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Seismic Control of Tall Building Using a New Optimum Controller Based on GA

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***Abstract*—**This paper emphasizes on the application of genetic algorithm (GA) to optimize the parameters of the TMD for achieving the best results in the reduction of the building response under earthquake excitations. The Integral of the Time multiplied Absolute value of the Error (ITAE) based on relative displacement of all floors in the building is taken as a performance index of the optimization criterion. The problem of robustly TMD controller design is formatted as an optimization problem based on the ITAE performance index to be solved using GA that has a story ability to find the most optimistic results. An 11–story realistic building, located in the city of Rasht, Iran is considered as a test system to demonstrate effectiveness of the proposed GA based TMD (GATMD) controller without specifying which mode should be controlled. The results of the proposed GATMD controller are compared with the uncontrolled structure through time-domain simulation and some performance indices. The results analysis reveals that the designed GA based TMD controller has an excellent capability in reduction of the seismically excited example building and the ITAE performance, that is so for remains as unknown, can be introduced a new criteria - method for structural dynamic design.

***Keywords*—**Tuned Mass Damper, Genetic Algorithm, Tall Buildings, Structural Dynamics.

I. INTRODUCTION

A critical aspect in the design of civil engineering structures is the reduction of response quantities such as velocities, deflections and forces induced by environmental dynamic loadings (i.e., wind and earthquake). Structural control methods are the most recent strategies for this purpose, which can be classified as active, semi-active, passive, and hybrid control methods [1]. In the last three decades or so, the reduction of structural response, caused by dynamic effects, has become a subject of research, and many structural control concepts have been implemented in practice. Tuned mass dampers (TMDs) are the oldest structural vibration control devices in existence. The concept of vibration control using a mass damper dates back to the year 1909, when Frahm invented a vibration control device called a dynamic corresponding vibration absorber [2]. Although active tuned mass damper systems nowadays has received considerable attention from many researchers [3]-[5], a passive control technique is still considered due to its simplicity. Moreover, many passive control devices such as TMD successfully installed in the real application to reduce the lateral motion of high rise buildings [2],[6]-[8]. In this paper, a TMD system is considered to be applied to multi- degree-of-freedom structure, but without specifying which mode should be controlled. Thus, there is no need to transfer the structure to a single-mode model as have been done in the available research.

Several cost or objective functions have been developed to meet a specified performance in the optimization process. In practice, many performance indices can be chosen, as the objective functions resulted in a different result of the optimization. In the active vibration control area, there are also many optimization criteria which have been used by researchers. The most common ones are LQR, LQG, H_2, H_∞, sliding mode control, pole placement, independent model space control and so on [1],[9]-[13]. It should be noted that in the active control optimization there is a trade off between the responses to be minimize the structural responses while maintaining the control energy to be used, the passive control optimization is free from balancing the two parameters. In this paper, the integral of time multiplied absolute value of error (ITAE) based on the displacement of all building's floors is taken as a performance index of the optimization criterion. Usually, the traditional gradient-based search methods are used for solution of this problem. Unfortunately, the optimization process requires computations of sensitivity factors and eigenvectors at each iteration. This gives rise to heavy computational burden and slow convergence. Moreover, there is no local criterion to decide whether a local solution is also the global solution. Thus, conventional optimization methods that make use of derivatives and gradients are, in general, not able to locate or identify the global optimum, but for real-world applications, one is often content with a good solution, even if it is not the best. Consequently, heuristic methods are widely used for global optimization problem. Recently, global optimization techniques like genetic algorithm (GA) have been used for TMD and ATMD parameter optimization [14]-[17]. In this paper, the genetic algorithm, as a robust algorithm, has been used to optimize the parameters of controller. Finally, an 11-story realistic building, located in the city of Rasht, Iran, under different earthquakes through time domain simulation and some performance indices has been analyzed. The result evaluation shows that the proposed method achieves good robust performance aspect response.

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II. Structural model

Consider an *N*-story shear structure with mass damper installed at top floor as shown in Fig. 1. The equations of motion of the structural system under earthquake loading can be written as:

$$M\ddot{x} + C\dot{x} + Kx = e\ddot{x}_g \tag{1}$$

Where *M*, *C* and *K* are mass, damping, and stiffness matrixes, respectively; e and $\ddot{x}_g$ are the matrix induced ground acceleration, and ground acceleration, respectively. If the *x* in (1) is taken as the relative displacement with respect to the ground, the mass matrix for a high rise building structure, with the assumption of masses lumped at floor levels, is a diagonal matrix in which the mass of each story is sorted on its diagonal, as given in the following:

$$M = diag(m_1, m_2, ..., m_N, m_d) \tag{2}$$

Where, mi is mass of ith floor (*i=1,2,...,N*) in building and m_d is mass of damper.

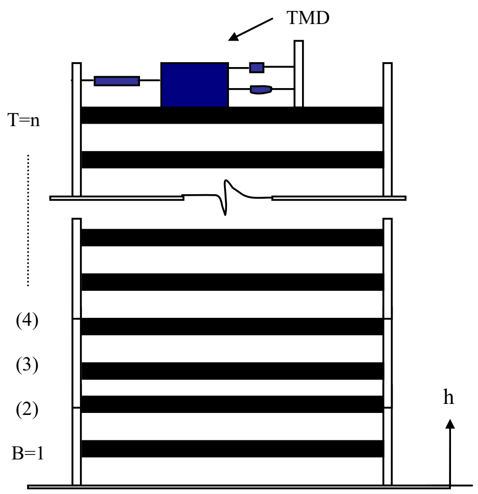

Fig.1. Example realistic building model and TMD mounted on its top floor.

The structural stiffness matrix [K] is developed based on the individual stiffness, k_i, of each floor, and is given in (3).

$$K = \begin{bmatrix} (k_1+k_2) & -k_2 & & & \\ -k_2 & (k_2+k_3) & -k_3 & & \\ & \cdot\ \cdot\ \cdot & & & \\ & & \cdot\ \cdot\ \cdot & & \\ & & & \cdot\ \cdot\ \cdot & \\ & & -k_N & (k_N+k_d) & -k_d \\ & & & -k_d & \\ & & & & k_d \end{bmatrix} \tag{3}$$

The structural damping matrix [C] is assumed to be proportional to the mass and stiffness matrices as [18]:

$$C = a_0 M + b_0 K \tag{4}$$

$$a_0 = \xi_i \frac{2\omega_i \omega_j}{\omega_i + \omega_j} \qquad b_0 = \xi_j \frac{2}{\omega_i + \omega_j} \tag{5}$$

Where, a_0 and b_0 are the proportional coefficients; ω_i and ω_j are the structural modal frequencies of modes *i* and *j*, respectively; and ξi and ξj are the structural damping ratios for modes *i* and *j*. The e and x vectors are as follows:

$$e = [-m_1, -m_2, ..., -m_N, -m_d]^T \tag{6}$$

$$X = [x_1, x_2, ..., x_N, x_d]^T \tag{7}$$

Where, k_i is stiffness of *i*th story (i=1,2,…,N); k_d is stiffness of damper; xi is displacement of *i*th floor relative to ground (*i=1,2,...,N*); x_d is displacement of damper relative to ground and x_g is ground displacement due to earthquake.

The equations of motion can then be converted to state-space realization as follows:

$$\dot{z} = Az + E\ddot{u}_g \tag{8}$$

Where,

$$A = \begin{bmatrix} 0_{(N+1)} & \mathrm{I}_{(N+1)} \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad ; \quad E = \begin{bmatrix} 0_{(N+1)\times 1} \\ M^{-1}e \end{bmatrix}$$

Note that by transforming the equations of motion (1) to state-space equation, we have transformed the second-order differential equation to the first-order one. Note also that the size of the matrixes in the state-space equation is two- times larger than that of the ordinary equation of motion.

The tuned mass damper is a classical engineering control device consisting of a mass, a spring and a viscous damper attached to a vibrating main system in order to attenuate and undesirable vibration. The natural frequency of a TMD is tuned to a frequency without specifying which mode of the main system should be controlled. Thus, there are three main parameters in a TMD system: TMD mass, TMD stiffness coefficient and TMD dumping ratio. Consequently, the objective is to find the optimum value of these parameters that involve in *A* in (8). Usually, this problem is converted to a problem of single-degree-of-freedom (SDOF) structure where the parameter of the structure is at a specified mode (usually the first mode) to be chosen. In view of seeking a more realistic model, this paper is used the multi-degree-of-freedom (MDOF) model as a structural model. By considering the structure as an MDOF structure the optimization process is coming more difficult to solve. Moreover, in case of an inherent damping presence in the structure, the closed-form solution may not be available. Thus, only numerical solution could be possible to solve the problem of MDOF structures with inherent damping. For this reason, the GA technique which is a useful tool for engineering optimization is being used to find optimal parameter of TMD for reduction of the structural vibrations [14]-[15], [17].

III. Genetic algorithms

In the genetic algorithm, the variable parameters of problem are coded in to a genetic string known as a chromosome. Each of these chromosomes has an associated fitness value, usually determined by the performance index, which is to be minimized. Each chromosome contains sub-strings known as genes, which contribute in different ways to the fitness of the chromosome. The genetic algorithm proceeds by taking a population, which is comprised of different chromosomes and generating a new population or generation by combining features of chromosomes with the highest fitness values. The aim of the algorithm is to produce chromosomes with increasing fitness, and to increase the average fitness of each successive generation. Only the fittest chromosomes pass to successive generations [19]-[20].

The genetic algorithm starts with random initial population and then uses three basic operations: selection, cross-over and mutation. Selection is the process of choosing the fittest string from the current population for use in further reproductive operations to yield fitter generations. Cross-over is the process whereby new chromosomes are generated from existing individuals by cutting each old string at a random location (cross-over point) and replace the tail of one string with that of the other. Figure 2 shows the cross-over operation.

$$stringA_1 = 100\ \underline{\underline{11}} \Rightarrow \xrightarrow{Crossover} A_1^i = 100\ \underline{00}$$
$$stringA_2 = 110\ \underline{00} \Rightarrow \xrightarrow{Crossover} A_2^i = 110\ \underline{\underline{11}}$$

Fig. 2. Cross-over operation

Mutation is a random process whereby values of element within a genetic string (chromosome) are changed. In a binary string, mutation is the random changing of 0,s to 1,s and vice versa. Figure 3 shows the mutation operation.

$$stringA_1 = 101\underline{1}1\underline{\underline{0}}0\underline{1} \Rightarrow A_1^i = 101\underline{0}1\underline{\underline{0}}1\underline{1}$$

Fig. 3. Mutation operation

A. Control Parameters of genetic algorithm

The Parameters of genetic algorithm are variables that if assigned fitter, they can avoid of soon- slow convergence and they can acquire better performance. They are: population size (popsize), probability of cross-over (Pc), probability of mutation (Pm), and maximum number of population (maxpop) and in some problems is the length of chromosome. Figure 4 shows the flowchart of the proposed genetic algorithm.

B. TMD design using GA

Tuned mass damper consisting of a mass, a damping, and a spring is an effective and reliable structural vibration control device commonly attached to the vibrating primary system for suppressing the undesirable vibrations induced by winds and earthquake loads. In the proposed method, we must find the TMD parameters optimally to get maximum reduction in building responses due to the different earthquake excitations. Thus, in optimization process the simulated earthquake using Kanai-Tajimi filter (9) [21] is shown in Fig. 5 by MATLAB software [22] is created and used as base earthquake excitation.

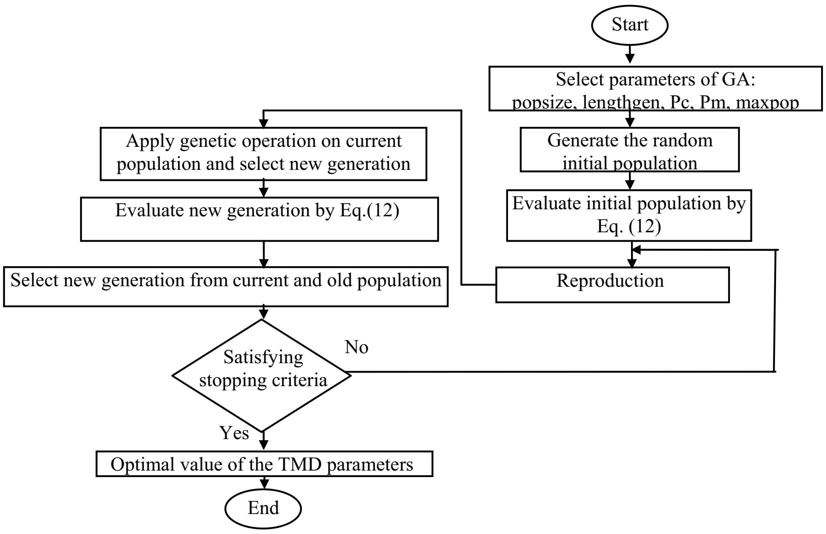

Fig. 4. Flowchart of the proposed GA technique

$$H(s) = S_0 \frac{(\omega_g^{\ 4} + 4\omega_g^{\ 2}\xi_g s^2)}{(s^2 - \omega_g^{\ 2})^2 + 4\omega_g^{\ 2}\xi_g^{\ 2}s^2} \qquad (9)$$
$$S_0 = 0.03\frac{\xi_g g2}{\pi\omega_g(4\xi_g^{\ 2} + 1)}$$

In this paper, ω_g and ξ_g is considered as 37.3 and 0.3, which are for usual soils, respectively.

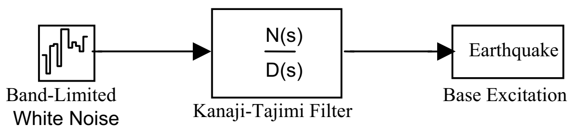

Fig. 5. Base excitation used for tuning of the TMD Parameters.

To acquire an optimal combination, this paper employs GA to find the global optimum value of fitness function. It should be noted that choosing of the properly objective function is very important in synthesis procedure for achieving the desired level of system robust performance. Because different objective functions promote different GA behaviors, which generator fitness value providing a performance measure of problem considered. For our optimization problem, the following objective function based on the system performance index of the ITAE is used [23].

$$J = \sum_{i=1}^{N} ITAE_i \qquad (10)$$
$$ITAE_i = \int_0^{t=tsim} t\left|x_i(t)\right| dt$$

Where, x_i is relative displacement of ith story building response under base earthquake excitation and is obtained using the solution of (8). It is worth mentioning that the lower the value of this objective function is, the better robustly the system performance in terms of time domain characteristics. The design problem can be formulated as the following constrained optimization problem, where, the constraints are the TMD parameters bounds.

Minimize J subject to

$$m_o^{\min} \le m_o \le m_o^{\max}$$
$$\beta_d^{\min} \le \beta_d \le \beta_d^{\max} \qquad (11)$$
$$\zeta_d^{\min} \le \zeta_d \le \zeta_d^{\max}$$

To improve the overall building response in a robust way and optimization synthesis, GA is used to solve the above optimization problem that search for optimal or near optimal set of TMD parameters.

IV. Case Study

In order to investigate the performance of the proposed control strategy in reducing the structural responses under earthquake loadings, an 11-story shear frame building, located in city of Rasht in the north of Iran, is chosen as an a test system. The structure represents a typical medium size multistory building. The structural properties of this building are listed in Table I [15].

The TMD frequency to the first mode frequency of the building with a frequency ratio β_d, the mass of the TMD system was chosen to be mo percent of total mass of the building and its damping ratio (ξ_d) was considered to be percent of the critical value. These three parameters (m_o, β_d and ξ_d) of TMD are optimized by evaluating the cost function as given in (11). In order to acquire better performance, maximum number of population, population size, number if iteration, Pc and Pm is chosen as 25, 3, 250, 0.8 and 0.08, respectively. It should be noted that GA algorithm is run several times and then optimal set of TMD parameters is selected. Results of TMD parameter set values based on the cost function given in (11) using GA method (see [24] for more detail about the problem solution) are given in Table II. Also, Fig. 6 shows the minimum fitness value evaluation process.

TABLE I
TEST BUILDING STRUCTURAL DATA.

Stories	Mass(kg)×10^5	Stiffness(N/m) ×10^8
1	2.15	4.68
2	2.01	4.76
3	2.01	4.68
4	2.00	4.5
5	2.01	4.5
6	2.01	4.5
7	2.01	4.5
8	2.03	4.37
9	2.03	4.37
10	2.03	4.37
11	1.76	3.12

TABLE II
OPTIMAL VALUE OF TMD PARAMETERS.

TMD Parameters	GA
m_0	0.08
β_d	0.38
ξ_d	0.15

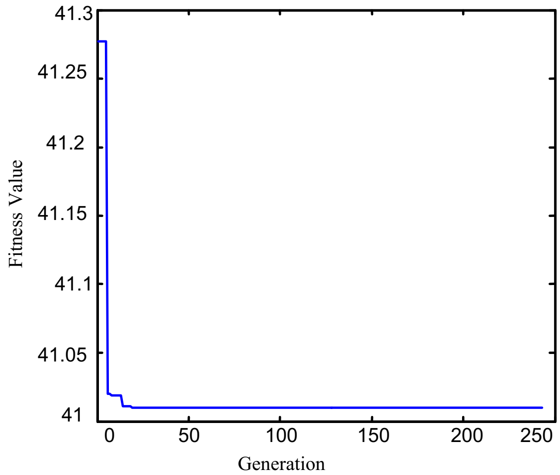

Fig. 6. Minimum fitness convergence by GA.

A. Simulation results

To investigate the effectiveness of the control system for different disturbances, three different seismic motions are used in the numerical simulations. These ground acceleration records are: El Centro 1940, Kobe 1995 and Tabas 1999 earthquakes. The absolute peak ground accelerations (PGAs) of these earthquake records are 0.3417, 0.8178 and 0.9512 g, respectively.

The result of controlled displacement response of the example building top story due to the El Centro NS earthquake calculated by the GA-based TMD designed systems are compared with the corresponding uncontrolled ones in Fig. 7 and Table III. Also, Fig. 8 depicted maximum displacement of floors using the proposed GA based TMD and uncontrolled systems. Fig. 9 shows the ITAE performance index. It can be seen from the Figures and Tables, the response reduction ratio (ratio of the controlled to uncontrolled response) for maximum displacement of top floor of the 11-story example building is about 35% for the GATMD.

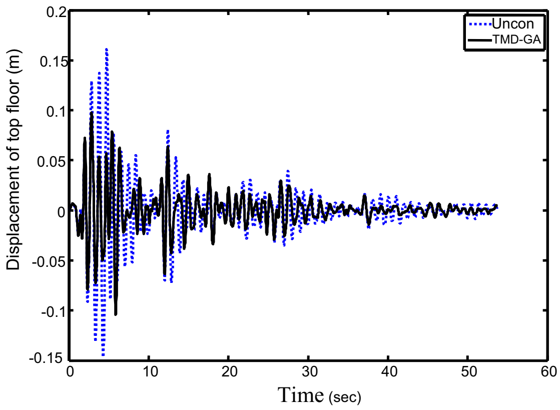

Fig.7. Displacement of top floor under El Centro 1940 earthquake GA based TMD.

TABLE III
COMPARISON OF THE EFFECTIVENESS CONTROLLER SYSTEM FOR THE ELCENTER 1940 EARTHQUAKE

Building floor	Maximum uncontrolled response (m)	Controlled to uncontrolled response ratio percent (Reduction Ratio)
1	0.0224	39.9131
2	0.0432	39.1771
3	0.0627	38.0799
4	0.0811	36.8794
5	0.0973	35.6166
6	0.1112	34.3665
7	0.1253	34.4651
8	0.1381	34.6575
9	0.1486	34.8911
10	0.1558	34.9620
11	0.1608	34.8984

The effectiveness of these control systems and ITAE in reducing the response of the example building due to other earthquakes is also shown for comparison in Figs. 10-15 and Tables IV-V. Almost the same behavior as for the El Centro earthquake can be observed for these earthquakes, too. Moreover, it is seen from Table 5 that the Kobe 1995 earthquake causes the maximum displacement (about 50 cm) at the top floor of the example building, which is a very high value in comparison with the other earthquake. This is expected due to fact that the PGA of the Kobe earthquake is very high (about 0.8178 g) and almost remains constant for a long period of time in comparison with other two earthquakes.

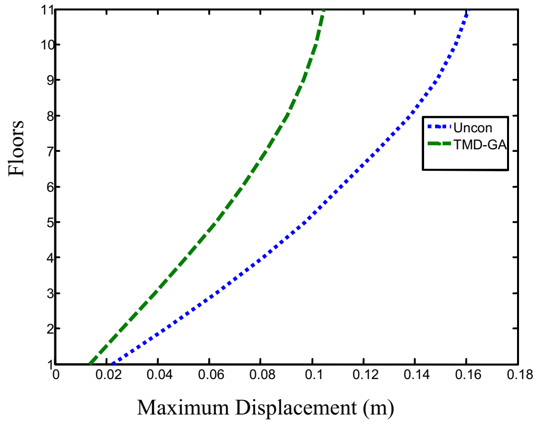

Fig. 8. Maximum displacement of floors under EL Centro 1940 earthquake.

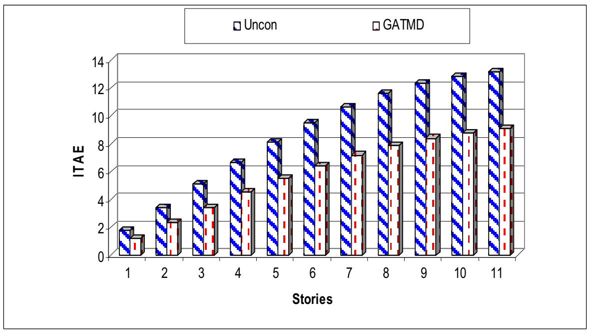

Fig. 9. ITAE performance index value for all floors under El Centro 1940 earthquake.

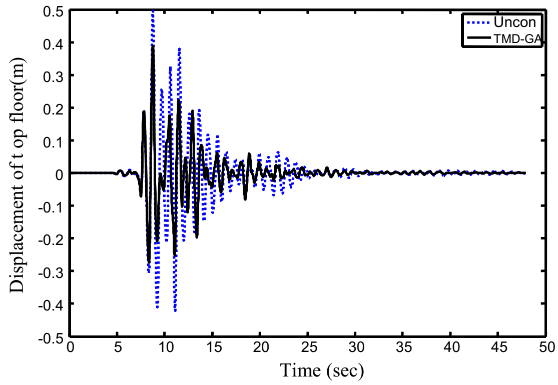

Fig.10. Displacement of top floor under Kobe 1995 earthquake GA based TMD.

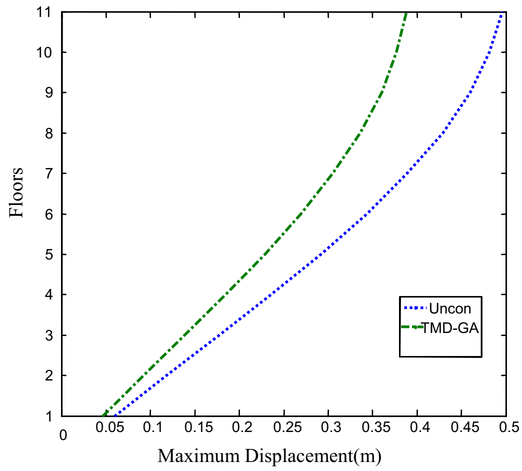

Fig.11. Maximum displacement of floors under Kobe 1995 earthquake.

TABLE IV
COMPARISON OF THE EFFECTIVENESS OF THE CONTROLLER SYSTEM FOR THE KOBE 1995 EARTHQUAKE

Building floor	Maximum uncontrolled response (m)	Controlled to uncontrolled response ratio percent (Reduction Ratio)) GATMD
1	0.0596	22.1935
2	0.1184	22.0018
3	0.1771	21.8348
4	0.2361	21.6975
5	0.2919	21.5819
6	0.3433	21.5130
7	0.3890	21.5280
8	0.4289	21.6464
9	0.4602	21.7161
10	0.4814	21.6765
11	0.4956	21.6974

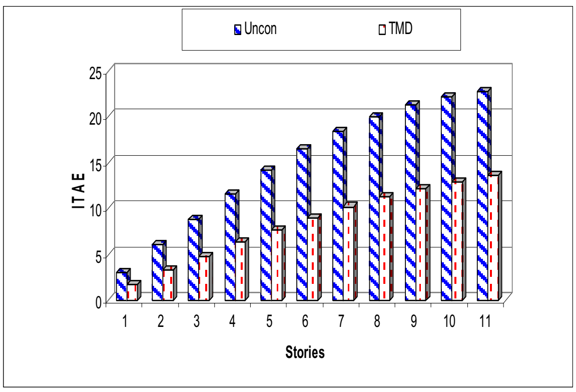

Fig. 12. ITAE performance index value for all floors under Kobe 1995 earthquake.

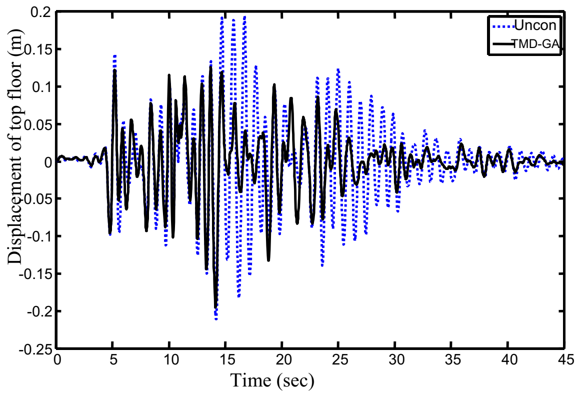

Fig. 13. Displacement of top floor under Tabas 1999 earthquake GA based TMD.

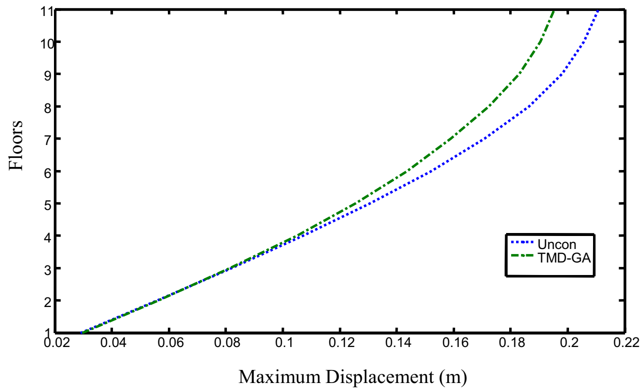

Fig. 14. Maximum displacement of floors under Tabas 1999 earthquake.

TABLE V
COMPARISON OF THE EFFECTIVENESS OF THE DIFFERENT CONTROLLER SYSTEMS FOR THE TABAS EARTHQUAKE

Building floor	Maximum uncontrolled response (m)	Controlled to uncontrolled response ratio percent (Reduction Ratio) GATMD
1	0.0596	-1.9926
2	0.1184	-0.6288
3	0.1771	0.6202
4	0.2361	2.0618
5	0.2919	3.8202
6	0.3433	5.5166
7	0.3890	6.8874
8	0.4289	7.6020
9	0.4602	7.5793
10	0.4814	7.3355
11	0.4956	7.3338

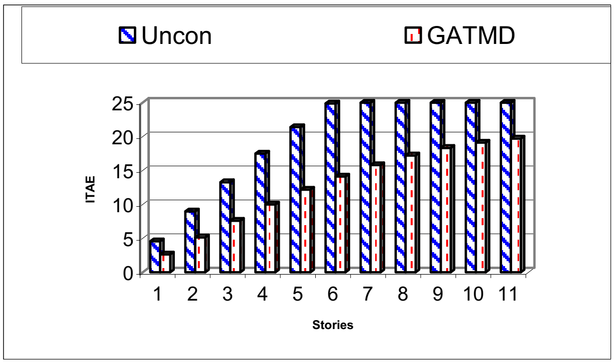

Fig. 15. ITAE performance index value for all floors under Tabas earthquake.

To demonstrate the effectiveness of the proposed method, the average reduction ratios (controlled to uncontrolled displacement and acceleration ratio) for all three earthquakes on all 11 stories of the example building are shown in Table X and XI, respectively. According to these Tables, it can be seen that in general the GATMD system is capable of reducing the maximum displacement and acceleration of the building in each story to about 20.7 and 22.12 of the uncontrolled response, respectively. Thus, the system is a effective method.

TABLE X
THE AVERAGE REDUCTION (FOR 11 FLOORS) IN MAXIMUM DISPLACEMENT RESPONSE OF THE EXAMPLE BUILDING`

Earthquake excitation	Average response reduction percent GATMD
Elcentro earthquake	36.1733
Kobe earthquake	21.7352
Tabas earthquake	4.1941
Total average	20.7009

TABLE XI
THE AVERAGE REDUCTION (FOR 11 FLOORS) IN MAXIMUM ACCELERATION RESPONSE OF THE EXAMPLE BUILDING

Earthquake excitation	Average response reduction percent GATMD
Elcentro earthquake	28.2203
Kobe earthquake	28.5470
Tabas earthquake	9.5947
Total average	22.1207

V. CONCLUSIONS

A new GA based TMD controller is proposed for the reduction of the high rise building dynamic responses subjected to earthquake excitations in this paper. This study emphasizes to design and optimize the parameters of the TMD control scheme for achieving the best results in the reduction of the building response under earthquake excitations. The problem of robustly TMD controller design is formatted as an optimization problem based on the ITAE performance index to be solved using GA technique. The GA algorithm proposed in this paper is easy to implement without additional computational complexity. Thereby experiments this algorithm gives quite promising results. The ability to jump out the local optima, the convergence precision and speed are remarkably enhanced and thus the high precision and efficiency are achieved.

I. For the numerical study, an 11-story realistic building is chosen and the problem is solved in state space, as well as a GA based TMD controller system are also designed to control the building response. The system performance characteristics in terms of 'ITAE' and 'the average reduction ratios' reveal that this control strategy is a promising control scheme for the getting the maximum reduction in displacement response of the building's stories .It is effective and ensures robust performance for different earthquakes excitations. Also, it has simple structure and easy to implement.

II. The ITAE performance that is multiply of energy-time and so for remains as unknown, can be introduced a new criteria - method for structural dynamic design that is contained almost all effective characteristics of the fittest design structure.

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