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THE EFFECT OF TIME DELAY ON ACTIVE SEISMIC CONTROL OF STRUCTURES USING PID CONTROLLER

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Abstract. *In this study, the performance of active tendon control system using proportional–integral–derivative (PID) type controllers were investigated for various time delays under different earthquake excitations. The damping of the vibrations is achieved by controlling the force on diagonal prestressed tendons connected to actuators placed on sides of the structure in active tendon control. Equation of motion of single degree of freedom structure was modelled with Matlab Simulink. On active seismic control of structures, time delay consideration is a parameter which must be taken into consideration during the tuning process of the controller system because of the stability problem. Parameters of the PID controller; K (Proportional gain), T_i (Integral time) and T_d (Derivation time) were obtained by using a numerical algorithm for each time delay. The objective of the algorithm is to find suitable PID controller parameters which reduce the maximum displacement of the structure under five different earthquake excitations by using a defined maximum limit for control force. The value of the time delay is a parameter which depends on the performance of the control system. For that reason, all controller parameters found for a time delay value were tested on controller systems with different time delays. The active control of structure using controller parameters tuned for a time delay is effective up to 45 ms change in time delay. According to the results, although the increase of the time delay has no significant negative effect on the reduction of maximum response of the structure, the maximum value of the control force increase. As a conclusion, structural vibrations resulting from earthquake excitations can be reduced and damped immediately with the help of the PID controlled active tendons by considering time delay.*

1 INTRODUCTION

Active structural control systems can produce time varying forces with actuators driven by automatic controller devices in order to stabilize vibration of structures. But, active control systems may need large external power supply. Also, a delay of time varying forces may cause stability problems of controller system. Amount of the time delay is a value related to the performance of control equipment such as sensors, microprocessors and actuators. To prevent stability problem arising from time delay, amount of time delay can be considered in the tuning of controller systems.

Several examples can be given for the active control of structures. Roorda proposed an active tendon control systems for masts and towers in order surpass vibrations resulted from turbulent wind conditions [1]. Yang and Giannopoulos proposed active tendon controlled structures modelled as cantilever beams by using the transfer matrix technique [2]. Abdel-Rohman and Leipholz actively controlled frame structures subjected to a steady state disturbance by using unloaded cables [3]. Yang and Samali controlled tall structures excited by a random wind flow [4]. Leipholz and Abdel-Rohman actively controlled the force on a single continuous prestressed cable in order to reduce wind response of tall structures [5]. Samali et al. investigated active tendon controlled torsionally irregular structures by using a closed-loop control law [6]. Chung at al. used active tendon control system for single degree of freedom experimental model under base motion [7]. Chung at al. sustained experimental studies with 1:4 scaled three storey building [8]. López-Almansa and Rodellar investigated active tendon controlled frame and shear wall buildings [9]. Reinhorn et al. investigated 1:4 scale models with active tendons and active tuned mass dampers [10]. Structures subjected to multiple support excitations were actively controlled by Betti and Panariello [11]. Chung et al. developed a modified instantaneous control algorithm with time delay consideration for active control of structures [12]. Wong and Hart numerically investigated active controlled inelastic structures by using force analogy method [13]. Chung et al. proposed a multi-step acceleration feedback control algorithm for active control of structures subjected to earthquake excitations [14]. Lu and Skelton used an iterative procedure in order to tune passive and active control parameters with respect to an H_2/H_∞ performance requirement [15]. Chung proposed a modified predictive control algorithm for active control of structures [16]. Sedarat et al. investigated single and multiple input control systems for different settlement cases [17]. Bakioglu and Aldemir developed a new algorithm for the sub-optimal solution of the optimal closed-open-loop control based on the prediction of earthquake excitation [18]. Aldemir et al. proposed an approximately optimal closed-open-loop control for the prediction of near future excitations [19]. Mei et al. presented a model predictive control based scheme using acceleration response feedback for active control of structures subjected to earthquake excitations [20]. Nigdeli and Boduroğlu investigated the active tendon control of structures using PID controllers in order to reduce structural responses resulted from ground motions [21-22]. Chang and Lin proposed an optimal H_∞ control algorithm for time delayed active control systems in order to reduce interstory drift [23]. Lin et al. investigated active tendon controlled torsionally irregular structure considering soil-structure interaction effects [24]. Nigdeli investigated the active brace control of a single span and single storey frame structure [25]. The performance of active tendon control systems on reduction of responses resulted from near fault ground motion excitations was investigated by Nigdeli and Boduroğlu [26]. Nigdeli proposed active tendon control systems using proportional–integral–derivative (PID) type controllers in order to reduce seismic responses of regular and torsionally irregular structures subjected to near-fault ground motions [27].

The main objective in the design of structural control systems is to tune mechanical properties for a passive system (for example: tuned mass dampers) [28-38] and controller parameters for an active system. In active control of structures, time delay must be considered in tuning process for the reliability and robustness of the system. In this study, active tendon control system using PID controllers were investigated for various amounts of time delay under five different earthquake excitations. In active tendon control systems, the damping of the vibrations is achieved by controlling the force on diagonal prestressed tendons connected to actuators placed on sides of the structure. Parameters of the PID controller; K (Proportional gain), T_i (Integral time) and T_d (Derivation time) were obtained by using a numerical algorithm for each time delay value. All controller parameters found for a time delay value was tested on controller systems with different time delay values.

2 METHODOLOGY

Active tendon control for different time delays was investigated with single degree of freedom (SDOF) structural models. Proportional Integral Derivation (PID) type controllers were used for control strategy. Motions of SDOF active tendon controlled structures were modelled in Matlab Simulink for time history analyses. Runge-Kutta method with 1e-3 s step size was used in order to conduct numerical simulations. A transport delay block was implemented after the generation of control signals in Matlab Simulink.

Proportional Integral Derivation (PID) type controllers were used in order to obtain control signal data, u(t) that is also the displacement of the activators. These types of controllers use feedback strategy and have three specific actions to set. Equation of the PID controller is given as Eq. (1).

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

By using Eq. (1), error signal, e(t) (undesired response obtained by using sensors) can be transform into control signal. Velocity feedback control was employed by using the velocity of the structure as error signal.

A numerical algorithm was used for tuning of PID controller parameters [26-27]. The algorithm scans several neighbouring values for parameters obtained by trials in order to find the best results for peak value of a desired structural response. In this study, the objective of the algorithm is to find suitable PID controller parameters which reduce the maximum displacement of the structure under five different earthquake excitations according to a defined maximum limit for control force. In numerical analyses, stability problem can occur for several controller coefficients. For that reason, trials must be done for these coefficients before numerical iterations. Also, scanning of a huge domain will take too much time.

Model of the active tendon controlled SDOF structure and control forces during static and dynamic state is given in Figure 1. 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. R, u_1, x_1 and $\ddot{x}_g$ represent pre-stressed force on tendons, actuator displacement or control signal, lateral displacement of structure and ground acceleration, respectively. The equations of motion for uncontrolled and active tendon controlled structure are given as seen in Eq. 2 and Eq. 3, respectively.

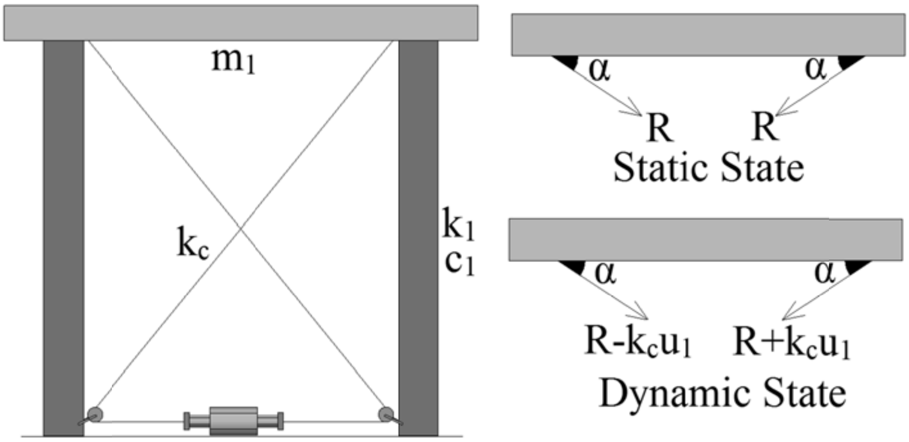

Figure 1: Model of the SDOF system with active tendons and control forces.

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -m_1\ddot{x}_g \tag{2}$$

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -m_1\ddot{x}_g - 4k_cu_1\cos\alpha \tag{3}$$

3 NUMERICAL EXMAPLE

A SDOF structure with 2924 kg mass (m_1), 1.39 MN/m stiffness coefficient (k_1) and 1.581 kNs/m damping coefficient (c_1) was controlled with active tendons. The angle of tendons respect to ground (α) is 36° and the stiffness of the tendons is 372.1 kN/m. [7]

Five different earthquake excitations were used in parameter tuning process. The aim of the optimization is to reduce peak displacement under the most critical earthquake. The information about the excitations including peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) is given in Table 1.

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

Table 1: Earthquake excitations.

The parameters of PID controller were tuned for time delays between 0 – 60 ms. The optimum PID control parameters is shown in Table 2. The maximum control force was limited with 10 kN. The absolute value of proportional gain (K) is reduced by the increase of time delay. After 40 ms time delay, the numerical values of optimum parameters are very different than others. The maximum structural responses of uncontrolled structure are given in Table 3. The most critical earthquake excitation is Northridge- Sylmar.

Time Delay (ms)	0	10	20	30	40	50	60
K (s)	-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 2: Optimum PID parameters.

Earthquake	x_1 (cm)	$\dot{x}_1$ (cm/s)	$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)
Kobe	4.63	82.19	21.99
Imperial Valley	1.81	38.66	8.62
Erzincan	2.31	43.71	10.99
Loma Prieta	4.94	96.71	23.49
Northridge	6.10	106.65	29.01

Table 3: Maximum structural responses of uncontrolled structure.

In Table 4, the maximum responses of controlled structure tuned without time delay are given. Stability problem is occurred after 45 ms delay. After 40 ms delay, a significant reduction on the performance of the control system is seen. Between 0-10 ms time delay, the maximum limit of the control force is not exceeded.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	4.3	Inf	Inf	Inf
$\dot{x}_1$ (cm/s)	52.4	52.7	53.2	53.8	54.6	55.3	56.0	56.5	66.2	97.3	Inf	Inf	Inf
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	17.0	17.1	17.2	17.3	17.5	17.7	18.1	18.4	18.7	26.5	Inf	Inf	Inf
Control force (kN)	10.0	10.0	10.0	10.2	10.3	10.6	10.8	11.0	12.3	19.0	Inf	Inf	Inf

Table 4: Maximum structural responses of uncontrolled structure (0 ms).

The maximum responses of controlled structure tuned with 10 ms time delay are given in Table 5. A stability problem is not seen until 50 ms. The controller system is significantly more effective than the system tuned without time delay consideration for a possible time delay value.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.1	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.2	4.1	Inf	Inf	Inf
$\dot{x}_1$ (cm/s)	53.1	53.5	54.0	54.6	55.3	56.0	56.7	57.3	65.8	92.2	Inf	Inf	Inf
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	17.2	17.2	17.3	17.5	17.6	17.9	18.2	18.6	18.8	25.2	Inf	Inf	Inf
Control force (kN)	9.8	9.8	9.9	10.0	10.2	10.4	10.6	10.8	11.9	17.6	Inf	Inf	Inf

Table 5: Maximum structural responses of uncontrolled structure (10 ms).

The maximum responses of controlled structure tuned with 20 ms time delay are shown in Table 6. The control system is stabile until 50 ms delay. The control force limit is not exceeded until 30 ms.

In Table 7, the maximum responses of controlled structure tuned with 30 ms time delay are given. Stability problem is occurred after 50 ms delay. Between 0-30 ms time delay, the maximum limit of the control force is not exceeded as seen in Table 7. Generally, Northridge-

Slymar excitation is the most critical earthquake. But, Kobe excitation is sometimes critical according to time delay. The maximum responses corresponding to the Kobe excitation are shown with **bold** and *italic*.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.2	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.4	Inf	Inf	Inf
$\dot{x}_1$ (cm/s)	54.1	54.3	54.7	55.3	55.9	56.6	57.3	57.9	58.3	75.2	Inf	Inf	Inf
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	17.3	17.4	17.4	17.5	17.7	17.9	18.2	18.5	18.8	20.6	Inf	Inf	Inf
Control force (kN)	9.5	9.5	9.6	9.7	9.8	10.0	10.2	10.4	10.6	13.4	Inf	Inf	Inf

Table 6: Maximum structural responses of uncontrolled structure (20 ms).

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.3	***3.6***	4.2	Inf	Inf
$\dot{x}_1$ (cm/s)	55.0	55.2	55.6	56.2	56.8	57.5	58.2	58.8	***64.6***	72.1	***99.2***	Inf	Inf
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	17.5	17.6	17.6	17.7	17.9	18.1	18.4	18.7	***19.3***	***21.2***	***25.9***	Inf	Inf
Control force (kN)	9.3	9.3	9.4	9.5	9.6	9.8	10.0	*10.3*	***11.4***	***12.5***	17.6	Inf	Inf

Table 7: Maximum structural responses of uncontrolled structure (30 ms).

The maximum responses of controlled structure tuned with 40 ms time delay are given in Table 8. A stability problem is seen after 55 ms time delay. Until 40 ms, the maximum control force is less than 10 kN.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.4	3.4	***3.6***	***4.2***	Inf
$\dot{x}_1$ (cm/s)	57.6	57.6	57.8	58.1	58.5	59.1	59.7	60.3	60.9	***65.0***	***72.9***	***86.4***	Inf
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	18.0	18.0	18.0	18.0	18.1	18.2	18.5	18.8	19.1	19.4	***21.4***	***24.7***	Inf
Control force (kN)	8.9	8.9	8.9	9.0	9.1	9.2	9.4	9.6	***9.9***	***10.8***	***12.0***	14.5	Inf

Table 8: Maximum structural responses of uncontrolled structure (40 ms).

In Table 9, the maximum responses of controlled structure tuned with 50 ms time delay are given. Stability problem of control system is not seen for all time delays. Between 0-50 ms time delay, the maximum limit of the control force is not exceeded. Comparing to results given in previous tables, a significant increase of the maximum responses is seen. In Figure 2, the displacement plots for 50 ms time delay under Kobe and Northridge excitation is given.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.7	***3.7***	***4.2***	***5.0***
$\dot{x}_1$ (cm/s)	64.6	64.1	63.9	63.8	63.8	64.0	64.3	64.7	65.1	***67.0***	***75.4***	***87.2***	***105***
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	19.2	19.1	19.1	19.1	19.1	19.2	19.3	19.4	19.7	19.9	***21.1***	***24.1***	***28.6***
Control force (kN)	8.6	8.6	8.5	8.5	8.5	8.5	8.6	8.6	8.7	***9.0***	***10.0***	***11.7***	***14.0***

Table 9: Maximum structural responses of uncontrolled structure (50 ms).

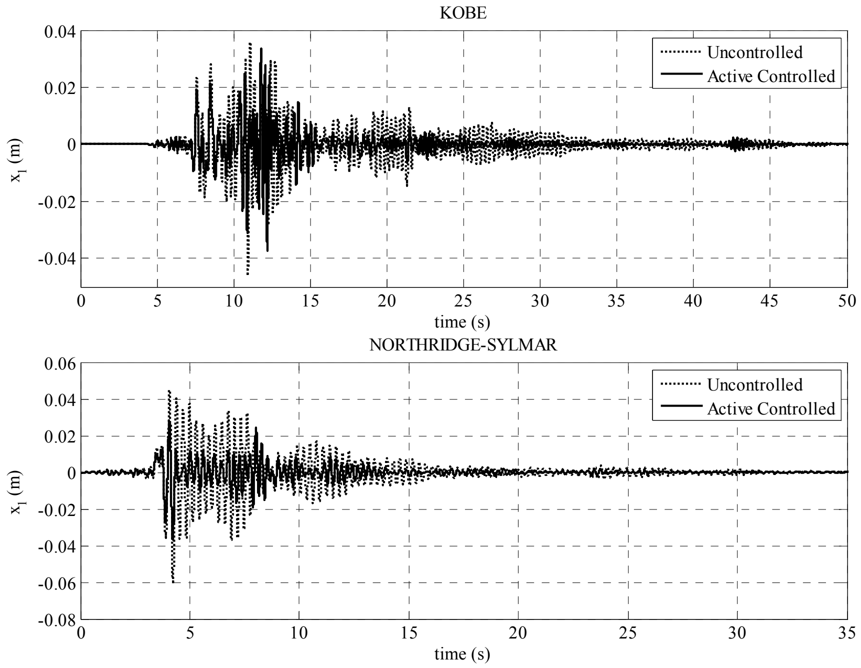

Figure 2: Time-history plots of displacements (50 ms).

The maximum responses of controlled structure tuned with 60 ms time delay are shown in Table 10. If the delay of the controller system is 60 ms, a reduction under Kobe excitation is not obtained. Although, the control force limit is 10 kN, the maximum control forces are between 4.7 kN and 5.7 kN. If the value of the force is increased, the stability of the system is not provided. It is not possible to tune the controller for a time delay more than 60 ms.

Time Delay (ms)	0	5	10	15	20	25	30	35	40	45	50	55	60
x_1 (cm)	4.9	4.8	4.8	4.8	4.7	4.7	4.7	4.7	4.8	4.8	4.8	4.9	***4.9***
$\dot{x}_1$ (cm/s)	82.6	82.2	81.9	81.9	81.9	82.1	82.4	82.8	83.4	84.0	84.8	***92.1***	***101***
$\ddot{x}_1 + \ddot{x}_g$ (m/s^2)	23.4	23.4	23.4	23.4	23.4	23.5	23.6	23.7	23.9	24.1	24.4	24.7	***25.4***
Control force (kN)	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.8	4.8	4.8	4.9	***5.2***	***5.7***

Table 10: Maximum structural responses of uncontrolled structure (60 ms).

4 CONCLUSIONS

The PID controlled active tendons were tuned and investigated for the seismic protection of a single degree of freedom structure by considering different time delays. The effect of five major earthquake records was taken into consideration and it is possible to tune the PID controller up to 60 ms time delay without a stability problem. The active control system is effective on reducing maximum displacement of the structure up to 51% under the most critical excitation (Northridge-Sylmar). The critical earthquake is generally the same for uncontrolled and controlled structure but Kobe excitation is sometimes more critical than Northridge-Sylmar for the controlled structure if the time delay is more than 40 ms and also, this excitation is the source of the stability problems. For high time delay values, a displacement increment is seen in the results for Kobe excitation. This situation shows that the effect of the excitation is the most important factor in time delay consideration and the tuning of active control system must be searched for random vibrations with different contents. The acceleration transfer function plots of uncontrolled and active controlled structures are given in Figure 3. All transfer function corresponding to all PID parameters for different time delays is seen in this figure. As expected, a reduction of the resonance peak is not seen for controlled structure with 50 ms and 60 ms time delay. The controller system is successful up to 40 ms time delay. Also, PID controller parameters are robust up to 45 ms change in time delay.

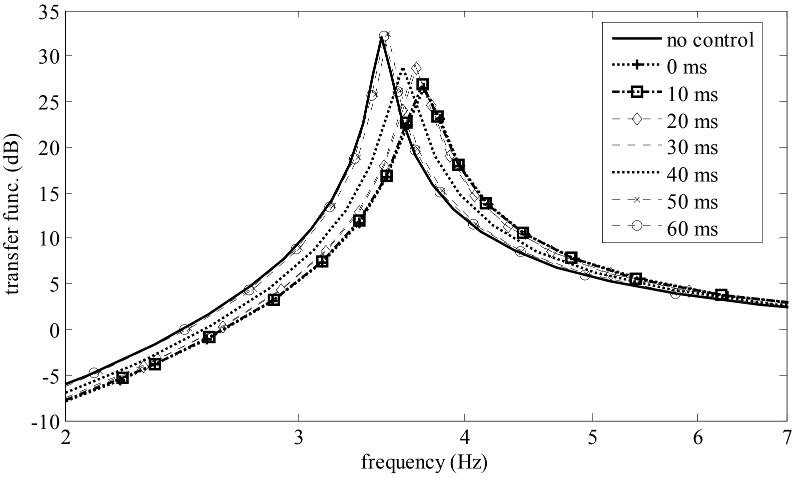

Figure 3: Transfer function plot.

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