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A Fuzzy Skyhook Algorithm Using Piecewise Linear Inverse Model

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Abstract

In this paper, the nonlinear damping force model is made to identify the properties of the ER damper using higher order spectrum. The higher order spectral analysis is used to investigate the nonlinear frequency coupling phenomena with the damping force signal according to the sinusoidal excitation of the damper.

Also, this paper presents an inverse model of the ER damper, i.e., the model can predict the required voltage so that the ER damper can produce the desired force for the requirement of vibration control of vehicle suspension systems. The inverse model has been constructed by using piecewise linear damping force model. In this paper, the fuzzy logic control based on heuristic knowledge is combined with the skyhook control. And it is simulated for a quarter car model. The acceleration of the sprung mass is included in the premise part of the fuzzy rules to reduce the vertical acceleration RMS value of the sprung mass. Then scaling factors and membership functions are tuned using genetic algorithm to obtain optimal performance.

Key words : Fuzzy Sky-hook, Inverse Model, Genetic Algorithm, Quarter-car Model, ER Damper

1. Introduction

Vehicle suspension systems improve ride comfort by reducing the transmitted vibration and ensure vehicle stability by keeping tire contact force properly. Active and semi-active suspension systems are developed to achieve better performance than the conventional passive suspension systems.

Active suspension system has been investigated since 1930. However, its complex hardware always has been a bottle neck for wide use of it. Semi-active suspension system has been considered as good alternative between active and passive suspension systems. Furthermore, the use of ER or MR fluid makes the structure of the semi-active suspension system much simpler than active one. During the past decade, very attractive and effective semi-active suspension system featuring electro-rheological (ER) fluid has been proposed in the literature [1-3].

The scientific challenges in the field of ER fluids and devices consist in the development of optimal control strategies and the mathematical modeling and numerical simulation. To take maximum advantage of ER fluids in control applications a reliable method is needed to predict their nonlinear response.

In this paper, analysis of higher order spectrum about measured damping force is performed and confirmed the existence of nonlinearity of ER damper. From the results, we propose damping force model expressed by the polynomial with the multiple power of piston velocity and show the accuracy of damping force model by comparing with experimental results.

Control of damping force of an ER damper is also very challenging because the strong nonlinearity and the semi-active relationship between the damping force and the input voltage. So the force generated by the ER damper cannot be commanded directly. In order to overcome these difficulties, several researches have been done.

CHOI proposed MR damper model that express the influence of magnetic field by the first order linear equation [4]. So the inverse model of ER damper can be obtained easily. XIA presented an inverse model which was constructed by using a multi-layer perceptron optimal neural network and system identification [5]. WANG proposed inverse model for modified Bouc-Wen model of MR fluid damper using feed-forward and recurrent neural networks [6]. In this paper, we proposed ER damper model that express the influence of electric field by piecewise linear equation in order to reflect nonlinearity of ER damper more precisely.

Also, we suggest a set of fuzzy rules which expands the skyhook control algorithm by adding acceleration term in the premise part of the fuzzy rules. It gives a possibility to make the conventional skyhook algorithm more flexible. Membership function and scaling factors are tuned by using genetic algorithm to achieve optimal performance. The simulation results show the validity of the proposed control algorithm.

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2. Modeling of ER Damper

2.1 Configuration of test bench

Figure 1 illustrates the ER damper designed for the semi-active suspension. The structure is far different from that of the conventional hydraulic or electromechanical damper. This damper has inner and outer cylinders. The ER fluid flows the gap between two cylinders used as the electrodes with the plus and minus polarities, respectively. The damping force is controlled by the intensity of the electric field applied to the gap. ER fluid, Bayer Company's TPAI 3566, flows through the duct between cylinder and accumulator.

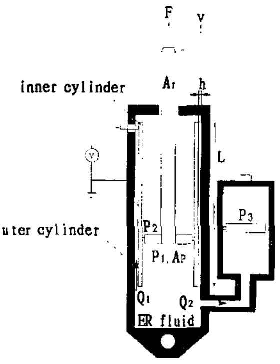


Fig. 1. Schematic diagram of the ER damper

ER damper test equipment is designed and implemented to excite ER damper using hydraulic servo system with Moog J072-011 servo valve and MTS T-LP-type LVDT (Linear Variable Differential Transformer). Figure 2 shows a schematic diagram of the test equipment used for the measurement of ER properties. The high voltage amplifier used in this study is 10/10A Amplifier, which was manufactured by TREK Corporation. In order to measure the damping force of ER damper, load cell (SENSOTEC Corporation Model 45) was used and its measuring range is 8896N.

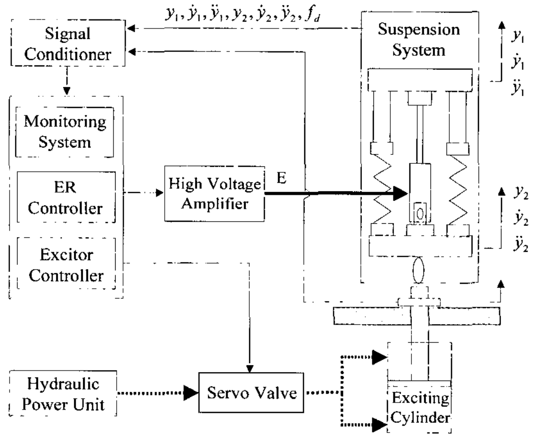


Fig. 2. Schematic diagram of the experimental setup for measuring the damping force

2.2 Modeling of ER damper

There are situations in practice in which the interaction between two harmonic components causes contribution to the power at their sum and/or difference frequencies. This frequency interaction means that the signal energy concentrated in input frequency is distributed to other output frequencies and can understand as energy transfer between frequencies.

Therefore it can utilize by useful means to analyze the nonlinear properties of the system through the perception of correlation between modes and analysis of amplitude. This frequency interaction can observe using higher order spectrum [7], [8].

From Figure 3, it is apparent that nonlinear characteristics can be achieved with the measured damping signal using higher order spectra analysis.

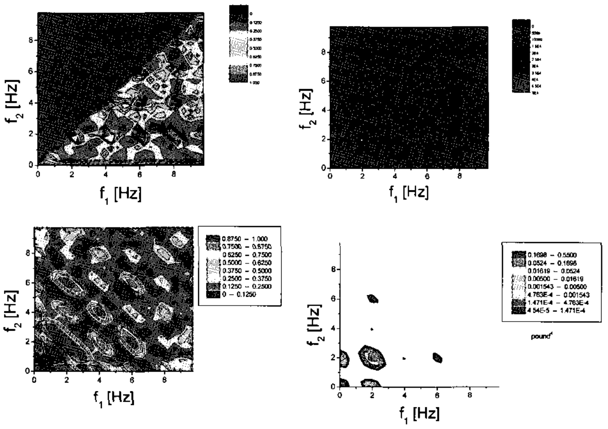


Fig. 3. Higher order spectrum of damping force signal at E=4kV/mm (Input frequency = 2Hz)

From the experimental results, we confirmed damping force model can expressed by k-th order polynomial. Therefore we proposed damping force model of 3rd order polynomial as equation (1).

$$f_d = c_1 v + c_2 v|v| + c_3 v^3 \tag{1}$$

Where c_1, c_2, and c_3 are the coefficient of damping force model, and v is the piston velocity. The coefficient c_1, c_2, and c_3 are obtained using least squared error methods.

The coefficients of damping force model are expressed by piecewise linear equation as shown in Figure 4. Therefore we can obtain piecewise linear damping force model using Figure 4. The damping force model is given by equation (2).

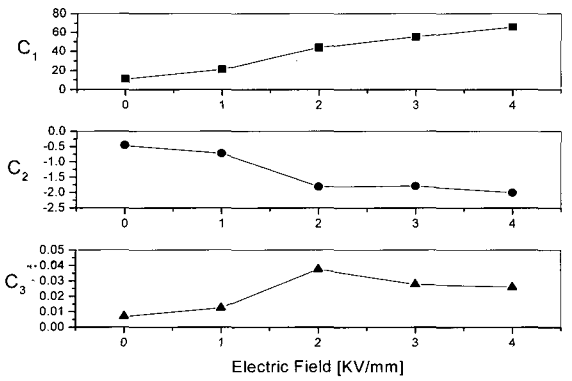
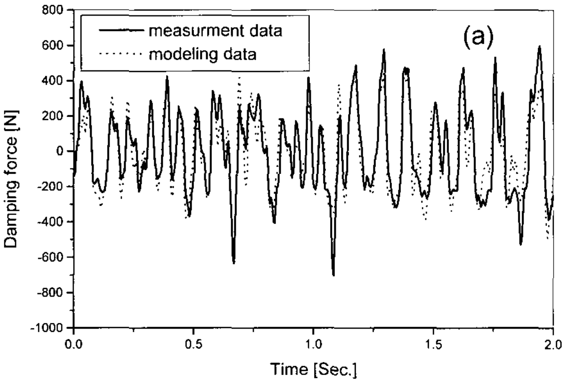
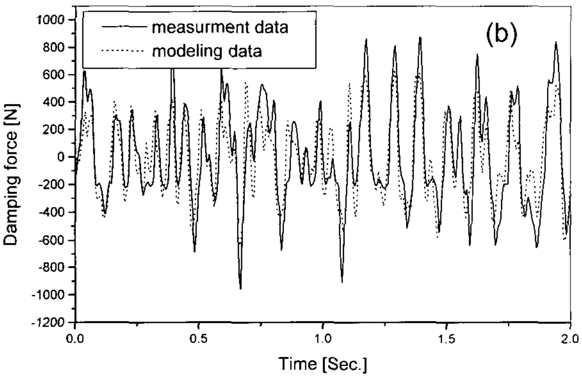


Fig. 4. Coefficients of nonlinear damping model with Gaussian Input Signal

Figure 5 shows that the measured data of experiment system and modeling data of damping force simulation with random input signal with 2kV/mm and 3kV/mm. As a result, proposed damping force model shows a good performance.



(A) 2KV/MM,



(B) 3KV/MM

Fig. 5. Measured data and modeling of the damping force with random input signal

In an active control system, the control force needs to be known to meet a required vibration level. If the ER damper is used for semi-active suspension system, it may be desirable to have an inverse model to predict preliminarily the applied voltage in order to generate the required control force.

In this paper, we obtained inverse model of ER damper using equation (2). The inverse model of ER damper can be expressed by equation (3).

$$f_d = \begin{cases} (10v - 0.28v\,|v| + 0.0055v^3)e + (12v - 0.45v\,|v| + 0.0075v^3), & 0 \le e < 1 \\ (22v - 1.07v\,|v| + 0.025v^3)e + (0.34v\,|v| - 0.012v^3), & 1 \le e < 2 \\ (12v + 0.02v\,|v| - 0.01v^3)e + (20v - 1.84v\,|v| + 0.058v^3), & 2 \le e < 3 \\ (11v - 0.22v\,|v| - 0.0025v^3)e + (23 - 1.12v\,|v| + 0.0355v^3), & 3 \le e \le 4 \end{cases} \tag{2}$$

$$e = \begin{cases} \dfrac{f_d - (12v - 0.45v\,|v| + 0.0075v^3)}{(10v - 0.28v\,|v| + 0.0055v^3)}, & 0 \le e < 1 \\ \dfrac{f_d - (0.34v\,|v| - 0.012v^3)}{(22v - 1.07v\,|v| + 0.025v^3)}, & 1 \le e < 2 \\ \dfrac{f_d - (20v - 1.84v\,|v| + 0.058v^3)}{(12v + 0.02v\,|v| - 0.01v^3)}, & 2 \le e < 3 \\ \dfrac{f_d - (23 - 1.12v\,|v| + 0.0355v^3)}{(11v - 0.22v\,|v| - 0.0025v^3)}, & 3 \le e \le 4 \end{cases} \tag{3}$$

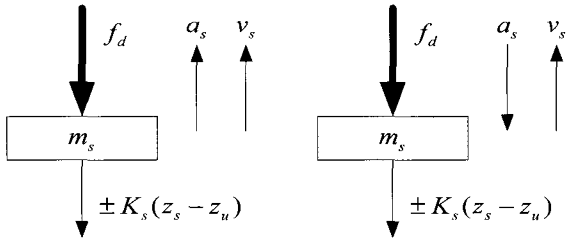
where e is the electric field [kV/mm]

3. Fuzzy Skyhook Algorithm using Genetic Algorithm

3.1 Fuzzy Skyhook Control

The linguistic fuzzy logic control, which is one of the knowledge-based approaches using rules like "if ~ then ~", can be constructed without considering nonlinearities and uncertainties mathematically because it does not require any accurate mathematical model of the system to be controlled. Liu et al. showed that the control performance of semi-active suspension system could be better than on-off control when proper fuzzy logic which depicts the skyhook algorithm is used [9, 10].

In this study, we improved Liu et al.'s work by including acceleration in the premise part of the fuzzy rules. Figure 6 shows that the acceleration of the sprung mass can have different directions when the sprung mass is moving upward. The conventional skyhook control treats both cases as the same situation since it uses only velocity of the sprung mass.



(a) (b)

Fig. 6. Reason for adding acceleration term in fuzzy rules

However, it is obvious that the two cases should be treated differently and fuzzy logic is good to handle such a need

Equation (4) is the switching law of the fuzzy skyhook control.

$$f_d = \begin{cases} 0, & \text{if } V_s \cdot (V_s - V_u) \le 0 \\ FLC(V_s,\, a_s), & \text{if } V_s \cdot (V_s - V_u) > 0 \end{cases} \tag{4}$$

The switching law is equivalent to the skyhook control but the role of acceleration is added to determine the damping force. Figure 7 shows a block diagram of the fuzzy logic.

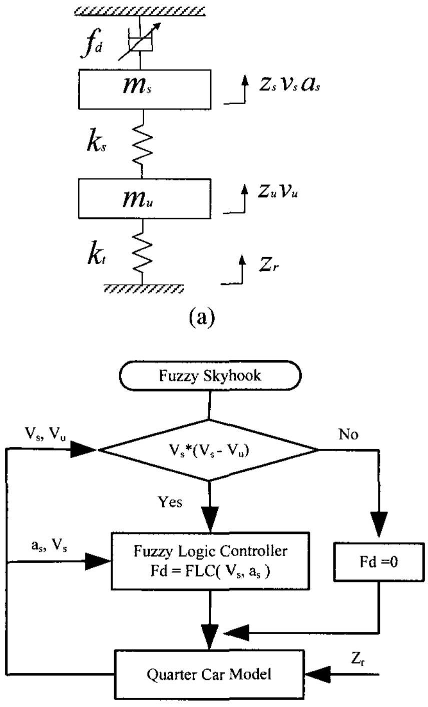
The generic form of the fuzzy rule is as follows,

If V_s *is* (*VF*) *and* a_s *is* (*AF*) *then* f_d *is* (*FF*)

where VF, AF, AND FF represent linguistic values for velocity of the sprung mass, acceleration of the sprung mass, and the damping force, respectively.

Table I. Fuzzy logic rules

		a_s						
		NB	NM	NS	ZR	PS	PM	PM
V_s	NB	PB	PB	PM	ZR	ZR	ZR	NS
	NM	PB	PB	PM	ZR	ZR	NS	NM
	NS	PB	PM	PS	ZR	ZR	NS	NM
	ZR	PB	PM	PS	ZR	NS	NM	NB
	PS	PM	PS	ZR	ZR	NS	NM	NB
	PM	PM	PS	ZR	ZR	NM	NB	NB
	PB	PS	ZR	ZR	ZR	NM	NB	NB



(a)

(b)

Fig. 7. Fuzzy skyhook configuration

The terms sets for input, output linguistic variable are defined as [NB, NM, NS, ZR, PS, PM, PB] and each membership function is triangular type. Table 1 shows the proposed fuzzy rules. The center of gravity method is used for defuzzification.

3.2 Tuning of the Fuzzy Skyhook controller using GA

Figure 8 represents the configuration for the proposed fuzzy skyhook controller. Performance of the controller can be adjusted by changing the input and output scaling factors and membership functions. GA is used for tuning those parameters.

Figure 9 shows the basic conceptual configuration of genetic algorithm.

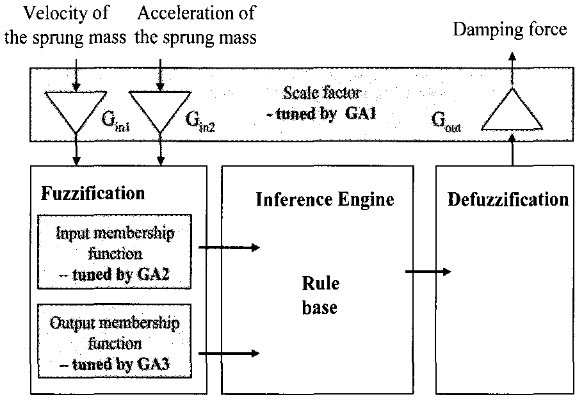


Fig. 8. Configuration of a fuzzy logic controller

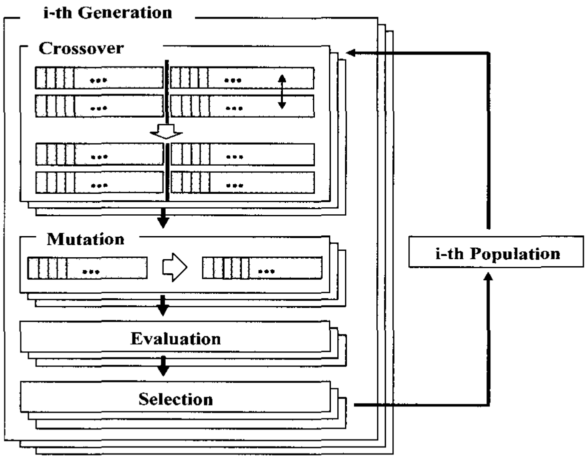


Fig. 9. Configuration of genetic algorithm

In this paper, GA is used for three stages. The first stage (GA1) is to determine the input scaling factors for the velocity and acceleration of the sprung mass and the output scale factor for the damping force. The second (GA2) and the third stages (GA3) are optimization of the membership functions of the premise and consequent parts of the fuzzy rules, respectively. Figure 10 shows the used membership functions and they are triangular types. Center points of each triangle are used as representatives for each membership functions for the encoding purpose of GA. Membership functions are restricted as symmetrical nature with respect to the center of ZR triangle for simplicity.

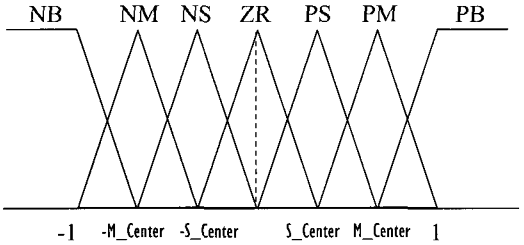


Fig. 10. Membership function of fuzzy logic controller

The fitness function is a main criterion to evaluate each chromosome and it decides the performance of the system. The fitness function used in this paper is expressed as equation (5).

$$J = \sqrt{\frac{1}{T}\int_{o}^{T} a_s^2 dt} \qquad (5)$$

where T is the time duration of simulation and a_s is the vertical acceleration of the sprung mass. It represents the RMS value of the acceleration of the sprung mass and minimization of the fitness function means better ride comfort.

The mutation rate and crossover rate are selected as 0.5% and 30%, respectively. The sorting method is used as the selection method of chromosome.

4. Simulation Results

A quarter-car suspension system is used for simulation and the parameters are given in Table II. The equations of motion are given by

$$\begin{aligned} m_s a_s + k_s(z_s - z_u) &= -f_d \\ m_u a_u + k_s(z_u - z_s) + k_t(z_u - z_r) &= f_d \end{aligned} \qquad (6).$$

where Z_s and Z_u are the displacements of the sprung and unsprung masses, respectively. Z_r is the road displace input and f_d represents the external input force of the suspension system. This input force is generated from the ER damper for semi-active control.

Table II. Simulation parameters

Parameter	Value
Sprung mass (m_s)	365 kg
Spring coefficient (k_s)	25080 N/m
Unsprung mass (m_u)	59.1 kg
Tire stiffness (k_t)	213640 N/m

The displacement input of road input is sinusoidal wave. The frequency and amplitude of road input are given as 0~8Hz and ±20cm. Figure 11 shows the simulation results of GA1, GA2, and GA3. The solid line shows the average value of fitness function in every generation and the dashed line shows the minimum value of fitness function in every generation.

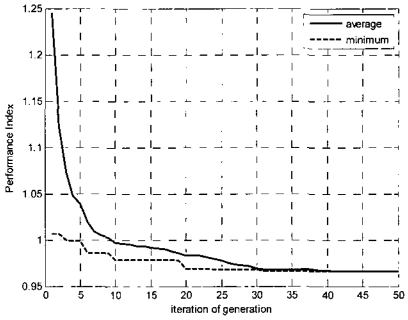
In genetic algorithm, the length of chromosome, the population size, and the number of generation are shown in Table III.

Table III. Genetic Algorithm parameters

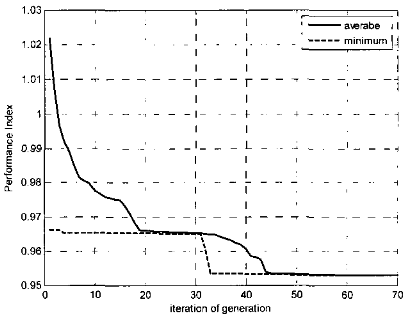
	Chromosome Length	Population Size	Number of Generation
GA1	44 bit	30	50
GA2	28 bit	50	100
GA3	28 bit	40	200

The scale factors obtained by Genetic algorithm are 13.117, 1198.1, and 0.1251. The optimized membership functions are shown in Figure 12.

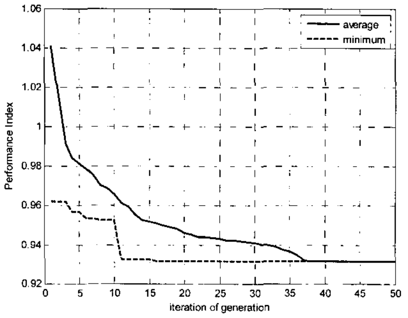
Figure 13 and Figure 14 show the simulation results of skyhook controller and fuzzy skyhook controller using genetic algorithms. As shown in Fig. 13, there is significant reduction in average RMS value due to semi-active fuzzy skyhook controller. The damping ratio of the continuous skyhook controller is selected through simulation by skyhook control which minimizes the average RMS value. By the tuning of scale factor using GA1, the average RMS value of sprung mass is decreased greatly. And the average RMS value of sprung mass is decreased a little by GA2 and GA3.



(a) GA1

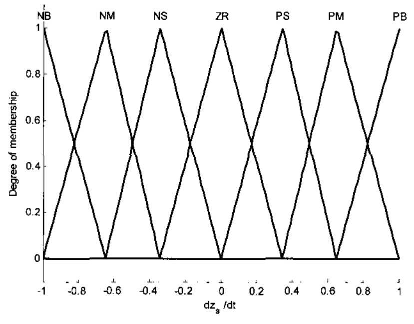


(b) GA2

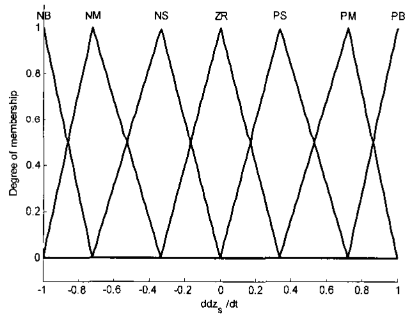


(c) GA3

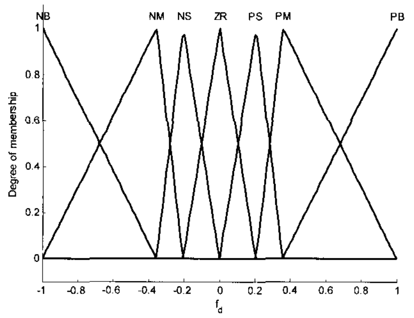
Fig. 11. Optimal value and average value history of fitness function of Genetic Algorithms



(a) Input velocity membership function

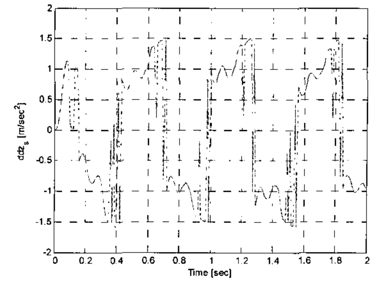


(b) Input acceleration membership function

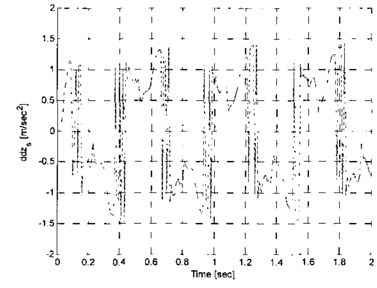


(c) Output damping force membership function

Fig. 12. Optimal membership function of the fuzzy logic controller tuned by GA



(a) skyhook controller



(b) fuzzy skyhook controller

Fig. 13. Acceleration RMS of skyhook and fuzzy skyhook controller

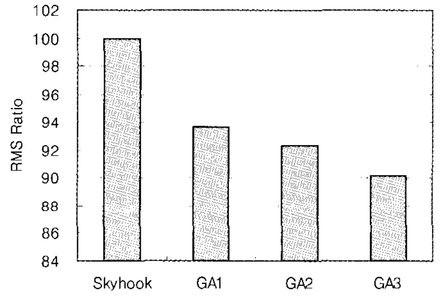


Fig. 14. Acceleration RMS comparison of sprung mass

5. Concluding Remarks

In this paper, we performed characteristic test using nonlinear frequency by measuring of the damping force and signal process of bispectrum and trispectrum. And we confirmed existence of nonlinear properties through test results. The damping force model of ER damper is obtained by higher order equation of damper velocity terms and the simulation results are compared with the experimental data on the mechanisms responsible for the vibration of the damping characteristics of the precision equipment a real commercial car. To generate desired damping force in applications of ER damper, the inverse model of ER damper is necessary. Therefore we implement inverse model by using piecewise linear damping force model.

Also, we proposed a fuzzy skyhook controller by adding the nonlinear property of fuzzy logic control in skyhook controller. The proposed fuzzy skyhook control method is based on skyhook principle but the damping force is decided by fuzzy logic controller. The nonlinear property of fuzzy logic control used to improve the performance of skyhook controller. Acceleration input of the sprung mass is used for the fuzzy logic controller in order to minimize the variation of acceleration. Also the scale factors and the membership function of fuzzy logic control are optimized using genetic algorithm. The optimized fuzzy skyhook controller used to simulation of a semi-active suspension system, and the simulation results show that the performance of the optimized fuzzy skyhook controller is improved about 10% more than performance of the continuous skyhook control.

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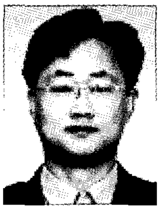

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