OPTIMAL CONTROL OF ACCELERATIONS IN A BASE-ISOLATED BUILDING USING SEMI-ACTIVE MR DAMPERS

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ABSTRACT :

This article presents a theoretical study aimed at improving effectiveness of the isolation system of a building by adding magneto-rheological (MR) dampers that act in parallel to the rubber bearings (RB). To this end, the building itself is modeled with uni-axial elements that consider axial, shear and flexural deformations. Nonlinear elements that include RBs and MR dampers, whose response is velocity dependent, are added at the base of the building. Properties of the MR dampers are obtained from laboratory tests previously performed. Genetic algorithms with local improvement of chromosomes that represent a fuzzy logic control system are used to optimize operation of the MR dampers. Maximum acceleration at the top of the building is taken as the variable to be minimized. Several records of destructive earthquakes that could affect the site are used as input. Structural responses for three different conditions are compared: a) building with the actual isolation system, but without any additional dampers. b) building with rubber isolation and the MR dampers as passive energy dissipaters, and c) building with rubber isolation and MR dampers that are controlled semi-actively. Results show that the average absolute peak acceleration, considering different types of earthquakes, can be reduced by up to 20% in comparison with the case where no dampers are installed.

KEYWORDS: Base isolation, structural control, MR dampers, genetic algorithms, fuzzy logic control

1. INTRODUCTION

The use of seismic isolation systems for control of the response of buildings has shown to be very effective, especially for shallow and rigid buildings. Recent experience with a building located in Santiago, Chile, that is supported by eight rubber bearings (RB) ratifies this fact. This building was constructed in 1992 as a domicile for families with low incomes and since then has been subjected to several small to medium earthquake motions, that have been recorded by a network of accelerometers. It has four stories and a 10 m × 6 m rectangular plan (see Fig. 1). Its structure consists of reinforced concrete walls for the first floor and confined masonry walls for the upper three floors, with reinforced concrete slabs at each floor level. [Moroni et al. 1998].

Figure 1. Comunidad Andalucía Building

Increasing damping in the isolation system is an effective way of reducing floor accelerations and relative displacements. However, if too much damping is added the result can be a greater participation of the higher modes of vibration in the response to earthquake excitation, thus reducing the effectiveness of the base isolation [Kelly, 1998] A better way for the introduction of large energy dissipation than simply adding passive dampers is the use of semi-active devices and smart systems with an optimal algorithm; in this case the objective function seeks to optimize the reduction of both floor absolute accelerations and floor relative displacements [Yan et al., 2006, Nitta et al., 2006, Lee et al., 2006]. This alternative has become feasible with the use of magneto-rheological (MR) dampers. Magneto-rheological dampers permit semi-active control by using a low intensity electric current that changes the viscosity of the fluid when it is subjected to a variable magnetic field. The MR fluid is sensitive to magnetic fields and thereby responds to changes in the force-velocity characteristic function of the damper as a function of time.

The main objectives of this study are as follows:

- To study the response of the previous building supported on rubber bearings with the addition in parallel of MR dampers.
- To design an algorithm for dynamic analysis of the structure such that it incorporates both the nonlinear MR forces and the viscoelastic rubber bearing resistance.
- To design a control system, based on a genetic algorithm, that minimizes the dynamic response of the structure.

2. METHODOLOGY

The building is first modeled by means of finite elements. Then, based on the elastic characteristics of this model, a simplified numerical model that uses equivalent lumped masses and column stiffnesses is defined. The equivalent model is first calibrated for the fixed-base case so that the isolation system does not influence dynamic characteristics of the building itself. Then the rubber bearings are included by considering their stiffness at 50% of the design deformation.

With regard to damping in the isolation system two cases are considered: a) The actual average damping in the bearings (12%), and b) a fictitious damping of 5%. In both cases the Rayleigh method is used to obtain the damping matrix of the structure.

The time-history response of the isolated structure and the isolated structure with installed MR dampers are numerically predicted using SIMULINK [The Mathworks, 2007]. The Dormand Prince method was used in the numerical simulation, [Dormand and Prince, 1980]. Four records obtained during the 1985 Chilean magnitude 7.8 earthquake are used: Llolleo N10E, Ventana WE, Llay Llay S10W, and Viña del Mar S20W. Motions similar to these are to be expected at the site of the building.

Dynamic characteristics of the MR damper are established using an adaptive network fuzzy interference system (ANFIS) that describes the relationship between the input (displacement, velocity, and voltage) and output (force) variables, where data from experimental results are used [Lin et al., 2005].

The control system uses fuzzy logic to make decisions concerning the level of current that is to be supplied to the MR dampers. Optimization of the control system is developed using two different genetic algorithms, as discussed in the following sections.

3. SIMPLIFIED MODEL

The finite element model of the four-story house was taken from [Aguilera, 2002]. SAP2000 NL was used for frequency and time-history analyses. Columns and tie beams were represented by FRAME elements while walls and slab were represented by SHELL elements. This model was calibrated so that it adequately represents the frequencies of the conventional building obtained from ambient vibration measurements by adjusting elastic moduli of the masonry (E_a = 1900 MPa) and the reinforced concrete (E_h = 32000 Mpa). Next, ISOLATOR 1 elements were introduced to represent the rubber bearings, and DAMPER elements in the vertical direction were introduced to represent equivalent damping in that direction. This model was calibrated so that it adequately represents the frequencies of the isolated building obtained from ambient vibration measurements by adjusting the effective horizontal and vertical stiffness of the bearings, K_h = 12500 ton/m and K_v = 3600000 ton/m, respectively. Finally, the model was calibrated so that it adequately represents the dynamic response of the isolated building for records obtained using instruments located in the building during the March 24, 1997, earthquake. For this rather moderate earthquake, predominant frequencies were 2 Hz and 1.92 Hz in the longitudinal and transverse directions, respectively. Therefore, effective horizontal and vertical stiffnesses were 440 ton/m and 50000 ton/m, respectively.

Next, a 2D model was developed that replicates motion of the building in the longitudinal direction. Masses were lumped at the center of gravity of each floor. For the model, the first period of vibration was obtained and compared with its counterpart from the finite element prediction. The values obtained were 0.137 sec for the finite element model and 0.130 sec for the simplified model; that is, the difference between the model predictions is 5%, which is considered to be sufficiently precise.

For the isolated building, a fourth mass was added at the base to represent the ground level floor. The isolators were modeled using a constant stiffness equal to 28 ton/m. The fundamental periods of vibration for the first mode are 1.82 sec and 1.65 sec for the finite element and lumped mass models, respectively, with a difference of 9%.

The damping matrix is computed as follows:

$$[\boldsymbol{C}] = a_0[\boldsymbol{M}] + a_1[\boldsymbol{K}] \tag{1}$$

where α_o and α_1 are obtained from the following system of equations:

$$\frac{1}{2}\begin{bmatrix} \dfrac{1}{w_i} & w_i \\ \dfrac{1}{w_j} & w_j \end{bmatrix}\begin{Bmatrix} a_0 \\ a_1 \end{Bmatrix} = \begin{Bmatrix} V_i \\ V_j \end{Bmatrix} \tag{2}$$

Two different cases of damping in the isolators, 12% and 5%, were considered. In both cases damping in the first mode was taken to be equal to that of the isolators, because almost all of the deformation energy of this mode corresponds to the deformation of the isolators. Damping of 5% was taken for the second mode (masonry and reinforced concrete) and the other modal damping resulted from the equations: 10% and 15% for the third and four modes, respectively, in the first case, and 6% and 9% for the same modes in the second case. The values for the third and four modes are rather high but they are not important in the structural response, as it was confirmed using a more sophisticated model.

4. MODEL OF MAGNETO-RHEOLOGICAL DISSIPATOR

Incorporation of the dissipator force in the time history analysis requires an adequate model of the dissipator. This model relates the input variables (displacement, velocity, and voltage) with the output variable (force). A dissipator that has a capacity of 2 ton was used in this case; its characteristics were reported by Lin et al. (2005). The required number of dissipators was determined by a trial and error process, leading to 8 MR dissipators for the 5% case and 4 MR dissipators for the 12% case.

5. DESIGN AND OPTIMIZATION OF THE CONTROL SYSTEM

A fuzzy logic control system is used in this investigation. Advantages of this kind of control system include their robustness and ability to handle uncertainties in the relevant variables. A fuzzy interference system, FIS, does not need complex equations and extensive computational time, which are typical for traditional control algorithms. The use of fuzzy logic substantively reduces computer time and allows treatment of non-linear processes with relative ease [Shook et al., 2008].

The objective of the control system is to minimize the structural response by determining at each instant of time the optimum voltage to be applied to the MR damper. Training of the controller is based on actual earthquake records. In the single-objective GA, the main variable that is minimized is the peak acceleration of the roof of the building. It is expected that minimizing this variable should minimize also the relative displacement of the roof of the building. By comparison, in the multi-objective GA the variables to be minimized are both peak acceleration and relative displacement of the top floor.

During design of the architecture of the control system it is also important to decide which variables will be monitored as inputs during a real earthquake. The input variables selected in this case are the acceleration and a delayed acceleration (at time = t – 0.025 sec), mostly because of its simplicity to record during an earthquake.

Four earthquake records that have different characteristics were used as input excitations. They correspond to the 1985 Llolleo (Chile) earthquake, with records taken at the following locations: Llay-Llay S10W, Ventanas WE, Viña del Mar S20W, and Llolleo N10E.

As outlined in the discussion that follows, two different genetic algorithms were used: one is a genetic algorithm with local optimization of chromosomes [Furuhashi et al., 1995] and the other uses a multi-objective approach, specifically the non-dominated sorting genetic algorithm, NSGAII [Deb et al., 2000].

Encoding is the genetic representation of an FLC solution. All the information represented by the FLC parameters is encoded in a structure called a chromosome. For both algorithms the same codification was used. The control system consists of 20 fuzzy logic rules, each of them relating the input variables (acceleration and delayed acceleration) with the output variable (voltage). The rules make use of so-called Gaussian membership functions. Each membership function is mathematically represented by two variables, mean and standard deviation. Then, each rule has six variables and therefore the chromosome has 120 variables in total for each controller.

6. ALGORITHM FLOW

6.1 Genetic algorithm with local improvement of chromosomes

The initial population consists of ten chromosomes that are randomly generated. Each chromosome is divided into equal parts, four in this case, and each part contains the 30 variables for five rules. First, the algorithm copies a chromosome m times. Of these copies, one remains untouched and the other $m-1$ are mutated. In this case $m=3$ is used. Only a part of the chromosome, randomly selected, is mutated. Then the m chromosomes are evaluated and only the one that gives the lower value of the objective function, in this case the average of the absolute peak acceleration for the four records, is kept for future evaluation. This is the fitness value. The process is then repeated for each part of the chromosome.

Once the mutation process is completed for all chromosomes, the two best chromosomes are conserved for the next generation and the remaining 8 are obtained by the crossover operator.

Two 'fathers' are needed to create an individual by crossover. In order to decide which chromosomes will be the fathers, the fitness of each of them is scaled to a more adequate range. This process assigns an expectation (number of sons) to each chromosome according to its fitness. A linear scaling process was selected in which an expectation of two is applied to the individual with the best fitness and then the expectation values are decreased in a linear fashion for the other chromosomes. Afterwards the process of selection is used to determine the fathers for the crossover. The selection process assigns a probability for fatherhood to each chromosome that is equal to its expectation. Once the fathers are selected, the crossover is applied (two-point crossover in this case). The range of the chromosome is randomly selected and then a crossover of the range of both fathers is done to obtain a son. The population of chromosomes is completed once the crossover process is finished and then everything is ready for the next generation.

6.2 Non-dominated sorting genetic algorithm (NSGAII)

The essential difference between a multi-objective GA and a single-objective GA is the method by which the fitness value is assigned to potential solutions. In the first approach each solution has a vector describing its performance for each variable that is to be minimized. In this case, as described above, these two variables are the peak acceleration and displacement. This vector must be transformed into a single scalar fitness value for the purpose of the GA selection mechanism. The transformation is achieved by ranking the population of solutions relative to each other, and then assigning a fitness value that is based on rank. Individual solutions are compared in terms of Pareto dominance. This means that if solution 'a' is better than solution 'b' for both objectives, then solution 'a' is said to dominate over solution 'b' or, in other words, solution 'b' is dominated by solution 'a'. If a solution is not dominated by any other, then that solution belongs to rank 1. After completing the creation of the first rank, all of the solutions that belong to that rank are taken out of the population and the same process is repeated to form ranks 2, 3, etc. This process continues until all solutions have been ranked. In effect, this process creates a series of non-dominated fronts.

Deb et al. [2000] adopted this approach for NSGAII. Multi-objective ranking, which impacts primarily on assignment of fitness, is the key difference between a multi-objective GA and a standard GA.

7. RESULTS

The genetic algorithms were used in numerical simulation for the cases of 5% and 12% damping in the isolators. In total, six fuzzy logic controllers (FLC) were designed, three for the 5% case and three for the 12% case. In each case, one FLC was created by a genetic algorithm with local improvement of chromosomes and two by the NSGAII (one with the lowest peak acceleration result and another with the lower peak displacement result). The passive-on (constant maximum voltage), passive-off (constant minimum voltage), and a case where no MR dampers were installed were also evaluated to compare solutions obtained by the different GAs.

Figure 2 shows the 20 fuzzy rules of a FLC, relating gaussian membership functions for the inputs and output variables. In this example, for an acceleration of -0.09 m/s^2 and a delayed acceleration of 1.43 m/s^2, a voltage of 0.532 V is applied (the control system sends the absolute value of the output variable to the MR damper).

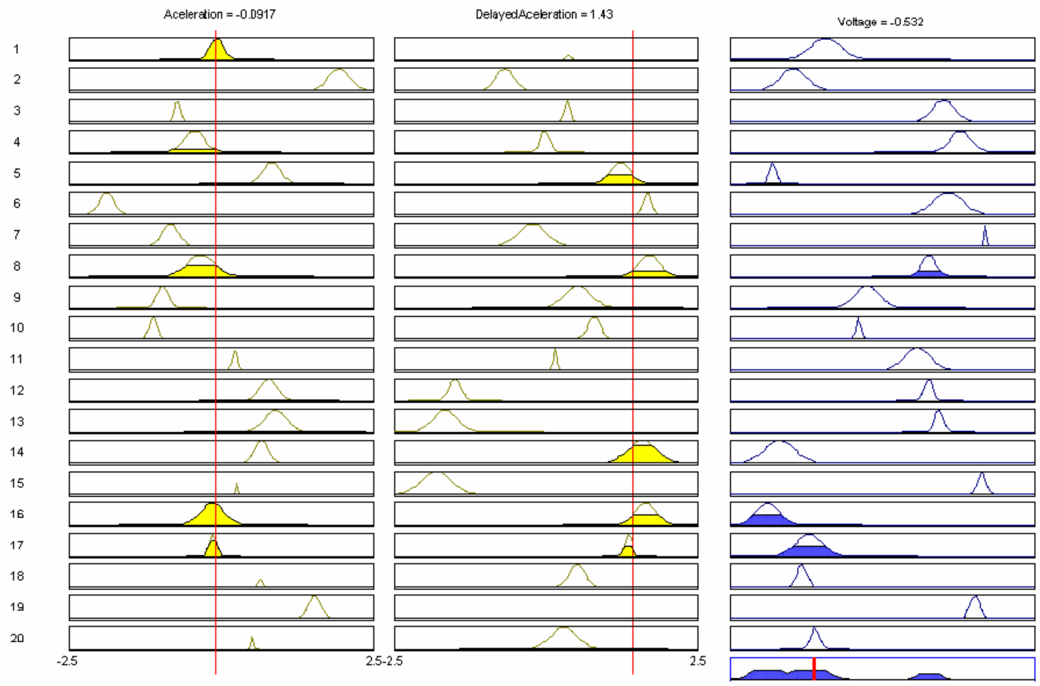

Figure 2. Fuzzy rules example

Results are shown in Figures 3 and 4 for the different cases evaluated, that is:
Case 1: No MR damper
Case 2: Passive-off
Case 3: Passive-on
Case 4: FLC obtained with genetic algorithm and local improvement of chromosomes (FLC 1 and 4)
Case 5a: FLC obtained with NSGAII, choosing optimal acceleration for rank 1 Pareto front (FLC 2 and 5)
Case 5b: FLC obtained with NSGAII, choosing optimal displacement for rank 1 Pareto front (FLC 3 and 6)

8. CONCLUSIONS

A numerical study of the effectiveness of using MR dampers in parallel with rubber bearings in an existing building has been presented. The building was constructed in 1992 as a domicile for families with low incomes. It is a four-story structure consisting of reinforced concrete walls in the first floor and confined masonry walls for the upper three floors, with reinforced concrete slabs at each floor level.

Operation of the MR dampers is optimized by using fuzzy logic control systems obtained through genetic algorithm techniques. The objective functions were peak acceleration and peak relative displacement at the top of the building. The average of the response to four earthquake records of high intensity that could strike the building was considered for the optimizations process.

In all cases it was possible to obtain fuzzy logic controllers that minimize the average of peak absolute acceleration and peak relative displacement at the top of the building for the set of earthquake records.

For the 5% isolation damping cases the conclusions are:

- The optimal FLC for acceleration control is the local improvement of chromosomes one (FLC1). The reduction in absolute acceleration with respect to the case without MR dampers is 27% and with respect to the passive-on case (case 3, the best passive case), is 9.3%.
- However, the best system for displacement reduction uses passive-on control (case 3); it gives a global reduction of 64.9% with respect to the non-MR damper case. The displacement reduction corresponding to case 4 (FLC1) is 63.4%, which is very close to that of case 3.

For the 12% isolation damping cases the conclusions are:

- As in the 5% cases, the optimal FLC for acceleration was the one with local improvement of chromosomes (FLC4), with reductions of 16.7% and 4.2% with respect to the cases without dampers and passive-on dampers, respectively.
- For displacement the best FLC is case 5b (FLC6), with reductions of 32.5% and 0.2% with respect to cases without dampers and passive-on, respectively.

With the obtained controllers the displacements were reduced during the total duration of the earthquakes. On the contrary, in some periods the accelerations in the uncontrolled structure were less than in the controlled one; to prevent this the RMS should be used as the variable to minimize.

FLC obtained with GA and local improvement of chromosomes required the application of less voltage. Adding the MR dampers to the 12% damping case is less effective than for the 5% damping.

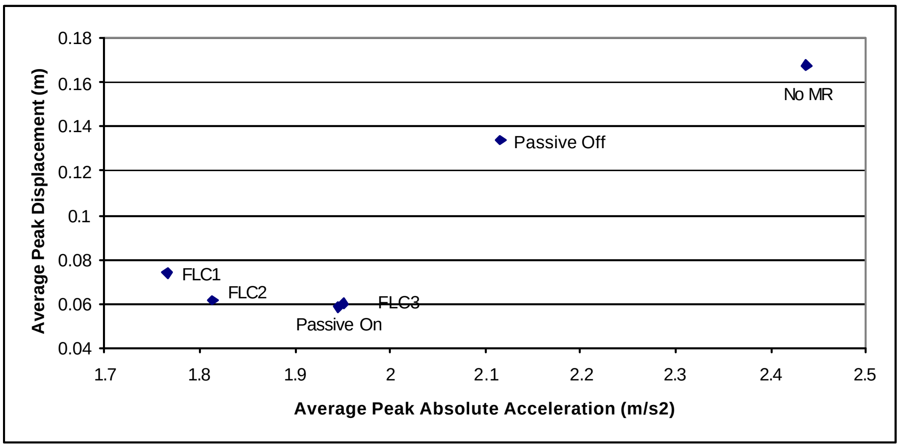

Figure 3. Damping : 5%, 8 MR dampers

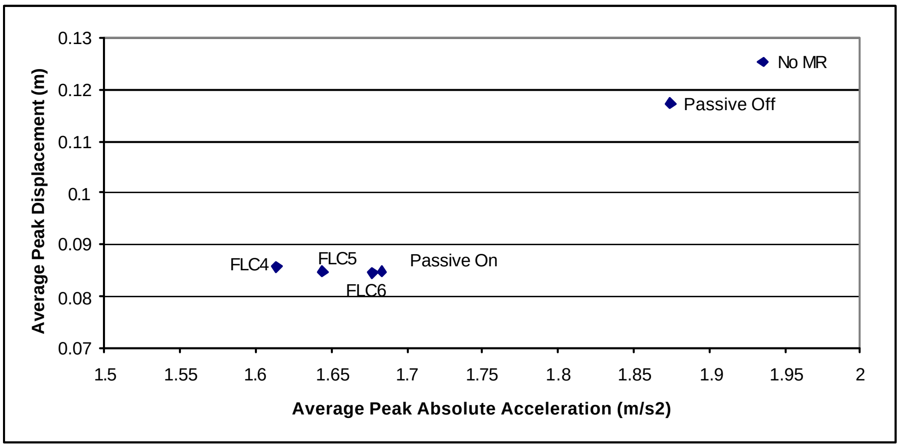

Figure 4. Damping : 12%, 4 MR dampers

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