Compensation of Time Delay Effect in Active Controlled MDOF Structures Using Neural Networks

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Abstract: During last few decades, Active control of civil structures has grown to an incredible limit that attracted a big deal of researchers in civil engineering. The problem of time delay effect is standing in the way of real world and wide spread of the active control application as it drives most of stable control strategies to an unstable case when its effect increases. This paper introduces a new technique in compensating the time delay in active control of structures. This technique uses an Artificial Neural Network to estimate the future earthquake record for a number of ahead steps online. By estimating the coming forces for few steps, and starting from the current state of the controlled structure, the future response is calculated and the required control force can be estimated. In this way the control force will be applied at nearly the same state from which it was calculated. This algorithm can be joined with any control law and any control device to overcome its inherent time delay. In this paper, optimal control with tendon controller is used. Different MDOF structures and different earthquakes were used to study the effect of time delay and to investigate the efficiency of the proposed technique in compensating it.

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Keywords: Active control, Tendon Control, Time Delay, Neural Networks, Earthquake Resistance.

1. Introduction

Modern structures are large in span and in height to a limit that needs new methods of controlling their response rather than traditional ones that take very high factors of safety in the design or increase dramatically the elements dimensions. Structural Active control proves to be the future of structural engineering science (Leipholz and Abdel-Rohman, 1986). Much work has been conducted on the theoretical development of the control algorithms. The achievement of these control strategies to real structures requires solution of practice-based important problems. One of the major issues is the time delay in receiving and applying the electrical signals. In a feedback control system, the structural response is monitored and the updated information is used to make continual corrections to the applied control actions. In reality, the electromechanical actuators have their own dynamics correlated with their motion which results in a time lag in applying the control force. This time lag may cause a harmful effect on the stability of the controlled structure. The importance of the time delay compensation in structural active control has been demonstrated by the experiments of McGreevy *et al.* (1988), Chu *et al.* (1995), Chung *et al.* (1995), and Korlin and Starossek (2007). Several time delay compensation methods which modify the control law according to the updated measured quantities have been proposed by Hammerstrom and Gros (1980), Abdel-Rohman (1985, 1987), Jun-Ping and Deh-Shiu (1988), Yang *et al.* (1990), Jun-Ping and Kelly (1991), Soliman and Ray (1992), Abdel-Rohman *et al.* (1993), Chung *et al.* (1995), Olgac *et al.* (1997), Olgac and Jalili (1998), Jalili and Olgac (1999), Olgac and Huang (2000), Chu *et al.* (2002), Filipovic and Olgac (2002), Sipahi and Olgac (2003), Masoud *et al.* (2004), Udwadia and Phohomisiri (2006), Udwadia *et al.* (2007) and Ahmadizadeh *et al.* (2008).

The Artificial Neural Networks (ANN) have verified to be a very promising tool in structural control in the few last decades. Many algorithms involved ANN in control process had been studied in civil engineering applications (Chen *et al.,* 1995, Ghaboussi and Joghataie, 1995, Bani-Hani and Ghaboussi, 1998, and Kim *et al.,* 2001). Kim *et al.,* 2002 applied Cerebellar Model Articulation Controller (CMAC) for suppression of structural vibration and compared the results of the CMAC with those of NN. Madan A. 2005 used self-organizing and self-learning Neural Networks to control building structures. Also, Kim *et al.,* 2007 introduced the probabilistic approach to train the Neural Networks and called them Probabilistic Neural Networks. In this way, they eliminated the time consumed in offline training of the Neural Network. Another participation of Kim *et al.,* 2008 was lattice type Probabilistic NN when they trained the Probabilistic NN based on the lattice pattern of state vector.

In this paper, a new technique in overcoming the time delay in active control cycle was implemented and tested. This technique uses an Artificial Neural Network to estimate the future earthquake record for a number of ahead steps online. This is done by training a feed forward back propagation NN to estimate the earthquake. The NN estimates the coming quake record based on the previous part of its record so a number of steps is given to the NN and it produces the next coming steps. This future record is used to estimate future response then the required control force is calculated and the control signal is generated. The NN can be trained to cover the mean time delay so reducing significantly the instability resulting from the time delay. In this way, the control force will be applied at nearly the same state from which it was calculated. This technique was applied on multi-story structures to prove its efficiency and to help applying it in real world applications.

2. Modeling

To investigate the effect of the efficiency of the proposed technique, four different five story structures were used. These structures are controlled by active tendon controller as shown in Fig. (1) and the optimal control theory is used in calculating the control force. The properties of the investigated structures are listed in table 1.

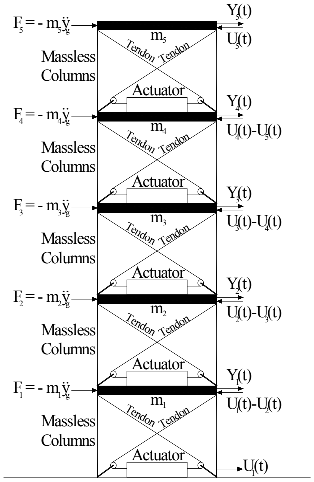

Fig. 1. Five story structure Controlled by Tendon system under ground acceleration excitation.

Table 1. Properties of used structures

Structure	Story Mass ($t.sec^2.m^{-1}$)	Story Stiffness (t/m)	Fundamental time period (sec)
S1	10	345000	0.5
S2	10	86342.5	1
S3	10	21580	2
S4	10	3453	5

These structures are studied in three cases. The first case when the control force apply at the same instant that the sensors scan the structure response, i.e. no time delay in control cycle. This case is called theoretical control as this case is not found in the real life. The second case when the time delay between the scanned response and the application of the control force is taken into consideration. This case is called time delay control. The third case is when the control devices are provided with Artificial Neural Networks (ANN) that estimate the earthquake record in the next time and then the response of the structure and the required applied control force is calculated. These structures are compared with the case of no control to emphasize the efficiency of the proposed technique. All structures are subjected to four earthquakes.

The equation of motion for this structure is given by:

$$[M]_{5x5}\{\ddot{y}\}_{5x1} + [C]_{5x5}\{\dot{y}\}_{5x1} + [K]_{5x5}\{y\}_{5x1} = -[M]_{5x5}\{1\}_{5x1}\ddot{y}_g + [b]_{5x5}\{U\}_{5x1} \quad (1)$$

where **M**, **C** & **K** are the mass, damping and stiffness matrices of the structure respectively, $\{1\}$ is a vector with elements equal to 1, $y, \dot{y}, \ddot{y}$ are the displacement, velocity and acceleration vectors of the structure respectively, is the ground acceleration record, b is the control force location matrix and U is the control force vector given by U = - Gx. where G is the state feedback gain matrix and $x = [y_{1x5} \quad \dot{y}_{1x5}]^T$ is the state vector. The equation of motion can be recasted in state space form as follows:

$$\begin{bmatrix} \dot{x}_{1-5} \\ \dot{x}_{6-10} \end{bmatrix} = \begin{bmatrix} 0_{5x5} & I_{5x5} \\ -M^{-1}.K & -M^{-1}.C \end{bmatrix} \begin{bmatrix} x_{1-5} \\ x_{6-10} \end{bmatrix} + \begin{bmatrix} 0_{5x5} \\ M^{-1}.b \end{bmatrix} U_{5x1} + \begin{bmatrix} 0_{5x5} \\ -I_{5x5} \end{bmatrix} \ddot{y}_{g5x1}$$

(2)

Regardless of the type of excitation, the above structure is abbreviated as :

$$\dot{x}_{10x1} = A_{10x10}x_{10x1} + B_{10x5}u_{5x1} \quad (3)$$

which is the equation to be optimally controlled by finding the optimal value of G matrix so as to minimize the following performance index for ordinary control

$$J = \int_0^{\infty} (x^T Q x + U^T R U)dt \quad (4)$$

where Q , and R are positive-definite real symmetric matrices that define the relative importance of response and control force respectively. And take the following form;

$$Q=\begin{bmatrix} q_{11}.I_{5x5} & 0_{5x5} \\ 0_{5x5} & q_{22}.I_{5x5} \end{bmatrix}, \qquad R=r.I_{5x5} \quad (5)$$

where

q_{11} : is the relative importance factor for displacement response.

q_{22} : is the relative importance factor for velocity response.

r : is the relative importance factor for control force.

The resulting gain matrix is :

$$G_{5x10}=\begin{bmatrix} g_{D_{5x5}} & g_{V_{5x5}} \end{bmatrix} \qquad (6)$$

where g_D is the displacement gain vector and g_V is the velocity gain vector.

By solving for G, the control force can be set.

The equation of motion of the actual controlled structure is

$$[M]_{5x5}\{\ddot{y}_t\}_{5x1}+[C]_{5x5}\{\dot{y}_t\}_{5x1}+[K]_{5x5}\{y_t\}=-[M]_{5x5}\{1\}_{5x1}\ddot{y}_g(t)+[b]_{5x5}\{U(t)_{t-\Delta t}\}_{5x1} \quad (7)$$

and

$$\{U(t)_{t-\Delta t}\}_{5x1}=-[G]^T_{5x10}.\{x_{t-\Delta t}\}_{5x1} \qquad (8)$$

where $U(t)_{t-\ t}$ is the control force vector calculated according to the previous responses as the force at any time will delay Δt from the structure state. In other words it takes the control system a Δt time to sense, interpret, calculate and finally generate the control force, so in terms of Δt steps we know that the sensed response x_t will be used to calculate a control force that will never affect the structure before Δt time. To solve the above equation a SIMULINK simulation model is made and shown in figure 2.

The equation of motion of the time delay compensation controlled structure is

$$[M]_{5x5}\{\ddot{y}_t\}_{5x1}+[C]_{5x5}\{\dot{y}_t\}_{5x1}+[K]_{5x5}\{y_t\}_{5x1}=-[M]_{5x5}\{1\}_{5x1}\ddot{y}_g(t)+[b]_{5x5}\{\hat{U}(t)_t\}_{5x1} \quad (9)$$

And

$$\{\hat{U}(t)_t\}_{5x1}=-[G]^T_{5x10}.\{\hat{x}_t\}_{5x1} \qquad (10)$$

where $\hat{U}(t)_t$ is the control force vector calculated according to the estimated responses using the introduced ANN. Here the ANN receives the ground acceleration record and estimates the rest of it at Δt ahead . Then a calculation is made to estimate the control force at Δt ahead. So the control force will be applied at nearly the same state according to which, the control force was calculated. To solve the above equation a SIMULINK simulation model is made and shown in figure 3.

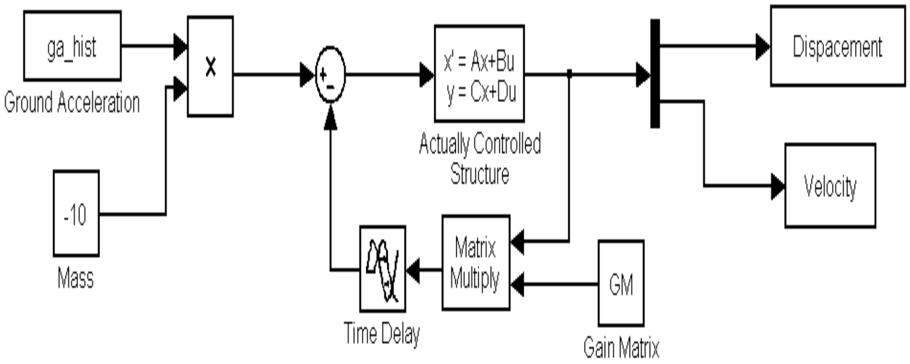

Fig. 2: Simulink model of Actual control

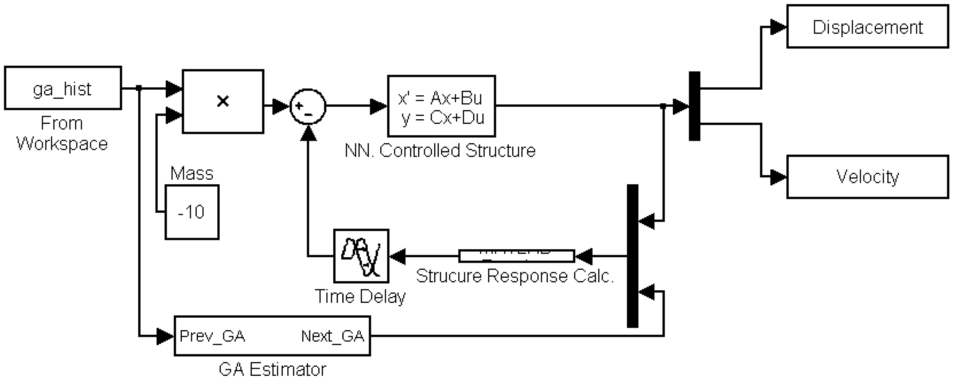

Fig. 3: Simulink model of control with time delay compensation by NN.

The NN is trained offline on a group of earthquakes then it is integrated in the control system to cover the delay effect. Back propagation neural networks are best appropriate to this function. The ANN consists of two layers back propagation. The first has a tan-sigmoid function and the second has a linear function. A schematic diagram of the NN is shown in Fig 4. The neural network estimates the earthquake record based on the given last part of it. Figure 5 represents the ANN job in the control cycle.

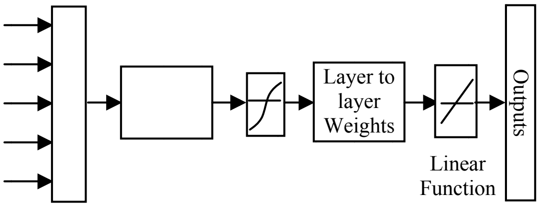

Fig. 4: Two layer Feed forward back propagation ANN.

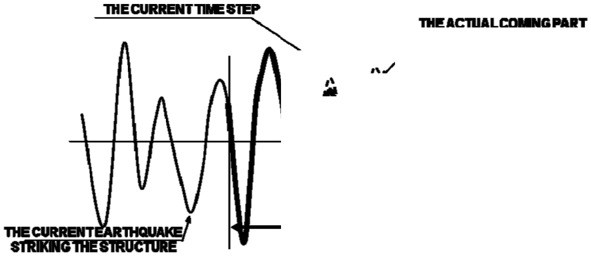

Fig. 5: ANN job in control cycle

3. Results and Discussion

For each time delay range, a separate ANN is created, trained and tested. Each ANN is trained offline using Long beach, Pacoima and Parkfield earthquake records with their three components after normalizing all of them to 0.3g. After training them, they were tested with 30 different earthquake records. The Root Mean of Sum of Squares of estimation Errors is presented in table 3. The 30 earthquakes used are listed in table 2.

Table. 2. Testing earthquakes.

Eq. Name	Dir.	Eq. Name	Dir.	Eq. Name	Dir.	Eq. Name	Dir.
Aqaba	N-S	COYOTE LAKE	E-W	CHALFANT	N-S	VICTORIA-MEXICO	N-S
CHI-CHI	N-S	COALINGA	N-S	HOLLISTER	E-W	LONG BEACH	N-S
LOMA PRIETA	E-W	FRIULI	E-W	OROVILLE	E-W	PACOIMA	N-S
IMPERIAL VALLEY	N-S	NW-CALIF	N-S	ERZIKAN	N-S	PARKFIELD	E-W
SUPERSTITION HILLS	E-W	LIVERMORE	N-S	MORGAN HILL	E-W	SAN-FERNANDO	N-S
WHITTIER	N-S	TABAS	E-W	LANDERS	N-S	EL-CENTRO	N-S
Anza	N-S	WESTMORELAND	N-S	DUZCE	E-W		
CAPE MENDOCINO	E-W	KOCAELI	E-W	HELENA MONTANA	E-W		

Table. 3. ANN estimation errors.

ANN	Average RMSE	ANN	Average RMSE
20 ms ANN	0.0784484	80 ms ANN	0.1382662
40 ms ANN	0.115591133	100 ms ANN	0.138449133
60 ms ANN	0.1184205	200 ms ANN	0.138661267

The minimum error was 0.02138 for NW-CALIF earthquake with 20 ms ANN, and the maximum error was 0.26448 for Imperial Valley earthquake with 80 ms ANN. Figure 6.a shows the estimation results of the 20 ms ANN for the Livermore earthquake, and figure 6.b shows its estimation results for Cape Mendocino Earthquake. Both figures show the high compatibility between the estimated and the real records although there is a big difference in the profiles of both earthquakes and both of them were not used in training the ANN. This indicates the efficiency of the proposed ANN estimator.

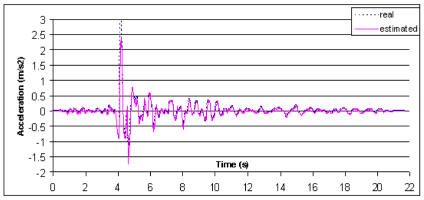

Fig. 6.a. Estimation results for the Livermore Earthquake using the 20 ms ANN

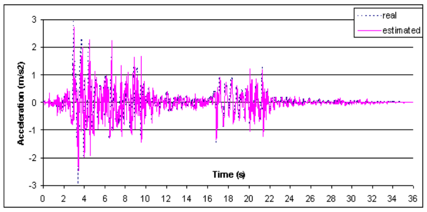

Fig. 6.b. Estimation results for the Cape Mendocino Earthquake using the 20 ms ANN

To show the effect of time delay, the results are presented for the three control strategies. The theoretical control which assumes zero time delay between sensing and control force application. The time delay control which takes into consideration the average delay encountered in sensing, calculation and control force application cycle. Finally the compensated time delay using neural network which will be referred to by The CTDNN control. The results of the three strategies are compared to the uncontrolled response of the structure by comparing the displacement ratios of maximum theoritically, actualy and Neural Network compensated peak displacements respectivley to the peak uncontrolled displacement of the top floor of the structure

Figure 7 shows the first 5 sec of the actual controlled response and the uncontrolled response of Structure 3 under El-Centro Quake with 40 ms. of delay. In figure 5 the graph shows that the actual behaviour of the control system will lead to instability in just 4 seconds. Although the NN technique used succeded to gurantee a maximum peak displacement of 37.5 % of its maximum uncontrolled peak displacement.

Figures 8 to 11 show the peak response ratio of the four studied structures in theoretical, actual and CTDNN control cases when subjected to Park field Earthquake with 20, 40,100 and 200 milliseconds of time delay respectively. In Fig. 8, it is shown that the CTDNN case is nearly identical with the theoretical case for all structures while the actual case gives lower efficiency in flexible structures and goes unstable for rigid ones (s1 and s2). This is because the estimation of single time step using the ANN is very easy and accurate, so it could totally eliminate the effect of time delay. In Fig. 9 , it is shown that the CTDNN case is stable for all structures but it is less efficient than the actual case for structure 4. Also, structure 1 has gone unstable in the actual case. This figure illustrates two facts; the first is that for low time delay values, compensation may not be needed in very flexible structures, and the second is that stiff structures are quickly affected by time delay and can easily go unstable, so they need to be controlled with the CTDNN case. In Fig. 10, the CTDNN case is still stable for structures 2,3 and 4 but it has gone unstable for structure 1. Also it is noticed that the Actual case has totally gone unstable for all structures. This assures the fact that rigid structures are affected badly by time delay that even this technique will have a limited range of time delay to compensate, after that range it will also fail. In figure 11, the CTDNN case is still stable for structures 3 and 4 only, and it has gone unstable for structures 1 and 2. Also it is noticed that the Actual case has totally gone unstable for all structures. At this very high level of time delay, even this technique begins to fail to stabilise medium stiff structures. It only succeeds with flexible structures. Generally, it is clear that for stiff structures (str 1 & 2) the time delay is very effective even in small delays the response becomes unstable. For flexible structures time delay becomes a serious problem as the delay increases. This is well proven from studying figure 8 and comparing it to the next figures. In figure 8 a very small amount of time delay (only 20 milleseconds) causesd both structures (1&2) to go unstable. Also it should be noticed that at only 60 milliseconds delay, all structures whether flexible or rigid have gone unstable and the NN algorithm could stabilize all of them and that is clear up to 80 ms. in figure 8 the most rigid structure 1 could'nt be stabilized even by this algortim. Continueing to figure 11 the effect reaches str 2. This trend is valid for a group of very famous earthquakes. Figure 12 shows that the four earthquakes are similar with slight individual variations. This figure shows that the technique is more successful in small time delays and its efficiency decreases with the time delay increase. Also the technique is relatively affected by individual variations between Earthquakes.

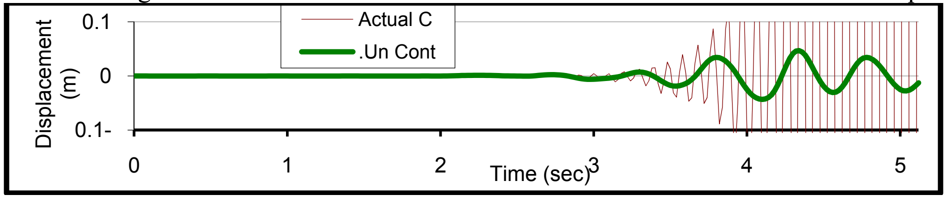

Fig. 7: Fifth storey Displacement Response. For Str.3 under El-Centro Quake with 40 ms. delay.

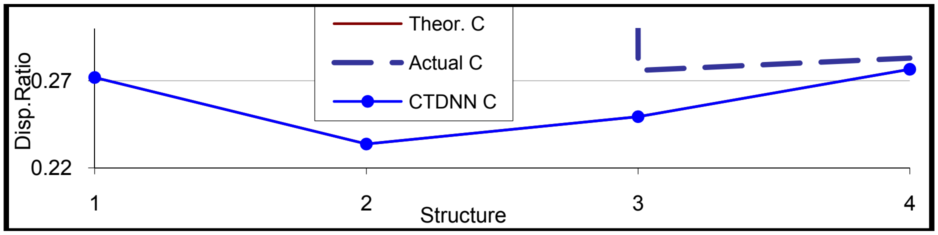

Fig. 8: Peak Resp. Ratios Vs Structures under Park Field quake with 20 milliseconds delay.

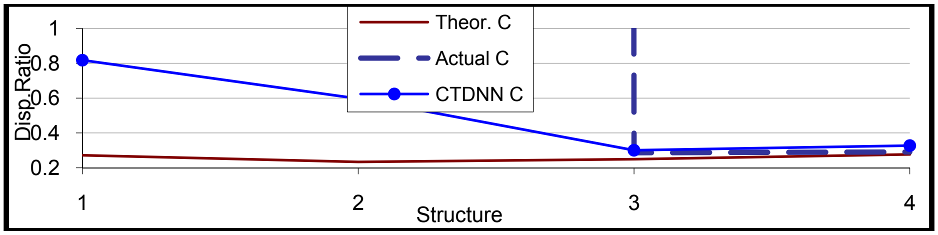

Fig. 9: Peak Resp. Ratios Vs Structures under Park Field quake with 40 milliseconds delay.

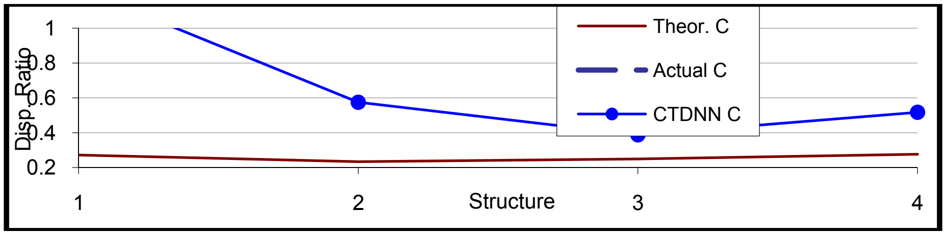

Fig. 10: Peak Resp. Ratios Vs Structures under Park Field quake with 100 milliseconds delay.

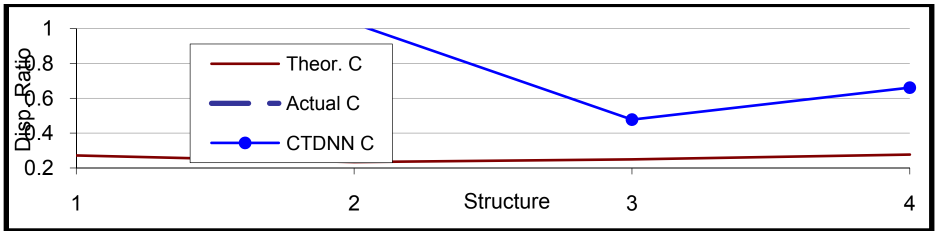

Fig. 11:- Peak Resp. Ratios Vs Structures under Park Field quake with 200 milliseconds delay.

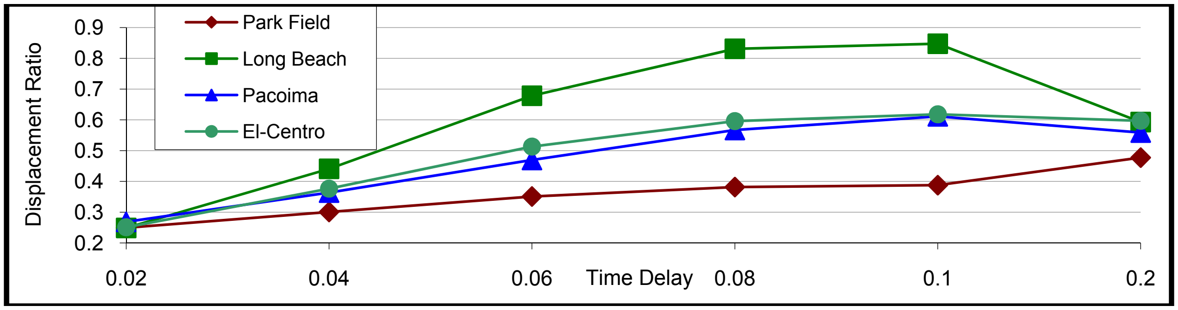

Fig. 12: Peak CTDNN Resp. Ratios Vs Delays under different quakes for Structure 3.

Conclusions

In this paper, a new technique to compensate time delay in active control was investigated. The study revealed the following conclusions.

1. Time delay has a considerable effect on actively controlled structures whether they are flexible or rigid.
2. Estimation of earth quake is not a simple process and cannot be done with 100 percent results if large steps ahead are required but at least this will lead to a stable solution without going into instability.
3. The NN estimator shows to be a good tool that can eliminate or minimize the effect of time delay and prevent the control process from instability caused by large time delays.
4. The effect of time delay should be considered in any design of active control systems, and its compensation is very important for the stability of the whole control process.

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