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Fuzzy Skyhook Control of A Semi-active Suspension System

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Abstract

In the recent years, the development of computer-controlled suspension dampers and actuators has improved the trade-off between the vehicle handling and ride comfort, and has led to the development of various damper control policies. The skyhook control is an effective control strategy for suppressing vehicle vibration. In this study, a fuzzy skyhook control is proposed and tuned by a genetic algorithm to improve ride comfort. The proposed fuzzy skyhook control is applied to a quarter-car model in order to compare its performance with continuous skyhook suspensions. To obtain optimized fuzzy skyhook control, scale factors and in-out membership functions are tuned by a genetic algorithm. The simulation results show that the fuzzy skyhook control offers more effective suspension performance over the continuous skyhook control.

Key Words : Skyhook, Fuzzy Skyhook, Semi-active Suspension, Genetic Algorithm

1. Introduction

Vehicle suspension systems improve ride comfort as reducing a transmitted vibration and ensure vehicle stability as keeping tire contact force properly. For this purpose, conventional suspension systems are made by springs and dampers, but it has a limit because that is composed of passive elements like springs and dampers. To improve passive suspension systems, active suspension and semi-active suspension systems are developed [1].

Active suspension systems have been investigated after 1930s. They resulted many accomplishments but had many problems to realization because hardware was complex and an amount of powers were required to generate the actuator force and failure mode etc. Semi-active suspension systems solved the disadvantage of active suspension systems using semi-active dampers. Semi-active dampers are able to enhance performance of suspension systems largely only to adjust the damping level by small amounts of energy. Therefore, semi-active dampers do not add any energy to the system - they only dissipate energy (the same as passive damper). So the suspension system hardware is able to be simple than active, and ensure failure mode [2,3].

Skyhook control strategy was introduced by Crosby and Karnopp [4]. They presented the benefits of Skyhook control as a reduction in the frequency response magnitude of a single degree of freedom semi-active isolator. Their simulation results showed that using Skyhook to control the semi-active damper reduces the transmissibility, or the ratio of the output to the input to less than the passive damper transmissibility.

The effect of the semi-active control on suspension performance has also been studied on a two degree of freedom system (two mass systems). One such study is an experimental investigation by Ivers and Miller. In their study they used a "quarter car test rig" (single suspension device), to generate their results. This quarter car rig was base excited by a random velocity input to represent a "real road input". Their results showed that Skyhook can be used to reduce the sprung mass RMS acceleration to below that of the passive acceleration and therefore should improve ride quality. They also found that using skyhook control for the case of a step input reduces the percent overshoot to below the overshoot of the passive case, with in limits [5].

Using a full-car model with seven degrees of freedom, Lieh also showed the effects of passive versus semi-active skyhook damping on body acceleration, suspension travel, and tire deflection. He showed that for a given damping ratio, the body accelerations were improved when using semi-active damping, while the suspension and tire deflections were improved while using passive damping [6].

Some studies are even more realistic because they use actual vehicles. Ahmadian has taken experimental data from a test truck fitted with sensors. The truck was driven along a road while acceleration measurements were taken from the truck. He found that for certain frequency ranges and speeds, the semi-active suspension was capable of producing lower peak acceleration intensities than the passive suspension [7]. More recently, Pare[8] and Goncalves[9] proposed that can be used to reduce both the sprung and unsprung mass natural frequency transmissibility as well as be altered to trade off sprung mass performance for unsprung mass performance.

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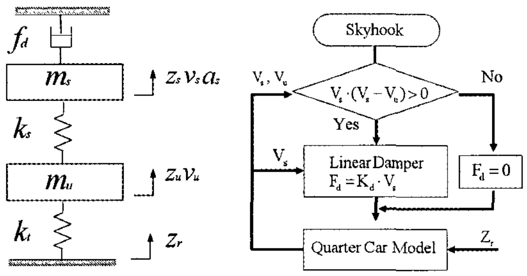
Fuzzy logic control was introduced by Zadeh[10] in 1965 and used in a number of controllers. The fuzzy inference, which is one of the knowledge-based approaches, is easier to control the system without considering the nonlinearity and uncertainty because it does not require an accurate model of the system to be controlled. Recently, The semi-active damper[11] to have this nonlinear characteristic, fast responses and continuous damper was developed . So, there are many investigations of the suspension system control using the fuzzy logic control [12,13].

In this paper, the fuzzy skyhook control, which is constructed by additional skyhook control principle, is suggested. The proposed fuzzy skyhook control minimize the vertical acceleration of the sprung mass that is a criterion of ride comfort. In the proposed fuzzy skyhook control, the acceleration elements are considered to reduce the acceleration by fuzzy rules. And other parameters deciding performance efficiency of the fuzzy skyhook control, membership functions and scale factors, are tuned by genetic algorithm as a kind of a optimization method. The tuned fuzzy skyhook controller is simulated in the quarter car model around the sprung mass natural frequency range where there are important range about evaluate ride comfort. The results obtained by the simulation are analyzed and exhibits that performance of the proposed control method is improved than skyhook control.

2. Skyhook and Fuzzy Skyhook

2.1 Skyhook control

Ideally, the configuration in Figure 1(a) represents the skyhook controlled quarter car model. Note the damper connected to an inertial reference in the sky (i.e., a ceiling that remains vertically fixed relative to a ground reference). By consider moving the damper from between the sprung mass and the unsprung mass, we can have another suspension properties, as compared with the passive damper.



(a) (b)

Fig. 1. Ideal Skyhook configuration.

If we plot the transmissibility for various values of the skyhook damping ratio ζ , we find the results shown in Figure 2. As in the passive case, as the skyhook damping ratio increases, the resonant transmissibility decreases. Increasing the skyhook damping ratio, however, does not increase the transmissibility all frequency range. For sufficiently large skyhook damping ratio, it can isolate even at the resonance frequency. This is encouraging since we have removed the tradeoff associated with passive dampers.

In order to implement ideal skyhook system, variable semi-active damper is used as shown in Figure 3. Following equation (1) represents the ideal skyhook control strategy to modulate a skyhook damper [4].

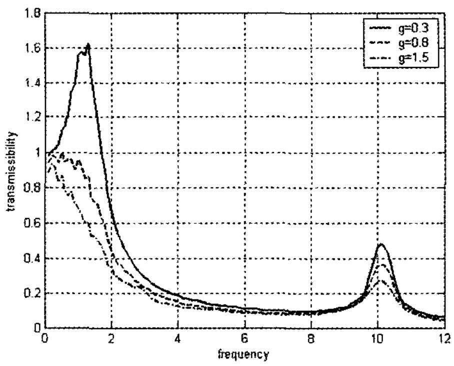


Fig. 2. Ideal Skyhook transmissibility

$$f_d = \begin{cases} 0, & if\ V_s \cdot (V_s - V_u) \le 0 \\ K_d \cdot V_s, & if\ V_s \cdot (V_s - V_u) > 0 \end{cases} \quad (1)$$

where K_d is the damping coefficient.

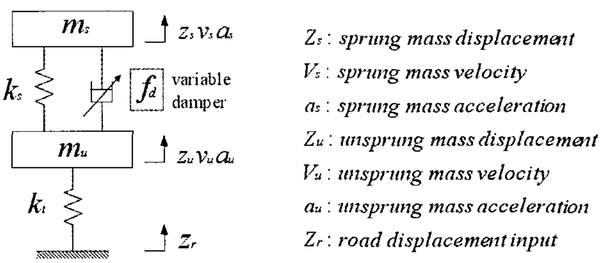


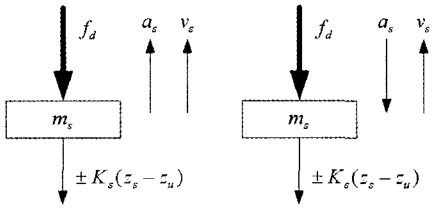
Fig. 3. Quarter-car model.

The switching law presented Equation (1) turns the damper off when the direction of the damper velocity showed in Figure 3 is not consistent with the direction of the desired damper force. In other words, if it is desired to have the variable suspension damper pull down on the sprung mass but that damper, of Figure 3, is being compressed, then only an upwards force is available from that damper. The control law will turn the damper off in an effort to minimize the upwards push from the variable suspension damper. Conversely, when the direction of the damper velocity and desired damping force are both same, the switching law turns damper on. The difference between proposed method and passive damper operation is the applied damping force that is decided by absolute velocity of sprung mass not to relative velocity between the sprung and the unsprung mass. In this case the sprung mass has the same effect like the ideal skyhook in Figure 1(a). Equation (1) provides a very simple method to emulate the ideal skyhook suspension system using only a semi-active damper. In real suspension systems, however, little difference is happened by semi-active damper characteristics that provide restricted damping range and nonlinearity. Figure 1(b) represents the control flow chart of the skyhook suspension system.

2.2 Fuzzy Skyhook control

The fuzzy logic control, which is one of the knowledge-based approaches using rules like "if ~ then ~", is easier to control the system without considering the nonlinearity and uncertainty because it does not require an accurate model of the system to be controlled. Liu et. al. applied the fuzzy logic control properties continuous damper systems having nonlinear character. They showed suspension performance is better than on-off damper control system [10,12].

In this study, we improve suspension performance. To minimize the vertical acceleration RMS of the sprung mass, the sprung mass's vertical acceleration and the velocity elements are directly used as fuzzy logic inputs.



(a) (b)

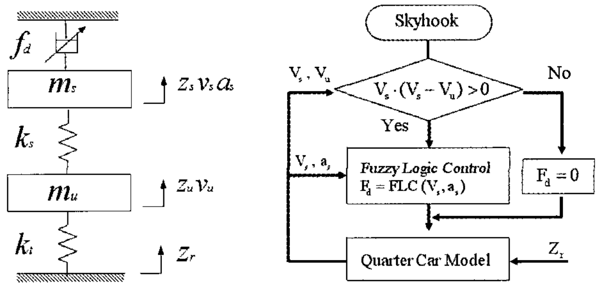
Fig. 4. A phenomenon in suspension operation.

Figure 4 shows the state of the sprung mass when the sprung mass is moving upwards and suspension damper is pulling down on the sprung mass. In figure 4(a), In case the direction of the velocity and the acceleration is same, the damping force will be bigger. If we consider incoming damping force as a small increase in advance, the acceleration of the sprung mass will be decreased. Like Figure 4(b), when the directions of the velocity and the acceleration of the sprung mass are opposite, the damping force will be increasing the acceleration of the sprung mass. These increasing of the acceleration affects bad influence to improving of ride comfort. Therefore, the damping force is recommended as the value shorter than current value. Exactly, if the direction of the velocity and the acceleration is same, the damping force shall be increased than existing value. In opposite case, the damping force is decreased. By considering that, the acceleration of the sprung mass will be decreased and ride comfort will be renovated.

Equation (2) shows the switching law of the fuzzy skyhook control.

$$f_d = \begin{cases} 0, & if\ V_s \cdot (V_s - V_u) \le 0 \\ FLC(V_s, a_s), & if\ V_s \cdot (V_s - V_u) > 0 \end{cases} \quad (2)$$

The switching law equivalents the skyhook control but damping force, that is provided by fuzzy logic control, is different. Ideal structure and a control flow chart of the fuzzy skyhook control are showed in Figure 5.



(a) (b)

Fig. 5. Fuzzy Skyhook configuration.

The discussed heuristic knowledge can reflect to the fuzzy logic control using linguistic variable. It is described by the form like this

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

Where input linguistic variable VF is the fuzzy set of the sprung mass velocity, AF is the fuzzy set of the sprung mass acceleration. And output linguistic variable FF is the fuzzy set of damping force.

Fuzzy sets of input, output linguistic variable are defined such as [NB, NM, NS, ZR, PS, PM, PB], respectively. The proposed control idea constructs inference engine has total 49 numbers of rules as Table I.

For each inputs and output, a triangular membership function is used and the center of gravity method is used as defuzzification method.

TABLE I. Fuzzy logic rule.

		V_s						
		NB	NM	NS	ZR	PS	PM	PB
a_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

3. Tuning the Fuzzy Skyhook Controller Using GA

In fuzzy logic control, the scale factors and the membership functions which are used in procedures, convert input and output values into linguistic variables or crisp values, are very important. If poor scale factors and membership functions are used, the sensibility of this system will be reduced, and the system will even slide into the stage of 'out of control'. Therefore, the scale factors and membership functions are selected properly to improve the performance of fuzzy logic control. Usually, a trial-and-error method is used to tuning of a fuzzy logic controller, but this method has limit to find best performance. Therefore, we use genetic algorithm (GA) to find optimal values of scale factors and membership functions of the fuzzy logic controller. Figure 6 shows the configuration of a fuzzy logic controller tuned by GA.

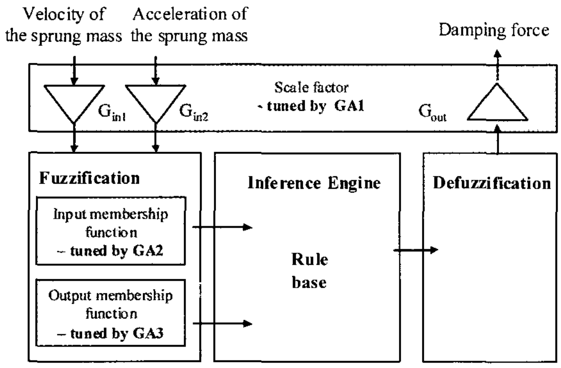


Fig. 6. Configuration of a Fuzzy Logic Controller.

Genetic algorithm is a kind of optimization method that imitates the process of organic evolution. It has been used in wide range to optimize after introduced by Goldberg in 1989. The GA approach to design fuzzy logic controllers was introduced by Karr in 1991 [14]. In his approach, the GA was used to adjust the parameters of the membership functions for fuzzy rules given by the designer. His approach was very powerful to improve control performance when the prior control knowledge was sufficient for the system.

Genetic algorithm has basic procedures such as encoding, crossover and mutation, evaluation, selection, termination. Figure 7 shows the configuration of genetic algorithm.

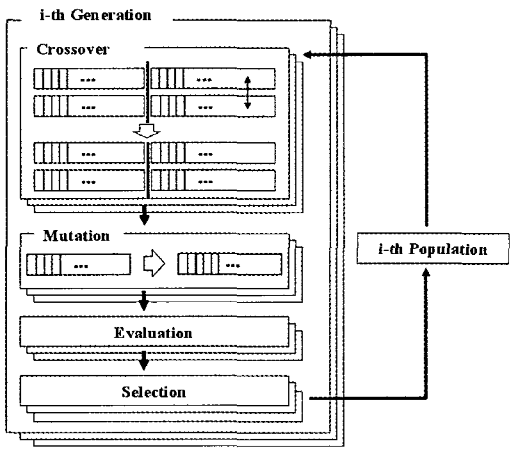


Fig. 7. Configuration of Genetic Algorithm.

In order to obtain the optimal fuzzy logic controller using genetic algorithm, it is necessary to encode the parameters. The encoding is method to convert information of parameters to binary structure named chromosome, which is a basic unit of a genetic algorithm operation.

In this paper, the optimization simulation using genetic algorithm is performed three times. The first simulation (GA1) optimizes the input scaling factor of velocity and acceleration and the output scale factor of damping force. And the second simulation (GA2) and third simulation (GA3) are optimizing the input membership function and output membership function, respectively.

The membership functions of the fuzzy logic controller are used triangular type membership functions as Figure 8. The encoding is selected as center value of triangular membership functions and made value of (+) and (-) get into symmetry.

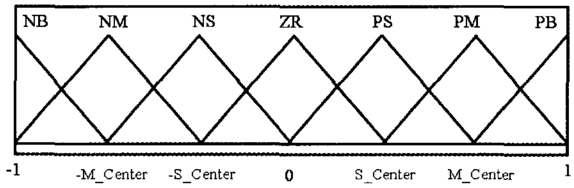


Fig. 8. Membership function of fuzzy logic controller.

The fitness function is a main criterion to evaluate chromosomes and it decide performance improvement direction of system. The fitness function is expressed as Equation (3)

$$J = \sum_{f=0.2}^{f=8} \sqrt{\frac{1}{T}\int_o^T {a_s}^2 dt} \Big/ N \tag{3}$$

where T is the simulation time, f is the frequency, and a_s is the vertical acceleration of the sprung mass obtained from simulation results, N is the number of samples.

The meaning of the fitness function is a average of RMS value of the sprung mass acceleration that is the simulation results at dividing frequency between 0.2Hz and 8Hz by 0.2 Hz. Usually, the road input with the lower natural frequency of vehicle aggravate more to ride comfort of a vehicle more than road input with other frequencies. Therefore, the fitness function is given to improve the performance of comfort ride over range of sextuple natural frequency of the sprung mass.

The mutation rate is 0.5%, the crossover rate is 30%, and the sorting method is used to selection of chromosome.

4. Simulations

In this section, the performance of the semi-active suspension using the simulation results of GA1, GA2, and GA3 are presented. The quarter-car suspension system parameters are given as Table II.

The Equation of motion for the sprung and unsprung mass of the quarter car system is given by

$$\begin{aligned} m_s a_s + k_s(z_s - z_u) &= -f_d \\ m_u a_u + k_s(z_u - z_s) + k_t(z_u - z_r) &= f_d \end{aligned} \tag{4}$$

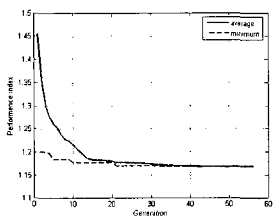
where z_s and z_u are the displacements of the sprung and unsprung mass, respectively. z_r is the road displace input and f_d represents the external input force of the suspension system. This input force can be generated by means of an ER damper for semi-active control.

TABLE II. Simulation parameters

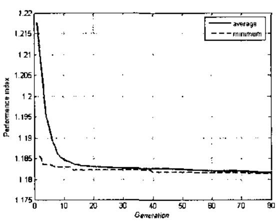
Parameter	Value
Sprung mass (m_s)	365 kg
Spring coefficient (K_s)	25080 N/m
Unsprung mass (m_u)	59.1 kg
Tire stiffness (K_t)	213640 N/m

The displacement input of road input is sinusoidal wave. The frequency and amplitude of road input are given as 0~8Hz and ±20cm. Figure 9 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.

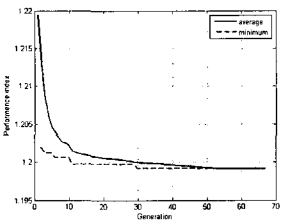
In genetic algorithm, the population size is given as 50 and if the average value and minimum value become same, the simulation is terminated because genetic algorithm is converged.



(a) GA1



(b) GA2

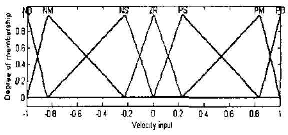


(c) GA3

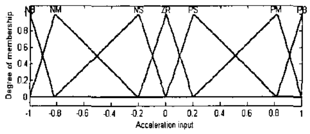
Fig. 9. Optimal value and average value history of Fitness function of GA1, GA2 and GA3.

The scale factors optimized by genetic algorithm are 8.0764, 0.3547 and 1017.3. The optimized membership functions are shown in Figure 10.

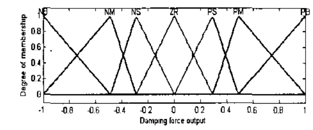
Figure 11 shows the simulation results of the fuzzy skyhook controller using genetic algorithm. As shown in Figure 11, there is significant reduction in average RMS value due to the semi-active fuzzy skyhook controller. The damping ratio of the continuous skyhook controller is selected through simulation by skyhook control which minimize the average acceleration RMS value of over 0~8Hz road input. By the tuning of the scale factors using GA1, the average acceleration RMS value of the sprung mass is decreased greatly. And the average acceleration RMS value of the sprung mass is decreased a little by GA2 and GA3.



(a) Input velocity



(b) Input acceleration



(c) Output damping force

Fig. 10. Optimal membership function of the Fuzzy logic controller tuned by GA.

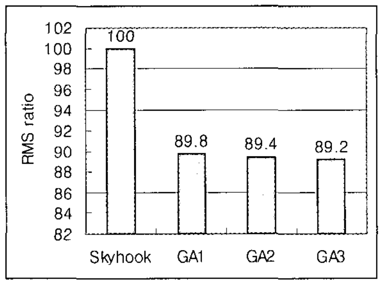


Fig. 11. Acceleration RMS comparison of sprung mass.

Figure 12 shows the frequency response of the fuzzy skyhook controller using the optimal scaling factors and membership functions. The dashed line is frequency response of the continuous skyhook controller and the solid line is frequency response of the fuzzy skyhook controller.

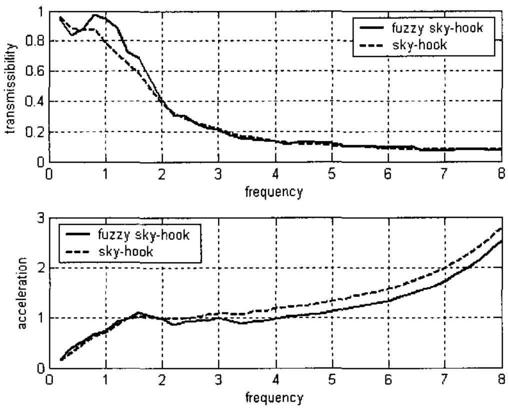


Fig. 12. Transmissibility and acceleration RMS as frequency range.

5. Concluding Remarks

In this paper, the fuzzy skyhook controller was proposed. The proposed fuzzy skyhook control method is based on skyhook principle but the damping force is decided by the fuzzy logic controller. The nonlinear property of fuzzy logic control used to improve the performance of the skyhook controller.

The fuzzy logic controller used a acceleration input of the sprung mass as a fuzzy input in order to minimize the acceleration. Also the scale factors and membership function of fuzzy logic control was optimized using genetic algorithm. The optimized fuzzy skyhook controller used to simulation of a semi-active suspension system, and the simulation results showed that the performance of the optimized fuzzy skyhook controller is improved about 10% more than performance of the continuous skyhook control.

In the future, the hybrid control using genetic algorithm can be implemented in order to minimize the effects of the natural frequency of the unsprung mass.

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