficient. Especially, near fault sources produce earthquakes with long velocity

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pulses. For a more effective seismic protection, control force must be varied automatically with time.

Active control systems can produce time varying forces with actuators driven by automatic control devices. Thus, active controlled structures can be stabilized immediately even during high impact earthquakes. Apart from all these, active control systems have some disadvantages. Because of using several control equipment such as computer, actuators and sensors, they may be expensive. During earthquakes, electrical source of the structures may fail. In order to carry out the control process, large external power supply may be needed. Semi-active systems need less energy than active ones and can run with a battery, but their capacity may be lesser. Hybrid systems are the combination of both active and passive systems. Hybrid systems can be also used as passive control systems without any energy. Switch of active control systems are always on while semi-active or hybrid systems can be switched off when the system is not under an excitation. Another disadvantage of active control systems is time delay resulting from equipment. Delay of the control signals must be considered in the design of active control systems. Stability problem can be occurred for active control systems. This situation must be checked in tuning process. The robustness of the active control systems for changing behavior of the controlled system must be evaluated.

The idea of active control of structure dates back to 1968 (Zuk 1968). Then, several approaches have been done after the first introduction of active structural control was done by Yao (1972). Active control of structures is still an active research area for new approaches and further investigations.

Roorda (1975) proposed an active tendon control systems for masts and towers subjected to forces caused by turbulent wind conditions by modeled structure as a uniform cantilever beam. Yang and Giannopoulos (1978) developed active tendon controlled structures modeled as cantilever beams by using the transfer matrix technique. Frame structures, which were subjected to a steady state disturbance, were controlled with active tendons by Abdel-Rohman and Leipholz (1979). Unloaded cables were used for generating control force at this study. Yang and Samali (1983) controlled tall structures excited by a random wind flow which is stationary in time and nonhomogenous in space. They obtained significant reduction of acceleration response by using either an active mass damper or an active tendon control system. Abdel-Rohman and Leipholz (1983) used active prestressed cable in order to reduce wind response of tall structures. A single continuous cable was implemented to all floors with pulleys in order to apply a single horizontal control force at the top of the building. They showed that active tendon control was more effective than active mass damper in reducing wind source vibrations but control force needed for application was more than active mass damper. A pole-placement method (Abdel-Rohman and Leipholz 1978) was considered as control algorithm. Samali *et al.* (1985) numerically analyzed active tendon controlled torsionally irregular structures under randomly generated earthquake. A closed-loop control law was used and building responses were obtained with Monte Carlo simulation. Chung *et al.* 1988) applied active tendon control system to single degree of freedom experimental model under base motion generated by a large-scale simulator. Chung *et al.* (1989) sustained experimental studies with 1:4 scaled three story frame building. López-Almansa and Rodellar (1989), numerically analyzed active tendon controlled frame and shear wall buildings. Reinhorn *et al.* (1989) tested 1:4 scale models with active tendons and active tuned mass dampers for aseismic protection.

Parallel algorithms for structural control have been proposed by Saleh and Adeli (1994), Saleh and Adeli (1996), Saleh and Adeli (1997), Adeli and Saleh (1997), Adeli and Saleh (1998) and

Saleh and Adeli (1998). In discrete-time formulation, a modified instantaneous control algorithm considering time delay is developed by Chung *et al.* (1997). A multi-step acceleration feedback control algorithm was proposed for active tendon control of structures by Chung *et al.* (1998). Predictive control algorithms for active structural control were proposed by Chung (1999) and Mei *et al.* (2002). Optimum placements of active and passive control systems were investigated for three dimensional structures by Arfiadi and Hadi (2000). Several active control algorithms have been proposed by Bakioglu and Aldemir (2001), Aldemir *et al.* (2001), Kim and Adeli (2004), Adeli and Kim (2004), Kim and Adeli (2005a), Min *et al.* (2005) and Chang and Lin (2009). A hybrid structural control system by the combination of a passive supplementary damper with a semi-active tuned liquid column damper was developed (Kim and Adeli 2005b, Kim and Adeli 2005c). An energy based technique was proposed for linear quadratic regulator (LQR) controllers by Alavinasab and Moharrami (2006). Several control algorithms employing fuzzy logic (Nomura *et al.* 2007) and neural networks (Jiang and Adeli 2008a, Jiang and Adeli 2008b and Lin *et al.* 2012) have also been used in active control algorithms. Active tendon controlled torsionally irregular structure was investigated by Lin *et al.* (2010) by considering soil-structure interaction. Optimal control was obtained according to minimization of a performance index defined as a simple integral type quadratic functional by Aldemir (2010). A direct adaptive control method was developed by Bitaraf *et al.* (2012) for control of an undamaged and a damaged structure. A decentralized control strategy was proposed by Lei *et al.* (2012). In order to consider the mechanical energy of the system, control and the seismic energy, Aldemir *et al.* (2012) developed a new performance index. A novel multi-objective genetic algorithm was developed for optimization of active control systems for vibration control of 3-dimensional buildings by Cha *et al.* (2013). Nigdeli and Boduroglu (2013) investigated active tendon control of torsionally irregular structures subjected to near fault effects by using a numerical algorithm for tuning of Proportional Integral Derivation (PID) type controllers.

In this paper, seismic structures were actively controlled by using different feedback control strategies. Proportional–integral–derivative (PID) type controllers were used and the parameters of PID controller were tuned by using a numerical algorithm considering several performance indexes. These indexes are time delay of the control signal, maximum allowed control force and time domain analyses of shear buildings under different earthquake excitations. The controller parameters for displacement, velocity and acceleration feedback control strategies were tuned for multi-story structures with different control schemes. The performance and robustness of different feedback controls on time and frequency responses are investigated and compared.

2. Equations of motion of multi-story structures

Equations of motions of a multiple degrees of freedom (MDOF) structures can be written as

$$M\underline{\ddot{X}} + C\underline{\dot{X}} + K\underline{X} = -M\underline{I}\ddot{x}_g \tag{1}$$

where M, C and K are mass, damping and stiffness matrices. In Eq. (1), $\underline{X}$, $\ddot{x}_g$ and $\underline{I}$ represents displacement vector of structure (dot on the top defines its derivative with respect to time), ground acceleration and vector of ones. Active tendon control applications given in Fig. 1 were investigated in this study.

In the first case, structure is controlled only from the first story. In cases II and III, active tendons are positioned for all floors. Alternatively in Case III, tendons lies from ground to floor level.

Tendon have reaction forces at upper floors in Case II. Because of this, the structure can only benefit from resultant forces shown in Fig. 2. In the other cases, all reaction forces are supported by the ground.

Case III is a more suitable case than Case II in performance, but it can only applied in special conditions, because all actuators are on the base and long cables lies from bottom to all stories. For example, Case III is suitable for structures constructed by using tunnel formwork (structure with shear walls and slabs). Active tendon control systems can be merged to a shear wall and cables can lie from a hole on the slabs. In frames structures, the dimension of a column may not be sufficient to connect all cables because all cables cannot be in same line and cables may past through a beam of the structure. In Case III, the vertical component of the control force which may be harmful for vertical supports of structure and has no positive benefit on structural control, is more than other cases for Case III due to change of tendon angles with respect to ground.

If each tendon is loaded with a pre-stressed force (R), in dynamic state, while one of the crosswise tendons is being loaded by tensile force, the other one is being unloaded because of compressive force. A tendon cannot carry compressive force. Thus, absolute value of control force must be smaller than pre-stress force in order to maintain desired control force with respect to the actuator displacement. According to this definition, equations of motion for actively controlled structures are given in Eq. (2), Eq. (3) and Eq. (4) for cases I, II and III, respectively. In these equations, k_c, α and u_i represent stiffness of tendons, tendon angles with respect to ground (in Case III; α, β and θ) and actuator displacement or control signal for i = 1-3, respectively.

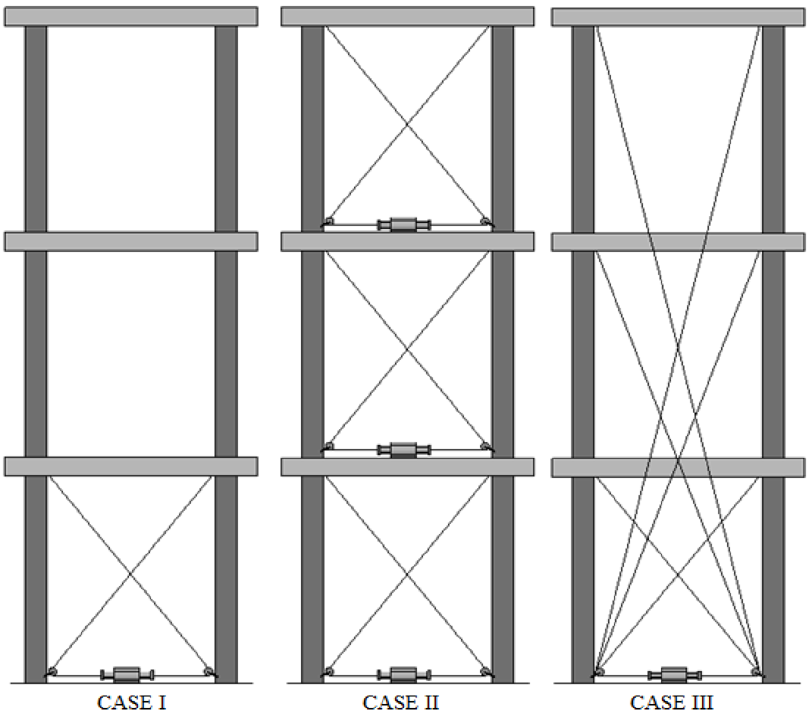

Fig. 1 Active tendon cases for multi-story structures

$$M\underline{\ddot{X}} + C\underline{\dot{X}} + K\underline{X} = -M\underline{I}\ddot{x}_g - 4k_c\cos\alpha\begin{bmatrix} u_1 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

$$M\underline{\ddot{X}} + C\underline{\dot{X}} + K\underline{X} = -M\underline{I}\ddot{x}_g + 4k_c\cos\alpha\begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{3}$$

$$M\underline{\ddot{X}} + C\underline{\dot{X}} + K\underline{X} = -M\underline{I}\ddot{x}_g - 4k_c\begin{bmatrix} u_1\cos\alpha \\ u_2\cos\beta \\ u_3\cos\theta \end{bmatrix} \tag{4}$$

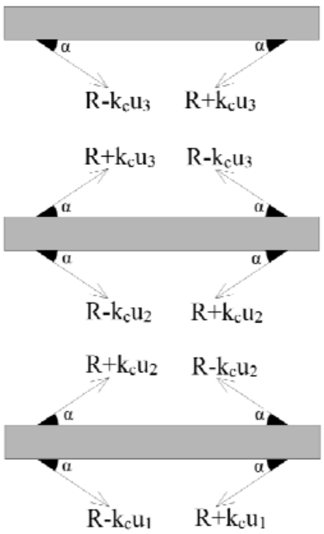

Fig. 2 Reaction forces for Case II

3. Active control of multi-story structures

Active control concept was verified with multiple degree of freedom (MDOF) structural model for different feedback control strategies. The controllers were tuned for all feedback strategies and orientation of active tendons. Proportional Integral Derivation (PID) type controllers were used for all feedback controls. Motions of active tendon controlled structures were modeled at Matlab Simulink (The MatWorks Inc. 2010) for time history analyses. Runge-Kutta method with 1e-3 step size was used in order to conduct numerical simulations. Time delay factor was also considered in the tuning process. Time delay was assumed as 20 ms at this study. A transport delay block was implemented after the generation of control signals at Matlab Simulink.

Proportional Integral Derivation (PID) type controllers were used to generate control signal data, $u(t)$ that is also the displacement of the activators. These types of controllers use feedback strategy according to a defined error signal. The controller have three specific actions to tune. These actions are P, I and D actions. P-action is important for increasing the speed of control response, D-action is effective on damping and I-action is proposed for eliminating steady-state error (De Cock *et al.* 1997).

Equation of the PID controller is written as

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt} \right) \tag{5}$$

in which K_p (Proportional gain), T_i (Integral time) and T_d (Derivation time) are the coefficients of the controller. These coefficients representing PID actions were found by applying the proposed methodology. By using Eq. (5), error signal, $e(t)$ (undesired response defined according to feedback) can be transformed into control signal. In control, displacement, velocity and acceleration of first story of the structure were taken as control signal for displacement, velocity and acceleration feedback controls, respectively. Control signal were generated according to responses respect to the ground, thus dominant effect of the excitations were prevented.

Classical PID tuning methods such as Ziegler-Nichols tuning method (Ziegler and Nichols 1942) may not be insufficient for randomly changing vibrations. Guclu (2006) investigated sliding mode and PID control of structural systems. Coefficients of PID actions were obtained by using Ziegler-Nichols tuning method but the results shows that PID controlled system is not so effective according to sliding mode control.

Nigdeli and Boduroglu (2013) proposed an iterative numeric algorithm for tuning of PID parameters. The time history analyses were conducted for impulsive motions resulting from near fault seismic sources.

In present study, a similar numerical algorithm is proposed for different feedback control strategies. In tuning process, time history analyses were done for five different earthquake records. The numerical algorithm presented in Nigdeli and Boduroglu (2013) considers only a single excitation for the tuning process. Also, differently from this numerical algorithm, a control force limit was considered during the tuning process in addition to time delay consideration. If the control force limit is exceeded for a set of PID controller parameters, this set of parameters are directly eliminated. The methodology is summarized in Fig. 3.

The excitations used in tuning must represent the seismic characteristic of the region. Thus, an optimum solution for a region can be found. A region may also suffer from earthquakes with different characteristics. For example, a near fault region may also be affected by earthquakes with epicenter far away from the region.

The information of earthquake records downloaded by Pacific Earthquake Engineering Research Center (PEER) database are given in Table 1. This table also includes peak ground

Table 1 Earthquake records used in tuning process

Earthquake	Date	Station	Component	PGA (g)	PGV (cm/s)	PGD (cm)
Kobe	1995	0 KJMA	KJM000	0.821	81.3	17.68
Imperial Valley	1940	117 El Centro Array #9	I-ELC180	0.313	29.8	13.32
Erzincan	1992	95 Erzincan	ERZ-NS	0.515	83.9	27.35
Northridge	1994	24514 Sylmar	SYL360	0.843	129.6	32.68
Loma Prieta	1989	16 LGPC	LGP000	0.563	94.8	41.18

acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) values of the excitations. Except Imperial Valley (El Centro) excitation, near fault ground motion records were used in the tuning process.

In methodology, the range of PID controller parameters are defined according to several trial because stability problem can occur for several combination of controller parameters. Stability error may prevent the iteration process. The algorithm iteratively scans neighboring values for controller parameters and save a desired response of structure. If maximum control force value is exceeding the desired value, relevant combination of parameters are eliminating. A range is also needed for minimizing the duration of the process.

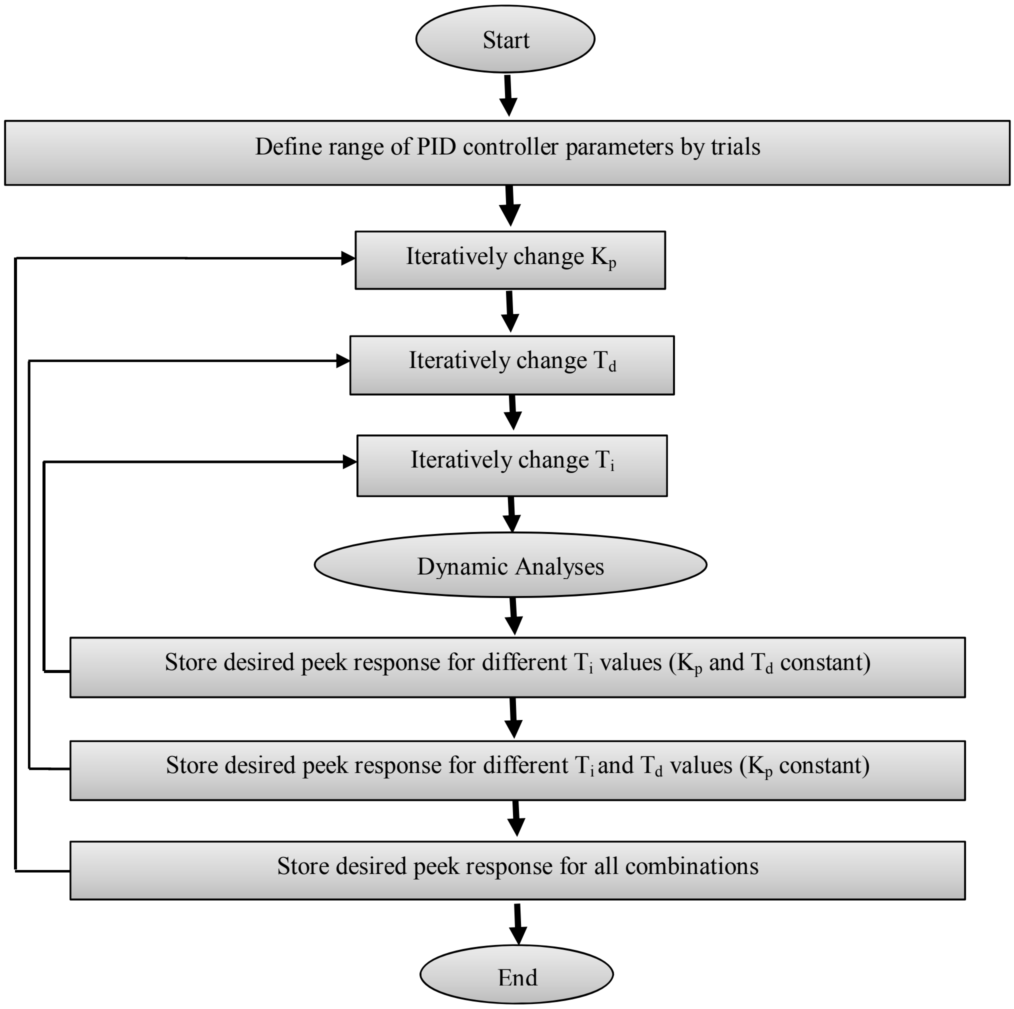

Fig. 3 Flowchart of the methodology

4. Numerical examples

The properties of three story structure are given in Table 2. Controller parameter were found for different cases and feedback controls. For cases II and III, resultant control forces were taken as the same for all floors. Also, resultant control forces are tuned as equal for Case II and III. Thus, T_d and T_i are the same for all control systems, but proportional gain (K_p) is different. Proportional gain (K_p) is 3 and 2 times of the value of third floor controller for Case II in the first and second floor, respectively. For Case III, K_p is 1.4 and 1.9 times of the first floor controller in the second and third floor, respectively. In tuning process, the objective is to minimize the maximum value of first story displacement without exceeding 5 kN (10 kN for Case I) control force for a story.

Table 2 Properties of three story structure (Chung *et al.* 1989)

Symbol	Definitions	Numerical value
M (kg)	Mass matrix of the MDOF structure	$\begin{bmatrix} 981 & 0 & 0 \\ 0 & 981 & 0 \\ 0 & 0 & 981 \end{bmatrix}$
K (N/m)	Stiffness matrix of the MDOF structure	$\begin{bmatrix} 2741700 & -1641600 & 369100 \\ -1641600 & 3022200 & -1624800 \\ 369100 & -1624800 & 1333600 \end{bmatrix}$
C (Ns/m)	Damping matrix of the MDOF structure	$\begin{bmatrix} 382.8 & -57.3 & 61.7 \\ -57.3 & 456.9 & -2.6 \\ 61.7 & -2.6 & 437.5 \end{bmatrix}$
α, β and θ (º)	Angles of tendons respect to ground	36, 55 and 65
k_c (N/m)	Stiffness of tendons	372100
T_1, T_2 and T_3 (s)	Periods of the MDOF structure	0.45, 0.15 and 0.09

4.1 Displacement feedback control

In displacement feedback control; K_d, T_d and T_i were found as -0.014, 0.75 s and 0.03 s, respectively for Case I. For other cases, K_d, T_d and T_i are equal to -0.011 (for the smallest one as described in section 4), 0.9 s and 0.022 s, respectively. The maximum responses are given in Table 3 for all cases. Also, maximum responses of uncontrolled structures are given in Table 3.

The maximum displacements and velocities are respect to the ground, but total acceleration values are given in tables. Maximum control forces are the resultant horizontal force on tendons. For uncontrolled structure, maximum responses occur under Kobe excitation.

In Case I, active control is effective on reducing all type of responses for all stories. Although the most critical excitation is Kobe for uncontrolled structure, the most critical one is Northridge in this feedback. Under Kobe excitation, maximum displacements, velocities and accelerations are reduced up to 34%, 38% and 35%, respectively for Case I and displacement feedback control.

The maximum reductions of displacements are between 20% and 65 % for Cases II-III and displacement feedback control. Reductions are between 45%-70% and 6%-67% for velocity and acceleration, respectively. Generally, the reduction percentages are nearly equal to each other for all stories, but reduction percentages may vary according to excitation.

In Fig. 4, time history plots of first and top story displacements for Kobe excitation are illustrated. The benefit of active control can be clearly seen for peak responses and steady state

Table 3 Maximum responses of controlled structure for displacement feedback control

	Excitation	Displacement (cm)			Velocity (m/s)			Acceleration (m/s^2)			Control force (N)
	Story	1	2	3	1	2	3	1	2	3	
Uncontrolled	Kobe	8.17	18.0	23.0	1.17	2.47	3.11	22.3	35.1	46.8	-
	Imperial Valley	2.87	5.9	7.2	0.37	0.72	1.00	10.2	15.2	15.4	-
	Erzincan	1.81	3.7	4.7	0.23	0.47	0.63	6.0	7.6	9.2	-
	Loma Prieta	6.32	13.0	16.1	0.71	1.58	2.18	19.0	29.4	29.5	-
	Northridge	6.29	13.4	17.0	0.83	1.90	2.51	20.8	28.2	32.1	-
CASE I	Kobe	5.56	12.0	15.2	0.72	1.54	2.01	16.2	25.0	30.4	7205.2
	Imperial Valley	1.91	4.0	4.9	0.26	0.52	0.65	7.7	11.5	10.1	2662.0
	Erzincan	1.67	3.6	4.5	0.15	0.33	0.42	5.1	7.4	8.7	1705.6
	Loma Prieta	4.79	10.5	13.2	0.59	1.34	1.72	13.3	23.6	25.0	5669.9
	Northridge	5.60	12.2	15.4	0.70	1.69	2.29	16.3	28.6	29.5	6963.7
CASE II-III	Kobe	3.21	6.5	8.1	0.35	0.76	1.02	12.7	15.7	15.6	3146.1
	Imperial Valley	1.07	2.1	2.6	0.16	0.31	0.43	6.2	6.4	6.4	1852.4
	Erzincan	1.40	3.0	3.8	0.12	0.26	0.31	5.2	7.1	8.3	1285.8
	Loma Prieta	2.36	4.9	6.1	0.29	0.60	0.80	11.1	13.0	14.1	2816.4
	Northridge	3.52	7.6	9.7	0.54	1.06	1.32	11.8	19.7	23.9	4989.7

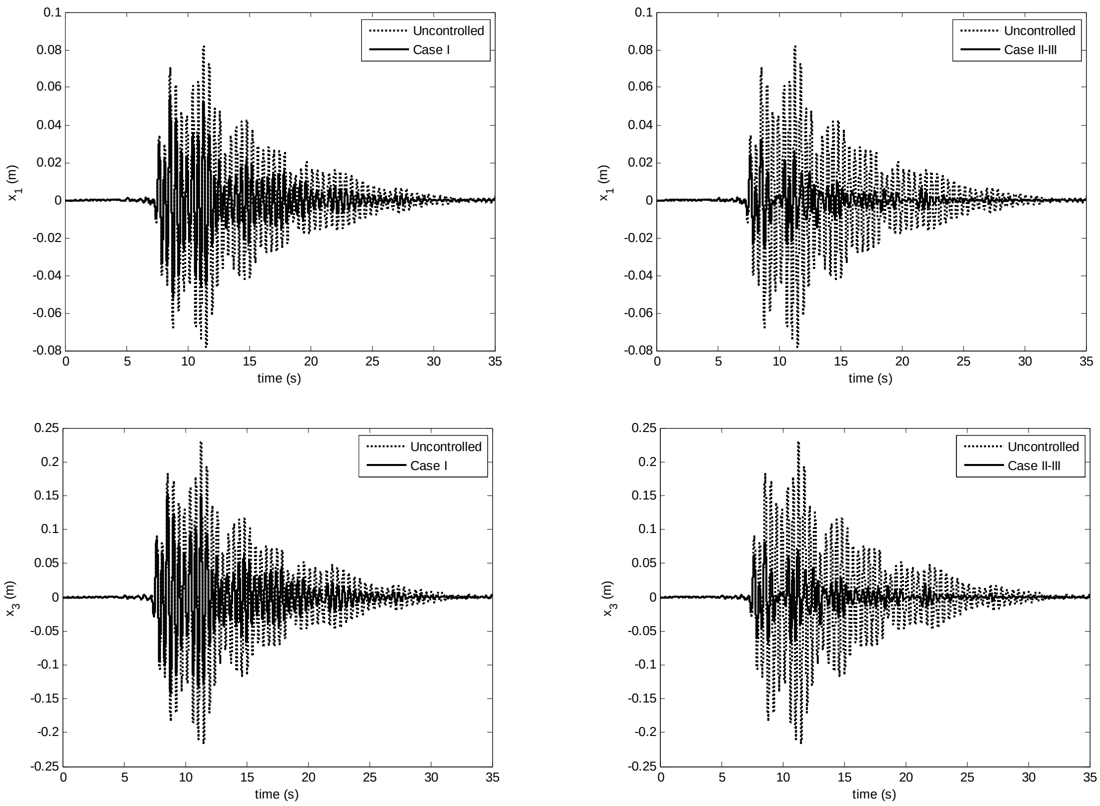

Fig. 4 First and top story displacement plots for displacement feedback control (Kobe excitation)

response of controlled structure. A better steady state response is obtained for Case II-III in comparison to Case I. First story acceleration transfer function plot for displacement feedback control is given in Fig. 5. For Case I, a reduction for peak values is not provided.

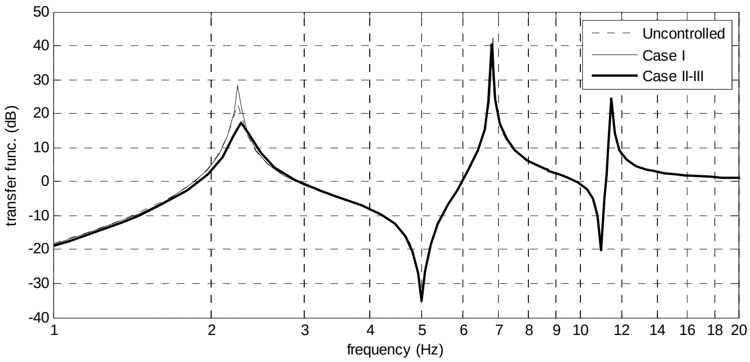

Fig. 5 First story acceleration transfer function plot for displacement feedback control

4.2 Velocity feedback control

Controller parameters; K_d, T_d and T_i were found as -0.009 s, 0.06 s and 0.05 s, respectively for Case I. For the other cases, K_d, T_d and T_i are equal to -0.0017 s (for the smallest one as described in section 4), 0.36 s and 0.01 s, respectively. The maximum responses are shown in Table 4.

Table 4 Maximum responses of controlled structure for velocity feedback control

	Excitation	Displacement (cm)			Velocity (m/s)			Acceleration (m/s^2)			Control force (N)
	Story	1	2	3	1	2	3	1	2	3	
Uncontrolled	Kobe	8.17	18.0	23.0	1.17	2.47	3.11	22.3	35.1	46.8	-
	Imperial Valley	2.87	5.9	7.2	0.37	0.72	1.00	10.2	15.2	15.4	-
	Erzincan	1.81	3.7	4.7	0.23	0.47	0.63	6.0	7.6	9.2	-
	Loma Prieta	6.32	13.0	16.1	0.71	1.58	2.18	19.0	29.4	29.5	-
	Northridge	6.29	13.4	17.0	0.83	1.90	2.51	20.8	28.2	32.1	-
CASE I	Kobe	5.15	11.4	14.6	0.65	1.50	1.96	15.6	24.3	29.4	9577.9
	Imperial Valley	1.54	3.4	4.4	0.20	0.45	0.59	4.8	8.1	8.4	3493.4
	Erzincan	1.51	3.4	4.4	0.14	0.31	0.41	4.8	7.0	8.9	3056.8
	Loma Prieta	4.39	10.0	12.9	0.59	1.29	1.67	11.0	20.8	26.4	8082.3
	Northridge	5.15	11.7	15.1	0.70	1.67	2.20	12.5	25.1	30.4	9223.9
CASE II-III	Kobe	4.17	8.8	11.2	0.51	1.10	1.40	14.7	21.7	25.4	4042.3
	Imperial Valley	1.04	2.2	2.9	0.16	0.32	0.41	3.7	5.2	7.3	1914.2
	Erzincan	1.19	2.6	3.3	0.12	0.25	0.30	5.1	6.8	8.3	1756.1
	Loma Prieta	3.15	7.0	9.1	0.49	0.93	1.16	10.1	16.3	22.5	3798.6
	Northridge	4.28	9.5	12.1	0.64	1.43	1.83	11.2	23.0	27.7	3737.0

Also for velocity feedback control, Northridge excitation is the most critical one for the responses of active controlled structure. Velocity feedback control is more effective than displacement feedback control for Case I, but opposite can be said for the other cases. Due to high peak ground velocity of Erzincan excitation, a better benefit than displacement feedback control is seen. In Case I, the reduction percentages of responses are vary between 8-46, 12-47 and 3-53 for displacement, velocity and acceleration, respectively. These reductions for the other cases are between 29-64, 23-59 and 11-66 for displacement, velocity and acceleration, respectively.

Time history plots of first and top story displacements for Kobe excitation are shown in Fig. 6 for velocity feedback control. Displacement feedback control is better on steady state response than velocity feedback control for Cases II and III. In velocity feedback control, a reduction for peak values of transfer function plot is provided as seen in Fig. 7. Case I has a better frequency response than the other cases.

Near fault ground motions are significant with their high peak ground velocities. For that reason, generating a control signal according to velocities which is the derivative of displacements and integration of accelerations, a successful control is achieved. Velocity is also a variable of the total energy.

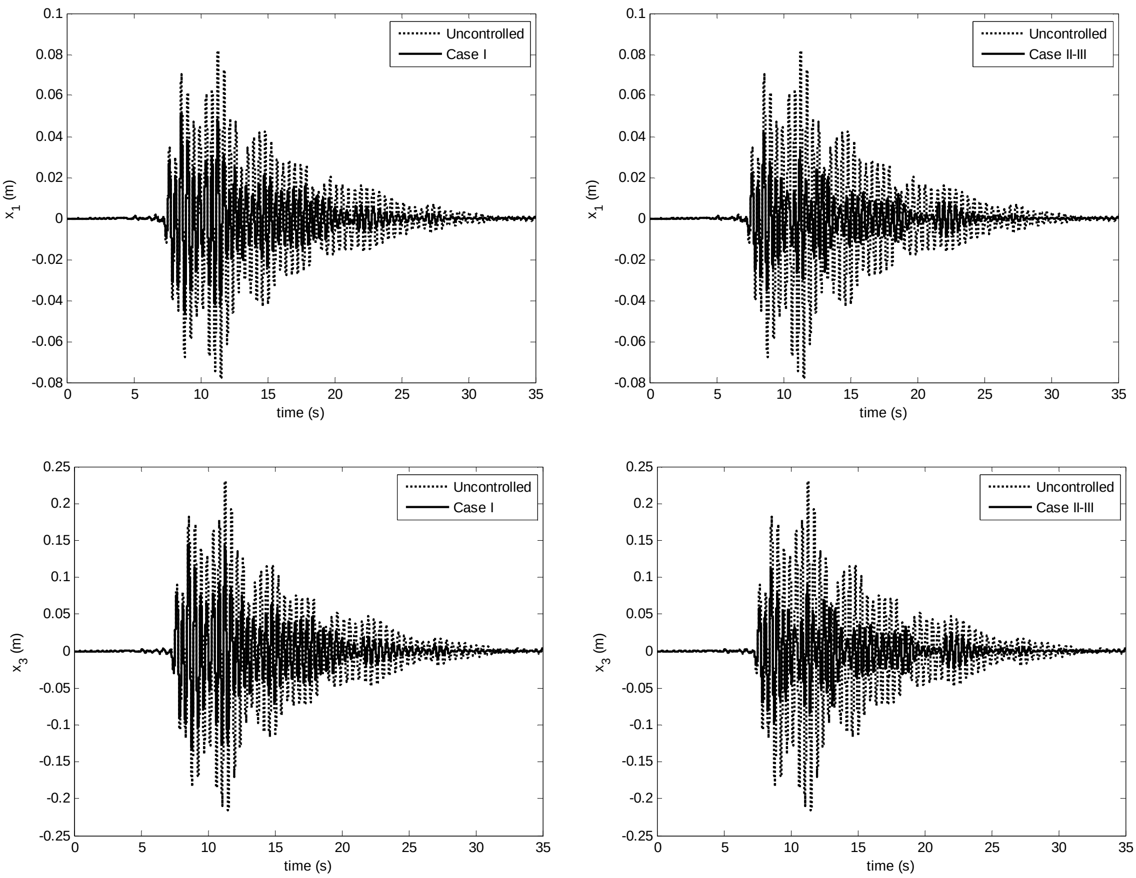

Fig. 6 First and top story displacement plots for velocity feedback control (Kobe excitation)

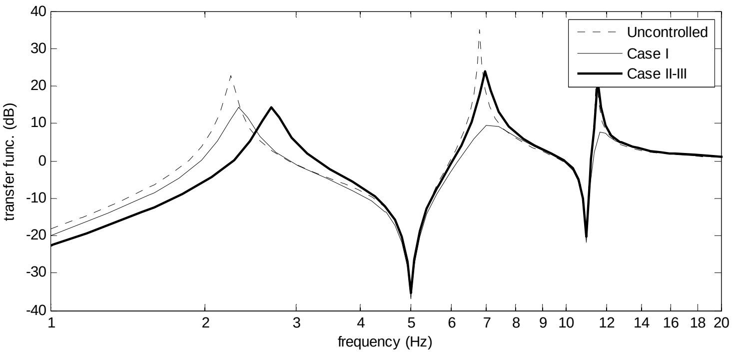

Fig. 7 First story acceleration transfer function plot for velocity feedback control

4.3 Acceleration feedback control

Controller parameters for acceleration feedback control and Case I are -0.00019 s^2, 0.001 s and 0.015 s for K_d, T_d and T_i, respectively. K_d, T_d and T_i are -0.0001 s^2, 0.0005 s and 0.01 s for the other cases, respectively. The maximum responses are obtained as seen in Table 5.

Table 5 Maximum responses of controlled structure for acceleration feedback control

	Excitation	Displacement (cm)			Velocity (m/s)			Acceleration (m/s^2)			Control force (N)
	Story	1	2	3	1	2	3	1	2	3	
Uncontrolled	Kobe	8.17	18.0	23.0	1.17	2.47	3.11	22.3	35.1	46.8	-
	Imperial Valley	2.87	5.9	7.2	0.37	0.72	1.00	10.2	15.2	15.4	-
	Erzincan	1.81	3.7	4.7	0.23	0.47	0.63	6.0	7.6	9.2	-
	Loma Prieta	6.32	13.0	16.1	0.71	1.58	2.18	19.0	29.4	29.5	-
	Northridge	6.29	13.4	17.0	0.83	1.90	2.51	20.8	28.2	32.1	-
CASE I	Kobe	5.10	10.8	13.6	0.60	1.33	1.72	14.7	21.9	25.4	9276.8
	Imperial Valley	1.67	3.5	4.4	0.19	0.43	0.58	5.4	8.0	8.6	3044.6
	Erzincan	1.67	3.5	4.5	0.13	0.29	0.37	4.9	7.0	8.6	2137.2
	Loma Prieta	4.16	8.9	11.3	0.51	1.12	1.48	10.7	18.0	22.0	7847.9
	Northridge	5.21	11.2	14.3	0.64	1.51	2.02	12.9	23.7	27.5	9960.3
CASE II-III	Kobe	2.82	5.8	7.2	0.30	0.67	0.88	11.3	12.9	12.9	3659.4
	Imperial Valley	0.93	1.9	2.4	0.12	0.25	0.39	4.6	5.6	5.2	1608.7
	Erzincan	1.44	3.0	3.8	0.09	0.22	0.31	5.1	6.5	7.8	1163.0
	Loma Prieta	1.96	4.0	5.0	0.23	0.50	0.69	8.7	9.9	11.7	2909.3
	Northridge	3.04	6.5	8.2	0.39	0.85	1.05	9.0	15.9	19.1	4845.3

Similar to the other feedbacks, Northridge excitation is the most critical one for active controlled structure. Generally, best reductions are obtained in this feedback with a perfect steady state response as seen in Fig. 8.

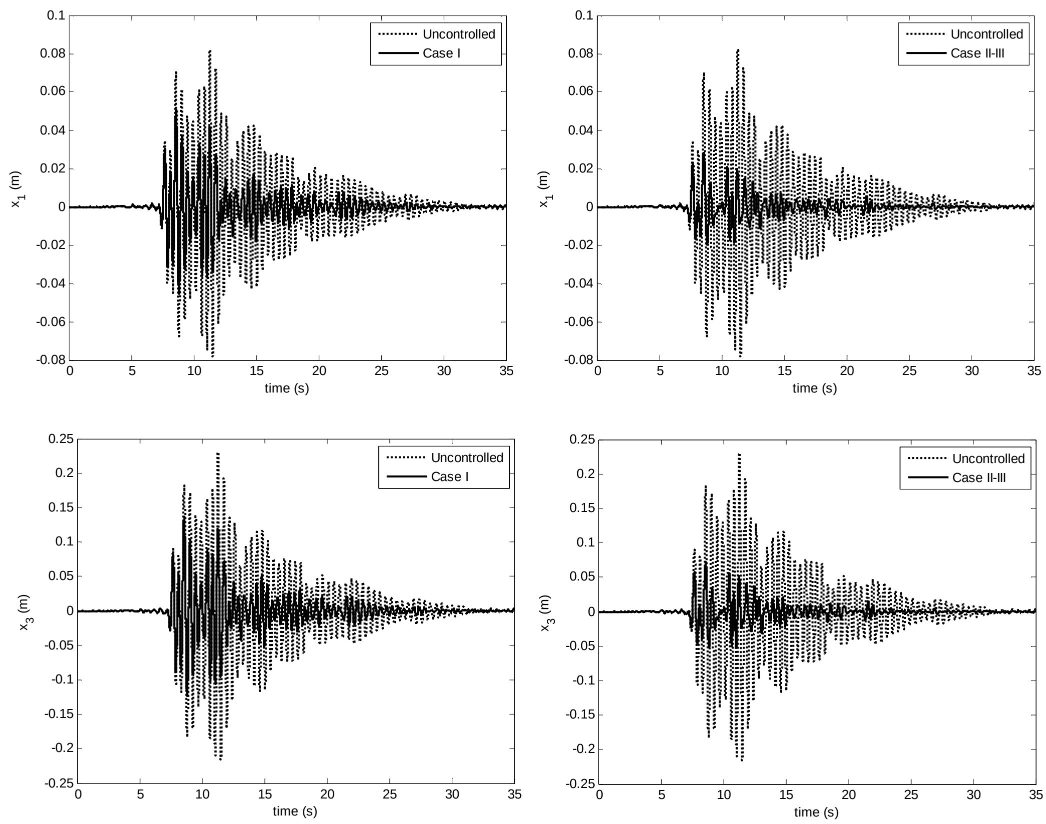

Fig. 8 First and top story displacement plots for acceleration feedback control (Kobe excitation)

In Case I, the reduction percentages are between 16-42, 19-49 and 14-47 for displacement, velocity and acceleration, respectively and for the other cases, reduction percentages are between 20-69, 53-74 and 40-73 for displacement, velocity and acceleration, respectively. Cases II-III has the best frequency response as seen in Fig. 9.

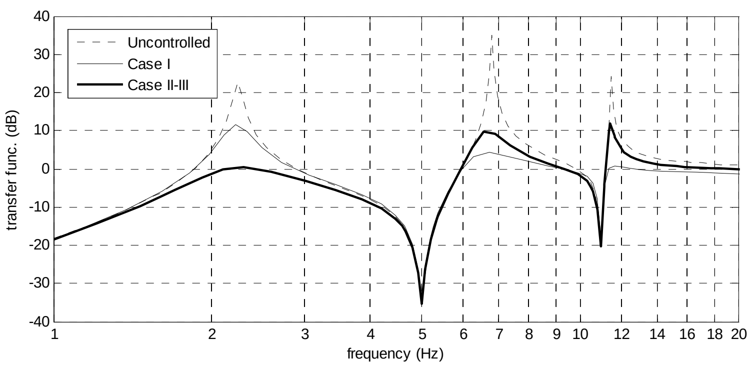

Fig. 9 First story acceleration transfer function plot for acceleration feedback control

4.4 Robustness of the control system

Control systems may lose their efficacy if period (or frequency) of the structure change. In order to investigate this, mass or stiffness of the structure may be changed by an amount.

The robustness of the control systems were evaluated for all feedbacks and cases. The total mass of the structure was changes between 70% and 130% with 5% differences in order to see any stability problem or a performance lost. In Table 6, maximum displacements for the most critical excitation are given. Also, maximum control forces are given in Table 7.

Table 6 Maximum displacements for different mass of structure (m)

Mass (%)	Uncont. structure	DFC Case I	DFC Case II-III	VFC Case I	VFC Case II-III	AFC Case I	AFC Case II-III
70	0.0497	853.8048	0.0241	1.399E+63	2.83E+64	0.0396	0.0215
75	0.0581	5.8213	0.0265	2.41E+27	1.259E+32	0.0423	0.0233
80	0.0577	0.0592	0.0284	0.0441	203.8654	0.0449	0.0250
85	0.0608	0.0507	0.0304	0.0466	0.0370	0.0473	0.0266
90	0.0626	0.0533	0.0323	0.0488	0.0392	0.0494	0.0280
95	0.0691	0.0549	0.0336	0.0504	0.0412	0.0509	0.0293
100	0.0817	0.0560	0.0352	0.0515	0.0428	0.0521	0.0304
105	0.0822	0.0584	0.0361	0.0545	0.0451	0.0535	0.0313
110	0.0834	0.0621	0.0374	0.0568	0.0523	0.0551	0.0322
115	0.0852	0.0651	0.0395	0.0604	0.0578	0.0571	0.0339
120	0.0843	0.0666	0.0406	0.0628	0.0580	0.0588	0.0352
125	0.0840	0.0671	0.0416	0.0639	0.0627	0.0594	0.0363
130	0.0815	0.0663	0.0433	0.0639	0.0632	0.0590	0.0372

Table 7 Maximum control forces for different mass of structure (N)

Mass (%)	DFC Case I	DFC Case II-III	VFC Case I	VFC Case II-III	AFC Case I	AFC Case II-III
70	9.489E+08	3568.094987	1.7512E+70	4.1547E+71	9461.48233	3532.412646
75	6281300	3652.76007	3.1928E+34	1.9610E+39	9854.797976	3780.301557
80	61170.06556	4129.001094	8688.258028	3399899884	10168.62276	4044.018781
85	7536.274835	4364.420584	8578.263875	4685.189855	10300.54856	4308.367235
90	7467.730179	4683.861646	8860.298441	4381.852333	10307.79504	4531.951541
95	6936.581632	4993.75192	9088.005509	4081.444244	10138.64734	4759.79686
100	7205.213258	4989.70686	9577.875474	4042.344195	9960.339118	4845.308194
105	7250.904481	5323.0819	10220.6572	4508.828542	9934.731953	4951.784104
110	7711.436973	5213.869781	10739.95983	4942.887697	10525.16211	4950.794759
115	8228.272851	5266.181351	11054.77634	5142.133193	10956.01199	4960.498045
120	8390.906598	5270.260675	11500.43733	5583.565753	11163.82673	4905.603378
125	8259.632153	5190.572984	11641.95959	5656.835486	11233.86122	4810.598423
130	8127.445484	5149.165057	11555.8176	6733.739281	11146.10069	5057.703308

Although the performance of control system is a little reduced for the increase of mass of the structure (increase of the period), a stability problem is not seen. The minimum performance lost is seen for acceleration feedback control. Due to decrease of earthquake forces, the displacement of the structure is getting lower by the decrease of the mass. After -20% mass different, stability problem is observed for Case I of displacement and velocity feedback controls. Case II and III of velocity feedback control is stabile up to -15% while other control types are not an issue of a stability problem. In some mass differences, the maximum control force exceeds the limits used in tuning process. This situation is especially seen for velocity feedback control (up to 35%).

The variation of stiffness of the structure was also evaluated. For different stiffness values, maximum displacements and control forces are given in Tables 8 and 9, respectively. For the variation of the stiffness values, a stability problem is not seen for all feedback controls. Additionally, only a feasible increase on the maximum control forces is seen.

Table 8 Maximum displacements for different stiffness of structure (m)

Stiffness (%)	Uncont. structure	DFC Case I	DFC Case II-III	VFC Case I	VFC Case II-III	AFC Case I	AFC Case II-III
70	0.0889	0.0571	0.0401	0.0550	0.0558	0.0511	0.0353
75	0.0794	0.0612	0.0383	0.0582	0.0551	0.0535	0.0341
80	0.0800	0.0631	0.0378	0.0591	0.0526	0.0547	0.0331
85	0.0803	0.0630	0.0370	0.0579	0.0530	0.0543	0.0321
90	0.0811	0.0607	0.0358	0.0551	0.0492	0.0534	0.0309
95	0.0806	0.0577	0.0351	0.0537	0.0441	0.0527	0.0304
100	0.0817	0.0560	0.0352	0.0515	0.0428	0.0521	0.0304
105	0.0711	0.0556	0.0347	0.0511	0.0421	0.0517	0.0303
110	0.0633	0.0547	0.0346	0.0504	0.0412	0.0510	0.0301
115	0.0624	0.0536	0.0338	0.0493	0.0401	0.0501	0.0297
120	0.0604	0.0519	0.0334	0.0480	0.0390	0.0489	0.0293
125	0.0607	0.0504	0.0327	0.0466	0.0386	0.0476	0.0289
130	0.0644	0.0490	0.0320	0.0453	0.0375	0.0463	0.0284

Table 9 Maximum control forces for different stiffness of structure (N)

Stiffness (%)	DFC Case I	DFC Case II-III	VFC Case I	VFC Case II-III	AFC Case I	AFC Case II-III
70	6565.74867	4628.783194	9952.253851	6265.029863	9237.401136	4503.018267
75	7217.907296	4777.004262	10507.59269	5859.690123	9807.519051	4376.851539
80	7619.057905	4984.652369	10782.92529	5222.628187	10262.12891	4326.670088
85	7800.917247	5135.354314	10607.98178	4970.666114	10380.14279	4562.185744
90	7439.697877	5083.775163	10440.33607	4696.92488	10165.67632	4691.264838
95	7129.497009	5252.808981	10062.25038	4409.779787	9737.67695	4812.963852
100	7205.213258	4989.70686	9577.875474	4042.344195	9960.339118	4845.308194
105	7039.124111	5109.319009	9213.608084	3913.405707	10272.01891	4941.739966
110	7660.356177	4765.069098	9100.074231	4041.938693	10585.74904	4892.467056
115	7631.656004	4858.717571	8938.352673	4052.105126	10788.62692	4888.683732
120	7862.226305	4578.897765	8705.604588	4010.764421	10889.05489	4770.167333
125	9393.461139	4555.754461	8448.374433	3964.942132	10936.68736	4684.361131
130	22585.89992	4385.707642	8379.791679	3905.709419	10880.01548	4586.517614

5. Conclusions

As a conclusion, all types of feedbacks are effective and generally robust for active control of seismic structures. When the efficiency of control system and robustness against the changing properties of the structure are evaluated, acceleration feedback control is the most useful one. In addition to that, an important performance index is the content of the base excitation. The best reductions for Erzincan earthquake is obtained for velocity feedback control. Erzincan excitation has a significant high PGV, although it has average PGA and PGV and has minimal effect on the structure used as numerical example. For that reason, type of excitation is an important factor for active control. The usage of excitations that characterizes the geophysical content of the region is effective on tuning and efficiency of controller system. Thus, a suitable feedback can be chosen.

Other important factors in active control are time delay and control force limits. These performance indexes can be considered in the tuning process of the controller. For changing properties of structure, the maximum value of control force may exceed the limit. This situation may prevent the process of active control or time delay of the system may be getting longer and stability of the structure mat be lost. For that reason, limit of the control force must be taken as lower than the expected in tuning process and the robustness of the system must be evaluated.

In this study, robustness of the structure is evaluated for the increase and decrease of the mass and stiffness. This situation will dramatically change the frequency content of the structure. All feedback controls are generally robust. Acceleration feedback control preserves its robustness and performance for ±30% mass and stiffness difference. Stability problems are only observes for the decrease of the mass for displacement and velocity feedback controls. The critical period of the structure in numerical example is 0.45 s. By the decrease of the mass, the period of the structure and seismic responses of structure are getting lower. For small periods, an acceleration spectrum of an earthquake may be very changeable according to soil conditions. In tuning of active controllers and dynamic analyses, a mass of structure is assumed according live and dead loads on the structure. Using the mass of a highly loaded structure in tuning of controllers may result with stability problems.

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