IJE TRANSACTIONS A: Bacsics Vol. 25, No. 3, (July 2012) 265-276

International Journal of Engineering

Journal Homepage: www.ije.ir

Multi-objective Optimization of Semi-active Control of Seismically Exited Buildings Using Variable Damper and Genetic Algorithms

S. Pourzeynali *, M. Malekzadeh, F. Esmaeilian

Department of Civil Engineering, Faculty of Engineering, The University of Guilan, Rasht, Iran

ARTICLE INFO

Article history:
Received 20 April 2012
Accepted in revised form 14 June 2012

Keywords:
Semi-active Control
Multi-objective Optimization
NSGA-II
Pareto Solution

ABSTRACT

Semi-active fluid viscous dampers as a subset of control systems have shown their ability to reduce seismic responses of tall buildings. In this paper, multi-objective optimization of the performance of this group of dampers in reducing the seismic responses of buildings is studied using multi-objective genetic algorithms. For numerical example, the 7 and 18 stories buildings are chosen and modeled as 3D frames. The equation of motion for each building subjected to earthquake accelerations is written in presence of semi-active fluid dampers and resolved in state-space. The optimal number and position of dampers are considered as decision variables while the structural responses such as displacement of top floor, base shear and etc. are considered as the objective functions to be minimized. The objective functions are taken part in multi-objective optimization as a group of three functions. The goal is finding so called Pareto-optimal solutions which are non-dominated to each other. It can optimize whole objectives as best as possible, simultaneously. In this case, any Pareto-optimal solution will be a certain configuration of some dampers in specific places of the structure. In this study, a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) has been used.

doi: *10.5829/idosi.ije.2012.25.03a.08*

1. INTRODUCTION

During the past decades, many new methods have been developed to promote designing of structures against environmental loadings such as earthquake excitations. In such methods, in addition of traditional design of structures, control systems are also used to increase safety and strength capacity of structural components against dynamic forces and prevent the undesirable damages of structures during earthquakes. These control systems reduce structural seismic responses by dissipating seismic input energy or modifying structural frequency. Four main categories of control systems are: passive, active, semi-active, and hybrid systems.

Passive control system is known as a system which does not require an external energy source for operation and utilizes the motion of structure to develop control forces. Although these systems have high reliability [1], they are unable to adapt the structural changes and loading conditions. Active control systems supply large amount of control forces to the structure by means of electro-hydraulic or electromechanical actuators and reduce dynamic responses of the structure. These systems have high potential to control the structures but the requirement of huge energy sources, make their operation complicated and costly. Semi-active control systems appear to combine the best features of both passive and active control systems and overcome the limitation of each group. Semi-active control systems have the adoptability of active control systems without need of large input energy, as well as the reliability of passive control systems [2, 3].

The tuned mass damper (TMD) system is a typical form of control devices including a mass, spring, and a viscous damper, which can be attached to the main structure at one of its degrees of freedom [4, 5]. This system is one of the well-accepted devices to control flexible structures, particularly, tall buildings [6]. In this passive control system, if its damping ratio or stiffness of the spring changes with time, then it is called as a semi-active tuned mass damper (STMD) [7]. In the present study, the STMD is considered with variable damping. Therefore, modeling procedure of the STMD system automatically includes modeling of the TMD

*Corresponding Author Email: *pourzeynali@guilan.ac.ir* (S. Pourzeynali)

system. The theory of TMD has been used for the first time by Frahm in 1911 [8] to reduce the movement of a structure subjected to monotonic harmonic forces, then this theory is extended by Ormondroyd and Den Hartog in 1928 [9].

In this paper, multi-objective optimization of semi-active fluid viscous dampers in reducing the dynamic responses of building structures against earthquake is studied. For this purpose, a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) has been used.

2. SEMI-ACTIVE FLUID VISCOUS DAMPER

Semi-active fluid viscous dampers are known as variable orifice dampers, because they are passive viscous dampers which completed by means of electromechanical control valves having variable orifices. These control valves alter the resistance against flow and provide variable damping values to the structure [10]. Semi-active fluid viscous dampers typically consist of a hydraulic cylinder containing a piston head which separates two sides of the cylinder. As the piston moves, the fluid within the damper (usually oil) is forced to pass through small orifices at high speed. The pressure differential across the piston head, and thus the output force is modulated by an external control valve which connects two sides of the cylinder. The control valve may be in the form of solenoid valve for on-off control or a servo valve for variable control [11].

Adoptability to structure’s behavior to overcome earthquake forces is one of the important advantages of semi-active fluid viscous dampers. Since the external power is used only for adjusting the control valve, these devices don’t need high energy sources, so they are very reliable. As these devices are small and light, it’s possible to use lots of them in a structure to reduce its seismic responses [3, 12].

Analytical models for describing dynamic behavior of fluid dampers (as extensive cyclic testing over a wide range of frequencies) have shown that a simple phenomenological model consist of a linear viscous dashpot with a voltage dependent damping coefficient, C(V) was sufficient for describing the damper behavior over frequency range of interest for structural control applications. Such a model is named the Maxwell model in mechanics. The output force F, is described by M. D. Symans and M. C. Constantinou [11]:

$$F = C(V)\dot{x} \tag{1}$$

where, $\dot{x}$ is the relative velocity of the piston head with respect to the damper housing, and V is the command voltage.

3. MULTI-OBJECTIVE OPTIMIZATION VIA NSGA-II

Multi-objective formulations are realistic models for many complex engineering optimization problems. In many real-life problems, objectives under consideration conflict with each other. In addition, optimizing a particular solution with respect to a single objective can result in unacceptable solutions with respect to the other objectives. A reasonable solution to a multi-objective problem is to investigate a set of solutions; each satisfies whole objectives at an acceptable level without being dominated by any other solution. Such set of solutions is known as a Pareto optimal set [13].

A practical and desirable approach to solve multi-objective problems is to determine entire Pareto optimal solution set or a representative subset. A Pareto optimal set is a set of solutions that are non-dominated to each other. Evolutionary algorithms are the best means to solve multi-objective problems with this approach because they can obtain a set of Pareto optimal solutions in one single simulation run. Since 1980s, a variety of evolutionary algorithms have been proposed and used in solving multi-objective optimization problems in various branches of engineering sciences. One of the most common multi-objective evolutionary algorithms is the fast and elitist nondominated sorting genetic algorithm (NSGA-II) proposed by Deb et al. [14] which is used in this study.

This algorithm is in fact an improved version of non dominated sorting genetic algorithms (NSGA) which had been proposed by Deb in 1994 [13], without the main drawbacks of the first version. In this algorithm, high computational complexity of non dominated sorting is decreased by a fast sorting approach. Thus, in new algorithm reviewing the whole population with respect to each of the objectives is applied once less. On the other hand, by presenting a new operator named crowded comparison operator, between two solutions belong to same Pareto front, the solution which is located in a less crowded region is selected for the next generation. This helps to preserve diversity in population without needing to specify sharing parameter any more. Furthermore, a selected operator is defined which creates a mating pool by combining the parent and offspring populations and selecting the best N solutions (with respect to fitness and spread), so the elitism is ensured to promote the performance of genetic algorithm [14].

4. SEMI-ACTIVE CONTROL OF BUILDINGS WITH FLUID VISCOUS DAMPERS

In this paper, two multi-story buildings with semi-active viscous dampers are analyzed through modeling as 3D frames. Irregularities in the buildings and unsymmetrical configuration of the added dampers have torsional effects on the systems which by 3D modeling these effects can be taken into account.

The equation of motion for a multi-story building subjected to multi-component earthquake excitations, when dampers don't exist, can be written as [15]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M][L]\{\ddot{x}_g(t)\} \;, \quad \{\ddot{x}_g(t)\} = \begin{Bmatrix} \ddot{x}_{gx}(t) \\ \ddot{x}_{gy}(t) \end{Bmatrix} \tag{2}$$

where, $[M]$, $[K]$ and $[C]$ are structural mass, stiffness, and damping matrices, respectively; $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are the acceleration, velocity, and displacement vectors, respectively; $[L]$ is the n by 2 influence matrix where n is the number of degrees of freedom for the MDOF structural system; and $\ddot{x}_{gx}$and $\ddot{x}_{gy}$ are the horizontal components of the earthquake ground horizontal accelerations in x and y directions, respectively.

There is possibility of utilizing the semi-active fluid dampers in strengthening the existing buildings, as well as in designing the new buildings. These dampers are typically installed in the bracing system of a building.

For writing the equation of motion of a MDOF structure in presence of dampers, by assuming that the jth damper is connected with a diagonal brace between (i-1)th and ith floors on the x-z plane and the offset of this damper from the mass center of ith floor is shown by $(e_{yj})_i$, the equation of motion of this system can be written as Pourzeynali and Mousanejad [16]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ -1 \\ +1 \\ 0 \\ \vdots \\ 0 \\ -(e_{yj})_{i-1} \\ (e_{yj})_i \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{n\times 1} f_j = -[M][L]\{\ddot{x}_g(t)\} \tag{3}$$

in which, f_j shows the jth damper's force.

Equation (3) relates to the case of adding only one damper, j, to the building. The generalized form of this equation, when m dampers are installed in x direction and k dampers are installed in y direction, is written as [16]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = [D]\{f\} - [M][L]\{\ddot{x}_g(t)\} \tag{4}$$

where, $[D]$ shows the location of dampers and is an n$*(m + k)$ matrix; when m and k dampers exist in x and y directions, respectively. This matrix is obtained according to the configuration of dampers in the structure [16].

Since the damping coefficients are unknown and function of time; therefore, elements of vector $\{f\}$ will also be unknown and function of time.

5. EVALUATION OF THE CONTROL FORCES USING LQR ALGORITHM

In order to use the LQR (Linear Quadratic Regulator) algorithm; first, the Equation (4) should be rewritten in state-space form [16, 17]:

$$\{\dot{z}\} = [A]\{z\} + [H]\{f\} + [B]\{w\} \tag{5}$$

where, the parameters are defined as follows:

$$\{z\} = \begin{Bmatrix} x \\ \dot{x} \end{Bmatrix} \;, \quad [H] = \begin{bmatrix} \mathbf{0} \\ [M]^{-1}[D] \end{bmatrix},$$
$$[A] = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix} \;, \quad [B] = \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}, \tag{6}$$
$$\{w\} = -[L]\{\ddot{x}_g(t)\}$$

in which $\mathbf{0}$ and $\mathbf{I}$ are zero and identity matrices, respectively.

In LQR control algorithm, to calculate the optimal values of the control forces, the following performance index, J, should be minimized [16]:

$$J = \int_0^{\infty} [\{z\}^T [Q]\{z\} + \{f\}^T [R]\{f\}] dt \tag{7}$$

in which the weighting matrices, [Q] and [R] are defined as:

$$[Q] = \begin{bmatrix} [Q_v] & 0 \\ 0 & 0 \end{bmatrix}, \quad [Q_v] = diag(1)$$
$$[R] = 10^{-q} diag(1) \tag{8}$$

where, q is a weighting coefficient, and it has been shown that by increasing q, building's responses decrease but the damping forces increase [16]. Because of the capacity limitation of each damper, there will be an optimal value for q which has been evaluated. Control force vector is obtained by minimizing J as follows [16]:

$$\{f\} = -[R]^{-1}[B]^T[P]\{z\} = -[G]\{z\} \tag{9}$$

where, $[G]$ is a feedback gain matrix; and $[P]$ is the solution of following algebraic Riccati equation [16, 18]:

$$[P][A] + [A]^T[P] + [Q] - [P][B][R]^{-1}[B]^T[P] = 0 \tag{10}$$

By obtaining $\{f\}$ as above, the state-space equation can be rewritten as:

$$\{\dot{z}\} = ([A] - [H][G])\{z\} + [B]\{w\} \tag{11}$$

6. OPTIMIZATION OF NUMBER AND POSITION OF DAMPERS USING NSGA-II

In this study, in order to optimize the number and position of dampers by considering multiple objective functions of structural responses, a variable should be defined in the form of binary chromosomes. To achieve this goal, a variable X(i) is defined in every likely position for installing a damper in the structure. Because the damping force is directly related to offset from the center of mass of stories, e_x and e_y , and by increasing them, the damping forces increase. Thus, the most external bracing axes of structures are more proper to placing dampers. Variable X(i) described above can take value of zero or one. When this variable is zero for a certain place i , it means that there is no damper in that position, and also taking one means that there is a damper in that location.

After defining strings (chromosomes), which show the population members of algorithm, there should be a criterion to determine how bad or good is an individual. So, the population evolves from a generation to the next and finally reaches the optimal values. In this study, reduction of structural responses with respect to those of the uncontrolled has been considered as the objectives in optimization problems. Since the number of dampers in a structure affects the cost of whole system, it can be considered as an objective. For considering the limitation of each damper capacity, the maximum control force in the system will be another objective. Thus, the following objectives are defined:

Objective 1: Ratio of maximum controlled top story displacement to that of the uncontrolled one.

Objective 2: Ratio of controlled base shear to that of the uncontrolled one.

Objective 3: Ratio of maximum controlled top story acceleration to that of the uncontrolled one.

Objective 4: Maximum control force of dampers.

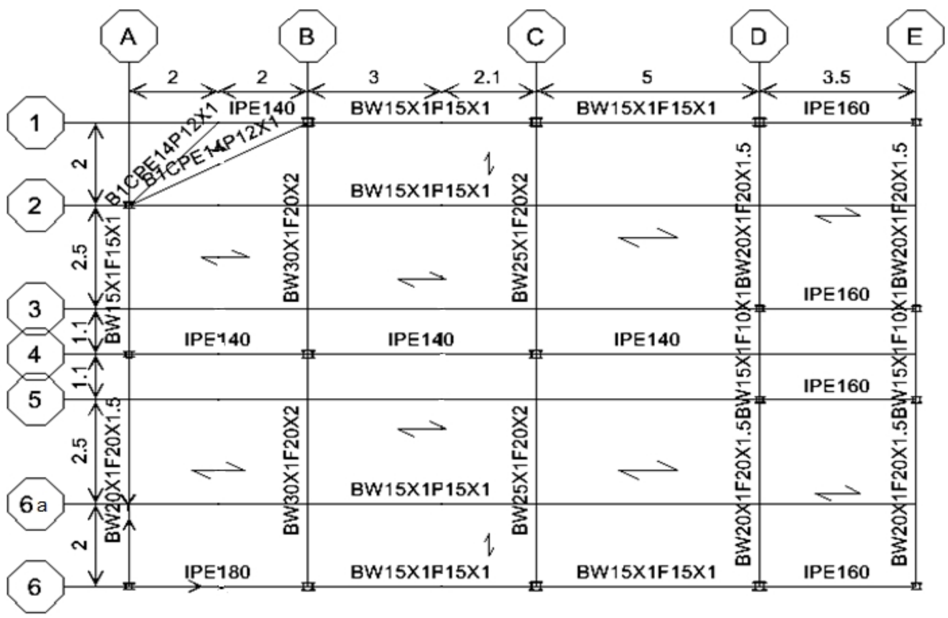
Objective 5: Number of dampers used to control the building responses.

Then, the multi-objective optimization process is performed for any triple function selected from the aforementioned objective functions, for each building. The multi-objective optimization is performed using the fast and elitist non-dominated sorting genetic algorithm (NSGA-II) to obtain the Pareto optimal solution set for each group of objectives. In fact, there will be several multi-objective optimization problems to solve. After this step, the final solution for each building is determined by comparing the whole solutions of the above problems by means of a human decision maker.

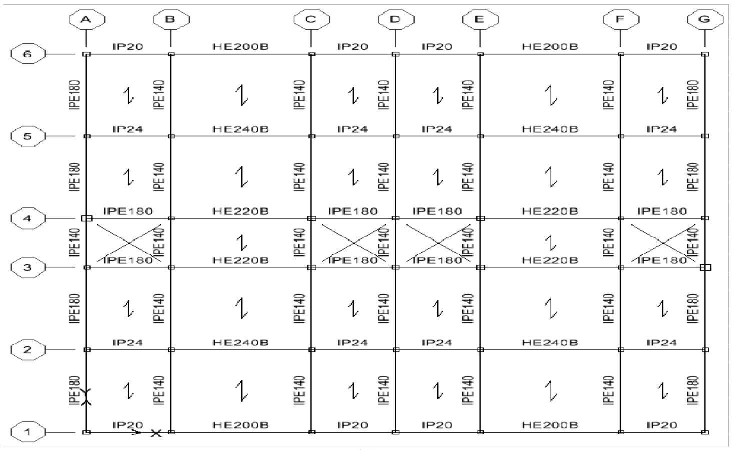
7. NUMERICAL STUDY

For numerical analysis, the 7 and 18 stories steel building structures having X-bracing systems in both directions are chosen. Typical floor plans of these buildings are shown in Figure (1). Heights of two building structures are about 21.65 and 57.6 meters, respectively. The buildings are modeled as 3-D frames; therefore, any irregularities exist in the building can be taken into account.

Figures (2) and (3) show the braced frames of each building, and the places over which the dampers can be installed. In these frames X(i) shows the variable which in genetic algorithm is considered to optimize the number and position of the dampers.



(a)



(b)

Figure 1. Typical floor plans of the example building structures, a) 7-story and b) 18-story

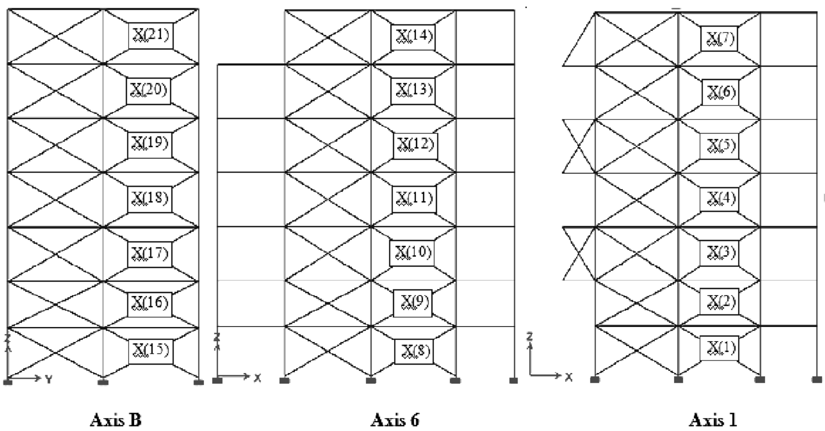
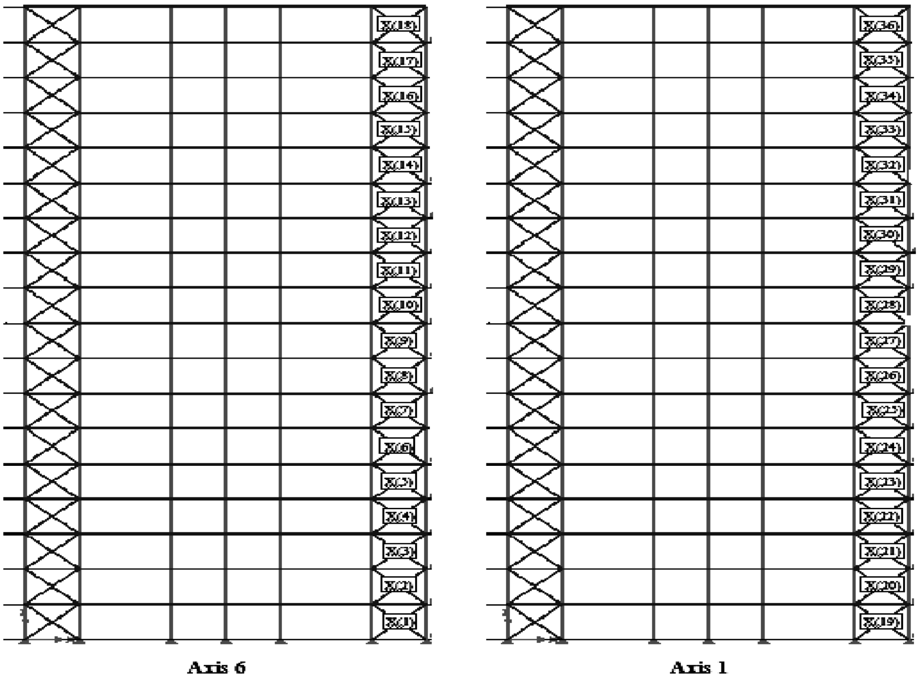


Figure 2. Braced frames of the 7-story buildings, and the places (X(i)) over which the dampers can be installed



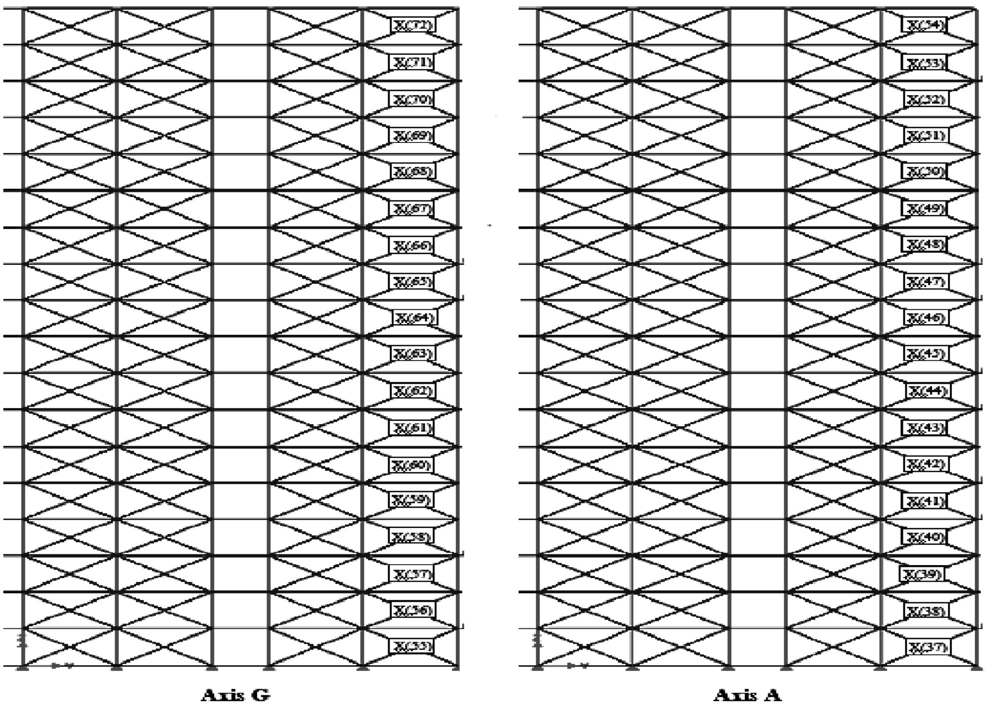


Figure 3. Braced frames of the 18-story building and the places (X(i)) over which the dampers can be installed.

TABLE 1. Earthquake acceleration records considered in this study for dynamic analyses

No.	Earthquake Name	Date	Station	Magnitude(Ms)	PGA(g)	Duration (sec)
1	Northridge, California	1994/01/17	Montebello	6.7	0.128	21.82
2	Chi-Chi, Taiwan	1999/09/20	CHY041	7.6	0.639	90.0
3	Imperial Valley, California	1979//10/15	El Centro	6.9	0.221	39.54
4	Kocaeli, Turkey	1999//08/17	Ambarli	7.8	0.249	150.39
5	Coalinga, California	1983/07/22	Transmitter Hill	6.0	1.083	21.76
6	Loma, Prieta	1989/10/18	Bran	7.1	0.605	24.96
7	Morgan Hill, California	1984/04/24	Coyoto Lake Dam	6.1	0.798	29.95
8	Nahanni, Canada	1985/12/13	Sitel	6.9	1.096	20.56
9	San Fernando, California	1971/02/09	Pacoima Dam	6.6	1.164	41.63
10	Gazli, Uzbekistan	1976/05/17	Karakyr	7.3	0.718	16.26
11	Kobe, Japan	1995/01/16	Abeno	6.9	0.821	47.98
12	Tabas	1978/09/16	Tabas	7.4	0.815	32.82

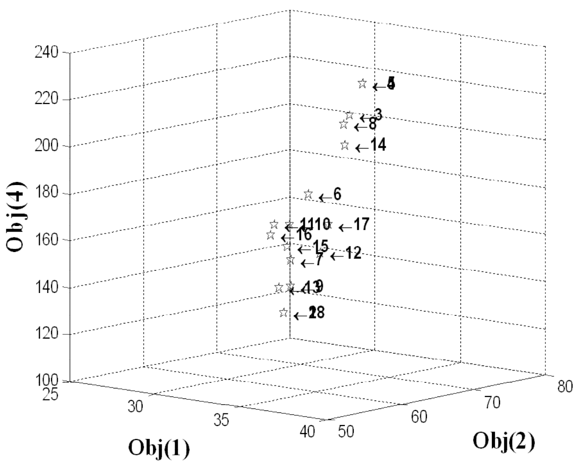


Figure 4. Pareto-optimal solutions of problem 1, for 7-story building.

In order to evaluate the building responses, the mass and stiffness matrices of buildings are calculated using the matrix analysis procedure. The damping matrices of the buildings are also constructed from a linear combination of the mass and stiffness matrices (Rayleigh method). To calculate the proportionality coefficients, modal damping ratios of the two first vibrational modes are assumed to be about 5% of the critical values.

For dynamic analysis of the building structures, 12 worldwide earthquake acceleration records shown in Table 1 have been used.

The selected accelerogrames have been corrected, filtered, and scaled according to the IBC 2006 [19] for using in time history analyses of the buildings.

In this research study, implementation of the NSGA-II has been done by means of MATLAB software. The algorithm is started with 50 chromosomes as the initial population and it is repeated for 200 generations. Probabilities of scattered cross over and mutation are considered to be about 25% and 1%, respectively.

As it was mentioned earlier, among the five defined objective functions, at each time, three objectives are taken to perform the optimization process. These objectives are described as different "problem" in the following.

7. 1. Problem 1 In this problem, objectives 1, 2, and 4 have been taken as the objective functions in optimization process. After running NSGA-II, Pareto-optimal solution sets for each of the structures are obtained which are explained in the following:

7. 1. 1. 7-Story Building Pareto-optimal solutions for this structure and the above mentioned objective functions are shown in Figure (4).

In this run, algorithm found 18 solutions and this shows that the selected functions are in conflict with each other. As it is mentioned earlier, deciding about the best solution among all Pareto-optimal solutions completely depends on human decision maker's opinion.

TABLE 2. Chromosomes correspond to the Pareto-optimal solutions of problem 1 for 7-story example building.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}	X_{20}	X_{21}
1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	0	1	0	0	1	0
4	1	1	1	0	1	1	0	1	1	1	0	1	0	0	1	0	0	1	0	1	0
5	1	1	1	0	1	1	0	1	1	1	0	1	0	0	1	0	0	1	0	1	0
6	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0
7	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	1	0	0	1	1
8	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	0	0	1	0
9	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
11	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	0
12	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0
13	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	1	1	1
14	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	0	0	1	0
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0
16	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1	1	0
17	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	0
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 2 shows the corresponding chromosomes for Pareto-optimal set of this problem. It is seen that solutions 2 and 18 show the arrangements of putting 21 dampers in every predefined positions of this building. These solutions are found because of considering the objective 4 in this problem. The applied algorithm does not distinguish any dominant between the objectives, so it will find solutions with least maximum control force which is equal to the maximum number of dampers. Absolutely, such solutions will not be more important for decision maker.

Table 3 shows the values of all objective functions correspond to the Pareto-optimal solutions of problem 1 shown in Figure (4). As it can be seen, the arrangements Pareto-optimal solutions for this problem result to at least a reduction of 62.25% in objective (1) (top story displacement) and 22.45% in objective (2) (base acceleration has not been reduced more.

7. 1. 2. 18-Story Building Moreover, Pareto-optimal solution set for this structure corresponding to objectives 1, 2, and 4 is shown in Figure (5).

TABLE 3. Values of all objective functions correspond to Pareto-optimal solutions of problem 1 shown in Figure (4).

Point No.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) kN	Obj (5)
1	31.38	65.10	86.78	164	14
2	25.70	77.55	94.18	113	21
3	37.07	59.96	85.30	220	13
4	37.75	60.20	85.33	234	12
5	37.75	60.20	85.33	234	12
6	33.54	62.71	91.75	181	18
7	28.22	72.67	94.80	141	15
8	36.39	60.74	84.33	215	14
9	26.41	76.98	95.64	125	18
10	31.38	65.10	86.78	164	14
11	30.38	65.37	87.49	163	15
12	28.23	76.77	97.13	141	19
13	27.41	72.95	92.29	128	18
14	36.71	60.15	86.98	207	14
15	28.59	71.40	94.28	148	17
16	29.72	66.49	86.52	157	17
17	28.97	76.03	99.52	155	16
18	25.70	77.55	94.18	113	21

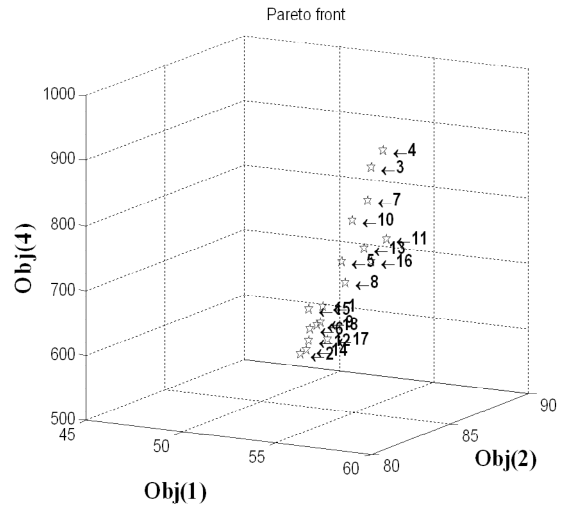


Figure 5. Pareto-optimal solutions of problem 1 for 18-story building.

Table (4) also shows the values of objective functions correspond to the Pareto-optimal solutions in Figure 5. For this structure, due to its height, the performance of the control system in reducing the dynamic responses of the structure is extremely decreased in comparison with the first building. This drawback of the control system is related to determining the weighting ratio, q, which is limited to a maximum value due to limitation of damper's capacity. So, using a damper with higher control force capacity lead to a chance to improve the performance of the control system for taller buildings. It should be noted that in this case there is still a good reduction on objective (1) (top story displacement) but it does not work well on objectives 2 and 3.

7. 2. Problem 2 In this problem, the objectives 1, 3, and 5 are chosen to take part in the multi-objective optimization process. The results of the optimization process are provided in the following.

7. 2. 1. 7-Story Building Figure (6) shows the Pareto-optimal set for this problem and 7-story building. According to the figure, NSGA-II has found 20 solutions for this case. But as it can be seen from the figure, the values of objective (3) for some of these solutions exceed 100%. This means that for such solutions, story accelerations are more than the uncontrolled one, and therefore should be eliminated from the solutions.

Since there is no way to put constraints on objective functions in NSGA-II by MATLAB software, and any other external loop has not been defined to limit the values of the objectives of problem, such solutions are obtained by the algorithm. In this study, declining this kind of solutions is left for decision maker too.

Presence of the objective 5 in this optimization problem results to the arrangements without any damper (minimization of objective 5). Although these solutions are still Pareto-optimal by logic of the algorithm, they are not important for final decision.

TABLE 4. Values of all objective functions correspond to pareto-optimal solutions of problem 1 shown in Figure (5).

Point No.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) KN	Obj(5)
2	25.75	81.25	88.98	117	20
4	26.67	81.00	90.06	125	18
5	93.92	86.03	91.83	457	1
6	83.67	77.73	87.33	460	4
7	25.75	81.25	88.98	117	20
8	32.89	72.52	89.02	198	12
9	39.90	62.80	81.29	275	10
10	27.07	81.40	90.99	129	17
12	47.02	81.30	88.62	428	5
13	39.16	67.22	82.01	275	10
14	43.35	78.99	89.03	371	6
16	85.40	81.64	89.32	523	3
18	27.76	78.77	88.37	142	15
19	35.32	87.95	98.80	259	7

TABLE 5. Values of all objective functions correspond to feasible set of Pareto-optimal solutions of problem 2 shown in Figure (6).

Point No.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) KN	Obj(5)
2	25.75	81.25	88.98	117	20
4	26.67	81.00	90.06	125	18
5	93.92	86.03	91.83	457	1
6	83.67	77.73	87.33	460	4
7	25.75	81.25	88.98	117	20
8	32.89	72.52	89.02	198	12
9	39.90	62.80	81.29	275	10
10	27.07	81.40	90.99	129	17
12	47.02	81.30	88.62	428	5
13	39.16	67.22	82.01	275	10
14	43.35	78.99	89.03	371	6
16	85.40	81.64	89.32	523	3
18	27.76	78.77	88.37	142	15
19	35.32	87.95	98.80	259	7

In fact, when the optimization problem has some constraints, definition of feasible and non-feasible sets is involved. In this case, among whole Pareto-optimal solutions, only solutions that satisfy problem constraints are feasible. By this definition, Table (5) shows the values of the objectives for feasible set of problem 2, 7-story building structure.

7. 2. 2. 18-Story Building In addition, for this building after running the program, NSGA-II obtained 20 Pareto-optimal solutions which is shown in Figure (7). But with the above considerations, feasible set for this building includes only 6 out of these 20 solutions for which the values of the objective functions are presented in Table (6).

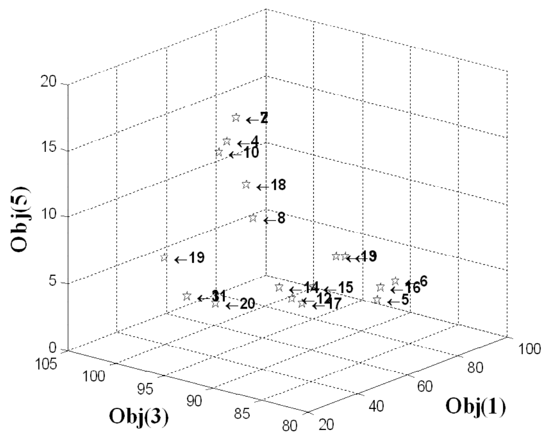


Figure 6. Pareto-optimal solutions of problem 2, for 7-story building.

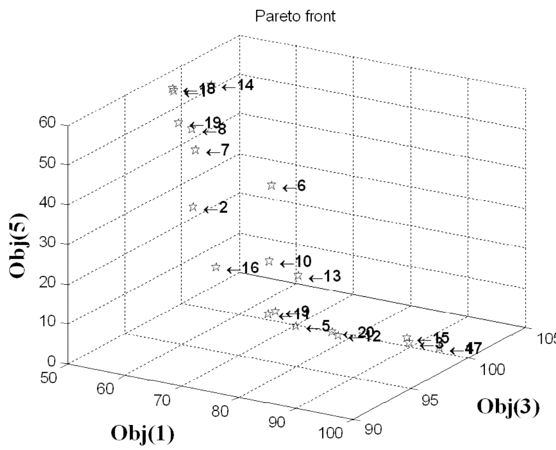


Figure 7. Pareto-optimal solutions of problem 2, for 18-story building

7. 3. Problem 3 In this problem, the objectives 2, 3, and 4 are selected to take part in multi-objective optimization via NSGA-II. After running of algorithm, the following results are obtained:

7. 3. 1. 7-Story Building All of the obtained Pareto-optimal solutions for this case (shown in Figure (8)) are located in feasible area of the problem.

This optimization shows up to 60% reduction on top story displacement and almost 40% reduction in base shear for many of solutions. This means that the implementation of the control systems according to such arrangements performs very well to reduce the building responses due to well earthquake excitations.

7. 3. 2. 18-Story Building Pareto-optimal set for this structure includes 18 solutions (Figure (9)), all of which are located in feasible area of the problem, so whole set can be considered in final decision. The values of objective functions for these solutions are presented in Table (8).

Table (7) shows the values of the objectives for optimal solutions of this problem. Again, algorithm found solution with 21 dampers in all predetermined positions (solution 11) to minimize the 'maximum control force'.

TABLE 6. Values of all objective functions correspond to feasible Pareto-optimal solutions of problem 2 shown in Figure (7).

Point No.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) KN	Obj(5)
1	51.55	86.97	98.51	615	56
2	63.13	88.64	94.47	753	36
7	53.99	86.59	99.21	733	41
8	53.27	87.12	99.23	681	46
18	51.94	86.62	98.31	604	57
19	53.16	86.97	98.15	663	49

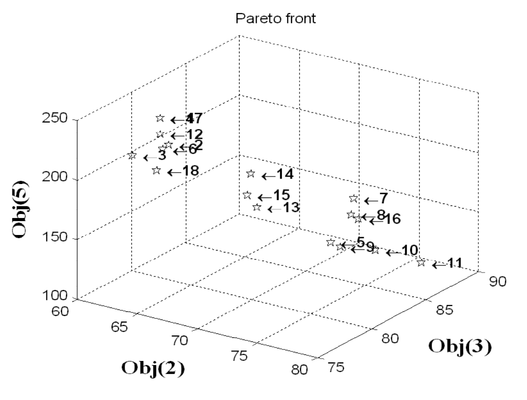


Figure 8. Pareto-optimal solutions of problem 3, for 7-story building

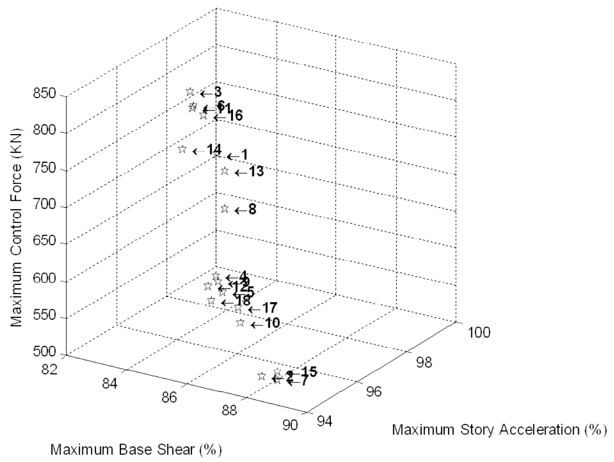


Figure 9. Pareto-optimal solutions of problem 3, for 18-story building

TABLE 7. Values of all objective functions correspond to Pareto-optimal solutions of problem 3 shown in Figure (8).

PointNo.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) KN	Obj(5)
1	34.10	61.75	80.37	186	17
2	37.62	61.37	81.95	200	15
3	35.43	60.66	79.33	201	15
4	36.49	60.24	82.41	217	13
5	27.52	72.37	84.71	131	17
6	35.44	60.74	82.06	194	15
7	28.50	71.15	88.24	148	17
8	28.02	71.72	87.38	140	19
9	27.41	72.96	85.01	128	18
10	26.37	75.02	85.97	125	18
11	25.70	77.55	87.43	113	21
12	35.81	60.32	82.27	205	14
13	29.53	67.20	83.71	153	18
14	31.22	65.54	84.90	171	14
15	30.40	66.22	83.84	160	16
16	27.92	72.12	87.59	137	20
17	36.49	60.24	82.41	217	13
18	34.10	61.75	80.37	186	17

7. 4. Decision Making To determine the best arrangement of dampers in each building, there should be some more new objectives or some human interest to select the final solutions. These new objectives can be defined for the optimization problem with a human decision maker. To achieve this goal, some limitations on number of dampers in each structure and the values of the first two objectives, are applied.

In 7-story building, maximum number of dampers is restricted to 13 and maximum values for objectives 1 and 2 are considered to be about 45% and 70% of the uncontrolled values, respectively.

For 18-story building, chromosome number 4 of problem 1 seems to be a good choice of arrangement for this building in which the minimum number of damper is used and the response reduction values are also in acceptable range.

TABLE 8. Values of all objective functions correspond to Pareto-optimal solutions of problem 3 shown in Figure (9).

Point No.	Obj(1) %	Obj(2) %	Obj(3) %	Obj(4) KN	Obj(5)
1	56.65	83.66	98.03	707	33
2	58.00	87.83	94.83	510	53
3	60.48	83.96	96.62	823	25
4	61.29	85.98	95.20	622	37
5	59.64	86.16	95.28	599	40
6	59.22	83.67	97.11	791	27
7	62.24	88.83	94.27	525	49
8	55.14	84.43	97.42	653	39
9	60.12	86.14	95.10	616	39
10	60.89	87.03	94.93	572	43
11	58.70	84.07	96.56	802	28
12	59.14	85.68	95.25	603	41
13	56.17	83.76	98.23	681	35
14	59.33	84.38	95.79	765	30
15	60.70	88.63	94.47	531	49
16	57.83	83.46	97.73	762	29
17	56.25	86.19	95.87	566	47
18	57.99	85.44	95.67	573	44

TABLE 9. Final solutions for the 7-story building

Pro No.	Point No.	Obj(1)%	Obj(2)%	Obj (3) %	Obj(4) kN	Obj(5)
1	3	37.07	59.96	85.30	220	13
	4	37.75	60.20	85.33	234	12
2	9	39.90	62.80	81.29	275	10
	13	39.16	67.22	82.01	275	10
3	4	36.49	60.24	82.41	217	13

TABLE 10. Final solutions for the 18-story building

Pro.No.	Point No.	Obj (1) %	Obj(2) %	Obj (3) %	Obj (4) kN	Obj (5)
1	3	57.16	83.46	97.85	898	29
	4	57.84	83.36	98.04	928	27
	5	54.95	84.22	98.59	739	39
	7	56.92	83.49	98.40	846	31
	10	55.90	83.73	98.40	811	34
	11	58.09	83.31	97.61	794	32
	13	56.43	83.88	97.84	767	36
	16	57.21	83.37	97.85	756	35
3	1	56.65	83.66	98.03	707	33
	6	59.22	83.67	97.11	791	27
	8	55.14	84.43	97.42	653	39
	11	58.70	84.07	96.56	802	28
	13	56.17	83.76	98.23	681	35
	14	59.33	84.38	95.79	765	30
	16	57.83	83.46	97.73	762	29

8. CONCLUSIONS

In the present paper, the multi-objective optimization of the semi-active fluid viscous dampers in reducing the seismic responses of buildings is studied using genetic algorithms. For numerical example, the 7 and 18 stories buildings are chosen and modeled as 3-D frames. The equation of motion for each building, subjected to earthquake accelerations, is written in presence of semi-active fluid dampers and resolved in state-space. The optimal number and position of dampers are evaluated by selecting the displacement of the top floor, base shear and etc. as the objective functions which to be minimized. The objective functions are taken part in multi-objective optimization as a group of three functions. The goal is finding so called Pareto-optimal solutions which are non-dominated to each other. It also can optimize whole objectives as best as possible, simultaneously. In this study, a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) has been used. From the numerical studies of this research, it is found that:

1) In 7-story building, the maximum number of dampers can be restricted to 13 for which the maximum values of the building top story displacement and that of the base shear are evaluated to be about 45% and 70% of the uncontrolled values, respectively.
2) In 18-story building, the maximum number of dampers is also restricted to 40 and the maximum values of the building top story displacement and that of the base shear are evaluated to be about 60% and 85% of the uncontrolled values, respectively.

3) Ability of the semi-active control system in reducing the seismic responses of buildings decreases with an increase in the building height.

9. REFERENCES

1. Pinkaew, T. and Fujino, Y., "Effectiveness of semi-active tuned mass dampers under harmonic excitation", *Engineering Structures,* Vol. 23, No. 7, (2001), 850-856.
2. Soong T.T., "State-of-the-art review: Active structure control in civil engineering", *Engineering Structures,* Vol. 10, No. 2, (1988), 73-84.
3. Chey, M.H., Chase, J.G., Mander, J.B. and Carr, A.J. "Energy-dissipative Semi-Active Tuned Mass Damper Building Systems for Structural Damage Reduction", Paper presented at the International Symposium, (2009).
4. Pourzeynali, S. and Datta, T. K., "Control of Flutter of Suspension Bridge Deck Using TMD", *International journal of Wind and Structure,* Vol. 5, No. 5, (2002), 407-422.
5. Pourzeynali, S. and Esteki, S., "Optimization of the TMD parameters to suppress the vertical vibrations of suspension bridges subjected to earthquake excitations", *Iranian International Journal of Engineering, IJE Transaction B (Application),* Vol. 22, No. 1, (2009), 23-34.
6. Cao, H. and Li, Q.S., "New control strategies for active tuned mass damper systems", *Computers and Structures,* Vol. 82, (2004), 2341–2350.
7. Pourzeynali, S. and Datta, T. K., "Semi active fuzzy control of suspension bridge flutter", *Journal of Structural Engineering, ASCE*, Vol. 131, No. 6, (2005), 900-912.
8. Frahm, H., "Devices for damping vibrations of bodies", U.S. Patent, 989, 958. (1911).
9. Ormondroyd, J. and Den Hartog, J.P., "The theory of the dynamic vibration absorber", *ASME, Transactions of the American Society of Mechanical Engineers*, Vol. 50, (1928), 9-22.
10. Spencer, BF. Jr. and Nagarajaiah, S., "State of the Art of Structural Control", *Journal of Structural Engineering, ASCE*, Vol. 129, No. 7, (2003), 845-856.
11. Symans, M.D. and Constantinou, M.C., "Semi-active control systems for seismic protection of structures: a state-of-the-art review", *Engineering Structures*, Vol. 21, (1999), 469-487.
12. Mulligan, K., "Experimental and Analytical Studies of Semi-Active and Passive Structural Control of Buildings", PhD Thesis, University of Canterbury, Christchurch, New Zealand, (2007).
13. Srinivas, N. and Deb, K., "Multi-objective optimization using non-dominated sorting in genetic algorithms", *Evolutionary Computation*, Vol. 2, No. 3, (1994), 221–248.
14. Deb, K., Pratap, A,. Agarwal, S. and Meyarivan, T., "A fast and elitist multi-objective genetic algorithm: NSGA-II", *IEEE Trans Evolutionary Computation*, Vol. 6, No. 2, (2002), 182–97.
15. Chopra, A.K., "Dynamics of Structures", Second Edition, Mc Graw-Hill, Inc. (1995).
16. Pourzeynali, S. and Mousanejad, T., "Optimization of Semi-Active Control of Seismically Excited Buildings using Genetic Algorithms", *Scientia Iranica, Transaction A, Civil Engineering,* Vol. 17, No. 1, (2010).
17. Ogata, K., "Modern control engineering", Engle Wood Cliffs, N.J. Prentice Hall Inc., (1982).
18. Kurata, N., Kobori, T., Takahashi, M., Niwa, N. and Midorikawa, H., "Actual seismic response controlled building with semi-active damper system", *Earthquake Engineering and structural dynamics,* Vol. 28, (1999), 1427-1447.
19. International Building Code, IBC, 2006.

Multi-objective Optimization of Semi-active Control of Seismically Exited Buildings Using Variable Damper and Genetic Algorithms

S. Pourzeynali, M. Malekzadeh, F. Esmaeilian

Department of Civil Engineering, Faculty of Engineering, The University of Guilan, Rasht, Iran

A R T I C L E I N F O

Article history:
Received 20 April 2012
Accepted in revised form 14 June 2012

Keywords:
Semi-active Control
Multi-objective Optimization
NSGA-II
Pareto Solution

چکیده

میراگرهای با سیال لزج (میراگرهای ویسکوز) به‌عنوان زیرمجموعه‌ای از سیستم‌های کنترل، قابلیت خود را در کاهش ارتعاش ساختمان‌های بلند نشان داده‌اند. در این مقاله، بهینه‌سازی چند هدفه متغیرهای طراحی این گروه از میراگرها با رویکرد نیمه فعال در کاهش ارتعاش ساختمان‌های بلند، با استفاده از الگوریتم‌های ژنتیکی مورد مطالعه قرار گرفته است. به‌عنوان مثال عددی، مطالعه دو ساختمان ۷ و ۱۸ طبقه که به‌صورت قاب‌های سه‌بعدی با کف صلب مدل شده‌اند ارایه شده است. معادلات دینامیکی هر مدل سازه‌ای تحت شتاب نگاشت‌های لرزه‌ای به‌همراه میراگرهای سیال نیمه فعال، در فضای حالت نوشته شده و با انتخاب تغییرمکان طبقه آخر، برش پایه و غیره، به‌عنوان توابع هدف، بهینه‌سازی پارامترهای طراحی مورد بررسی قرار گرفته‌اند. توابع هدف مذکور،جهت بهینه‌سازی چند منظوره به دسته‌های سه‌تایی تقسیم بندی و با استفاده از الگوریتم‌های ژنتیکی جواب‌های بهینه *پارتو*، تعیین شده‌اند. در این حالت، هر جواب بهینه *پارتو*، در واقع یک پیکربندی معین از تعدادی میراگردر مکان‌های مشخص از سازه خواهد بود. در این مطالعه، الگوریتم ژنتیکی NSGA-II مورد استفاده قرار گرفته است.

doi: *10.5829/idosi.ije.2012.25.03a.08*