부분개선 유전자알고리즘을 이용한 퍼지제어기의 설계
Design of Fuzzy Controller using Genetic Algorithm with a Local Improvement Mechanism

김현수* Roschke, Paul N.** 이동근***
Kim, Hyun-Su Roschke, Paul N. Lee, Dong-Guen

ABSTRACT

To date, many viable smart base isolation systems have been proposed. In this study, a novel friction pendulum system (FPS) and an MR damper are employed as the isolator and supplemental damping device, respectively. A fuzzy logic controller (FLC) is used to modulate the MR damper. A genetic algorithm (GA) is used for optimization of the FLC. The main purpose of employing a GA is to determine appropriate fuzzy control rules as well to adjust parameters of the membership functions. To this end, a GA with a local improvement mechanism is applied. Neuro-fuzzy models are used to represent dynamic behavior of the MR damper and FPS. Effectiveness of the proposed method for optimal design of the FLC is judged based on computed responses to several historical earthquakes. It has been shown that the proposed method can find appropriate fuzzy rules and the GA-optimized FLC outperforms not only a passive control strategy but also a human-designed FLC and a conventional semi-active control algorithm.

1. Introduction

Base isolation is one of the most widely used and accepted seismic protection systems. While standard base isolation techniques, such as insertion of rubber bearings or friction pendulum bearings between the ground and a structure that is to be protected, have been applied for a number of years(1), the addition of supplemental damping devices is being considered for large structures in order to reduce the base drift. However, the addition of

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* 정회원 · 성균관대학교 건축공학과, 박사후연구원
** Professor, Department of civil engineering, Texas A&M University, U.S.A
*** 정회원 · 성균관대학교 건축공학과, 교수

damping to minimize base drift may increase both internal deformation and absolute accelerations of the superstructure, thus defeating many of the gains for which base isolation is intended. In general, protection of the contents of a structure is achieved through minimization of structural accelerations. Active or semi-active strategies may be able to reduce base drifts without the significant increase in superstructure motion that occurs with the installation of passive devices. Several researchers have investigated the use of semi-active smart dampers for seismic response mitigation as a component of a hybrid control system(2-4). It has been shown that smart base isolation can protect a structure from extreme earthquakes without sacrificing performance. Because of the inherent robustness and ability to handle nonlinearites and uncertainties, FLC is used in this study to operate a large MR damper. Although FLC has been used to control a number of structural systems, selection of acceptable fuzzy membership functions has been subjective and time-consuming. To overcome this difficulty, Karr proposed application of a genetic algorithm (GA) to the design of a FLC. The GA applied in this study focuses on finding appropriate fuzzy control rules as well as adjusting the membership functions. To this end, an effective method that uses a GA with a local improvement mechanism (Nagoya approach)(5) is employed for efficient improvement of fuzzy rules.

The proposed design approach using the GA-optimized FLC for a smart base isolation system is demonstrated with the help of numerical simulations. Parameters from a large scale experimental model are employed as the basis for numerical simulation. The large scale experimental test was conducted at National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. Powerful modeling capabilities of adaptive neuro-fuzzy inference system (ANFIS) are used to develop a neuro-fuzzy model of the MR damper and the four FPSs that support the mass. A neuro-fuzzy model is used to represent dynamic behavior of the MR damper for various displacement, velocity, and voltage combinations that are obtained from a series of performance tests. Modeling of the FPS is carried out with a nonlinear analytical equation and neuro-fuzzy training. A passive damping strategy, human-designed FLC and conventional semi-active controller (i.e. skyhook) are used to compare the efficiency of the proposed GA-optimized FLC. Based on computed responses to several historical earthquakes, the proposed approach is shown to provide an optimal FLC for a smart base isolation system that is equipped with a FPS and a controllable MR damper.

2. Model of the smart base isolation system

A series of large-scale experimental tests on a smart base isolated system was recently conducted at NCREE. The smart base isolation system consists of a set of four specially-designed FPSs and a 300 kN MR damper. The effectiveness of the hybrid base isolated system was experimentally verified. The system reduced base drifts without increasing accompanying accelerations that are manifested during use of a human-designed FLC. Although the expert's knowledge-based FLC controls the smart base isolation system effectively in comparison with passive control strategies during the experimental test, there seems to be considerable room for improvement through use of an optimal design method. Therefore, this experimental model of a smart base isolation system is employed as a numerical example in order to demonstrate improved performance of the FLC by using the proposed design approach. The isolated structure is constructed with a steel frame and lead blocks that provide a 24,000-kg mass that behaves as a single degree of freedom. The 300 kN MR damper used for control is manufactured by Sanwa Tekki Corporation, Tokyo, Japan.

3. Modeling of MR damper

Extensive performance testing of the 300-kN MR damper is conducted to collect a sufficient quantity of data that are evenly distributed over the operational range of the MR damper. These data enable training of neuro-fuzzy model that can be used to numerically simulate dynamic behavior of an MR damper. Special properties of an MR damper include relationships of parameters such as displacement, velocity, applied voltage, and resisting force. These three input and force output parameters are used in what follows to model the 300-kN MR damper. After extensive training through ANFIS, a satisfactory fuzzy model of the MR damper is obtained as shown in Fig. 1.

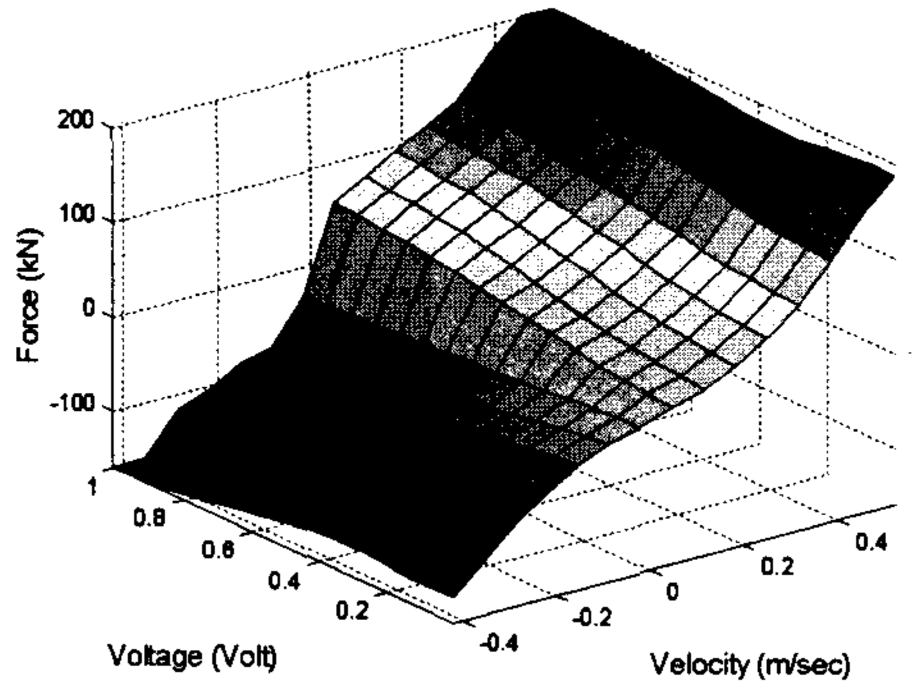

Fig. 1. Fuzzy inference surface of trained MR damper model.

4. Modeling of FPS

An FPS is a mechanical device that isolates a structure from its support. Four FPSs are used to support the mass of the structure. For all data generated in this paper a coefficient of friction is considered as 0.03 and the radius is set at one meter. In order to establish pseudo-experimental data that describes the nonlinear force-displacement relationship of a typical FPS system, the following equations can be employed. They are established by a simple analytical relationship from fundamental principles of mechanics.

$$F = W\left[\frac{u+\operatorname{sgn}(\dot{u})\mu\sqrt{R^2-u^2}}{\sqrt{R^2-u^2}-\operatorname{sgn}(\dot{u})\mu u}\right] \tag{1}$$

where F is the external force acting on the FPS, R is the radius of the spherical bearing surface, u is horizontal displacement, $\dot{u}$ is horizontal velocity, μ is the coefficient of friction, sgn indicates a positive or negative sign of its function, and W is the weight of the mass supported by the FPS. ANFIS is also used to develop a neuro-fuzzy model of the FPS. Here, displacement and velocity signals are generated from numerical simulation using filtered white noise for excitation while the resisting FPS force is based on the nonlinear equation as shown in Eq. (1). A sufficiently long history of white noise minimizes the amount of interpolation required by a fuzzy model of the FPS, thus increasing accuracy of force prediction within the actual range of operation.

5. Optimization of FLC using GA

5.1 Encoding method

Encoding is the genetic representation of a FLC solution. All of the information represented by the FLC parameters is encoded in a structure called a chromosome or string. Gaussian membership functions are used for all input and output variables because they can approximate almost all other types of membership functions by changing the parameters shown in Eq. (2).

$$\mu = \exp\left(-\frac{(x-c)^2}{2\sigma^2}\right) \tag{2}$$

The shape of the Gaussian membership function can be defined by two parameters: c and σ. Here c is the central position, and σ is the width. These two parameters are encoded into the gene with a real-valued representation as shown in Fig. 2.

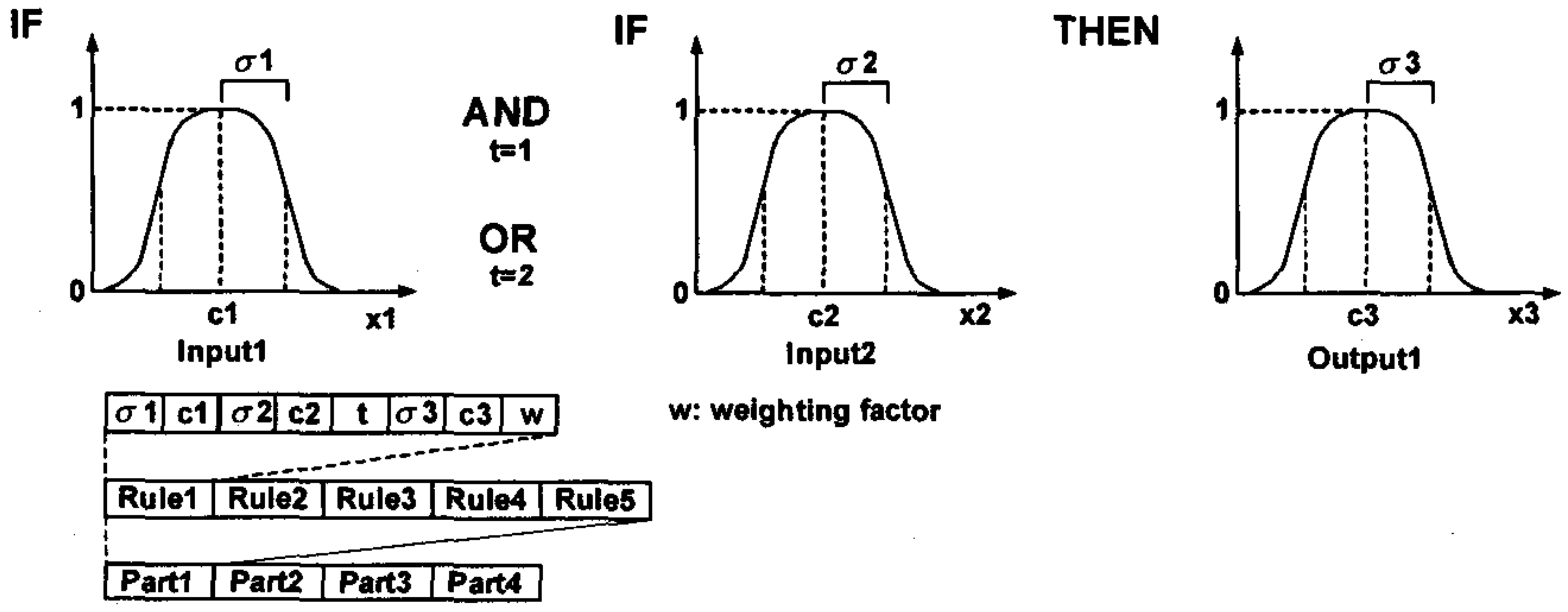

Fig. 2. Encoding structure of a chromosome.

5.2 GA with a local improvement mechanism

One of the drawbacks in using a GA for control is that it often needs a huge population. Also a GA often takes a very large number of generations to achieve a satisfying performance. The latter drawback can be surmounted by using a GA with a local improvement mechanism. Fig. 3 shows the flow of the modified Nagoya scheme used in this study. The basic idea is to evaluate mutations of the chromosomes in shorter intervals so as to improve the effectiveness of the mutation operator.

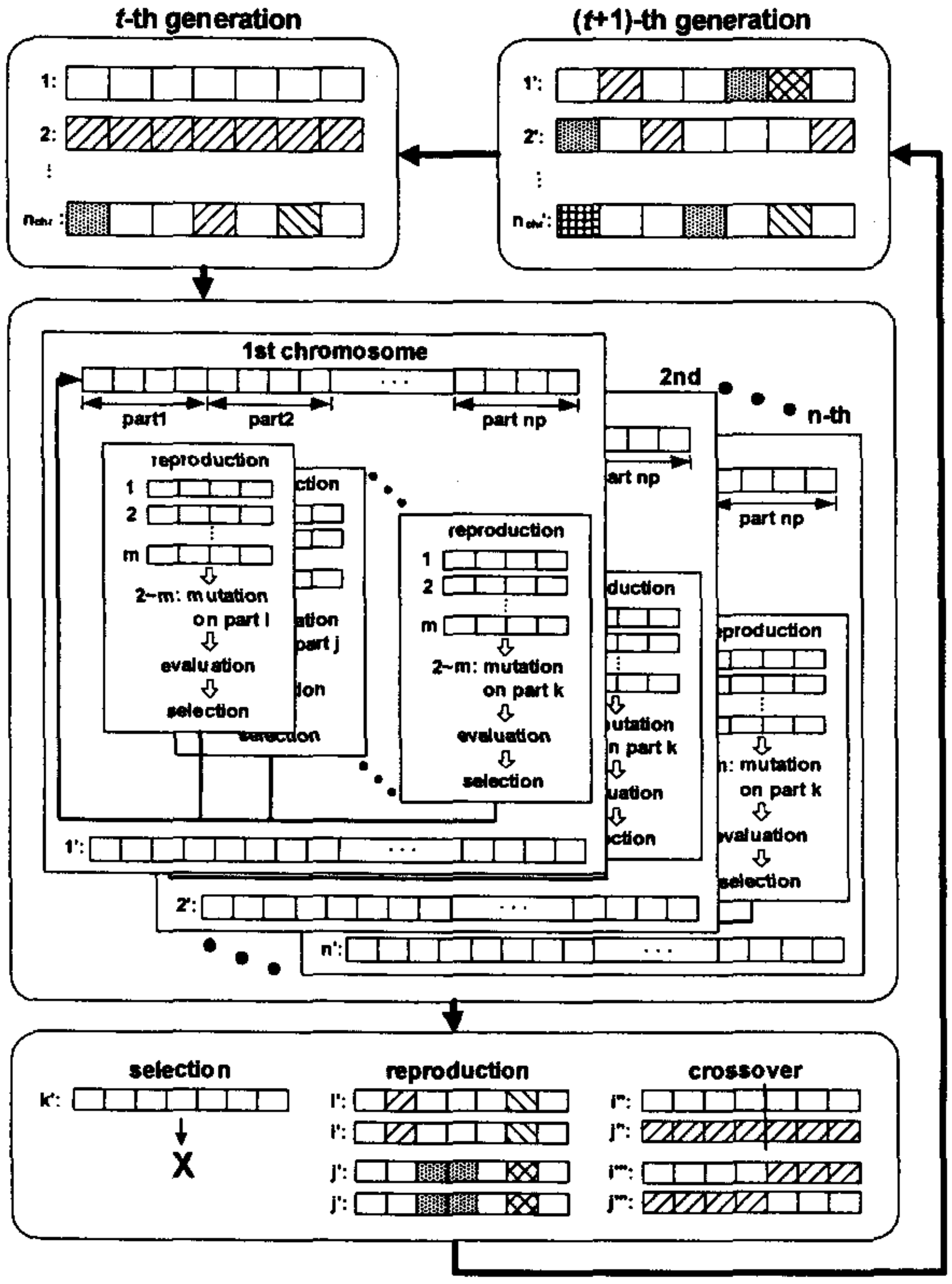

Fig. 3. Flow of GA with a local improvement mechanism

To this end, each chromosome is divided into several parts. GA operations proceed as follows: First, chromosome 1 in the current population is copied m times and m-1clones are mutated. The mutation operation is applied to the randomly chosen *i*th part. The m clones are then evaluated using the GA fitness function and the fittest clone survives. The *i*th part once selected is never selected again in the same generation. This procedure is repeated for all parts of the chromosome and for all chromosomes. After this process, other genetic operators such as selection, reproduction and crossover operators are applied to whole chromosomes in the population. This GA is efficient in local improvement of chromosomes, since the evolution is carried out on the level of chromosomal genes.

5.3 Fitness function

The fitness function is the main criterion that is used to evaluate each chromosome. It provides an important connection between the GA and the physical system that is being modeled. A good fitness function can embody requirements of the base isolation system and evaluate the chromosomes properly. As stated earlier a good base isolation system simultaneously reduces base drift and structural acceleration thereby limiting or avoiding damage, not only to the structure but also to its contents. Therefore, the objectives in the design of a FLC for a smart base isolation system are to minimize both base drift and structural acceleration. In other words, optimization of the FLC for a smart base isolation system is a multi-objective optimization problem. There are several methods that can combine multiple objective functions to make a single fitness function in a multi-objective optimization problem. One of these methods, a weighted sum approach, is employed in this study as shown in Eq. (3).

$$F = w_1 \times (f_{peak\_drift} + f_{RMS\_drift}) + w_2 \times (f_{peak\_accel} + f_{RMS\_accel}) \quad (3)$$

where, w_1 and w_2 are the drift and acceleration weighting (importance) factors, respectively. Base drift and structural acceleration responses normalized with respect to the uncontrolled base drift and structural acceleration responses, respectively, are used here as the multi-objectives. These objectives include RMS responses as well as peak responses. Therefore, the fitness function which has to be minimized, has been obtained by combining normalized peak base drift (f_{peak_drift}), normalized RMS base drift (f_{RMS_drift}), normalized peak acceleration (f_{peak_accel}) and normalized RMS acceleration (f_{RMS_accel}) with two weighting factors.

6. Numerical Study

A numerical model of the smart base isolation system with a FPS and MR damper is implemented in SIMULINK as shown in Fig. 3. Excitation records that are used for numerical simulation include three commonly used earthquakes: El Centro (18 May 1940) Kobe (17 January 1995) and Northridge (17 January 1994). In order to find the appropriate weighting factor that can effectively reduce both base drift and absolute acceleration, a series of numerical simulations is conducted with various weighting factors from 0 to 1. Variation of the objective f_{peak_drift} with the corresponding value of the objective f_{peak_accel} is shown in Fig. 4.

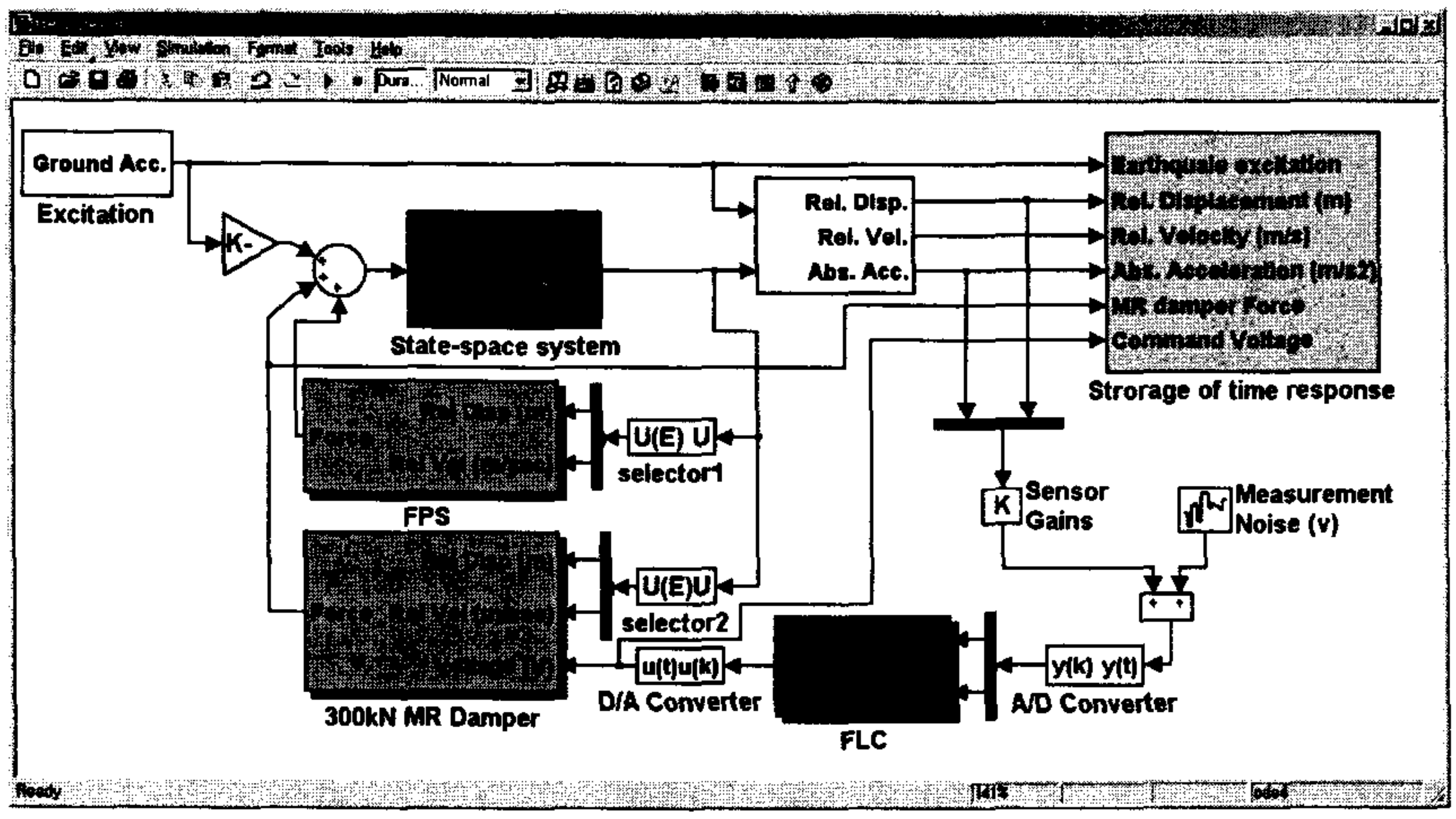

Fig. 3. SIMULINK block diagram for the smart base isolation system.

Fig. 5 shows the results of RMS responses. The objectives f_{peak_drift} and f_{RMS_drift} can be improved at the cost of the degraded objectives f_{peak_accel} and f_{RMS_accel}, respectively. Therefore, an engineer needs to choose a proper FLC that can satisfy the desired performance requirements by selecting appropriate weighting factors. Results from the human-designed FLC, passive-on case and skyhook control are also shown in Figs. 4 and 5.

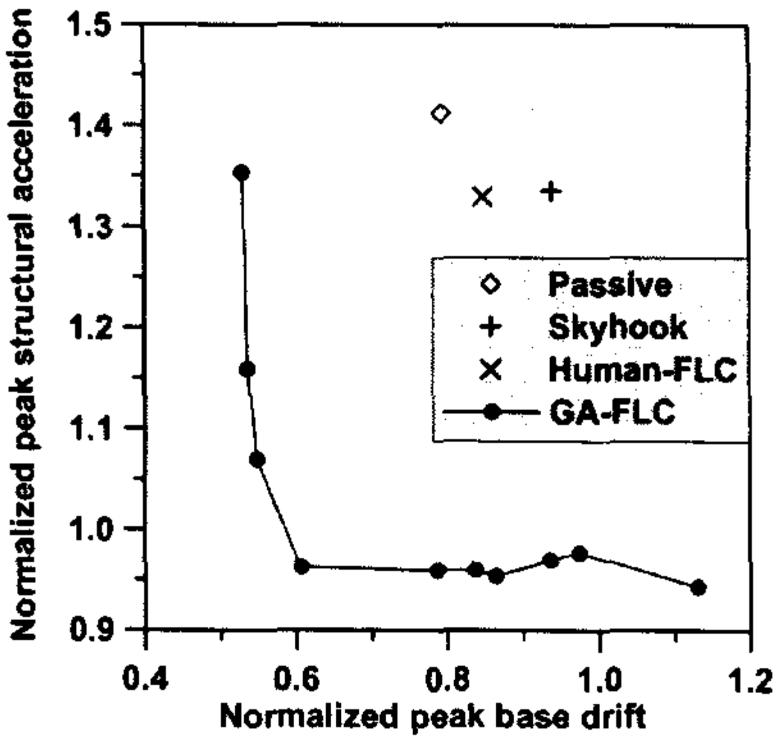

Fig. 4. Comparison of the peak responses

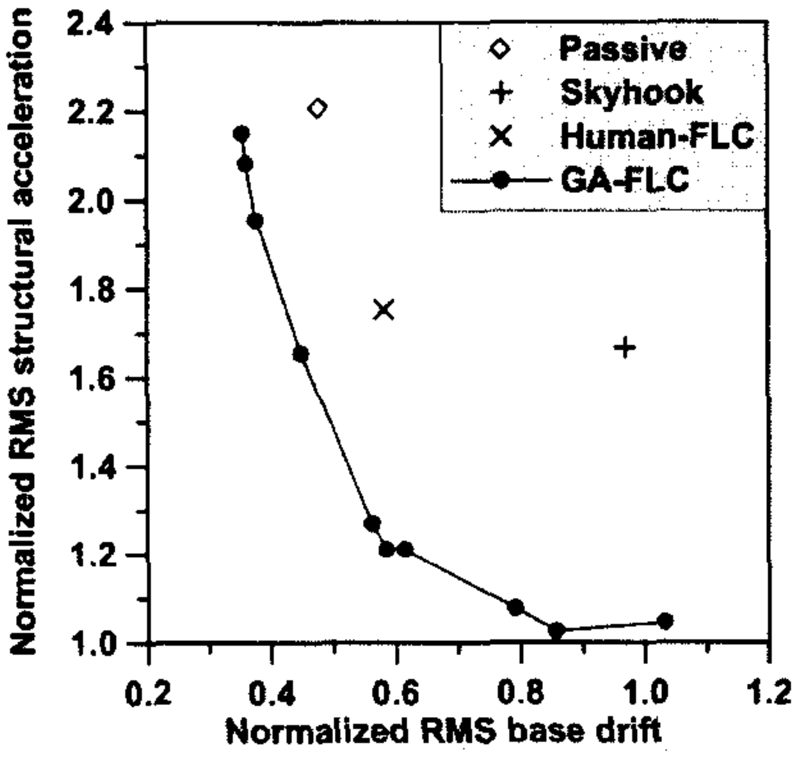

Fig. 5. Comparison of the RMS responses

The passive-on case can be thought of as the best passive case for the reduction of base drift. As expected, normalized peak and RMS base drift for the passive-on case are smaller than those of human-designed FLC and skyhook controller. On the other hand, the skyhook controller shows better performance for the normalized structural acceleration compared to the passive-on case. It can be seen that the control performance of the human-designed FLC is intermediate between passive-on and skyhook controller results namely, it can reduce base drift better than the skyhook controller and it can reduce structural acceleration better than the passive-on controller.

7. Conclusion

This study investigates performance of a GA-designed FLC for a hybrid base isolation system consisting of an FPS isolator and an MR damper. The FLC is designed using a GA with a local improvement mechanism. Passive, skyhook, and a human-designed FLC are used as comparative controllers to investigate the effectiveness of the GA-optimized FLC. In the passive-on control case, base drift can be significantly reduced but structural acceleration is not well controlled. The skyhook controller reduces structural acceleration in comparison with passive-on control, but only at the expense of larger base drifts for all earthquakes that are numerically simulated. A human-designed FLC can reduce base drift better than the skyhook approach and it can reduce structural acceleration better than passive-on operation of the MR damper. That is, a human-designed FLC can appropriately control both base drift and structural acceleration. Finally, a GA-optimized FLC shows better performance in comparison with the human-designed FLC for most evaluation criteria. Furthermore, performance of the GA-optimized FLC can be easily adjusted by selecting an appropriate weighting factor according to desired performance requirements.

Acknowledgement

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