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Research Article

Optimization of PID controller parameters for active control of single degree of freedom structures

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ABSTRACT

In active control of structures, the parameters of controllers used application must be perfectly tuned. In that case, a good vibration reduction performance can be obtained without a stability problem. During the tuning process, the limit of control force and time delay of controller system must be considered for applicable design. In the study, the optimum parameters of Proportional-Derivative-Integral (PID) type controllers that are proportional gain (K), integral time (T_i) and derivative time (T_d) were optimized by using teaching learning-based optimization (TLBO). TLBO is a metaheuristic algorithm imitating the teaching and learning phases of education in classroom. The optimization was done according to the responses of the structure under a directivity pulse of near fault ground motions. In the study, time delay was considered as 20 ms and the optimum parameters of PID controller for a single degree of freedom (SDOF) structural model was found for different control force limits. The performances and feasibility of the method were evaluated by using sets of near fault earthquake records.

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1. Introduction

In structural control, active control methods are generally the best option due to high energy damping, but practical application of active control systems is not preferred because of several disadvantages. These disadvantages are time delay, stability problem and physical application of control force. These factors need to be detailly investigated.

In the last decade, several studies about active control of structures have been conducted. These studies include several types of control algorithms such as proportional integral (PID) (Nigdeli and Boduroğlu, 2013; Ulusoy et al, 2018; Nigdeli and Boduroğlu, 2014) H∞ control (Chang and Lin, 2009; Lin et al., 2010) direct adaptive control (Bitaraf et al., 2012), wavelet-based adaptive pole assignment control (Amini and Samani, 2014), self-constructing wavelet neural network algorithm (Wang and Adeli, 2015), decentralized network control (Bakule et al., 2016), sliding mode control (Yang et al., 1997; Wu et al., 1998), linear quadratic regulator (LQR) (Aldemir and Bakioğlu, 2001) and fuzzy control (Nazarimofrad and Zahrai, 2017) to reduce the structural responses and to investigate some disadvantages of control systems.

In the present study, active tendon control of structure was presented by using PID type controllers. The tuning of PID controller was done by employing a metaheuristic method called teaching learning-based optimization (TLBO) (Rao et al., 2011). The performance of the system is evaluated by using different control force limits and a wide range historical ground motions presented in FEMA P695: Quantification of Building Seismic Performance Factors (FEMA, 2009).

2. Methodology

In Fig. 1, a single degree of freedom (SDOF) structure with active tendons is shown. The structural parameters

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such as mass, stiffness and damping coefficients are shown as m_1, k_1 and c_1, respectively. R is the pre-stress force, which is adjusted at control of structure in dynamic state. The properties of tendon are the stiffness (k_c) and angle respect to ground (α). u_1 is the control signal provided by PID controller. The equation of motion and the equation of control signal (u_1) are given as Eqs. (1) and (2), respectively. The PID parameters are proportional gain (K_p), Integral Time (T_i) and derivative time (T_d) and these parameters are optimized. $e(t)$ is the error signal, which is taken as the velocity of structure respect to ground ($\dot{x}_1$). x_1 is the displacement of structure and the earthquake acceleration is shown as $\ddot{x}_{\sigma}$.

$$m_1\ddot{x}(1)+c_1\dot{x}(t)+k_1x(t)=-m_1\ddot{x}_g-4k_cu_1\cos\alpha \tag{1}$$

$$u_1=K_P\left[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}\right] \tag{2}$$

$$e(t)=x_r-x \tag{3}$$

x_r is taken as zero to minimize the displacement of structure. In that case, the final equation of control signal is as follows:

$$u_1=K_P\left[-x+\frac{1}{T_i}\int_0^t -xdt+T_d\frac{d}{dt}\right] \tag{4}$$

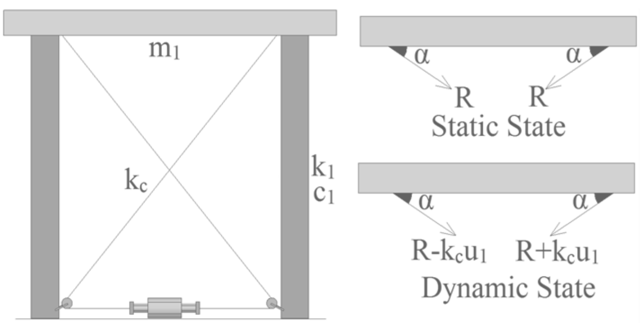

Fig. 1. The shear building model.

During the optimization process, a directivity pulse with 1.5s period and 230 cm/s peak ground velocity is used. The near fault pulse is generated according to the equations of Makris (Makris, 1997). The delay of control signal is taken as 20ms. A limit taken for the control signal and the objective function is penalized for the violations of the limit. The stages of the optimization process are summarized as follows:

- Define problem parameters and ranges of design variables (PID controller parameters)
- Generate candidate design variable solutions randomly and calculate the objective function value by using dynamic analysis.
- Start optimization process.
- Modify existing candidate solutions by using teacher phase considering the best existing solution and update solutions with minimum objective function.
- Modify existing candidate solutions by using learner phase considering two existing solutions and update solutions with minimum objective function.
- Continue optimization process for several iterations.

3. Numerical Examples

The constant parameters such as m_1, k_1, c_1, α and k_c are 2924 kg, 1.39 MN/m, 1.581 kNs/m, 360 and 372.1 kN/m, respectively. The maximum control force is limited to 10%, 30% and 50% of the weight of the structure. The optimum results are given as Table 1 and flowchart of the optimization process is given in Fig. 2. The maximum displacement under impulsive pulse is 3.77 cm for uncontrolled structure. This value reduces to 3.5 cm, 2.96 cm and 2.46 cm by using several amount of control forces.

Table 1. The optimum results.

Control limit	K_p	T_d	T_i	x_1 (m)
10%	-0.0168	0.3010	0.9086	0.0350
30%	-0.0185	1.0219	1.4020	0.0296
50%	-0.0544	0.6298	2.6096	0.0246

4. Discussion and Results

The optimum PID parameters were validated by using sets of near-fault ground excitation records. As presented in FEMA P695, the benchmark earthquake records with and without pulse were shown in Tables 2 and 3, respectively.

The maximum displacement, acceleration, control signal and force values for different levels of control force were presented in Tables 4-6 for records without pulse. The maximum displacement is 9.71 cm for uncontrolled structure. This maximum value occurs under fault parallel (FP) component of LA-Sepulveda VA record of 1994 Northridge earthquake. For this excitation, active control system is very effective. The maximum displacement reduces to 5.86 cm, 3.15cm and 2.59 cm by using 10%, 30% and 50% control force, respectively. For the structure with active tendon control, the critical excitation is the fault normal (FN) component of Cape Mendocino record of Cape Mendocino earthquake. By this excitation, the displacement, acceleration and control force plots are given as Figs. 3-5, respectively. As seen from the plots, the active control system is always effective in obtaining a quick damping. For the peak value of vibrations, reduction can be seen, but the reduction is significant for 30% and 50% control force. The reduction percentages of displacements are 16.28%, 38.08% and 50.77% for 10%, 30% and 50% control force, respectively. Although the optimization objective is the displacement of the structure, a significant effect on acceleration can be also seen. For the other excitations with pulse, the maximum responses are presented as Tables 7-9. The critical excitation for structure with and without control is FP component of Sylmar-Olive View record of 1994 Northridge earthquake and the displacement, acceleration and control force plots are presented as Figs. 6-8, respectively. Similar conclusion of records without pulse can be also seen for records with pulse, but the active control system is more effective for the records with pulse since the optimization is done for a directivity pulse. In that case, the reduction percentages of maximum displacement under the critical excitation are 23.93%, 53.28% and 68.2% for 10%, 30% and 50% control force, respectively. As the conclusion, the control parameters optimized by using teaching learning- based optimization are robust under different types of near fault records.

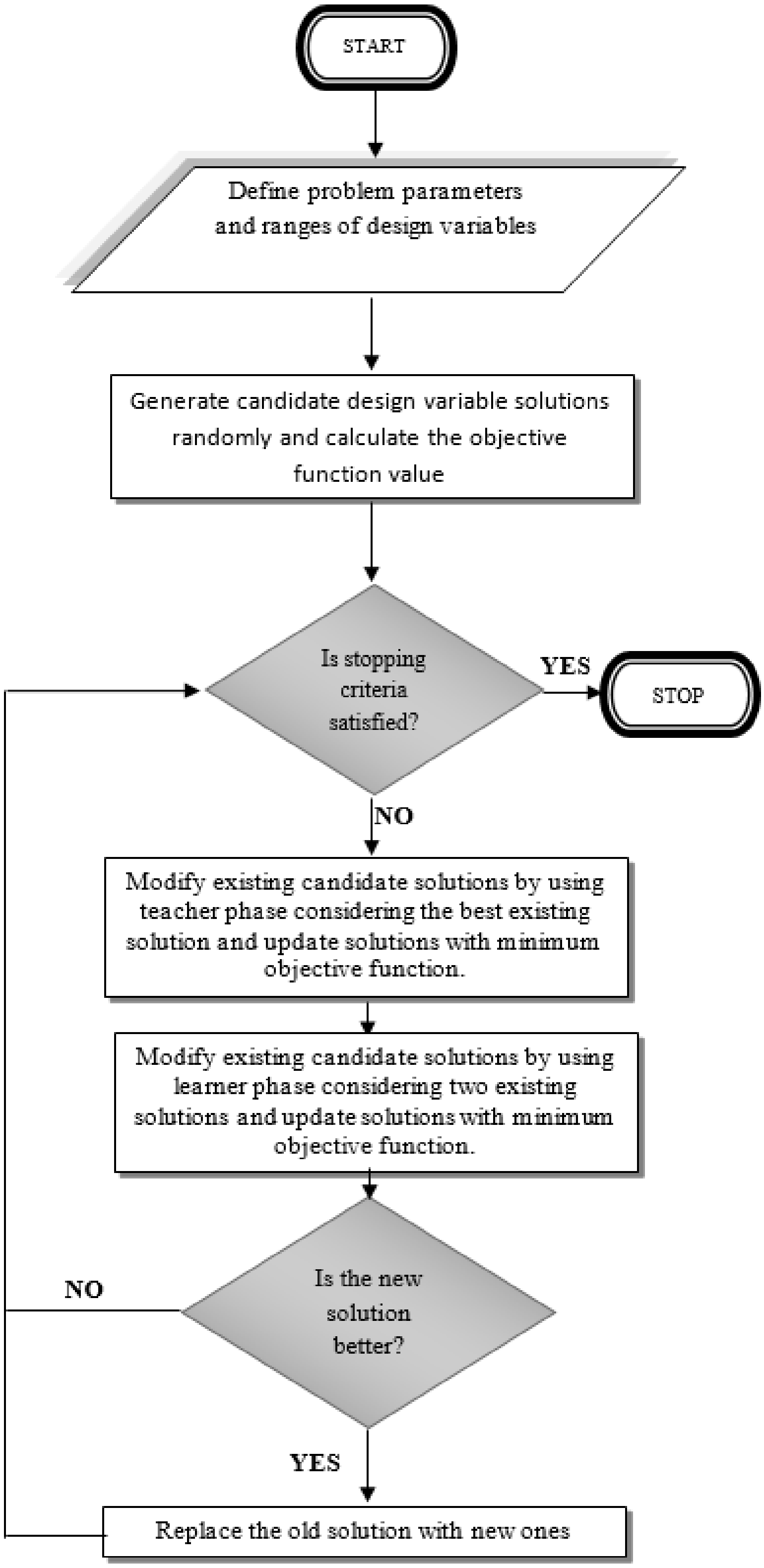

Fig. 2. Flowchart of the optimization process.

Table 2. Earthquake set for near-field excitations with pulses.

Earthquake No.	Earthquake Name	Recording Station	Year	Magnitude
1	Irpinia, Italy-01	Sturno	1980	6.9
2	Superstition Hills-02	Parachute Test Site	1987	6.5
3	Duzce, Turkey	Duzce	1999	7.1
4	Erzican, Turkey	Erzican	1992	6.7
5	Imperial Valley-06	El Centro Array #6	1979	6.5
6	Imperial Valley-06	El Centro Array #7	1979	6.5
7	Kocaeli, Turkey	Izmit	1999	7.5
8	Landers	Lucerne	1992	7.3
9	Cape Mendocino	Petrolia	1992	7.0
10	Northridge-01	01 Rinaldi Receiving Sta	1994	6.7
11	Loma Prieta	Saratoga – Aloha	1989	6.9
12	Northridge-01	01 Sylmar – Olive View	1994	6.7
13	Chi-Chi, Taiwan	TCU065	1999	7.6
14	Chi-Chi, Taiwan	TCU102	1999	7.6

Table 3. Earthquake set for near-field excitations without pulses.

Earthquake No.	Earthquake Name	Recording Station	Year	Magnitude
1	Northridge-01	LA - Sepulveda VA	1994	6.7
2	Loma Prieta	Bran	1989	6.9
3	Loma Prieta	Corralitos	1989	6.9
4	Cape Mendocino	Cape Mendocino	1992	7.0
5	Gazli, USSR	Karakyr	1976	6.8
6	Imperial Valley-06	Bonds Corner	1979	6.5
7	Imperial Valley-06	Chıhuahua	1979	6.5
8	Denali, Alaska	TAPS Pump Sta. #10	2002	7.9
9	Nahanni, Canada	Site 1	1985	6.8
10	Nahanni, Canada	Site 1	1985	6.8
11	Northridge-01	Northridge – Saticoy	1994	6.7
12	Chi-Chi, Taiwan	TCU067	1999	7.6
13	Chi-Chi, Taiwan	TCU084	1999	7.6
14	Kocaeli, Turkey	Yarimca	1999	7.5

Table 4. The maximum responses of SDOF under near-fault ground motions without pulse (0.1 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	4.29	2.41	20.40	11.92	0.23	5.60	2.75
	FP	9.71	5.86	46.17	29.87	0.64	14.1	7.65
2	FN	3.57	2.72	17.00	13.85	0.29	6.24	3.50
	FP	4.37	2.88	20.80	14.63	0.34	7.92	4.10
3	FN	5.96	4.42	28.32	22.63	0.50	11.6	6.07
	FP	3.33	1.90	15.82	9.65	0.23	6.24	2.76
4	FN	7.80	6.53	37.10	33.41	0.76	18.2	9.09
	FP	3.31	2.73	15.72	14.11	0.33	10.8	4.03
5	FN	4.75	3.11	22.60	15.83	0.32	7.78	3.86
	FP	3.82	2.15	18.18	11.00	0.22	5.37	2.70
6	FN	3.33	2.02	15.84	10.23	0.21	5.40	2.51
	FP	5.55	3.67	26.40	18.50	0.35	8.50	4.27
7	FN	1.83	1.57	8.72	8.05	0.18	4.35	2.20
	FP	1.69	1.14	8.05	5.78	0.11	2.81	1.34
8	FN	1.57	1.28	7.48	6.36	0.09	1.82	1.04
	FP	1.48	0.81	7.04	4.04	0.08	1.71	0.96
9	FN	4.70	2.71	22.36	13.79	0.31	6.85	3.68
	FP	4.17	2.42	19.83	12.43	0.25	6.35	3.01
10	FN	1.73	1.51	8.22	7.64	0.14	3.45	1.65
	FP	1.08	0.84	5.13	4.20	0.09	2.30	1.08
11	FN	2.83	1.76	13.45	8.92	0.17	4.57	2.00
	FP	3.71	2.01	17.65	10.08	0.21	4.18	2.48
12	FN	2.35	1.77	11.18	8.80	0.18	4.06	2.12
	FP	3.06	1.66	14.56	8.39	0.16	3.20	1.99
13	FN	4.45	3.10	21.16	15.44	0.27	5.70	3.29
	FP	2.89	2.21	13.74	11.26	0.23	5.40	2.76
14	FN	2.54	1.30	12.09	6.58	0.14	2.98	1.64
	FP	1.57	1.21	7.44	6.10	0.11	2.58	1.36

Table 5. The maximum responses of SDOF under near-fault ground motions without pulse (0.3 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	4.29	2.13	20.40	11.53	0.76	22.76	9.15
	FP	9.71	3.15	46.17	18.56	1.22	31.95	14.7
2	FN	3.57	1.52	17.00	8.80	0.51	14.41	6.10
	FP	4.37	1.64	20.80	9.39	0.64	17.81	7.71
3	FN	5.96	2.46	28.32	14.91	1.02	24.38	12.2
	FP	3.33	1.27	15.82	7.85	0.66	18.73	7.91
4	FN	7.80	4.83	37.10	28.90	2.05	56.57	24.7
	FP	3.31	1.72	15.72	11.34	0.90	32.18	10.9
5	FN	4.75	1.59	22.60	9.60	0.63	18.00	7.56
	FP	3.82	1.22	18.18	7.41	0.55	19.38	6.63
6	FN	3.33	1.33	15.84	8.39	0.54	15.89	6.56
	FP	5.55	2.70	26.40	15.30	1.01	28.22	12.1
7	FN	1.83	0.93	8.72	5.93	0.44	10.71	5.29
	FP	1.69	0.64	8.05	3.78	0.22	6.020	2.68
8	FN	1.57	1.07	7.48	5.95	0.29	5.610	3.54
	FP	1.48	0.06	7.04	3.31	0.21	4.080	2.47
9	FN	4.70	1.14	22.36	7.01	0.50	17.59	6.00
	FP	4.17	1.60	19.83	9.75	0.66	19.64	8.00
10	FN	1.73	0.96	8.22	5.55	0.32	8.040	3.81
	FP	1.08	0.59	5.13	3.26	0.21	8.120	2.52
11	FN	2.83	1.16	13.45	7.03	0.52	15.06	6.28
	FP	3.71	1.42	17.65	8.02	0.56	11.24	6.76
12	FN	2.35	1.42	11.18	7.63	0.37	8.420	4.43
	FP	3.06	1.14	14.56	6.41	0.40	7.210	4.82
13	FN	4.45	2.96	21.16	16.30	0.85	17.95	10.2
	FP	2.89	1.41	13.74	8.37	0.58	14.64	7.02
14	FN	2.54	0.78	12.09	4.49	0.30	7.470	3.67
	FP	1.57	0.87	7.44	4.81	0.26	6.870	3.12

Table 6. The maximum responses of SDOF under near-fault ground motions without pulse (0.5 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	4.29	1.80	20.40	10.97	1.25	38.13	15.1
	FP	9.71	2.59	46.17	18.80	1.75	53.84	21.1
2	FN	3.57	1.09	17.00	7.45	0.80	24.24	9.64
	FP	4.37	1.33	20.80	8.69	0.87	32.29	10.5
3	FN	5.96	1.64	28.32	11.17	1.13	28.16	13.6
	FP	3.33	0.99	15.82	7.54	0.96	27.70	11.6
4	FN	7.80	3.84	37.10	27.61	3.03	91.14	36.5
	FP	3.31	1.26	15.72	11.33	1.40	58.34	16.9
5	FN	4.75	1.19	22.60	9.25	0.96	30.59	11.5
	FP	3.82	0.94	18.18	7.89	0.95	34.30	11.4
6	FN	3.33	1.08	15.84	8.31	0.80	33.52	9.65
	FP	5.55	1.83	26.40	13.95	1.60	50.31	19.3
7	FN	1.83	0.60	8.72	4.77	0.53	14.81	6.33
	FP	1.69	0.48	8.05	2.87	0.30	8.850	3.66
8	FN	1.57	0.83	7.48	5.45	0.47	8.110	5.63
	FP	1.48	0.61	7.04	3.59	0.34	7.890	4.04
9	FN	4.70	0.83	22.36	6.67	0.77	35.52	9.23
	FP	4.17	1.28	19.83	9.66	1.06	33.56	12.8
10	FN	1.73	0.66	8.22	4.38	0.41	11.82	4.90
	FP	1.08	0.47	5.13	3.57	0.40	16.21	4.79
11	FN	2.83	0.86	13.45	7.28	0.83	23.90	10.0
	FP	3.71	1.20	17.65	8.63	0.77	22.58	9.30
12	FN	2.35	1.14	11.18	7.12	0.56	11.87	6.74
	FP	3.06	0.91	14.56	6.21	0.56	10.69	6.68
13	FN	4.45	2.64	21.16	16.53	1.14	29.26	13.7
	FP	2.89	1.02	13.74	6.49	0.81	24.80	9.76
14	FN	2.54	0.64	12.09	4.19	0.42	11.25	5.10
	FP	1.57	0.74	7.44	4.54	0.38	11.60	4.53

The structural reactions of the single degree of freedom system under the effect of the earthquake records without 28 pulse vibrations are given in Tables 2-4 for the control limit 0.1, 0.3 and 0.5, respectively. The maximum displacement and total acceleration of the uncontrolled structure is 9.71 cm and 46.17 m/s^2 under FP component of EQ 2. In case with a control limit 0.1, the maximum displacement and total acceleration of the single degree of freedom system reduce to 6.53 cm and 33.41 m/s^2 under FN component of EQ 4. There is a significant reduction in the displacement and acceleration of all records. These reduction percentages are between 12.72% under FN Component of EQ 10 and 48.82% under FN component of EQ 14 in the displacement and between 7.05% under FN Component of EQ 10 and 45.57% under FN component of EQ 14 in the total acceleration. In addition, the maximum control signal and the control force are 0.76 cm and 9.09 kN under FN component of EQ 4, respectively. In the second case with a control limit 0.3, the maximum displacement and total acceleration of the single degree of freedom system reduce to 4.83 cm and 28.90 m/s^2 under FN component of EQ 4. The displacement and total acceleration values decreased by 26% and 13.50% compared to the previous situation but the required control force increased by 63.25%. In the last case with a control limit 0.5, the maximum displacement and total acceleration of the uncontrolled single degree of freedom system decreased to 3.84 cm and 27.61 m/s^2 with the increase of the control force limit under all records. As a result, a percentage decrease in displacement and acceleration value of 60.45% and 40.20% occurred, respectively. The required control force is 36.51 kN.

The structural reactions of the single degree of freedom system under the effect of the earthquake records with 28 pulse vibrations are given in Tables 7-9 for the control limit 0.1, 0.3 and 0.5, respectively. The maximum displacement and total acceleration of the uncontrolled structure is 6.12 cm and 29.12 m/s^2 under FP component of EQ 10. In case with a control limit 0.1, the maximum displacement and total acceleration of the single degree of freedom system reduce to 4.64 cm and 23.29 m/s^2 under FP component of EQ 12. There is a significant reduction in the displacement and acceleration of all records except FP component of EQ 6 in the total acceleration. This reduction percentages are between 3.64% under FP Component of EQ 6 and 48.06% under FN component of EQ 1 in the displacement and between 2.98% under FP Component of EQ 7 and 43.94% under FN component of EQ 14 in the total acceleration. In addition, the maximum control signal and the control force are 0.42 cm and 5.04 kN under FP component of EQ 12, respectively. In the second case with a control limit 0.3, the maximum displacement and total acceleration of the single degree of freedom system reduce to 2.85 cm and 16.00 m/s^2 under FP component of EQ 12. The displacement and total acceleration values decreased by 38.58% and 31.30% compared to the previous situation but the required control force increased by 56.55%. In the last case with a control limit 0.5, the maximum displacement and total acceleration of the uncontrolled single degree of freedom system decreased to 1.94 cm and 12.18 m/s^2 with the increase of the control force limit under all records. As a result, a percentage decrease in displacement and acceleration value of 68.30% and 58.17% occurred, respectively. The required control force is 14.8 kN.

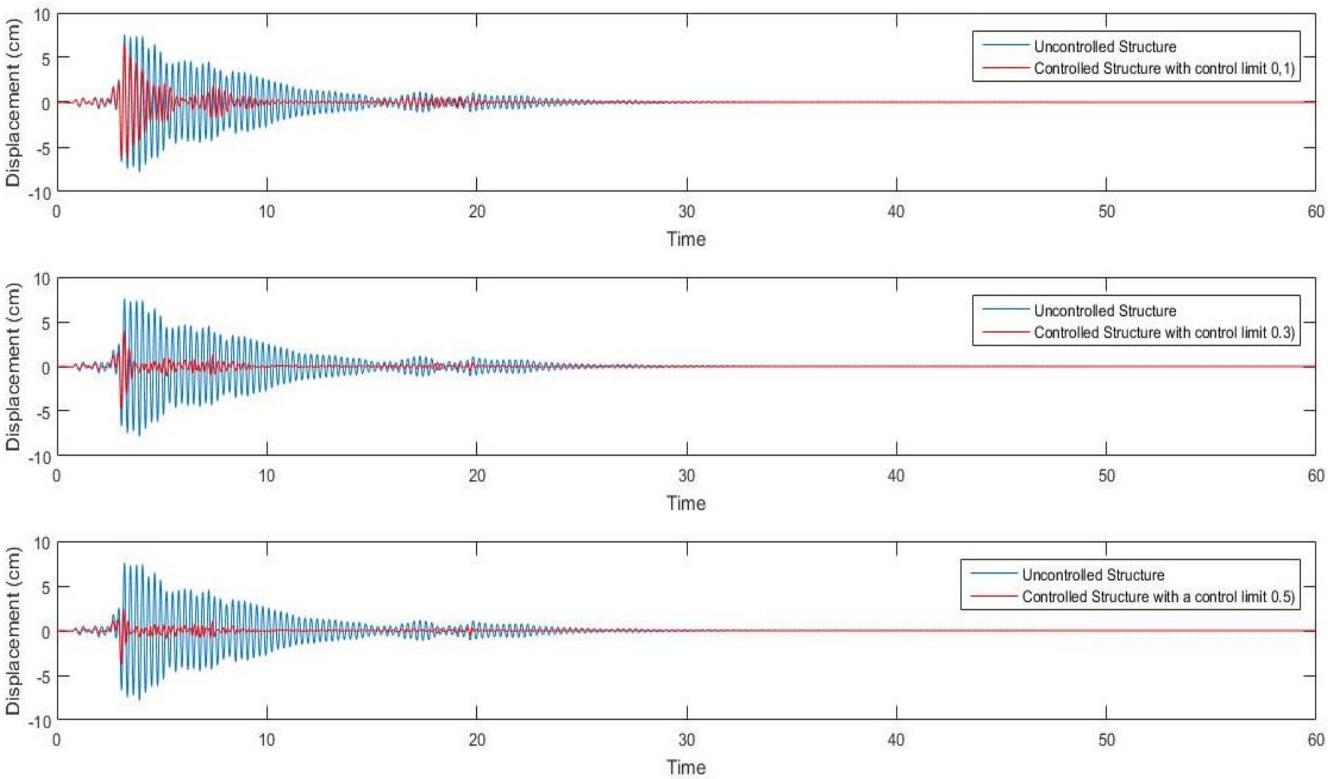

Fig. 3. Displacement time history of controlled and uncontrolled SDOF under Cape Mendocino, Cape Mendocino - FN component.

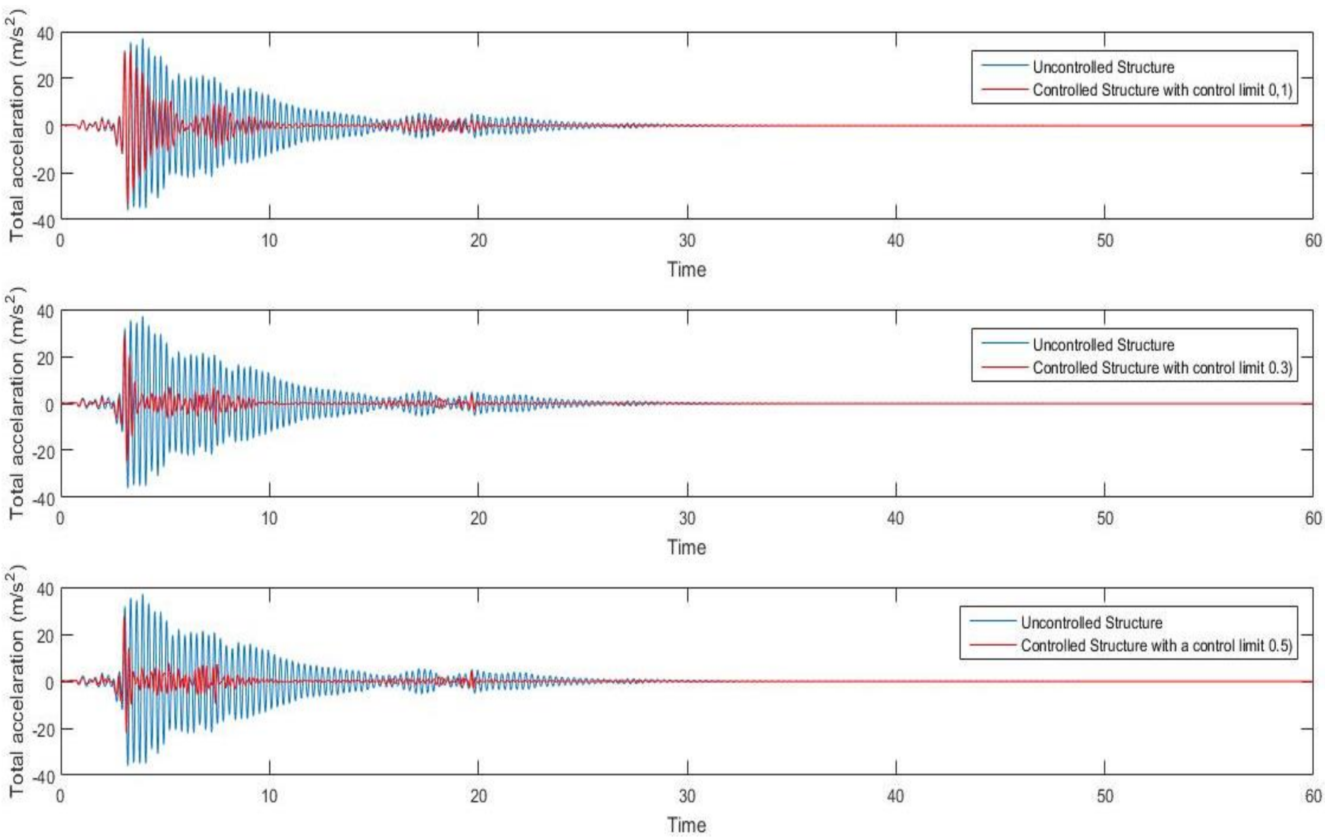

Fig. 4. Total acceleration time history of controlled and uncontrolled SDOF under Cape Mendocino, Cape Mendocino - FN component.

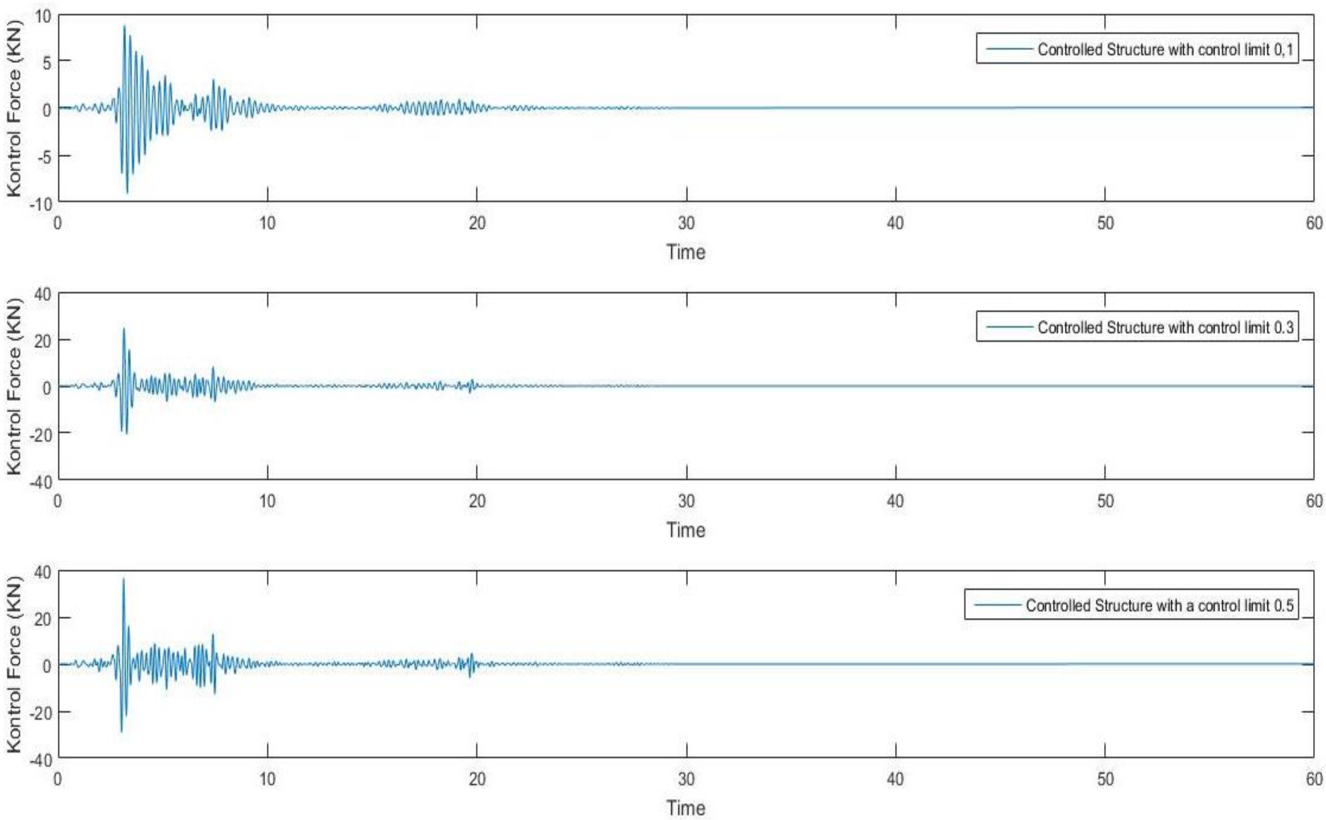

Fig. 5. Control force time history of controlled and uncontrolled SDOF under Cape Mendocino, Cape Mendocino - FN component.

Table 7. The maximum responses of SDOF under near-fault ground motions with pulse (0.1 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	2.33	1.21	11.06	6.20	0.13	2.79	1.61
	FP	3.50	1.92	16.66	9.77	0.20	4.69	2.39
2	FN	3.74	2.39	17.76	12.00	0.20	4.44	2.39
	FP	2.72	1.75	12.94	8.91	0.18	4.05	2.21
3	FN	3.23	2.30	15.35	11.61	0.21	4.38	2.59
	FP	2.55	2.18	12.14	11.00	0.20	3.92	2.41
4	FN	4.32	2.95	20.53	15.04	0.30	7.23	3.58
	FP	2.31	1.82	11.00	9.05	0.15	3.23	1.77
5	FN	2.07	1.58	9.85	8.00	0.15	3.15	1.77
	FP	2.65	1.64	12.61	8.34	0.18	4.45	2.18
6	FN	2.11	1.51	10.01	7.55	0.15	3.02	1.86
	FP	1.65	1.59	7.84	7.89	0.10	1.77	1.19
7	FN	3.02	2.27	14.37	11.62	0.26	5.71	3.12
	FP	1.69	1.52	8.05	7.81	0.18	4.00	2.14
8	FN	3.43	2.68	16.31	13.74	0.32	8.75	3.86
	FP	2.53	2.02	12.00	10.51	0.24	7.90	2.95
9	FN	3.33	1.82	15.85	9.27	0.21	4.75	2.58
	FP	2.86	2.22	13.58	11.26	0.24	5.18	2.83
10	FN	4.32	3.49	20.54	17.40	0.33	7.86	3.97
	FP	6.12	3.63	29.12	18.45	0.38	8.81	4.52
11	FN	2.88	1.72	13.70	8.76	0.20	4.60	2.41
	FP	1.15	0.89	5.46	4.48	0.11	2.77	1.34
12	FN	2.54	1.84	12.08	9.12	0.18	3.60	2.14
	FP	6.10	4.64	29.00	23.29	0.42	8.30	5.04
13	FN	3.63	2.51	17.26	12.62	0.25	5.78	3.03
	FP	2.85	1.70	13.54	8.46	0.16	3.26	1.87
14	FN	1.07	0.74	5.08	3.66	0.05	1.01	0.56
	FP	0.91	0.61	4.31	3.08	0.06	1.22	0.65

Table 8. The maximum responses of SDOF under near-fault ground motions with pulse (0.3 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	2.33	0.82	11.06	4.72	0.32	6.52	3.86
	FP	3.50	1.12	16.66	6.87	0.46	13.4	5.54
2	FN	3.74	1.37	17.76	7.61	0.33	8.40	3.91
	FP	2.72	1.17	12.94	6.86	0.46	11.9	5.57
3	FN	3.23	1.21	15.35	7.01	0.42	9.91	5.11
	FP	2.55	1.64	12.14	9.40	0.63	14.6	7.61
4	FN	4.32	1.80	20.53	10.98	0.72	18.4	8.73
	FP	2.31	1.49	11.00	8.08	0.31	8.14	3.78
5	FN	2.07	1.06	9.85	6.21	0.38	9.06	4.53
	FP	2.65	1.09	12.61	6.23	0.42	10.9	5.08
6	FN	2.11	0.95	10.01	5.15	0.30	7.01	3.62
	FP	1.65	1.33	7.84	7.20	0.30	5.45	3.57
7	FN	3.02	0.98	14.37	6.00	0.43	9.57	5.16
	FP	1.69	0.64	8.05	3.95	0.29	7.00	3.51
8	FN	3.43	1.47	16.31	9.57	0.71	25.3	8.52
	FP	2.53	1.23	12.00	7.48	0.57	23.7	6.92
9	FN	3.33	1.39	15.85	7.98	0.42	14.8	5.06
	FP	2.86	1.34	13.58	7.16	0.41	11.2	4.91
10	FN	4.32	2.66	20.54	14.84	0.83	19.8	10.0
	FP	6.12	1.91	29.12	11.57	0.80	18.7	9.67
11	FN	2.88	1.16	13.70	6.91	0.44	14.0	5.28
	FP	1.15	0.93	5.46	5.77	0.47	12.5	5.60
12	FN	2.54	1.48	12.08	7.80	0.44	9.27	5.33
	FP	6.10	2.85	29.00	16.00	0.96	18.8	11.6
13	FN	3.63	1.83	17.26	10.35	0.64	15.8	7.72
	FP	2.85	1.45	13.54	7.96	0.37	8.57	4.49
14	FN	1.07	0.66	5.08	3.34	0.13	2.54	1.58
	FP	0.91	0.46	4.31	2.46	0.13	2.79	1.62

Table 9. The maximum responses of SDOF under near-fault ground motions with pulse (0.5 control force limit).

EQ	CPNT	Displacement (cm)		Acceleration (m/s²)		Control		
		Uncontrolled	Controlled	Uncontrolled	Controlled	Signal (cm)	Velocity (cm/s)	Force (kN)
1	FN	2.33	0.63	11.06	4.55	0.41	12.46	4.93
	FP	3.50	0.92	16.66	7.64	0.91	28.16	11.0
2	FN	3.74	1.17	17.76	7.70	0.59	14.46	7.06
	FP	2.72	0.89	12.94	5.94	0.60	17.30	7.25
3	FN	3.23	0.85	15.35	5.64	0.55	13.60	6.60
	FP	2.55	1.36	12.14	8.76	0.81	21.49	9.80
4	FN	4.32	1.33	20.53	10.43	1.14	28.48	13.7
	FP	2.31	1.26	11.00	7.79	0.53	11.89	6.36
5	FN	2.07	0.72	9.85	5.00	0.46	17.94	5.52
	FP	2.65	0.93	12.61	5.38	0.52	17.33	6.24
6	FN	2.11	0.74	10.01	4.26	0.43	10.97	5.12
	FP	1.65	1.09	7.84	6.76	0.49	8.660	5.95
7	FN	3.02	0.61	14.37	4.42	0.48	14.23	5.82
	FP	1.69	0.42	8.05	3.05	0.33	8.750	3.92
8	FN	3.43	1.11	16.31	8.33	1.05	38.10	12.7
	FP	2.53	0.86	12.00	8.32	1.08	40.13	13.0
9	FN	3.33	1.20	15.85	8.10	0.60	24.63	7.17
	FP	2.86	1.34	13.58	8.48	0.66	23.23	7.91
10	FN	4.32	2.09	20.54	13.76	1.18	32.55	14.2
	FP	6.12	1.27	29.12	9.82	1.11	27.57	13.3
11	FN	2.88	1.06	13.70	7.46	0.75	23.38	9.08
	FP	1.15	0.86	5.460	6.60	0.79	25.97	9.54
12	FN	2.54	1.12	12.08	6.67	0.69	17.62	8.36
	FP	6.10	1.94	29.00	12.18	1.23	29.00	14.8
13	FN	3.63	1.64	17.26	10.74	1.00	26.86	12.0
	FP	2.85	1.29	13.54	8.09	0.58	17.36	7.02
14	FN	1.07	0.59	5.08	3.15	0.21	3.570	2.52
	FP	0.91	0.38	4.31	2.29	0.18	3.740	2.21

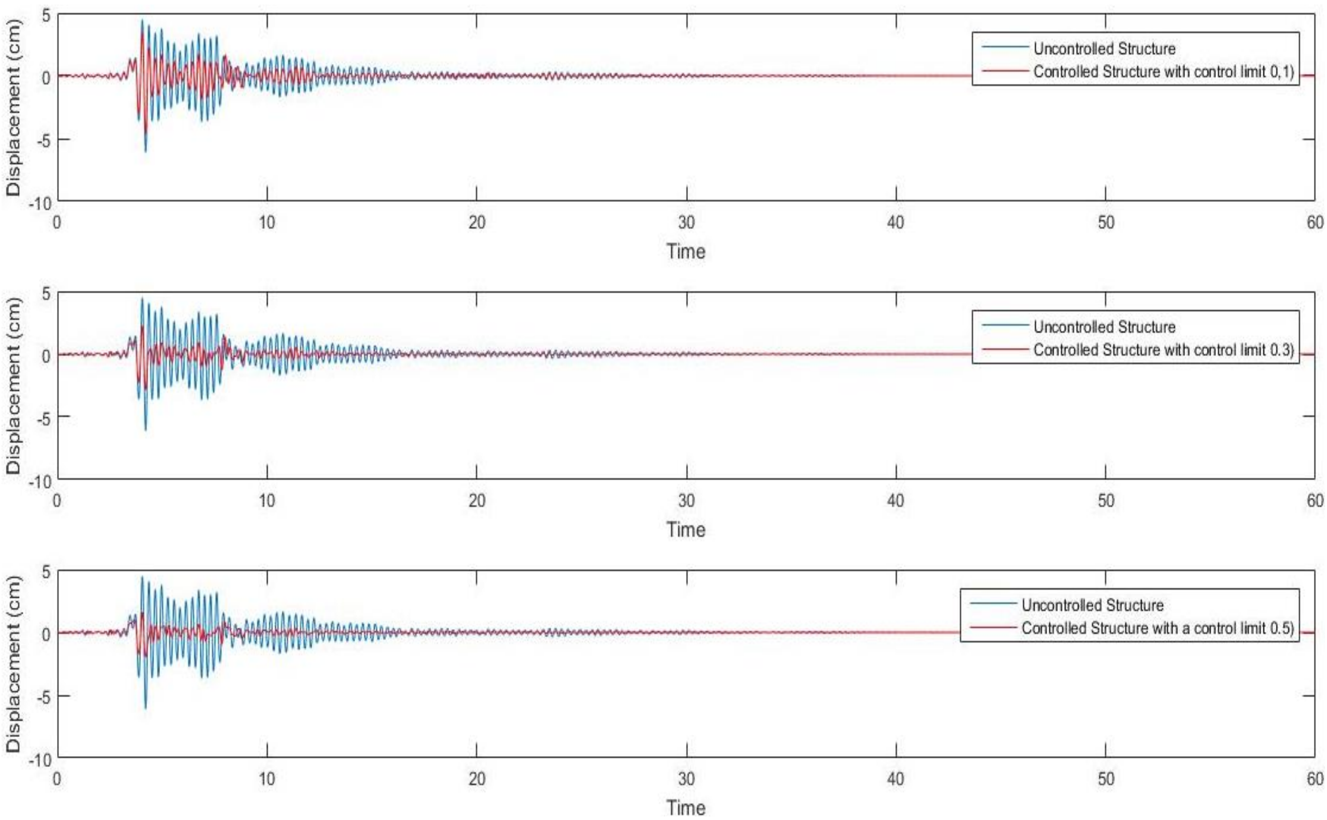

Fig. 6. Displacement time history of controlled and uncontrolled SDOF under Northridge-01, 01 Sylmar - Olive View- FP component.

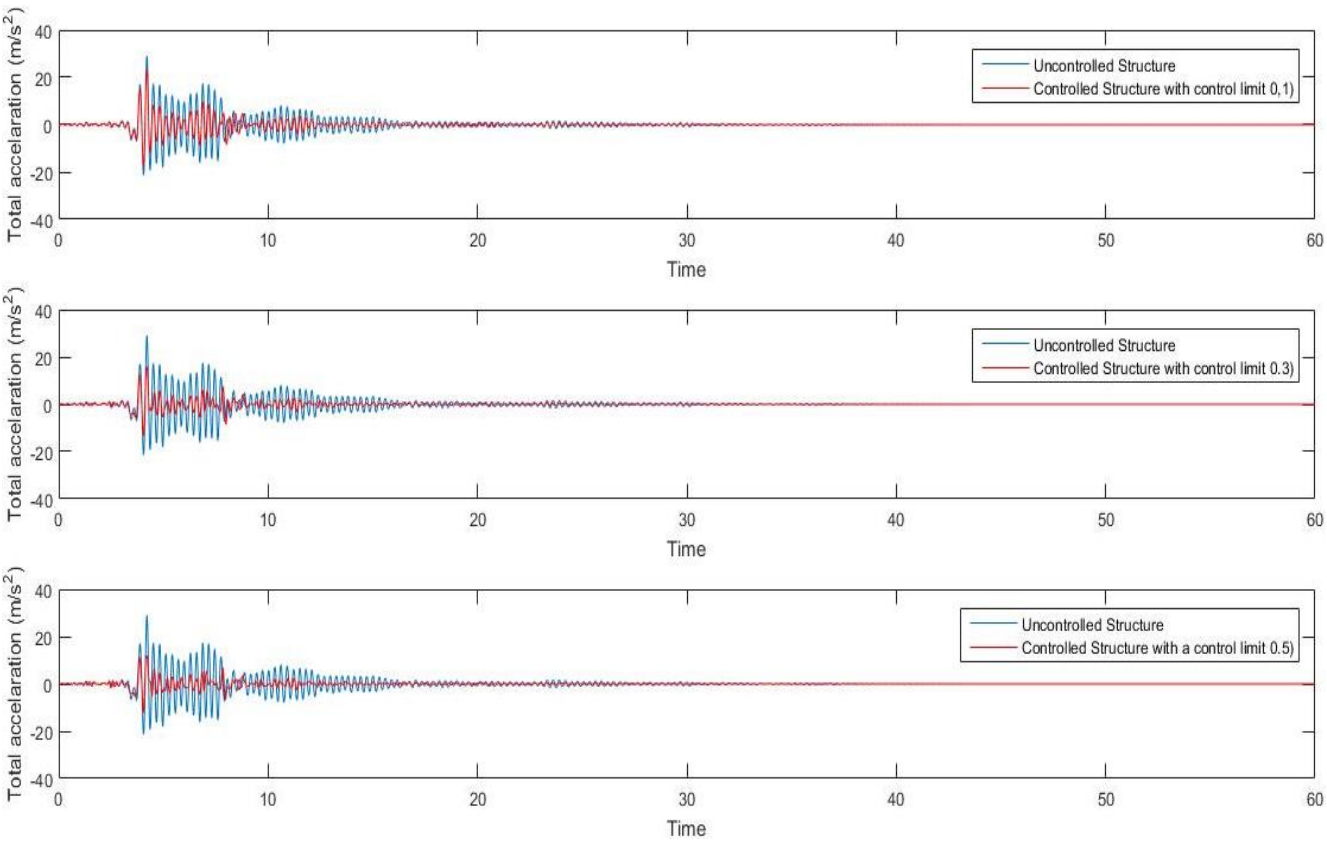

Fig. 7. Total acceleration time history of controlled and uncontrolled SDOF under Northridge-01, 01 Sylmar - Olive View- FP component.

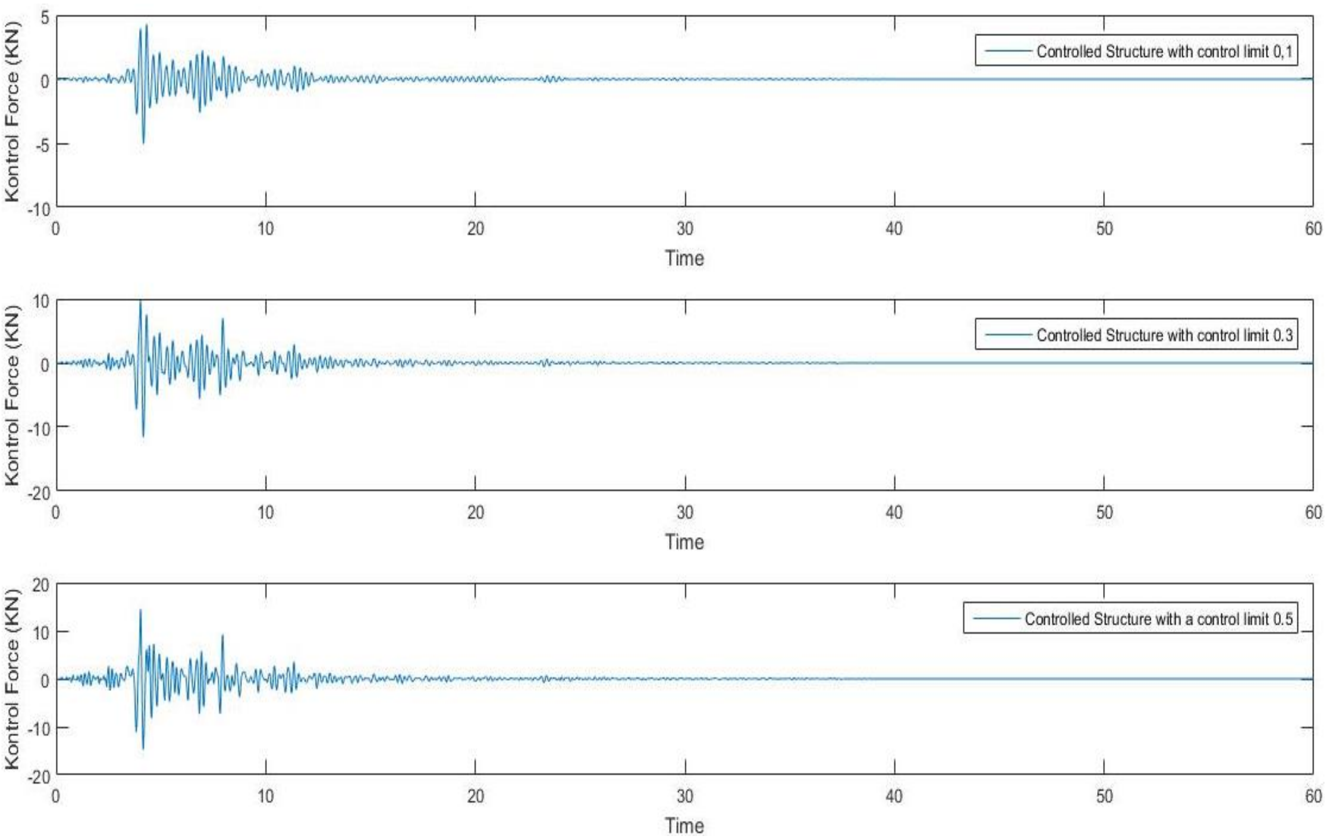

Fig. 8. The control force time history of controlled and uncontrolled SDOF under Northridge-01, 01 Sylmar - Olive View- FP component.

5. Conclusions

In this study, active structural control on single degree of freedom structures using teaching learning based algorithm are proposed. The conclusions about these structures with optimized PID are as follows:

- The optimum PID parameters were calculated in a short time using teaching learning based algorithm.
- The behavior of single degree of freedom structures with different control limits was examined under 56 earthquake recordings, not a few earthquake recordings, and structural reactions were significantly reduced in all records.
- The effects of the control force on single degree of freedom structures were examined carefully and it was determined that the generated control force was actually applicable.

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