Semi-active Base isolation System for Buildings using MR Dampers

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Due to limitations on the use of passive base isolation systems which show poor performance in near field seismic excitations or active systems which require high external power, as stand alone control devices for a range of seismic excitations, a hybrid control system that mitigates the limitations of either passive or active control systems is preferred. The present study examines the use of semi–active base isolation systems for vibration mitigation. A combination of base isolation and MR-dampers forms the control device that has been deployed as a base isolation unit in the building. A combination of GA–fuzzy based control algorithm has been proposed to be implemented as a control strategy. Scaled seismic inputs for both near and far field excitations have been used in this study on three story (base + three) building. The paper presents the analytical modeling and results obtained through numerical experiments.

1 INTRODUCTION

Mitigation of structural damage induced by large loads, stemming from earthquake, is of particular interest to engineers. Specifically, in seismic regions, earthquakes pose a serious threat to both the infrastructure and human lives. The protection of civil structures, including its material content and the human occupants, is without doubt a priority to the designers worldwide. The extent of protection may range from reliable operation and occupant comfort to human and structural survival. Base–isolation is one of the most widely applied structural protection technique against seismic events (Soong, 1990). Various researchers have studied the potential of base isolation under far–field and near–field earthquake (Agrawal et.al. 2006). Studies reveled that base isolation strategy perform poor under near source excitation. Various benchmark exercises have also been undertaken to improving base isolation performance using hybrid control strategies, such as the hybrid isolation system, consisting of a passive base isolation system (either rubber bearing isolators or sliding bearing isolators) and either active, or semi-active, or smart or passive control devices (Narashiman et.al. 2006).

The philosophy of hybrid control technique is to reduce the structural responses under the limitation of both the control force level (limited by the number and actuator capacity and the required amount of energy to drive the system) and the number of measured signals. This approach is used to provide optimal solution to linear systems. In addition, hardware related constraints, such as saturation and resolution of the sensor, analog-to-digital converter (ADC), and digital-to-analog converter (DAC), lead to quantization errors (Soong, 1990). Recently, the application of intelligent controllers [*e.g.*, fuzzy logic controller (FLC), neural network Controller, ANFIS *etc*] to structural control problem have been studied extensively. Some characteristics of intelligent systems appealing to control engineers are its effectiveness and ease in handling structural nonlinearities, uncertainties, and heuristic knowledge. Considerable research has been reported on the development and application of neural networks (Ghaboussi & Joghataie, 1995) for active control of civil structures. The advantage of these techniques is that they are independent of structural models and relies only on the input–output mapping. Vibration control using fuzzy logic, although has been studied earlier (Joghataie & Ghaboussi, 1994), (Battaini et.al. 1998), is on rise only recently. There has been an increasing interest in applying FLC to structures (Ali & Ramaswamy, 2007), (Ahlawat & Ramaswamy, 2004), (Jang et.al 2005) where some interesting results have been reported. Fuzzy control offers a simple and robust framework with which to specify nonlinear control laws, that can accommodate uncertainties and imprecision in the system model. A major advantage of fuzzy control is that it requires only a linguistic description of the control law with fuzzy rules and does not require a detailed analytical description of the structure. Moreover fuzzy control can handle the hysteretic behaviour of structures under earthquake (Battaini et.al. 1998). Another advantage of the FLC model in collaboration with MR damper is unlike clipped optimal and Lyapunov control techniques, the change in voltage input to the MR damper is gradual and it covers all voltage values in the range of maximum and minimum damper voltage $[0,1]$. This particular advantage not only permits the designer to use any voltage value between $[0,1]$ but also provides an inherent stability to the closed loop system (Ali & Ramaswamy, 2006).

A FLC includes a fuzzifier (fuzzification interface), an inference engine (rule base) and a defuzzifier to simulate linguistic and structured knowledge by means of fuzzy set theory. It is up to the experts knowledge to establish the fuzzy parameters (prescale gain, rule base, membership function type and parameters) (Ali & Ramaswamy, 2007). Therefore, formation of appropriate fuzzy if-then rules and membership functions remains an intractable issue. Furthermore, static fuzzy rules and membership function are vulnerable to changes in system parameters. One way to overcome this sensitivity to parametric changes is to combine a fuzzy system with an optimization technique such that optimal parameters are selected for a predefined class of objective functions.

2 BASE ISOLATED BUILDING MODEL

A three storey rectangular building model built for experimental studies using fuzzy logic controller, has been taken for the present analytical work. Base isolation has been done using a set of springs and linear roller shafts at the base of the building model. Linear shafts were set in two tiers (each tier provides motion in one direction) such that a 3D analysis can be performed. The super structure and the base are modeled using three master degrees of freedom per floor at the center of mass and are assumed to linear for the present analysis. Floor slabs and the base are assumed to be rigid in plane. The super structure is assumed to be undamped. Base isolated buildings are designed such that the superstructure remains elastic. The equations of motion are developed in such a way that the fixed base properties are used for modeling the linear superstructure. The MR dampers are assumed to be attached at the base of the building and the shake table (in both directions), so that it can restrict the large deformation of the linear shafts. The equations of motion for the elastic superstructure are expressed in the following form:

$$\begin{gathered}\mathbf{M}_{n\times n}\,\ddot{\mathbf{U}}_{n\times 1}+\mathbf{C}_{n\times n}\,\dot{\mathbf{U}}_{n\times 1}+\mathbf{K}_{n\times n}\,\mathbf{U}_{n\times 1}=\\ -\mathbf{M}_{n\times n}\,\mathbf{R}_{n\times 3}\left(\ddot{\mathbf{U}}_g+\ddot{\mathbf{U}}_b\right)_{3\times 1}\end{gathered} \tag{1}$$

in which, n is three times the number of floors (excluding base), $\mathbf{M}$ is the superstructure mass matrix, $\mathbf{C}$ is the superstructure damping matrix in the fixed-base case, $\mathbf{K}$ is the superstructure stiffness matrix in the fixed-base case and $\mathbf{R}$ is the matrix of earthquake influence coefficients. Furthermore, $\ddot{\mathbf{U}}$, $\dot{\mathbf{U}}$, and $\mathbf{U}$ represent the floor acceleration, velocity and displacement vectors relative to the base, $\ddot{\mathbf{U}}_b$ is the vector of base accelerations relative to the ground and $\ddot{\mathbf{U}}_g$ is the vector of ground accelerations. The equations of motion for the base are as follows:

$$\begin{gathered}\mathbf{R}^T_{3\times n}\,\mathbf{M}_{n\times n}\left[\ddot{\mathbf{U}}_{n\times 1}+\mathbf{R}_{n\times 3}\left(\ddot{\mathbf{U}}_g+\ddot{\mathbf{U}}_b\right)_{3\times 1}\right]_{n\times 1}\\ +\mathbf{M}_{b_{3\times 3}}\left(\ddot{\mathbf{U}}_g+\ddot{\mathbf{U}}_b\right)_{3\times 1}+\mathbf{C}_{b_{3\times 3}}\,\dot{\mathbf{U}}_{b_{3\times 1}}+\\ \mathbf{K}_{b_{3\times 3}}\,\mathbf{U}_{b_{3\times 1}}+\mathbf{f}_{3\times 1}=0\end{gathered} \tag{2}$$

in which $\mathbf{M}_b$ is the diagonal mass matrix of the rigid base, $\mathbf{C}_b$ is the resultant damping matrix of viscous isolation elements, $\mathbf{K}_b$ is the resultant stiffness matrix of elastic isolation elements, $\mathbf{f}$ is the vector containing the MR damper control forces. Combining Equation 1 and Equation 2, we get the following equation of motion of the system.

$$\hat{\mathbf{M}}\,\ddot{\hat{\mathbf{X}}}+\hat{\mathbf{C}}\,\dot{\hat{\mathbf{X}}}+\hat{\mathbf{K}}\,\hat{\mathbf{X}}+\hat{\mathbf{F}}_{\mathbf{c}}=-\bar{\mathbf{M}}\,\ddot{\mathbf{U}}_{\mathbf{g}} \tag{3}$$

where $\hat{\mathbf{M}}$, $\hat{\mathbf{C}}$, $\hat{\mathbf{K}}$ are matrices of appropriate form and dimension 12×12. The $\hat{\mathbf{X}}$ is a vector containing the super structure motion in X-direction, Y-direction, super structure rotation, base motion in two directions and base rotation. Since, the model is rectangular and symmetric about the axes present analysis does not take into account the rotational components of the motion.

3 CONTROLLER DESIGN

A hybrid strategy has been taken to suppress the building vibrational levels under seismic excitations. A combination of base isolation and the semi–active magnetorheological (MR) damper forms the hybrid mechanism.

3.1 *Magnetorheological damper model*

For analytical studies simple Bouc-Wen hysteretic model has been taken. The equations governing the force produced by this model are given as

$$\begin{gathered}f=c_0\,\dot{U}_b+\alpha\,z\\ \dot{z}=-\gamma\,\|\dot{U}_b\|\,z\,\|z\|^{n-1}-\beta\,\dot{U}_b\,\|z\|^n+A\,\dot{U}_b\end{gathered} \tag{4}$$

where U_b is the displacement of the base; z is the evolutionary variable, and $\gamma,\ \beta,\ n,\ A$ are parameters controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. The functional dependence of the device parameters on the command voltage u_c is expressed as

$$\alpha(u_c) = \alpha_a + \alpha_b\, u_c \quad c_0(u_c) = c_{0a} + c_{0b}\, u_c \tag{5}$$

In addition, the resistance and inductance present in the circuit introduce dynamics into this system. These dynamics are accounted for by the first order filter on the control input given by

$$\dot{u}_c = -\eta(u_c - v) \tag{6}$$

where η is the time constant associated with the first order filter and v is the command voltage applied to the current driver. Equation 4 to Equation 6 show a nonlinear force–command voltage relation. One can determine the force required to suppress the building vibration using feedback technique, but it is very hard to determine the amount of voltage required by the damper to provide that particular force requirement. The advantage of the intelligent algorithms like ANN, fuzzy systems *etc.* is in the ease with which they handle nonlinearity in the system. The advantages of fuzzy control include simplicity and intrinsic robustness since it is not affected by the plant model selection. In the present paper the voltage requirement of the MR damper is monitored using a GA based fuzzy logic system (FLC).

3.2 *GA based optimal fuzzy logic control*

The performance of conventional controllers (LQG, H2 *etc.*) depend fully on the accuracy in the modeling of the system dynamics and are effective in control of linear structural behavior. Complex structural systems posses nonlinearities and uncertainties in the structural properties and measurements. Consequently, standard analytical model based control techniques are impracticable. As an alternative to conventional control theory, FLC allows the resolution of imprecise or uncertain informations. It maps the nonlinear input–output relation effectively and easily. It can also handle the hysteretic behaviour of structures under earthquake loads (Battaini et.al. 1998). Furthermore, FLC output $[v(t)]$, used to monitor the voltage requirement of the MR damper, can take any value between $[0,1]$ and therefore covers full voltage range available for the damper (Ali & Ramaswamy, 2006). In the process the voltage switch is gradual and does not jump between maximum and minimum voltage values as in Lyapunov or LQG clipped optimal cases.

The design of an optimal FLC can be viewed as a search in a multi-dimensional space, or hypersurface, where combinations of differing component properties of the fuzzy system (rule base, input–output membership functions, their properties and scaling gains) correspond to a point in that space. Fuzzy search surfaces are large, since the choice in the number and properties of fuzzy sets for each variable is unlimited, non-differentiable as changes in fuzzy set numbers and rules are discrete and therefore create points of discontinuity on the surface and multi–modal, since different rule bases and MFs may have comparable performance (Shi et.al. 1999). This characteristics of FLC makes application of a GA to find an optimal location within search surface, feasible and an attractive one.

In this paper GA has been used for automatically generating the rule base, membership functions (MFs) parameters in order to optimize the FLC response. In this study, an optimization of the FLC was attempted with a priori information in relation to of the number of rules and the number of MFs that give meaning to these rules. For the GA used in this study, each chromosome represents a complete FLC as defined by *MATLAB*® (MATLAB, 2004) fuzzy inference files (FIS). FLC input–output relation in the first mode of vibration of the structure (Ali & Ramaswamy, 2007), (Ahlawat & Ramaswamy, 2004) is exploited to design the adaptive rule base keeping the symmetry in the rule base intact. To achieve the symmetry in rule base, a geometric approach is taken which reduces the required chromosome length and thereby the search space is reduced. This reduces the computational overhead of the optimization scheme. The choice of initial rule base pattern is dependent on the first mode of vibration of the structure, in effect it represents an a priori knowledge being made available to the algorithm.

Present FLC has two inputs (premises), relative velocity and acceleration at the point of the action of the damper and one output (consequent), control voltage, $v(t) \in [0,1]$, which is then passed to MR damper. The input variables are normalized over the UOD (universe of discourse) of [-1 1]. The input variables range their respective UOD using five membership functions (NL=Negative Large, NS=Negative Small, ZE=Zero, PS=Positive Small, PL=Positive Large), whereas the output space is mapped using seven membership function. It is to be noted that the output contains negative values, this has been done to keep symmetry about the zero in UOD. Therefore to get output voltage as positive values between [0, 1], the MATLAB® *abs* function has been used, which takes any input value $[-\infty,\ \infty]$ and gives only the absolute value $[0,\ \infty]$ as an output.

In this geometric approach the consequent space is overlayed upon the 'premise coordinate system' and is in effect partitioned into non–overlapping small regions (in our case 5), where each region represents a consequent fuzzy set (see Fig. 1). To design the adaptive rule base we define a consequent line as shown in Figure 1. The line is made pivotal on premise zero–zero position (*i.e.* both inputs being zero) and it is

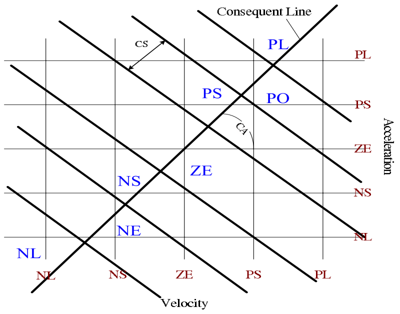

Figure 1: Adaptive rule base design

free to rotate over the consequent space and therefore the rule base adapts according to the optimization scheme. It is to be noted that the rule base remains symmetrical what ever be the position of the consequent line. The rule base is then extracted by determining the consequent region in which each premise combination point lies. The geometric approach is made possible using two different parameters.

- Slope of the consequent line angle CA: It has been used to create the output space partitions (angles between $0-180°$), as the output $v(t)$ range is $[0,1]$.
- Consequent-region spacing (CS): As seen from Figure 1 CS is the proportion of the fixed-distance between the premises (NL, NE, NS, ZE, PS, PO, PL) on the coordinate system and is used to define the distance between consequent points along the consequent line.

Generalized bell shaped (MATLAB, 2004) membership function (MF) is used for all the input–output variables in the analysis, as it can assume any other MF shape. The MF properties altered by the GA are MF shape, MF center shift and MF slope at 0.5 membership grade. While attempting to encode the FLC membership functions associated with the 2 inputs and 1 output, the UOD is kept symmetrical about the central, zero region for each variable. The extreme MF for input variables are kept unbounded in the respective positive (s-shaped) and negative (z-shaped) UOD. To enable evaluation of non-uniform distributed MFs, slope at 0.5 membership grade is also encoded. This is achieved by raising each of the MF to the power that ranges from 0.5 to 2.

4 NUMERICAL ANALYSIS

Time history analysis of the 3D analytical building model has been done for five near source earthquakes namely, Jiji (1999), NorthPalm Spring (1986), Northridge (1994), KobeNIS (1995), Chichi (1999), and Terkey Bolu (1999) with bi–directional excitations. The state space form of the differential equation (Equation 3) has been deduced and solved using *ode45* in MATLAB®. The schematic diagram of the

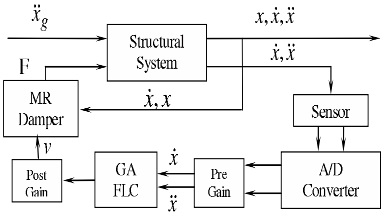

Figure 2: Simulation model

simulation is shown in Figure 2. Two different fuzzy models have been used in two orthogonal direction, *i.e.* one genetically optimized FLC has been used for the controller in X–direction and another GA optimized FLC for the controller in Y–direction. The rule base has been modified at every second of the simulation to save computational time. Each evaluation of GA uses a genetically-altered version of the original FLC which is defined using the MATLAB® *FIS* structure (MATLAB, 2004).

Base isolations are provided to separate the superstructure from catastrophic earthquake excitations. But, the excessive displacement that the isolators undergo in near–fault ground motion brings in a cause of concern to the structural engineers (Narashiman & Nagarajaiah, 2006). Non-linear passive dampers are provided to limit the bearing displacement in such situations. This however, increases the forces in the superstructure and at the isolation level. In the present study MR dampers are provided to minimize bearing displacement as well as to keep the bearing acceleration to a minimum, as the bearing acceleration is directly proportional to bearing shear force. The FLC has been optimized using GA to meet this demand. Therefore, the weighted multi-objective function to be optimized by GA is taken to be

$$\phi = w_1 \times U_b^2 + w_2 \times \ddot{U}_b^2 \qquad (7)$$

Where w_i's are the weights for each objective. By suitably adjusting the weights a set of nondominated pareto optimal solution can be obtained. In the present study, only one such solution corresponding to $w_1 = w_2 = 1.0$ *i.e.* equal importance to all objectives has been reported. Results have been shown for Chichi and Jiji earthquakes. Simple genetic algorithm (Goldberg, 1989) has been used to optimize the objective function. Figures 3– 4 show the maximum storey displacement normalized *w.r.t* fixed base maximum displacement. Figures 3– 4 contains two figures each, first one is for X-direction and the second one is for Y-direction. It is clear from these figures that the maximum storey displacement is reduced for both passive base isolation and base isolation with fuzzy driven MR damper system. Hybrid system consisting of base isolation and MR damper provides better control as the displacements are far less.

Base displacements for Chichi and Jiji earthquakes are shown in Figures 5– 6. The motivation of employ-

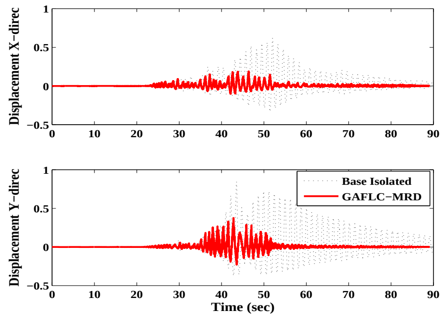

Figure 3: Maximum storey displacement (Chichi)

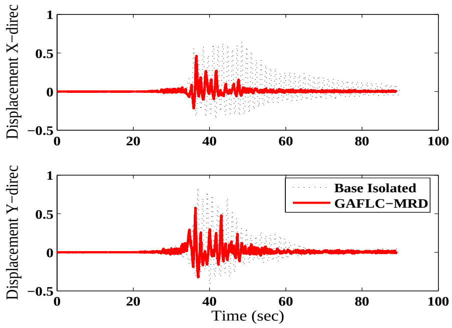

Figure 4: Maximum storey displacement (Jiji)

ing MR damper has been fulfilled as seen from the figures that the displacements of isolation devices are minimized for these near source excitations.

The objective of the GA fuzzy system was to reduce the base displacement and the base acceleration. This objective has also been satisfied as seen from Figures 7–8. MR damper force required to control the base displacement is shown in Figure 9 for both Chichi and Jiji earthquakes. Force deformation relations for MR damper are show in Figure 10. The damper force is never found to reach its maximum of 2250N, and so the damper saturation is avoided.

5 CONCLUSIONS

An adaptive hybrid control strategy has been proposed to minimize building vibration levels. Base isolation and a semi–active MR damper driven by GA optimized fuzzy logic system forms the hybrid system. Simple genetic algorithm has been used to adaptively change the fuzzy logic parameters like

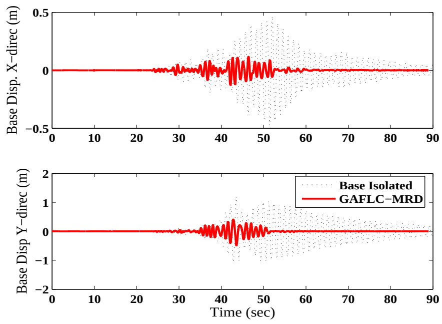

Figure 5: Base displacement (Chichi)

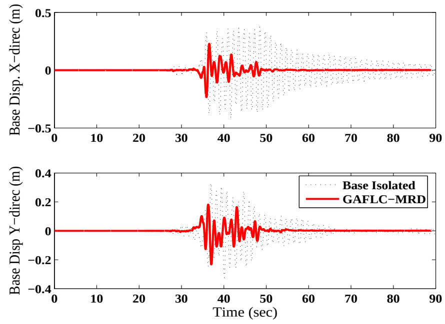

Figure 6: Base displacement (Jiji)

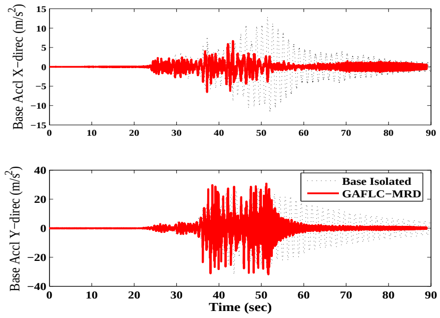

Figure 7: Base acceleration (Chichi)

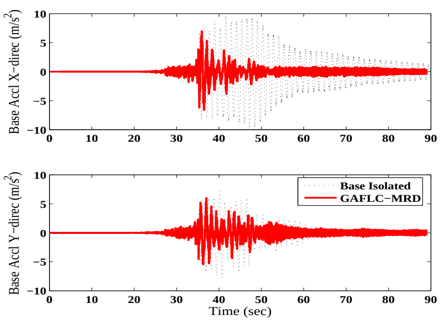

Figure 8: Base acceleration (Jiji)

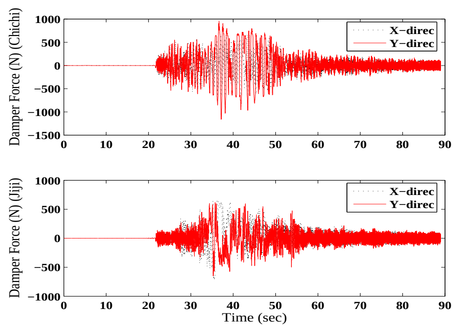

Figure 9: Damper Force (i) Chichi (ii) Jiji

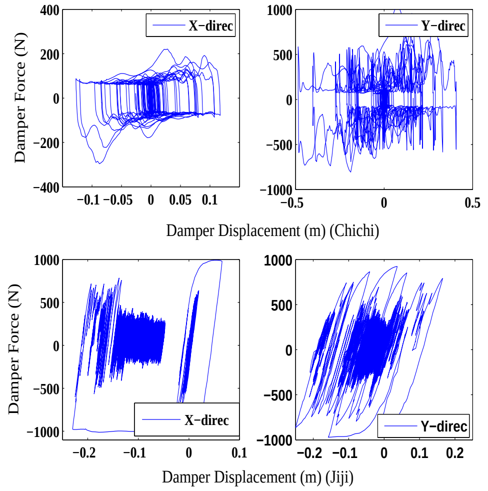

Figure 10: Force deformation relation

rule base, membership function parameters and input gains. The on–line adaption has been taken at every second of the simulation to minimize computational effort. The adaptive FLC provides damper voltage as an output, which can take any required voltage between its minimum and maximum operating range, unlike LQG or Lyapunov control techniques. This not only provides added robustness to the closed loop system, but also uses reduced peak control force. The variable rule base has been designed based on a geometric approach and therefore has less computational overhead. The variable rule base maintains a symmetry in the input–output space pattern and therefore assures stability. A multiobjective cost function with equal weights has been reported in this study. Simulation with variable weights to obtain a set of nondominated solution in a pareto optimal form can be studied as an alternate which may provide further improvements.

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