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MR DAMPER OPTIMAL PLACEMENT FOR SEMI-ACTIVE CONTROL OF BUILDINGS USING AN EFFICIENT MULTI-OBJECTIVE BINARY GENETIC ALGORITHM

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ABSTRACT

In order to ensure the survival of building structures during earthquake periods, induced vibrations have to be mitigated. In this regard, semi-active control of smart structures using magneto-rheological dampers is becoming an emerging technology. Improvements on vibration reduction are foreshadowed when the dampers are installed at critical locations on the building structure. In this paper, the placement of dampers is cast as a multi-objective optimization problem in the sense of minimum resultant vibration magnitudes and with a minimum number of dampers. A binary-coded genetic algorithm is employed as the optimizer owing to its computational flexibility and high performance. Simulation results are included to illustrate the effectiveness of the proposed approach on a high-rise building model subject to benchmark earthquake records.

KEYWORDS

Building Control, Damper Placement, Genetic Algorithm, Multi-Objective Optimization

1. INTRODUCTION

Casualties during earthquake periods could be very extensive. Particularly, in urban areas, loss of human lives and economic costs paid are mainly caused by collapsing of building structures due to induced vibrations. Intuitively, buildings have to be built with sufficient resistances to vibrations but there is always a limit in the affordable capitals invested in their constructions. Control schemes aimed at vibration reductions [1], hence, are becoming attractive alternative approaches. Practically, there are a number of devices available such as tune mass dampers [2]; however, power sources may not be available during earthquake periods. To this end, dampers with controllable characteristics, for example, the magneto-rheological (MR) dampers are widely adopted in this problem domain [3]. Furthermore, to reduce system complexity, power consumption and to ensure satisfactory performances, it is important to place the dampers in their critical locations in the building.

The importance of damper locations affecting the vibration characteristics of structures has been noted more than a decade ago [4], where a multi-body system was used as a study example. Vibration reduction in building structures can be regarded as the problem of maximizing the efficiency taking into account the energy dissipated in dampers [5]. Obviously, minimum vibration magnitudes are crucial criteria for judging the effectiveness [6]. Therefore, placing the dampers can be naturally tackled as an optimization process and was addressed in [7] where the use of steepest direction search might call for analytical system models. Alternatively, heuristic approaches [8] such as Tabu search or simulated annealing have been attempted.

On the other hand, established techniques in the evolutionary computation area have been recognised as attractive candidates in tackling the damper placement problem considered. A genetic algorithm (GA) is used in [9] to obtain optimal placements of sensors/actuators on civil structures. The work reported in [10], considering the damper location problem also used the GA in conjunction with criteria derived from the system transfer function. The GA with a weighted-sum approach was proposed in [11] for optimal locations in a civil structure where dampers are installed. However, assignment of proper important weights is generally difficult.

While evolutionary computation techniques are effective strategies to solve the damper placement problem, optimization for multiple objectives has not been fully emphasized. In this direction, the GA operating as a multi-objective optimizer has recently appeared in the literature [12], where the vibration magnitude and the number of dampers used are adopted as objective functions.

The remainder of the paper is organized as follows. In Section 2, the semi-active control problem for smart structures with MR dampers is briefly presented. Section 3 reviews the use of binary-coded GA in the multi-objective optimization paradigm. The optimal placement of dampers is considered in Section 4 and preliminary results are given in Section 5. In Section 6, a conclusion is drawn.

2. MR-DAMPER CIVIL STRUCTURES

The civil structure considered is a multi-storey building consisting, for simplicity, of an aggregation of single degree-of-freedom bays. The building is subject to simulated earthquake excitations, e.g., from a shake-table facility, and magneto-rheological (MR) dampers are to be installed to alleviate the vibrations induced on the floors.

2.1 System Description

Consider the n-storey building structure shown in Fig.1, the equation of motion can be expressed as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{\Gamma}\mathbf{f} + \mathbf{M}\mathbf{\Lambda}\ddot{x}_g, \qquad (1)$$

where $\mathbf{x}$ is the floor displacement vector, $\mathbf{M},\mathbf{C},\mathbf{K}$ are the mass, damping and stiffness matrices, $\mathbf{\Gamma},\mathbf{\Lambda}$ are the distribution vectors for the damper force $\mathbf{f}$ and ground acceleration, $\ddot{x}_g$. An augmented system state equation is further formulated as

$$\dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{B}\mathbf{u} + \mathbf{E}, \qquad (2)$$

where $\mathbf{z} = [\mathbf{x}^T\ \dot{\mathbf{x}}^T]^T$ is the state vector,

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{\Gamma} \end{bmatrix}, \qquad (3)$$

are the system and gain matrices, and earthquake induced disturbance is given by $\mathbf{E}$. The smart structure control $\mathbf{u}$ may be via the damper force $\mathbf{f}(t)$, or by applying directly appropriate current $\mathbf{i}(t)$ to pairs of MR dampers set in a differential configuration, as shown in Fig. 1, to cancel out the offset forces. The control development has been described in [13].

2.2 Optimal Damper Placement— A Rationale

The response of the building structure, under the effect of random earthquake excitation, largely depends on the system matrix $\mathbf{A}$ and the control effort $\mathbf{u}$. In fact, installation of the MR dampers will affect the system matrix elements via its lumped parameters on stiffness $\mathbf{K}$ and viscous damping $\mathbf{C}$. Furthermore, in direct control, the influence of the current input would also give way to the parametric dependence of the control gain matrix $\mathbf{B}$, whereby a zero entry is related to the absence of a damper pair installed at the corresponding storey. The control goals require therefore not only robustness and feasibility of the system but also the satisfaction of seismic response performance in an economic manner. To achieve these goals, a multi-objective optimization approach is proposed as in the following section.

3. MULTI-OBJECTIVE GENETIC ALGORITHM

In order to achieve optimum for both the number of dampers used and for the suppression of quake-induced vibrations, the control problem is cast as an optimization process for which several approaches that can be applicable. Here, for the sake of simplicity, flexibility and good performance, a multi-objective binary-coded GA is used.

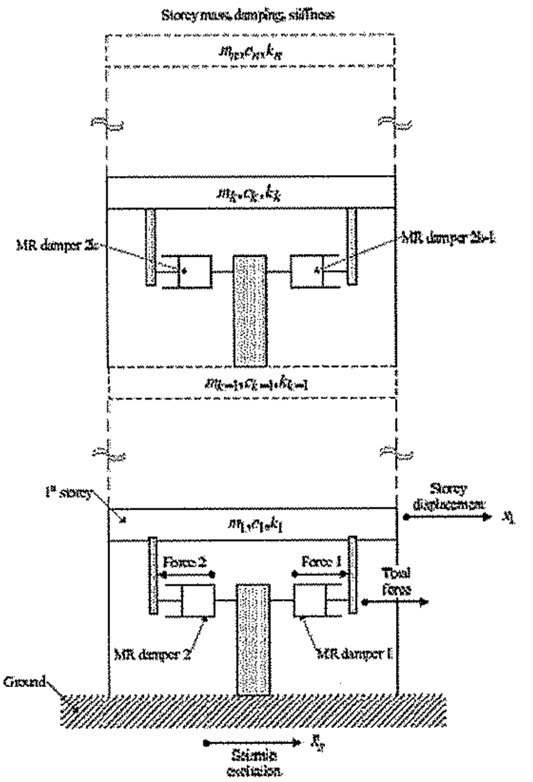

Figure 1 Multi-Storey Building Under Control

3.1 Binary-Coded Genetic Algorithm

Genetic algorithms are search routines inspired by the evolution of living species. In the course of evolution, descendants inherit favourable genetic ingredients from their ascendants such that the survivability of the whole population increases over generations. When using the principle of "survival of the fittest" to optimization algorithms, chromosomes of living organisms are coded in binary strings which represent potential solutions to the problem, see Fig. 2.

The quality of the solution to the problem is embedded as a fitness value assigned to each chromosome. A near-optimal solution is obtained by manipulating the population using genetic operators including *selection, crossover* and *mutation.* At the first generation (iteration) binary strings are generated in random to cover the solution space.

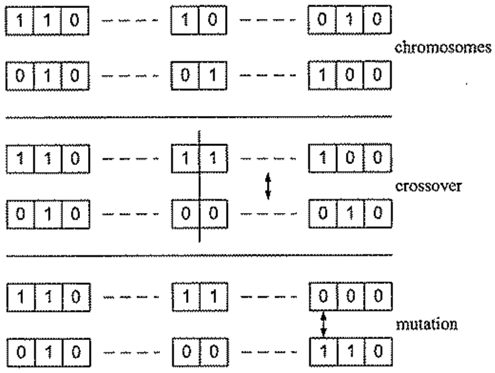

Figure 2 Operations of Genetic Algorithm

Their objective functions are evaluated and normalized to give the corresponding fitness. The chromosomes are selected to the next generation according to their fitness. A pair of chromosomes is then randomly picked and part of the string is exchanged by the crossover operator. Before evaluating the fitness, a random bit is flipped in the mutation process. The process is repeated until the number of generations reaches a pre-specified count.

3.2 Multi-Objective Genetic Algorithm

The problem of damper placement is concerned with obtaining minimum storey vibrations while using a minimum number of dampers. Without much *a priori* knowledge on control schemes, our intention is to formulate the damper placement as a multi-objective optimization problem.

The evaluation of the chromosome fitness has to be catered for this requirement. The objectives can be augmented into a single fitness by the use of importance weights. Although commonly-used in optimization, there has not been a generic methodology for the choice of weights available in the relevant literature.

In the context of evolutionary computation, several approaches have been proposed for this kind of optimization with genetic algorithms [12], including vector evaluated GA (VEGA) and fitness sharing (FSGA). In VEGA, sub-populations are used for evaluating a single objective and then combined by the selection operator. On the other hand, FSGA modifies the fitness by sectoring the objective-space. The fitness of chromosomes in close objective-space vicinities is reduced to promote searching for better solutions.

In this work, the principle of Pareto front is applied making use of the fact that it does not need to determine the required sub-populations. In essence, chromosomes at the frontier of the fitness landscape are assigned with higher ranks. The ranking is defined as

$$R_i = \sum_{m=1}^{M} N(f_i^m < f_{j\neq i}^m), M = 2 \qquad (4)$$

where i is the chromosome index, m is the objective index, $N(.)$ is the operator that gives the number of satisfactions for condition inside the bracket.

4. OPTIMAL DAMPER PLACEMENT

The damping devices used are briefly presented in this section. Then a optimization procedure implemented with GA is developed for placing them in the civil structure.

4.1 Damper Model

The MR damper used in this study is a LORD RD-1005-3 model. The damper force generated is a function of the compression/extension displacement and velocity, described by a static hysteresis model as given in [14]:

$$\begin{aligned} f_{di} &= c_d \dot{x}_{di} + k_d x_{di} + \alpha z_d \\ z_d &= \tanh(\beta \dot{x}_{di} + \delta \text{sign}(x_{di})), \end{aligned} \qquad (5)$$

to represent the non-linear force/displacement relationship, where z_d is the hysteretic variable, and

$$x_{di} = x_{i+1} - x_i, \qquad (6)$$

is the inter-storey displacement. The equation of motion can be written, for an individual storey, as

$$\begin{aligned} & m\ddot{x}_i + c\dot{x}_i + kx_i = -f_{di} + m\ddot{x}_g \\ &= -c_d \dot{x}_{i+1} + c_d \dot{x}_i - k_d x_{i+1} + k_d x_i - \alpha z_d + m\ddot{x}_g, \end{aligned} \qquad (6)$$

or

$$\begin{aligned} & m\ddot{x}_i + (c - c_d)\dot{x}_i + (k - k_d)x_i \\ &= -c_d \dot{x}_{i+1} - k_d x_{i+1} - \alpha z_d + m\ddot{x}_g, \end{aligned} \qquad (7)$$

which clearly shows the modification of the storey response when a damper is installed.

4.2 GA Modified Gain Matrix

The gain matrix $\mathbf{B}$ given in (2) contains an upper $n \times n$ zero matrix corresponding to the number of storeys. The lower part $\mathbf{\Gamma}$ is an identity matrix also of $n \times n$ scaled inversely by the mass of the storey. If a damper is not installed, the corresponding element of the matrix $\mathbf{\Gamma}$ becomes zero instead. This special matrix structure naturally poses the optimization problem in the domain of a binary-coded genetic algorithm (BCGA) optimization. Here, the chromosome depicted in Fig. 2 is used to represent the diagonal elements in matrix $\mathbf{\Gamma}$ and will be manipulated through generations in the algorithm.

4.3 Optimization Problem

The goal of reducing the root-mean-square vibration magnitudes induced on the building and the use of a minimum number of dampers together constitutes to a multi-objective optimization (minimization) problem. It is stated as follows:

Minimize:	Storey RMS displacement AND Number of dampers
Subject to:	Supplied damper current $0 \le i_d \le i_{d,\max}$.

A chromosome in GA is encoded as a string of 1's and 0's, for example

$$\mathbf{C}_i = [0,\cdots,1,\cdots,1]^T, i = 1,\cdots P, \qquad (8)$$

where the length of the i-th chromosome corresponds to the number of storeys n with entries 1 corresponding to the damper-installed storey, and P is the number of chromosomes to form a population.

The fitness of one of the objectives, the minimization of number of dampers used is

$$f_i^d = \sum_{k=1}^{n} C_{i,k}, \qquad (9)$$

where k is the index for the gene inside a chromosome. The other objective fitness, the root-mean-squared (RMS) displacement is calculated as

$$\tilde{f}_i^r = \sqrt{\frac{1}{N}\sum_{t=1}^{\tau}(x_i^t)^2}, \; f_i^r = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(\tilde{f}_j^r)^2} \qquad (10)$$

here, N is the number of displacement time series x_i^t, and τ is the maximum earthquake time considered. Finally, the overall Pareto-ranked fitness is given as in (4), where for the sake of simplicity M is set to 2 in this work. The final solution is given by the chromosome with highest rank in the terminating generation.

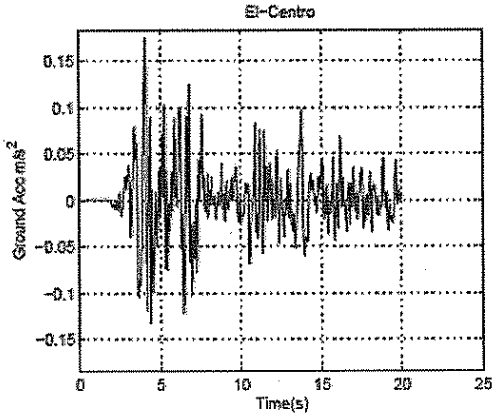

Figure 3 El-Centro Earthquake Record

5. RESULTS

Simulation studies are conducted using the scaled down (50%) benchmark El-Centro earthquake record, Fig. 3, for 20 seconds. The building model is designed such that the natural vibration mode frequencies are ranged from 1Hz to 23Hz for a 20-storey building. The masses and stiffness are assumed equal in every floor and a damping ratio of 2%, also for every floor, is assumed.

5.1 Passive-off MR Dampers

In this case, dampers are supplied with zero currents (in passive-off mode) and the resultant RMS displacements are depicted in Fig. 4.

The dotted line represents the displacement when no dampers are installed and the building structure is in the so-called free vibration. The case with dampers installed at all the stores are given by the solid line where dots indicate the floor level.

The effect of the use of a reduced number of dampers, 8 damper pairs in this case, is illustrated by the dark solid line with squares indicating the stores where dampers are employed. It is shown that the use of a smaller number of dampers is acceptable with the satisfactory resultant displacement.

5.2 Passive-on MR Dampers

Two cases are considered when the dampers are supplied with a moderate current (1A) and the maximum current (2A). Their corresponding effectiveness is illustrated as below.

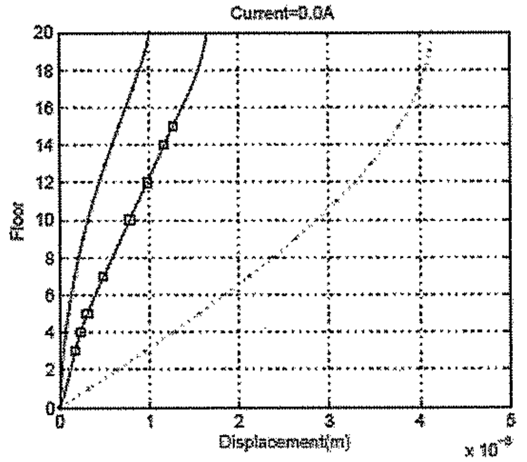

Figure 4 RMS Displacements from Passive-off test (dash dot: no damper, solid dot: max. no. of dampers used, solid square: optimal placed dampers)

5.2.1 Moderate supply current

Figure 5 shows the RMS displacements under this test scenario. As illustrated and with the use of 9 damper pairs under the effect of a moderate supply current, the response is slightly better than the full-installation configuration with passive-off dampers.

It is believed that due to the modified overall structural stiffness, with the installation of dampers at critical points, resonant characteristics are altered and vibrations have been reduced. On the other hand, full-installation may result in a too large rigidity where vibration energies have not been completely absorbed.

5.2.2 Maximum supply current

Simulation results are illustrated in Fig. 6. It is noted that the vibration of full-installed configuration is largest among the three cases. This could be explained that the structural rigidity is further increased and results in insufficient vibration absorption. However, the displacement is smaller than the free-vibration case.

With the use of a reduced number of dampers, 3 damper pairs used in this case, the response is comparable to the previous case with a moderate supply current. It should be noted, that only a few dampers could be used where larger currents supplied increases the capability of vibration absorption. To this end, simultaneous achievement of both optimization objectives is evident.

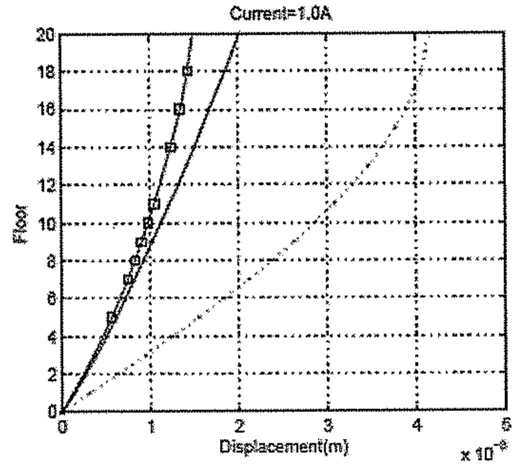

Figure 5 RMS Displacements from Passive-on Test, Moderate Supply Current

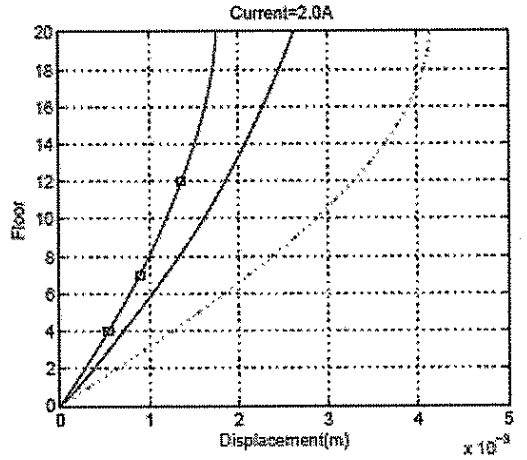

Figure 6 RMS Displacements from Passive-on Test, Maximum Supply Current

6. CONCLUSION

This paper has addressed the problem of optimal placement of semi-active resources in the control of civil structures against earthquake excitations. The problem is tackled from a multi-objective optimization perspective where a binary-coded genetic algorithm is used as the optimizer to obtain near-optimum locations to install the MR dampers. The use of the BCGA together with the Pareto-front approach is effective in this problem domain, in which the objectives for the use of resources and performance are simultaneously achieved. Satisfactory results using the El-Centro benchmark earthquake records have verified the proposed approach. Future work will be directed towards the incorporation of controllers on the damper supply currents, together with an increase in the number of objectives, in an integrated manner to address optimality in the smart structure technology.

7. ACKNOWLEDGMENT

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