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Designing market-based control with a genetic algorithm

S. Khorsand[a] and F. Amini[b,*]

a. *School of Civil Engineering, Sharif University of Technology, P.O. Box 11155-9313, Iran.*
b. *School of Civil Engineering, Iran University of Science and Technology, Tehran, P.O. Box 16844-13114, Iran.*

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Genetic Algorithm (GA).

Abstract. Semi-active devices are low-cost as well as small, and, by changing the properties of low-power intensive structures, the aims of control are accomplished. On the other hand, the limited control force, which can be applied to the structure for each damper, causes more dampers to be used in structures compared to larger and stronger control devices which are more costly. These dampers coupled with sensors and the structure themselves make a complex dynamic system which is best controlled by a decentralized method, such as Market-Based Control (MBC). In MBC, the actuators and the supply energy are modeled as the buyer and the seller, respectively, in the market place. To define the demand function of the buyer and the supply function of the seller, some weighting constants have to be chosen. The performance of the MBC correlates with prudent selection of the weighting constants. In this study, a novel method for designing MBC using a Genetic Algorithm (GA) is presented. The MBC approach is applied to three linear structures having five, ten and twenty floors, and the resulting solutions show the merits of the new methods for tuning MBC as opposed to solutions using a centralized Linear Quadratic Regulator (LQR).

1. Introduction

Controlling the responses of structures, such as tall buildings, irregular steel highrise buildings and cable-stayed bridges, to wind, earthquake and blast loading has been studied comprehensively over the years [1-10].

The current state of practice for limiting structural responses throughout seismic disturbance is active and semi-active control of which the latter has attained more popularity, being cheaper and consuming less energy compared to the active control method [11-13].

Semi-active control forces are not big enough to limit the structural response to horizontal loads such as earthquake. Therefore, a large number of control devices must be employed to achieve the goal. To control a large-scale complex system, the conventional method of using a central computer by coordinating the collection of state information from system sensors and calculating, according to these dates, the control forces of the entire system in one computer becomes less agreeable [14-18].

An alternative to centralization is a decentralized method system that is often more appropriate for complex distributed systems [4]. In the decentralized system, some control devices have the facilities of on-board computational power to calculate their own control force based on the measurements of the system sensors. The advantages of the system are installation modularity, facilitating low-cost installations, diagnostics and module replacements, improved control system

*. *Corresponding author. Tel.: +98 21 77240332; Fax: +98 21 77240398
E-mail addresses: khorsand2010@gmail.com (S. Khorsand); famini@iust.ac.ir (F. Amini)*

performance in non-linear systems, greater stability robustness and elevated system performance due to system uncertainty [19].

While many agent-based control methods used for complex distributed systems have a decentralized approach, this study focuses on developing Market-Based Control (MBC) because of its effectiveness when applied to structural control problems [16,18].

MBC is inspired by the free-market system. In this system, a scarce system resource is optimally distributed in a decentralized manner from the seller (according to their supply) to the buyer agents (depending on their demands). This distribution is based on the Pareto optimal price of the control energy that can be determined from supply and demand functions. Easy implementation, with inexpensive partially-decentralized large-scale wireless sensing and control networks, is allowed by agent-based control architecture in MBC [16,18].

To design an MBC method, the weighting coefficients of the supply and demand functions have to be defined. The MBC's performance is dependent upon a logical selection of the weighting coefficients. Using a Genetic Algorithm (GA) is one way to find the weighting coefficients. In this paper, the theory of MBC is presented and then the process of using GA for finding the weighting coefficients is described. Finally, the MBC method, with the weighting coefficients produced by GA, is applied to five-, ten- and twenty-story structures, where the semi-active devices are used as their main source of control in them all. The proposed method is compared with the results of the widely-used Linear Quadratic Regulation (LQR) centralized control approach [20-25].

2. Market-based control

Implementing a large number of semi-active actuators to control a structure and limit its response to loads, such as earthquakes and winds, makes a highly complex problem, causing difficulty using centralized methods. A decentralized approach is an alternative to the centralized method, which shows its effectiveness when applied to these problems. A decentralized approach is MBC where the structure with all the actuators, sensors and energy supplies make up the market. The actuators in this market are assumed as buyers wanting to buy energy from suppliers assumed as sellers. The energy is allocated like a scarce resource in the free-market systems to buy from the seller. The factor determining the amount of scarce resource for selling to the buyers is the market price. The price results from the accumulated effect of the buy-sell communication between market agents. Buyers desire to attain maximum utility through purchasing power, P_b, and sellers seek to maximize their profit by selling their power to the buyers, P_s. Because of the closed system, including n sellers and m buyers, the summation power supplied from all the n sellers is equal to the summation power demanded by all the m buyers:

$$\sum_{i=1}^{n} Psi = \sum_{i-0}^{m} Pbi. \tag{1}$$

Each buyer and seller in the market seeks to maximize its profit. But the profit of each agent is a function of other agent benefits. To reach a global optimization in the market, where each agent gains maximal benefit without adversely affecting another agent's profit, Pareto's is an optimal solution to the problems of multiple objectives optimization. In this optimal solution, the demand functions of all buyers are aggregated, comprising the market demand function. Similarly, a combination of the sellers' supply function creates the supply function of the market. At each point of time, the interception of the demand and supply function indicates the equilibrium of the competitive price of power. Having defined the price, the buyers purchase the power consumed to apply control forces to the structure.

To define the demand function, two factors are important. The first is the structural response directly affecting the demand function, and the second is the equilibrium price. When the price rises, the buyer demand decreases. The following linear demand function of the ith DOF is chosen because of its simplicity:

$$\rho = \left(\sum_{i=1}^{m} Wi\,|Rx + S\dot{x}|\right) \Big/ \left(\frac{n}{\alpha} + \sum_{i=1}^{m} \frac{Wi}{|Tx + Q\dot{x}|}\right), \tag{2}$$

where slope, f, and intercept, g, are the function of displacement, x, and the velocity, $\dot{x}_i$. ρ is the price of the power in this formula. The negative slope shows the opposite relation of the price of the power and demand function. Assuming that the demand of the buyer is tied to structural response, slope, f, and intercept, g, are defined as follows:

$$f(x, \dot{x}) = 1/\left(Tx + Q\right), \tag{3}$$

$$g(x, \dot{x}) = Rx + S\dot{x}. \tag{4}$$

T, Q, R and S are used as various tuning constants to provide freedom setting up the relationship between demand and response.

As shown in Figure 1, the demand function increases as the structural response increases, thereby increasing the price of the power. In similar methods, the following linear supply function is selected:

$$Ps = \frac{1}{\alpha}\rho, \tag{5}$$

where $1/\alpha$ is a constant slope of the supply function.

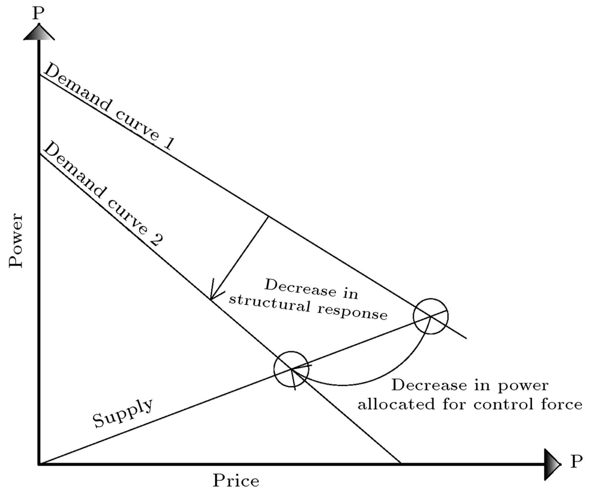


Figure 1. Relation of the structural response and the equilibrium price with the demand function.

The positive slope ensures that by raising the price of power, the eagerness to sell more power increases. There is no need for supply in the absence of demand, so that the intercept of the function is zero and the curve starts at the origin.

In a SDOF system, the equilibrium price is achieved by equating the supply (Eq. (5)) and demand (Eq. (2)) functions. By converting constant, K, the equilibrium price is translated to control force, U:

$$U = K\left(\frac{|Rx + S\dot{x}|}{|Tx + Q\dot{x}| + \alpha}Tx + \frac{|Rx + S\dot{x}|}{|Tx + Q\dot{x}| + \alpha}Q\dot{x}\right). \quad (6)$$

A fictitious wealth is introduced in the MDOF system. This wealth gives each buyer a different allocation control authority in the design of the MBC system. When the buyer has more wealth, the eagerness to buy power will increase, thereby affecting the demand function in a direct manner. When the price of the power is greater than the buyer's wealth, the power will not be sold to the buyers and no control force will be applied. The total wealth remains constant in the system and the selling agent will not have permission to accumulate the wealth gained by selling power to the buyer. Thus, the money spent on buying power is collected and reallocated evenly for the buyer [16]. The equilibrium price for the MDOF system is:

$$\rho = \left(\sum_{i=1}^{m} Wi\,|Rx + S\dot{x}|\right) \Big/ \left(\frac{n}{\alpha} + \sum_{i=1}^{m}\frac{Wi}{|Tx + Q\dot{x}|}\right), \quad (7)$$

where Wi shows the wealth of the ith agent of the market. The control force of the ith agent in the system is [18]:

$$U_i = K\left(\frac{-\rho Wi}{|Tx + Q\dot{x}|} + Wi|Rx + S\dot{x}|\,\mathrm{sign}\,(Rx + S\dot{x})\right). \quad (8)$$

At each time juncture, the amount of the control power purchased is subtracted from the buyer agent's wealth and then the profit from the power sold is accumulated and redistributed in a uniform manner among all buyers in the network. This results in maintaining constant wealth in the system.

3. Designing MBC with a genetic algorithm

To choose prudent constants in designing MBC properly, it is necessary to minimize the cost function, including structural response $X(t)$ and control force $U(t)$. The cost function is:

$$J = \int_0^\infty (X'Qx + U'RU)\,dt, \quad (9)$$

where Q and R are the weighting matrices on the state response and control effort, respectively, which have to be positive and definite to ensure that a minimum of the cost function is found.

The Genetic Algorithm (GA) is a heuristic random search technique. In this algorithm, inspired by nature, the optimal combination of design variables can be found. The set of variables forms one individual. GA considers the potential solution of any problem as an individual. The fitness value is the value of the individual depending on the fitness function to be optimized. At each step, the GA chooses individuals at random from the existing population to become parents, which make children for the next generation. The individual with a high fitness value has more chance for selection as a parent, such that, over successive generations, individuals with a high fitness value will remain, thereby helping the population develop toward an optimal solution [26].

In comparison with traditional optimization methods, the benefits of the GA are:

- GA changes the variables to the codes and deals with the codes, not with the variables themselves.
- GA decreases the possibility of stopping the algorithm in a local optimum, due to the search of a population of points rather than the development of a single point.
- GA utilizes the information of the objective function without any gradient information.
- GA utilizes probabilistic transition rules despite gradient information used by traditional methods.

Several pieces of work [27-30] have used GA for solving optimization problems, such as discrete and combinatorial optimization, and the results show the merits of the method.

In order to find prudent constants for the MBC controller with the GA, first and foremost, the algorithm configuration, such as population, method of

Maximum control force	1000 kN
Maximum displacement	+/- 6 cm
Stiffness of SHD	400,000 kN/m
Maximum damping coefficient	200,000 kN-s/m
Minimum damping coefficient	1,000 kN-s/m
Maximum shaft velocity	25 cm/s
Power consumption	70 Watts

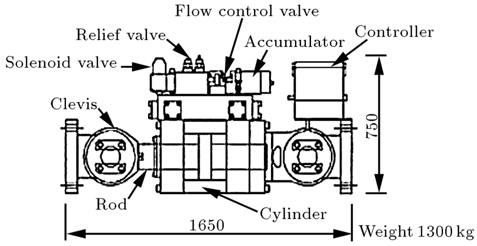


Figure 2. Application and properties of SHD [31].

selection and crossover etc., should be accurately set up in order to obtain a better chance of convergence to a near global optimum [27-30]. At each step, the structural responses to the specific seismic disturbance and the control efforts are calculated, and then, the cost function of each group of constants making the individual is computed. The lower-cost function value gives the individual the higher fitness value. On the other hand, the individual with a high fitness value is more likely to be selected as a parent for producing the next generation, so that, after some generations, the optimum set of constants for MBC controllers, which has the lowest cost function value, will be produced by GA.

4. Linear quadratic regulator algorithm

The Linear Quadratic Regulator (LQR) is the most effective and widely used method of centralized controller approaches to control the response of large structures, like bridges, to wind, earthquake and blast loading [8,20-25]. The optimal control solution is provided by LQR through minimization of the cost function, which is introduced in Eq. (10). If the control force vector, $U(t)$, is generated by feedback of the state vector, $X(t)$, applied to the optimal control theory, the optimal control force will be:

$$U(t) = -R^{-1}B^T PX(t) = -KX(t), \tag{10}$$

where K is a static gain matrix resulting from minimization of the cost function, and P is the Ricatti matrix, which is obtained by solving the following Riccati matrix equation:

$$PA + A^T P + Q - PBR^{-1}B^T P = 0. \tag{11}$$

5. Application to analytical structure

To illustrate the efficacy of an MBC design using GA, three multiple-degree-of-freedom systems are analyzed. A lumped mass structural system is considered for each structural system experiencing elastic responses. The purpose of the analysis is to evaluate the effectiveness of the new method for designing MBC.

The first structure is the Kajima-Shizuoka Building constructed in Shizuoka, Japan [31]. Eight Semi-active Hydraulic Dampers (SHD) on the first four floors of the five-story structure have been implemented and oriented in a weak direction. The second one is the ten-story building having 12 SHD dampers logically designed into this building. The third system is a twenty-story steel structure with 36 SHD dampers distributed throughout the structure. SHD variable dampers are used as control devices in all structures. These dampers are mostly installed between the apex of a K- or V-brace and the floor. To get the command control force, the damping coefficient of the SHD damper is calculated by dividing the command force from the relative velocity between the two floors where SHD is installed. When the relative velocity between the two floors to which SHD is connected is not in the direction of the desired control force, the control force will be applied. However, if the response is not in the same direction, the default minimum value will be considered for SHD. Detailed properties of the SHD and the installation are illustrated in Figure 2.

The SHD damper and the brace are modeled as a Maxwell damping element because of the flexibility of the K-brace implemented to attach the SHD device to the structural system [32]. A Maxwell element is a dashpot and spring in series, whose force, $p(t)$, is defined by a second-order differential equation:

$$\dot{P}(t) + \frac{k_{\text{eff}}}{C_{\text{SHD}}} P(t) = k_{\text{eff}} \dot{X}(t). \tag{12}$$

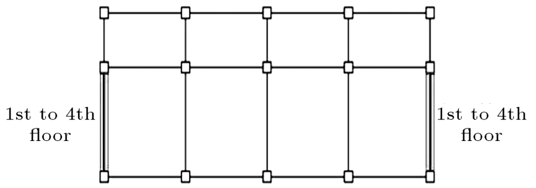
The effective stiffness, k_{eff}, of the Maxwell element is the combined stiffness of the bracing element in series with the inherent stiffness of the damper.

To evaluate the new method for designing the MBC, four earthquakes, such as El Centro (1940), Taft (1952), Northridge (1994) and Kobe (1995), were used. All these earthquakes were scaled with a peak ground acceleration of 2.923 m/s^2.

5.1. The Shizuoka structure

The Shizuoka building is one of the structures used to evaluate the new method for designing. The structural details of the building and location of SHD devices are presented in Figure 3. To access the performance of the new method of designing MBC, solutions using the MBC method will be compared to that of a centralized LQR controller.

Floor	Seismic mass (kg)	Story stiffness (kN/m)	Damping
1	215.2^*10^3	147.0^*10^3	5% natural damping
2	209.2^*10^3	113.0^*10^3	
3	207.2^*10^3	99.0^*10^3	
4	204.8^*10^3	89.0^*10^3	
5	266.1^*10^3	84.0^*10^3	



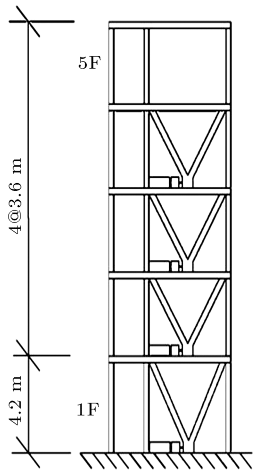


Figure 3. Shizuoka building.

Table 1. The weighting terms for the MBC design of the Shizuoka building.

T	1348.3	k	5331.6	W_3	1214.2
R	-0.9	α	0.00079	W_4	647.3
Q	1427.6	W_1	279.4	W_5	0 (No control devices)
S	1.4	W_2	-164.6		

The weighting terms summarized in Table 1 are obtained by using a genetic algorithm to design the MBC.

The negative wealth means that the damper does not have sufficient wealth to buy the power at the point of time. The wealth at each time is increased so that it becomes positive after a while and then the damper will be able to buy power.

For the design of the LQR controller, the waiting matrix on the state response, Q, is chosen, with the aim of decreasing the system velocity responses.

The weighting of actuation effort, R, is selected depending on the actuation saturation. In Eq. (13), the Q and R matrices are shown:

$$Q = \begin{bmatrix} I & 10I \\ 10I & 100I \end{bmatrix} \;\&\; R = 2.5^*10^{-12}[I]. \tag{13}$$

As can be seen in Figure 4, both the MBC and LQR controllers significantly reduce the maximum absolute displacements and maximum inter-story drifts of the uncontrolled response of the Shizuoka Building, with minimal differences between the two solutions. Figure 5 presents the total control effort of the control system. The MBC controller consumed energy by approximately 4% more than the LQR controller during all four earthquakes. In comparison to the performance of the MBC designed with a Genetic Algorithm and LQR, the merit of the robust method for designing MBC can be seen in both a reduction in uncontrolled responses, and the total energy used was approximately as much as that for the LQR controller during seismic disturbances. Figures 6 and 7 illustrate the time histories of the displacement, drift and force response of the controlled systems, respectively, to the Taft (PGA=0.298 g(m/s^2)) earthquake.

5.2. The ten-story structure

The second structure is a ten-story structure having 12 SHD dampers logically designed into this building. The structural properties, as well as the location of the SHD, are shown in Figure 8.

In Table 2, the weighting terms are obtained using a genetic algorithm for the MBC design of the ten-story building.

Again, for the design of the LQR controller, the waiting matrix on the state response, Q, is selected, with heavy emphasis on the velocity response of the structural system. Eq. (14) presents the Q and R weighting matrices:

$$Q = \begin{bmatrix} I & 10I \\ 10I & 100I \end{bmatrix} \;\&\; R = 3.5^*10^{-11}[I]. \tag{14}$$

Figure 9 presents the maximum absolute inter-story drift and the maximum absolute displacement of the ten-story structure for the four earthquakes, respectively.

Table 2. The weighting terms for the MBC design of the ten-story building.

T	2869	W_3	802.7
R	0.194	W_4	3951
Q	3186	W_5	1209
S	2.246	W_6	0 (No control devices)
k	562.3	W_7	2821
α	0.0049	W_8	3072
W_1	0 (No control devices)	W_9	348.9
W_2	-3492.5	W_{10}	1333

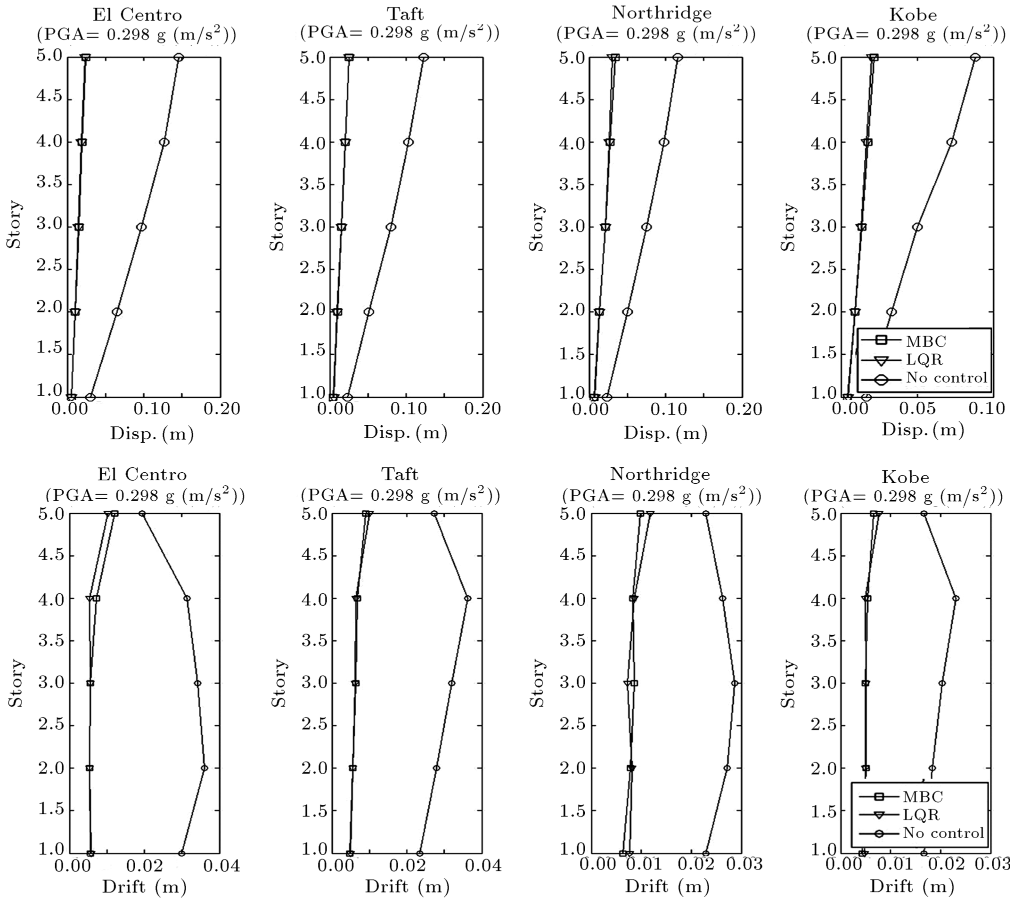


Figure 4. Shizuko maximum absolute displacement and inter-story drift.

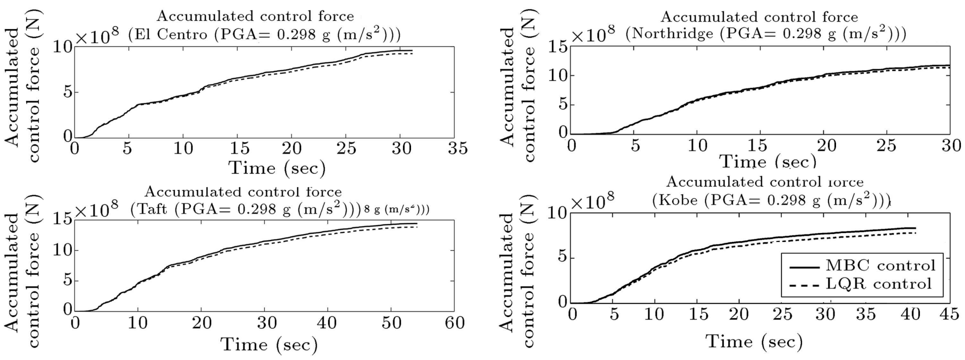


Figure 5. Accumulated control effort of Shizuoka using MBC and LQR controllers.

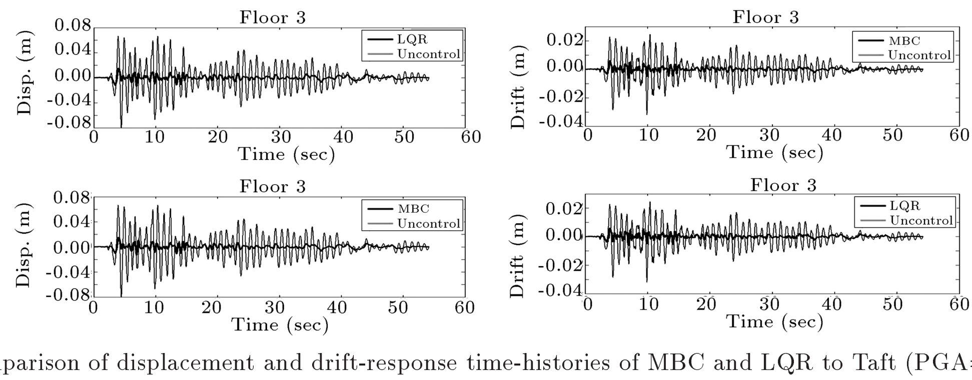


Figure 6. Comparison of displacement and drift-response time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for third floor.

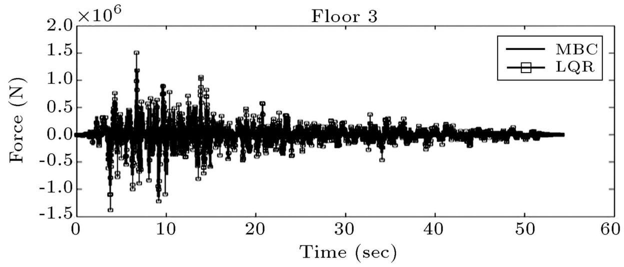
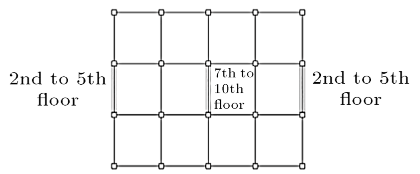


Figure 7. Comparison of control force time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for third floor.

Floor	Seismic mass (kg)	Story stiffness (kN/m)	Damping
1	450^*10^3	326.2^*10^3	**5% natural damping**
2-5	430^*10^3	326.2^*10^3	
6-7	430^*10^3	226.6^*10^3	
8-9	430^*10^3	187.9^*10^3	
10	445^*10^3	102.8^*10^3	



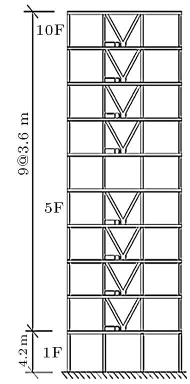


Figure 8. Ten-story building.

The responses during the four earthquakes obtained from MBC and LQR controllers were again approximately identical. Both controllers reduced the response of the ten-story structures by more than 50%. The energy consumption of the MBC controller is nearly 2% more than that of the LQR controller throughout all four earthquakes. Figure 10 illustrates the total control effort of the control system.

Figures 11 and 12 illustrate the time histories of the displacement, drift and force response of the controlled systems, respectively, to the Taft (PGA=0.298 g(m/s^2)) earthquake.

In comparison with the Shizuoka building, the performance of the MBC controller is better in large and complex systems.

5.3. The twenty-story structure

The third structure is a twenty-story structure designed for the Southern Los Angeles region as part of the Structural Engineering Association of California's SAC project. 36 SHD dampers are logically designed into this building [17]. The structural properties, as well as the location of the SHD, are shown in Figure 13.

In Table 3, by employing a genetic algorithm, the

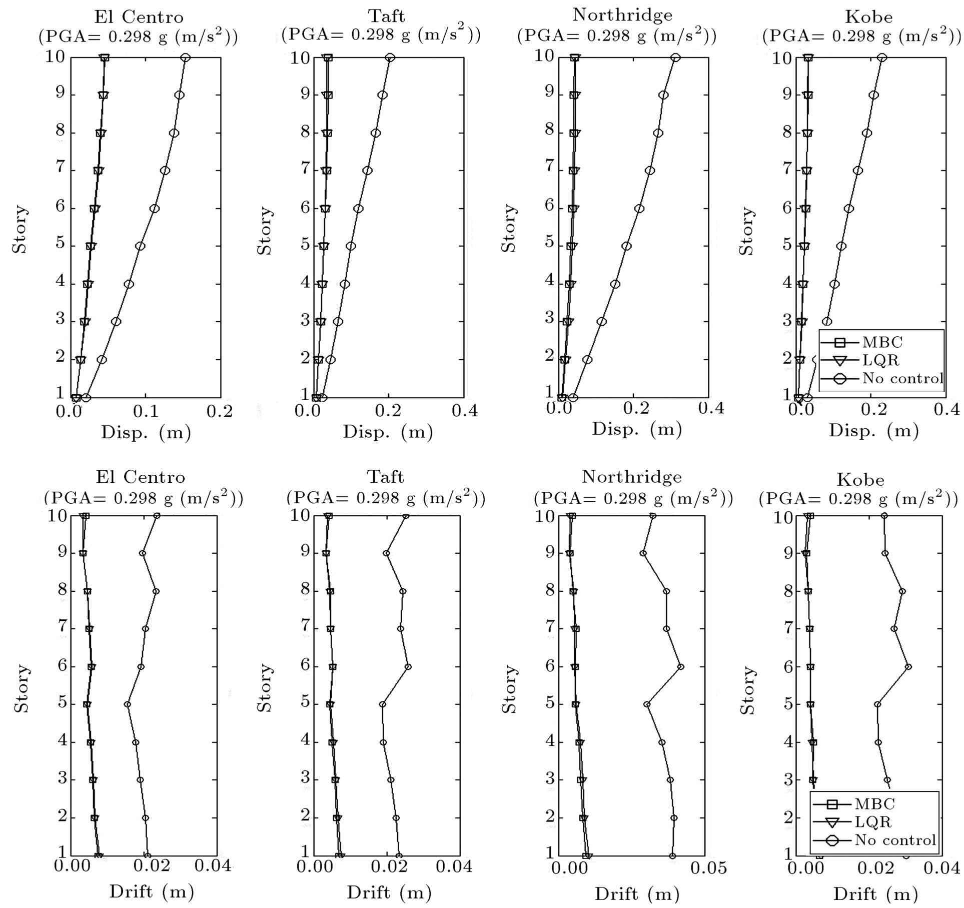


Figure 9. Ten-story structure displacement and maximum absolute inter-story drift.

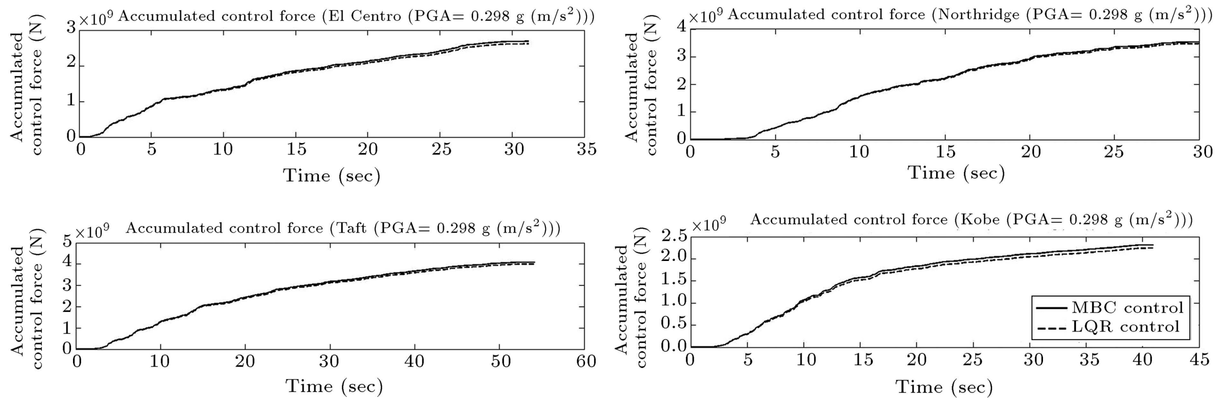


Figure 10. Accumulated control force of the ten-story structure controlled by MBC and LQR methods.

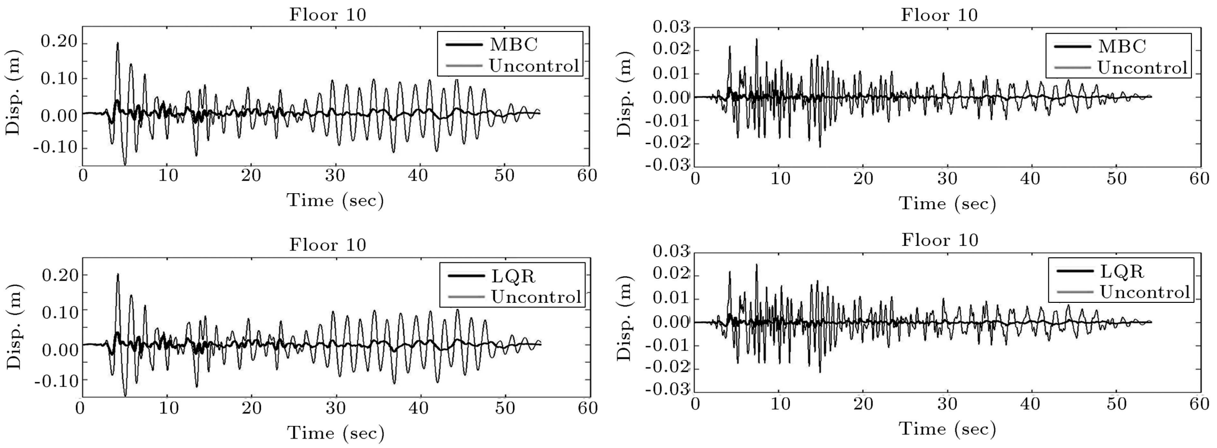


Figure 11. Comparison of displacement-response time-histories and drift-response time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for tenth floor.

Table 3. The weighting terms for the MBC design of the twenty-story building.

T	2046.6	W_4	1048.6	W_{13}	1972.4
R	0.096	W_5	-2050.5	W_{14}	241.5
Q	2911.6	W_6	0 (No control devices)	W_{15}	1168.4
S	1.845	W_7	-2395.4	W_{16}	0 (No control devices)
k	4094.5	W_8	3106.2	W_{17}	1040.1
α	0.0069	W_9	427.7	W_{18}	525.6
W_1	0 (No control devices)	W_{10}	-383.2	W_{19}	181.4
W_2	-145.4	W_{11}	0 (No control devices)	W_{20}	763.1
W_3	3161.6	W_{12}	1864.7		

weighting terms for the MBC design of the twenty-story building are obtained.

In a similar method for designing the LQR controller for the ten story-building, Q is chosen with heavy emphasis on the velocity response of the structural system. The Q and R weighting matrices are presented in Eq. (15):

$$Q = \begin{bmatrix} I & 10I \\ 10I & 100I \end{bmatrix} \& \quad R = 2.5^{*}10^{-12}[I]. \tag{15}$$

The maximum absolute inter-story drift and the max-

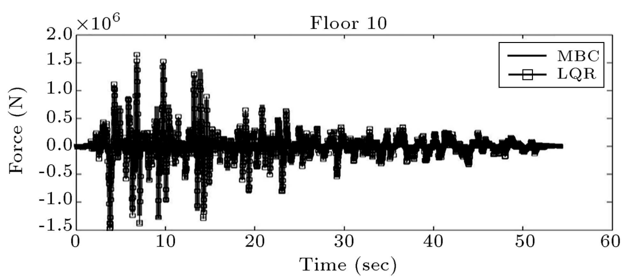


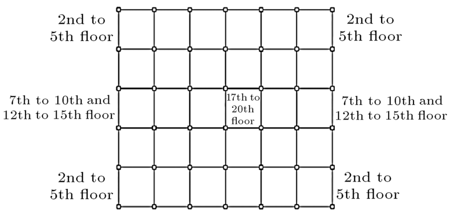
Figure 12. Comparison of control force time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for tenth floor.

imum absolute displacement of the twenty-story structure for the four earthquakes are plotted in Figure 14.

Figure 15 shows the merits of the new method to design MBC. The MBC and LQR controllers' responses during four earthquakes were identical. The response reduction of the MBC and LQR controllers were more than 50%. However, MBC consumed energy by approximately 11% less than LQR during the four seismic disturbances. Among performance is best in the twenty-story structure, demonstrating the merit of the MBC controller in complicated systems.

The time histories of the displacement, drift and force response of the controlled systems to the Taft (PGA=0.298 g(m/s^2)) earthquake are plotted in Figures 16 and 17, respectively.

Floor	Seismic mass (kg)	Story stiffness (kN/m)	Damping
1	1126*10^3	862.07*10^3	5% natural damping
2-5	1100*10^3	862.07*10^3	
6-11	1100*10^3	554.17*10^3	
12-14	1100*10^3	453.51*10^3	
15-17	1100*10^3	291.23*10^3	
18-19	1100*10^3	256.46*10^3	
20	1170*10^3	171.70*10^3	



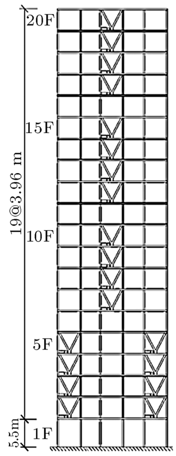


Figure 13. Twenty-story SAC building.

6. Conclusion

This paper has presented a new method for designing the MBC approach with a Genetic Algorithm. At each step in the GA, the groups of constants more suited in designing the MBC approach are selected randomly to serve as the producer of the next generation. Over successive generations, the optimal group of constants for designing MBC controllers will be found by the GA.

The numeric analysis shows the merits of the

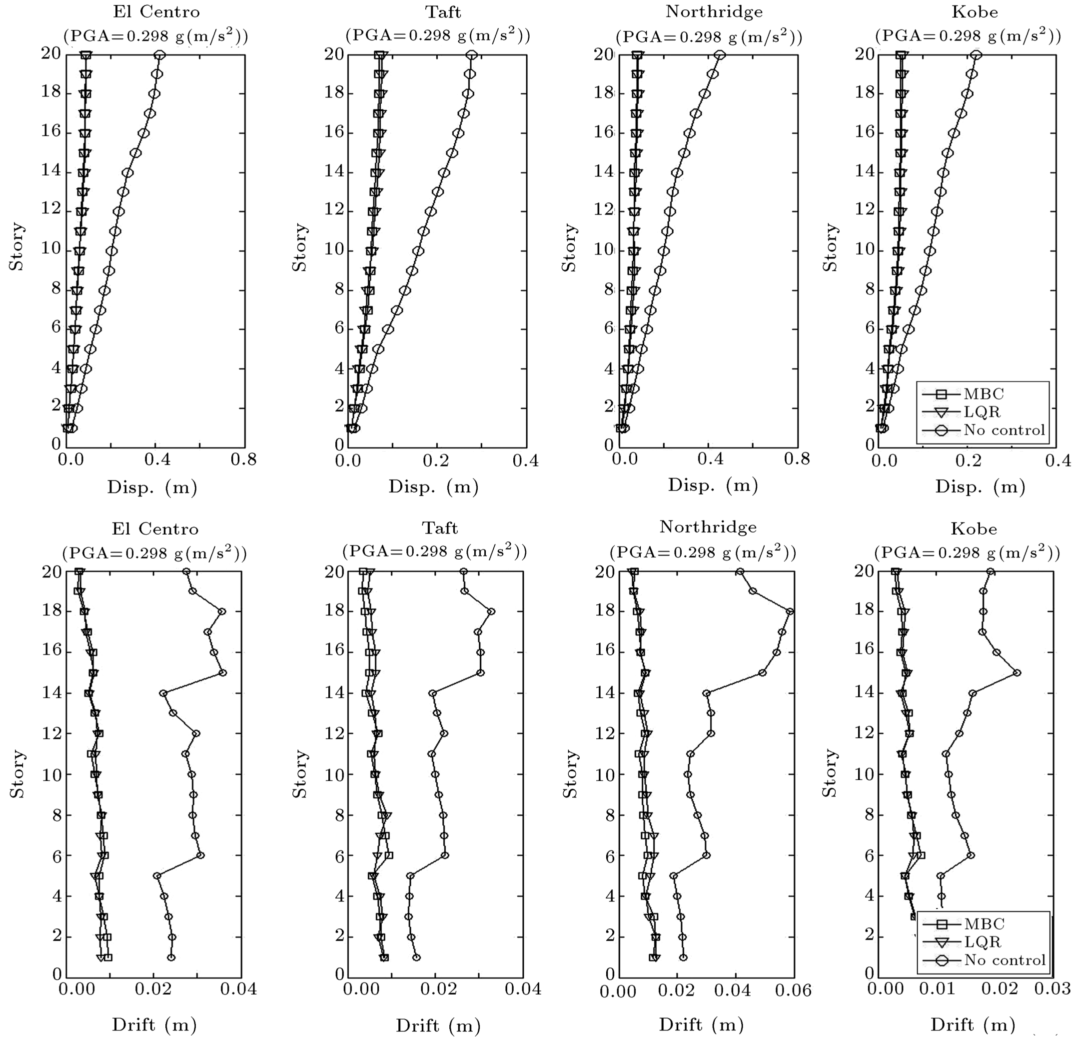


Figure 14. Twenty-story structure maximum absolute displacement and inter-story drift.

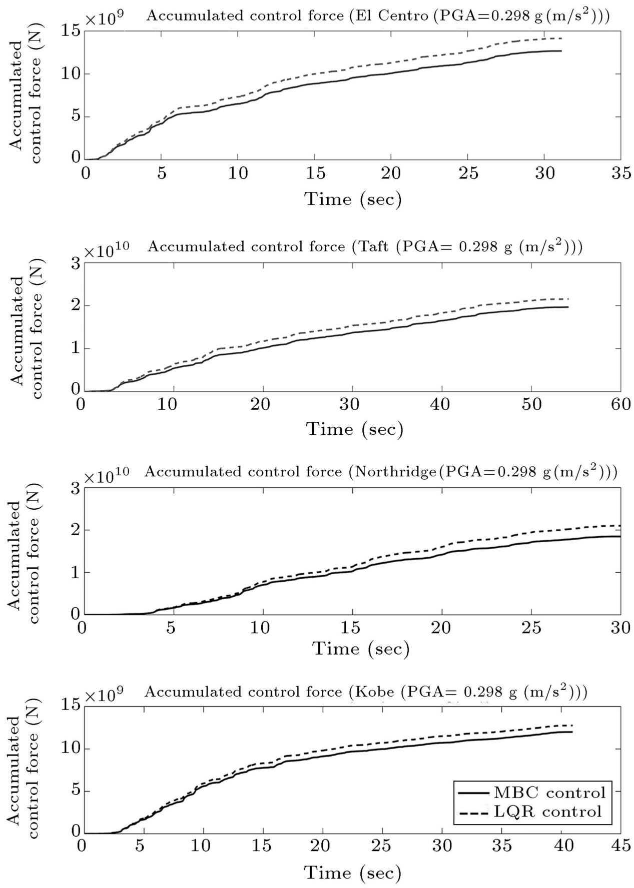


Figure 15. Accumulated control force of the twenty-story structure controlled by MBC and LQR methods.

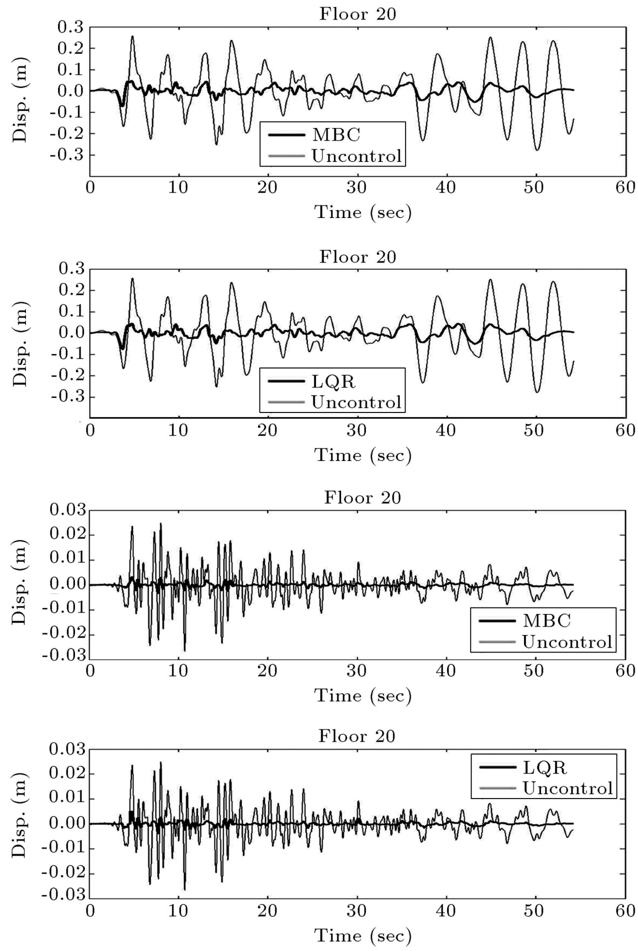


Figure 16. Comparison of displacement-response time-histories and drift-response time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for twentieth floor.

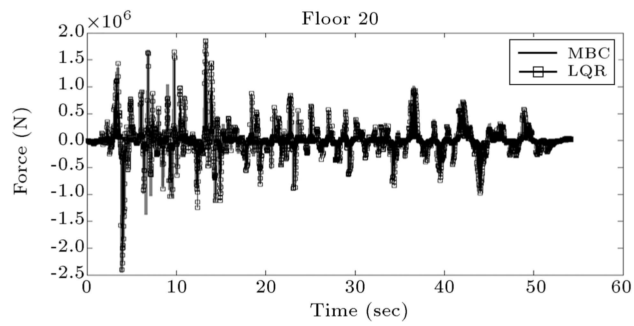


Figure 17. Comparison of control force time-histories of MBC and LQR to Taft (PGA=0.298 g(m/s^2)) earthquake for twentieth floor.

new method. In all sample structures, maximum absolute displacement and maximum inter-story drift were reduced by more than 50%. In contrast with the famous Linear Quadratic Regulator (LQR) centralized method, the MBC controller used energy by approximately 4% and 2% more than the LQR controller for the five-story building and the ten-story building, respectively, during all four earthquakes. However, in the twenty-story building, the MBC consumed energy by nearly 11% less than the LQR, even though both responses of the two controllers were approximately identical. This shows that the MBC controllers perform better in large-scale complex systems, as a decentralized approach, than the conventional centralized approach.

On the other hand, the decentralized MBC method better suited the control systems employing a wireless monitoring system for the optimal control law which will not only consider the power of the actuation but also the costs of the sensor power. The agent-based control architecture in the MBC results in effortless implementation with low-priced, partially-decentralized, large-scale wireless sensing and control networks. In conclusion, the MBC approach with the new design method could be a great alternative to the centralized LQR solution widely used in structural control systems.

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Biographies

Saeid Khorsand received a BS degree with honors in Civil Engineering from Iran University of Science and Technology (IUST), Tehran, Iran, in 2012, and is currently studying for an MS in Earthquake Engineering at Sharif University of Technology (SUT), Tehran, Iran. His research interests lie in the areas of structural control, health monitoring, and reliability.

Fereidoun Amini received a PhD degree in Structural Engineering from the Polytechnic Institute of New York, USA, in 1982, and is currently Professor of Civil Engineering at Iran University of Science and Technology (IUST), Tehran, Iran. Professor Amini has also been member of several national committees on various civil engineering issues. His research interests lie in the areas of structural control and smart structures.