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ROBUSTNESS OF TIME DELAYED ACTIVE SYRUCTURAL CONTROL SYSTEMS

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ABSTRACT

Robustness of active structural control systems is a more important factor than performance in absorbing seismic vibrations. This paper investigates the robustness of active tendon control systems with different time delays. This investigation was done with single degree of freedom structures. The active control is sustained with active tendons using proportional–integral–derivative (PID) controllers. In tuning of the controllers, a numerical algorithm is used to find the PID controller parameters such as proportional gain, integral time and derivation time. Due to stability errors, the control system can be tuned up to 60 ms time delay. The PID controller parameters found for all time delay values were checked for the change of the mass of the structure up to ±30%. Generally, the active control is robust for all time delay values.

INTRODUCTION

In active structural control, the most important factors are tuning of controllers and robustness of control system against changing properties of excitation and structure. In design of structures, dynamic analyses are done for a mass of structure. The exact mass of structures changes due to live loads. For that reason, stability problems can be seen in active controlled structures if the mass of the structure change with an unexpected percentage. Time delay is also another reason for stability problems in active structural control.

In this paper, single degree of freedom (SDOF) structures were controlled with active tendon control system using time delayed proportional–integral–derivative (PID) controllers in order to investigate the robustness of control system for different time delay values. PID controlled active tendon control systems have been proposed in several papers for reducing the seismic vibrations of structures.

The active tendon control was proposed for shear plane structures by using PID controllers (Nigdeli and Boduroğlu, 2010). Also, plane shear structures are controlled for superimposed ground motions and impulsive motions in order to investigate the PID controlled active tendon control systems for near fault excitations (Nigdeli and Boduroğlu, 2012). Nigdeli and Boduroğlu (2013a) investigated the time delay factor for active tendon control systems. Reinforced concrete frame structures with different compressive strength of concrete were controlled in order to ensure ductility conditions by reducing shear forces (Nigdeli and Boduroğlu, 2013b). Torsionally irregular structures at near fault regions were controlled with active tendon control systems using PID controllers (Nigdeli and Boduroğlu, 2013c). Also, several approaches have been recently proposed for active control of structures (Lin et al., 2010; Bitaraf et al., 2012; Aldemir et al., 2013; Cha et al., 2013).

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METHODOLOGY

In the analyses, the robustness of active tendon control for different time delays was verified with single degree of freedom (SDOF) structural model by changing the mass of structure up to ±30%. Matlab with Simulink (Mathworks, 2010) was used for modelling the equations of motions of single degrees of freedom structure for uncontrolled (Eq.(1)) and active controlled (Eq.(2)) cases.

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -m_1\ddot{x}_g \tag{1}$$

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -m_1\ddot{x}_g - 4k_c u_1 \cos\alpha \tag{2}$$

In the Eqs. (1) and (2), m_1, c_1, k_1, x_1, $\ddot{x}_g$, k_c, u_1 and α represent mass, damping coefficient, stiffness coefficient, displacement (dots on x_1 symbolize its derivatives in time), ground acceleration, stiffness of tendons, control signal and angle of tendons with respect to ground, respectively. Runge-Kutta method with 0.001 s step size was chosen for time history analyses. Error signal data (e(t)) is converted to control signal by using the equation of PID controllers given in Eq.(3). In the present study, displacements were taken as error signal.

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt} \right) \tag{3}$$

In Eq. (3), K (Proportional gain), T_i (Integral time) and T_d (Derivation time) are controller parameters which were tuned by using a numerical algorithm. After several trial attempts for finding the ranges for the controller parameters, the algorithm scans neighboring values of parameters. The aim is the algorithm is to reduce a desired maximum structural response which is maximum displacement of structure under five different earthquake excitations.

NUMERICAL EXAMPLE

A model structure taken from Chung et al. (1998) was investigated as numerical example. The mass, stiffness and damping coefficient of structure are 2924 kg, 1.581 kNs/m and 1.39 MN/m, respectively. Tendons with 36° angle respect to ground (α) and 372.1 kN/m stiffness were used. The earthquake excitations used in the tuning are given in Table 1. These records were downloaded by Pacific Earthquake Engineering Research Center (PEER) database.

Table 1. Earthquake excitations 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	I-ELC180	0.313	29.8	13.32
Erzincan	1992	95 Erzincan	ERZ-NS	0.515	83.9	27.35
Loma Prieta	1989	16 LGPC	LGP000	0.563	94.8	41.18
Northridge	1994	24514 Sylmar	SYL360	0.843	129.6	32.68

The optimum parameters of PID controller are given in Table 2 for time delay values between 0 ms and 60 ms. It is not possible to tune the PID controller for time delay values more than 60 ms because of stability problem. These parameters were found for 10 kN control force limit. Displacement feedback control was used in control.

The mass of the structure was changed up to ±30% in order to consider the change of the mass because of the unforeseen live loads. In Table 3, maximum displacements are given for different mass percentages. In Figures 1, 2 and 3, displacement (x) responses of structure with 20 ms time delayed control system under Northridge-Sylmar excitation are given for 70%, 100% and 130% masses, respectively. In these time histories, displacements are damped immediately for all masses.

Table 2. The PID controller parameters for different time delay values

Time Delay	0 ms	10 ms	20 ms	30 ms	40 ms	50 ms	60 ms
K	-0.175	-0.17	-0.145	-0.14	-0.084	-0.022	-0.01
T_d (s)	0.1	0.1	0.115	0.115	0.195	0.5	0.47
T_i (s)	0.08	0.08	0.08	0.08	0.05	1	1.2

Table 3. Maximum displacements in cm

Mass (%)	70	75	80	85	90	95	100	105	110	115	120	125	130
no control	2,39	2,97	4,33	5,22	5,10	5,24	6,10	6,82	7,42	7,97	8,35	8,92	9,66
0 ms time delay	1,52	1,72	1,94	2,18	2,44	2,72	3,01	3,33	3,66	3,99	4,33	4,67	5,00
10 ms time delay	1,49	1,70	1,92	2,16	2,43	2,72	3,04	3,38	3,74	4,12	4,51	4,90	5,28
20 ms time delay	1,52	1,72	1,95	2,20	2,48	2,78	3,12	3,49	3,88	4,30	4,74	5,17	5,59
30 ms time delay	1,60	1,77	2,01	2,28	2,55	2,85	3,21	3,62	4,08	4,57	5,08	5,60	6,09
40 ms time delay	1,73	1,86	2,11	2,41	2,67	2,99	3,37	3,82	4,32	4,85	5,40	5,94	6,46
50 ms time delay	1,98	2,03	2,36	2,54	2,84	3,22	3,73	4,20	4,74	5,29	5,85	6,37	6,83
60 ms time delay	2,66	2,54	3,32	3,65	4,97	5,34	4,93	5,64	6,39	7,02	7,55	8,01	8,35

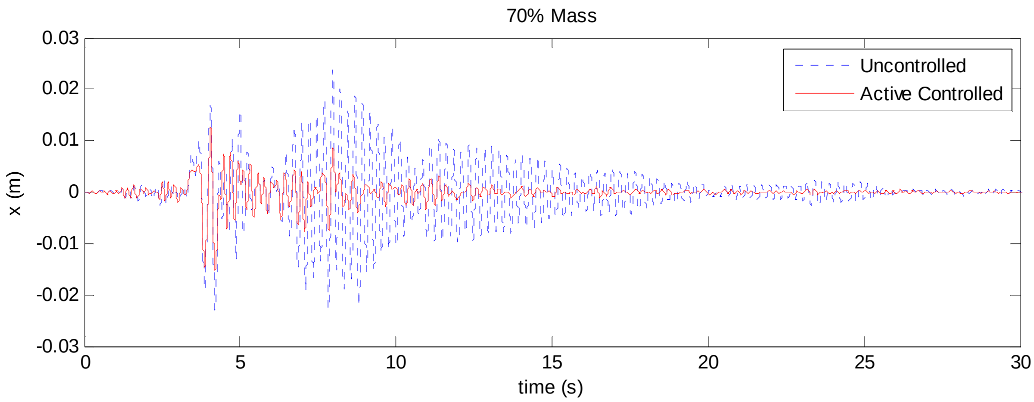

Figure 1. Displacement of structure for 20 ms time delay (70% mass)

In Figures 4, 5 and 6, displacement (x) time histories of the structure with 60 ms time delayed control system under Northridge-Sylmar excitation are respectively given for 70%, 100% and 130% masses. Differently from the time histories given in Figures 1-3, vibrations are not immediately damped. Also, active control has inverse benefit for the structure with 70% mass but the case of the reduction of the mass is not critical since the displacement values are very low comparing to the heavy structures.

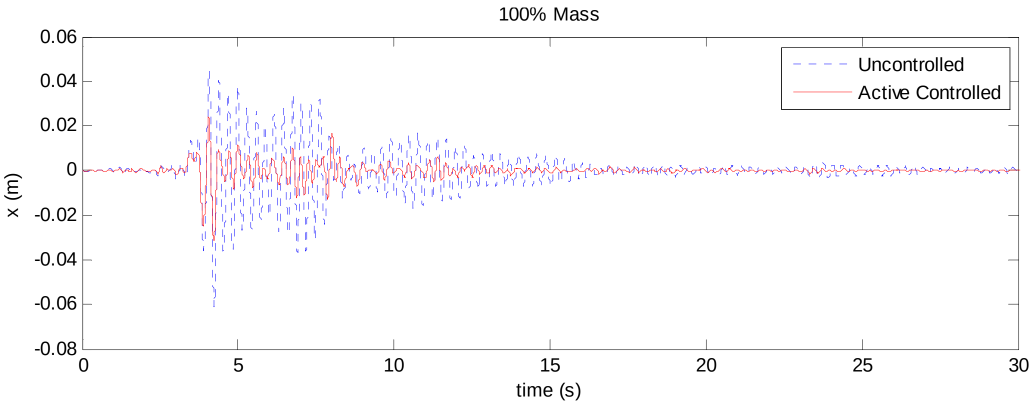

Figure 2. Displacement of structure for 20 ms time delay (100% mass)

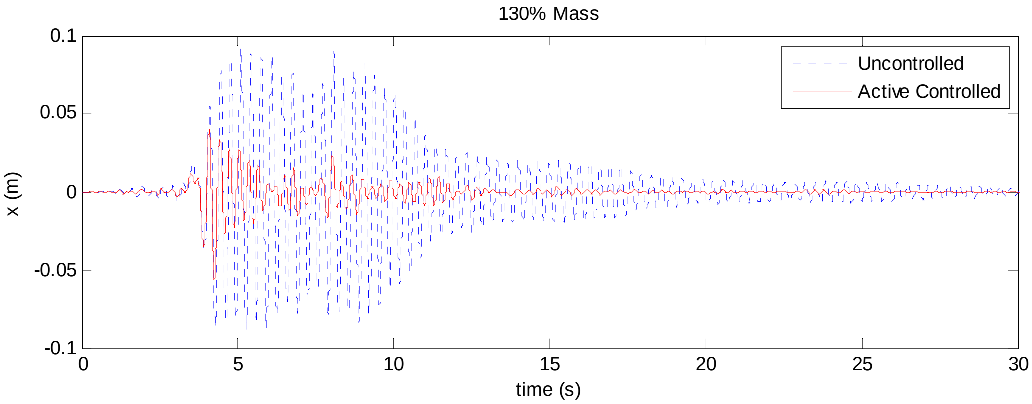

Figure 3. Displacement of structure for 20 ms time delay (130% mass)

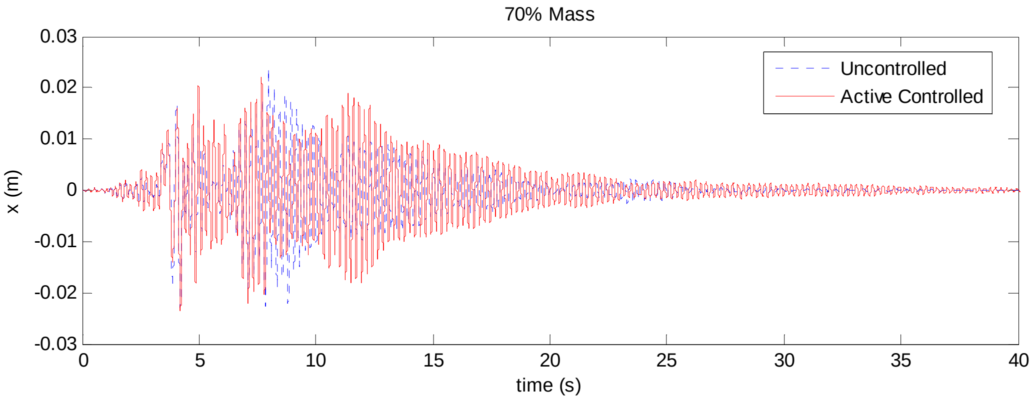

Figure 4. Displacement of structure for 60 ms time delay (70% mass)

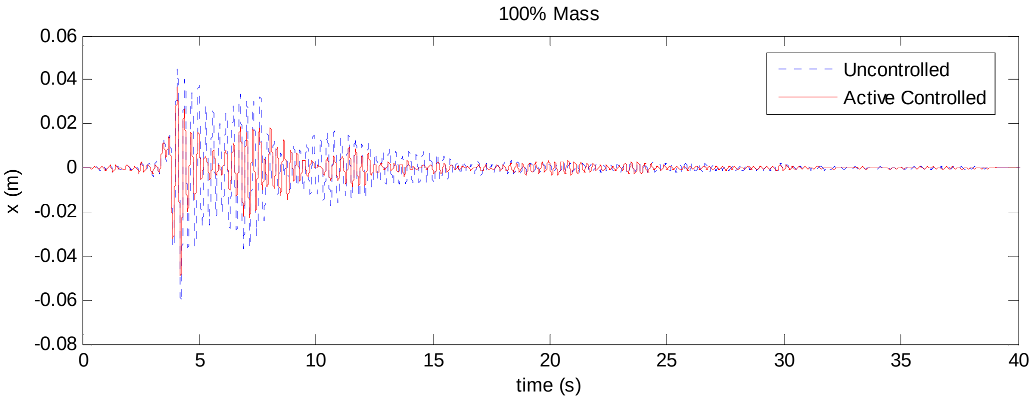

Figure 5. Displacement of structure for 60 ms time delay (100% mass)

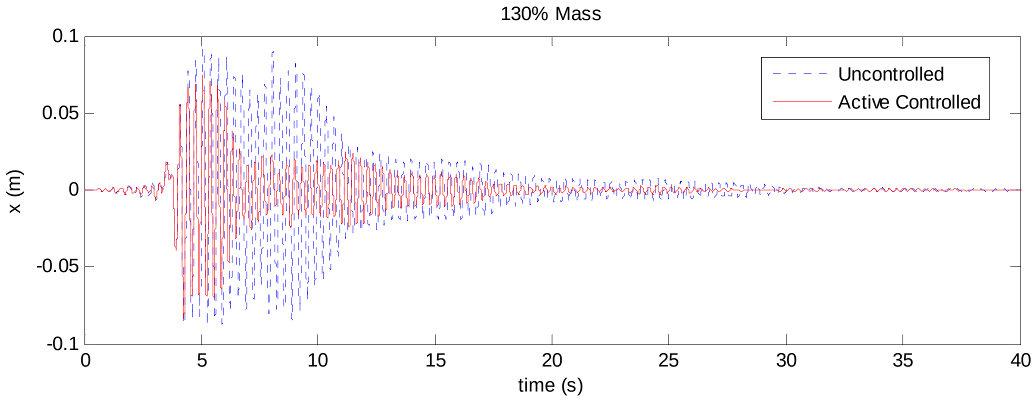

Figure 6. Displacement of structure for 60 ms time delay (130% mass)

CONCLUSIONS

In Figure 7, the ratio of maximum displacements of the uncontrolled and the active controlled structures versus mass percentage is plotted for all time delay values. According to results, a major performance loss is not seen up to -25% change of the mass for all time delay values. For -30% change of the mass, significant performance losses are observed. Especially, active control has negative effects for several masses when the time delay value is 60 ms and the mass of the structure is decreased.

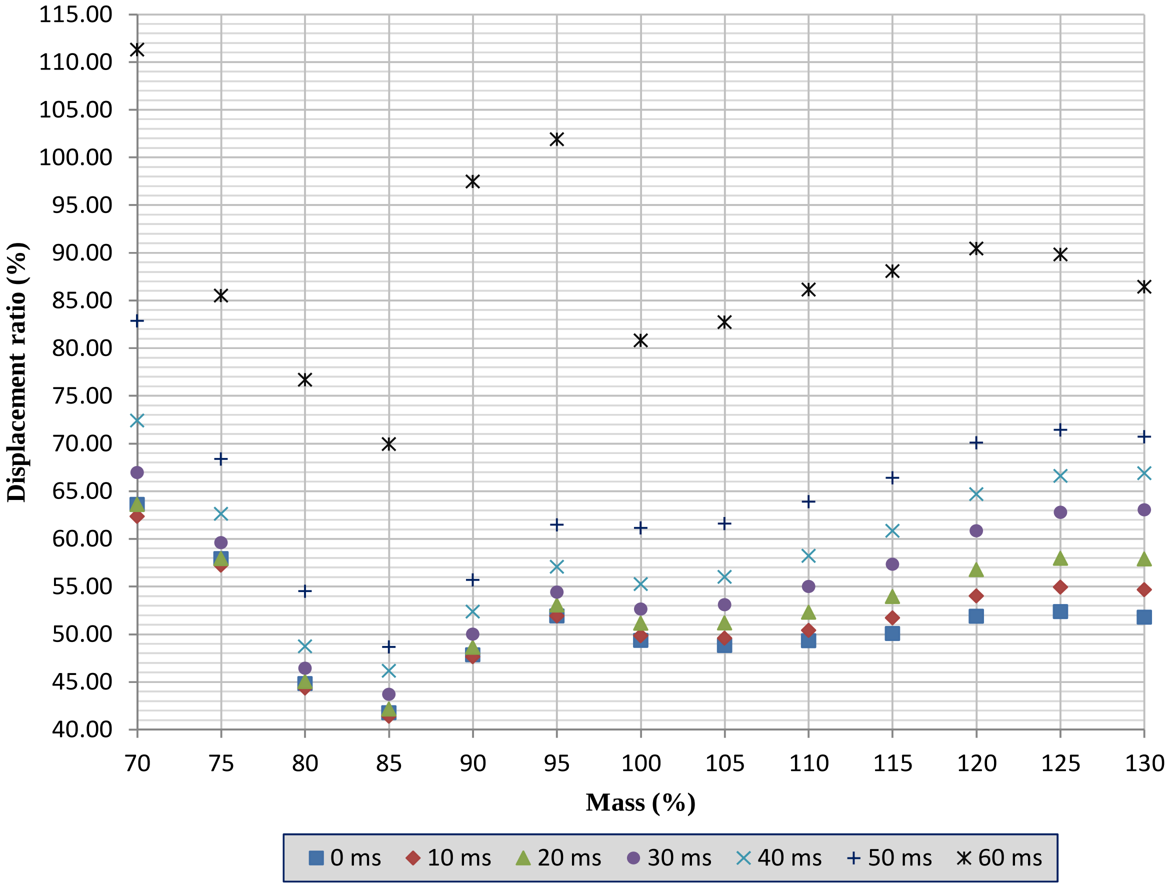

Figure 7. Displacement ratio vs Mass plot

By the increase of the mass of structures, the earthquake loads are increasing and the maximum displacements are getting higher for the uncontrolled and the active controlled structures. In this situation, the control system preserves its effectiveness up to 11% performance lost. Since the general performance is low for 60 ms time delay, the performance loss is lower than other time delay values.

Table 4 shows the maximum control forces for different time delays and masses. By the increase of the mass, the control force exceeds the 10 kN limit. If the maximum performance of the actuators is not capable to produce this force with the same time delay value, the results given in Table 3 cannot be provided. But, the force is always lower than 10 kN for 60 ms time delay. The maximum limit for 100% mass is 5.66 kN when the time delay value used in tuning is 60 ms. By the increase of the force, stability problem is seen for 60 ms time delay. Thus, addition to 10 kN limit, stability problem of the control system is also limiting the maximum control force. According to verification of control system for different mass changes, the controller parameters are generally robust for all time delay values.

Table 4. Maximum control force in kN

Mass (%)	70	75	80	85	90	95	100	105	110	115	120	125	130
0 ms time delay	5,70	6,18	6,71	7,30	8,08	8,97	9,95	11,0	12,2	13,4	14,5	15,7	16,9
10 ms time delay	5,66	6,10	6,61	7,21	8,00	8,88	9,86	10,9	12,1	13,4	14,7	16,0	17,3
20 ms time delay	5,67	6,04	6,56	7,25	8,00	8,85	9,81	10,9	12,0	13,3	14,6	15,9	17,2
30 ms time delay	6,86	6,80	6,72	7,44	8,14	8,97	9,98	11,2	12,5	13,9	15,3	16,8	18,3
40 ms time delay	8,08	7,59	7,66	7,64	7,96	8,72	9,85	11,3	12,2	13,5	14,8	16,1	17,4
50 ms time delay	6,52	6,25	6,10	6,27	7,13	8,47	10,0	10,7	11,1	12,1	13,2	14,1	14,9
60 ms time delay	3,52	3,30	4,45	4,35	5,98	6,28	5,66	5,63	6,25	6,72	7,09	7,49	8,05

REFERENCES

Chung LL, Reinhorn AM, Soong TT (1988) "Experiments on active control of seismic structures", *Journal of Engineering Mechanics (ASCE)*, 114(2):241-255.

Mathworks (2010) MATLAB R2010a, 2nd Ed., The MathWorks Inc., Natick, MA, USA.

Nigdeli SM and Boduroğlu MH (2010) "Active tendons for seismic control of buildings", *International conference on mechanical science and engineering*, Paris, France, 28-30 July.

Nigdeli SM and Boduroğlu MH (2012) "Active tendon control of structures under near-fault ground motion excitation", *10th international congress on advances in civil engineering*, Ankara, Turkey, 17-19 October.

Nigdeli SM and Boduroğlu MH (2013a) "The effect of time delay on active seismic control of structures using PID controller", *11th biennial international conference on vibration problems*, Lisbon, Portugal, 9-12 September.

Nigdeli SM and Boduroğlu MH (2013b) "Active tendon control of reinforced concrete frame structures subjected to near-fault effects", *11th international conference of numerical analysis and applied mathematics*, Rhodos, Greece, 21-27 September.

Nigdeli SM and Boduroğlu MH (2013c) "Active tendon control of torsionally irregular structures under near-fault ground motion excitation", *Computer-aided Civil and Infrastructure Engineering*, 28(9):718-736.

Pacific Earthquake Engineering Research Center (PEER) http://peer.berkeley.edu/nga, University of California, Berkeley, CA, USA.

Aldemir, U, Yanik A and Bakioglu M. (2012) "Control of structural response under earthquake excitation", *Computer-aided Civil and Infrastructure Engineering*, 27(8):620-638.

Bitaraf M, Hurlebaus S and Barroso LR (2012) "Active and semi-active adaptive control for undamaged and damaged building structures under seismic load", *Computer-aided Civil and Infrastructure Engineering*, 27(1):48-64.

Cha Y-J, Kim Y, Raich AM and Agrawal AK (2013) "Multi-objective optimization for actuator and sensor layouts of actively controlled 3D buildings", *Journal of Vibration and Control*, 19(6):942-960.

Lin C, Chang C and Wang J (2010) "Active control of irregular buildings considering soil-structure interaction effects", *Soil Dynamics and Earthquake Engineering*, 30(3):98-109.