Modeling and Intelligent Control of Vehicle Active Suspension System

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***Abstract*—Due to the inherent nonlinear nature of vehicle fluid damper, an intelligent control algorithm which fuzzy control rule table can be obtained with the numerical calculation is advanced. The algorithm can adjust the rectification factor of fuzzy controller by adaptive filter method. Suspension dynamics are modeled using a two degree-of-freedom, linear and time-invariant vehicle model. The acceleration of the sprung mass is included in the premise part of the fuzzy rules to reduce the vertical acceleration of the sprung mass. For riding comfort and handling safety of vehicle, the simulation of vehicle performance in road signal is studied. Its results show the intelligent controller can effectively control the vibration of vehicle system and reduce the acceleration of the sprung mass.**

***Keywords*—vehicle, active suspension, intelligent control, adaptive algorithm, fuzzy logic**

I. INTRODUCTION

As a common property to vehicle, the suspension system isolates the vehicle body from road disturbances for comfortable ride and controls vehicle body attitude for safe and stabile ride. Most passive suspension systems mainly employ some type of springs in combination with shock absorber. Through many years experimentation and testing, this arrangement has evolved into a near optimal design. It is commonly accepted that passive suspensions have limited performance because their components can only store or dissipate energy. It cannot satisfy the comfort and handling requirements under varying road conditions. The idea of adding active components was introduced to improve vehicle handling and ride comfort. An active suspension system can provide high control performance in a wide frequency range.

In China, the semi-active suspension and active suspension have been studied since 1980's. Active suspension employs pneumatic or hydraulic actuators which in turn create the desired force in the suspension system [1-3]. Active suspension requires sensors to be located at different points of the vehicle to measure the motions of the body, suspension system and/or the unsprung mass. This information is used in the online controller to command the actuator in order to provide the exact amount of force required.

The intelligent control method is applied for active suspension system. And fuzzy logic algorithm has been successfully implemented in the control of linear and nonlinear systems. Unlike conventional controllers, fuzzy logic controllers do not require accurate mathematical model and they can easily deal with the nonlinearities and uncertainties of the controlled systems. With the fast response and robustness, the method is valid control algorithm for active suspension. Many persons have done some simulation studies and elementary experiments on the active suspension, and they attained some success [4-7]. However, the effect of experiments much depended on expert experience, which has influenced and restricted its engineering application. So the engineers pay more attention to the adjustable fuzzy control.

The paper describes the design of a fuzzy logic controller that is applied to the active suspension system. According to the nonlinearity of vehicle suspension, fuzzy control method based on LMS adaptive technology is applied to active control of the vehicle suspension system. Simulations of a quarter-car model with the designed fuzzy controller under a certain road condition are used to confirm the validity of the proposed controller and study the response characteristics of vehicle active suspension system.

II. MODELING OF ACTIVE SUSPENSION SYSTEM

At first, with a two degree-of-freedom, linear and time-invariant vehicle model, 1/4 vehicle suspension system is established, as shown in fig. 1. Its dynamic differential equation is:

$$\begin{cases} m_1\ddot{z}_1 - c_2(\dot{z}_2 - \dot{z}_1) - k_2(z_2 - z_1) + k_1(z_1 - z_0) = -u \\ m_2\ddot{z}_2 + c_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) = u \end{cases} \quad (1)$$

Where m_1 and m_2 are the sprung mass and the unsprung mass of vehicle system, k_1 is the suspension rigidity, k_2 is the tyre rigidity, C_2 is the suspension damper, z_1 and z_2 are the displacements of the sprung mass and the unsprung mass.

Let $x_1 = z_1$, $x_2 = z_2$, $x_3 = \dot{z}_1$, $x_4 = \dot{z}_2$, the state equation of system is

$$\dot{X} = AX + BU \qquad (2)$$

Where the state vector $X=[x_1, \; x_2, \; x_3, \; x_4]^T$;

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1+k_2}{m_1} & \frac{k_2}{m_1} & -\frac{c_2}{m_1} & \frac{c_2}{m_1} \\ \frac{k_2}{m_2} & -\frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{c_2}{m_2} \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{k_1}{m_1} & \frac{1}{m_1} \\ 0 & -\frac{1}{m_2} \end{bmatrix}$$

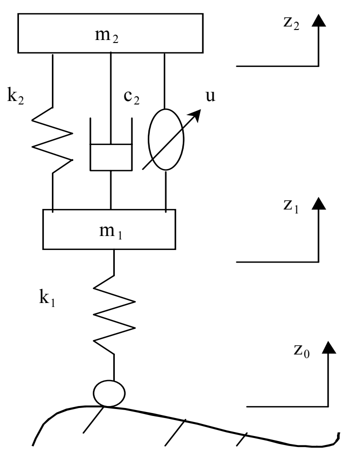

Fig. 1 Model of vehicle suspension system

III. DESIGN OF INTELLIGENT CONTROLLER

So far no accurate mathematic model can be used to describe this system. If we depend on common PID or optimal control methods, it must be far away from the actual condition. Therefore, it is necessary to design an intelligent fuzzy controller with adaptive ability.

A. Fuzzy Controller with Rectification Factor

Vehicle suspension system is a complicated nonlinear system. For the elementary fuzzy controller with single input or double inputs, establishing membership function accurately is very difficult. Otherwise, it is also a difficult problem that fuzzy control list are determined according to expert experience in practice. For these problems, adopted ways are auto-adjusting proportion factor or quantization factor, or changing fuzzy relation matrix directly, which have been applied in power and welding engineering [8-10]. The analytic control rule in fuzzy control was introduced and a formula can be summed up:

$$U = -\langle \alpha E + (1-\alpha) C \rangle \qquad \alpha \in [0,1] \qquad (3)$$

It is obvious that the output of the controller can be changed by changing rectification factor α. So the fuzzy controller is simpler. Active control force of vehicle suspension system can be got by reading the fuzzy control list which is computed according to the formula (3).

B. LMS Adaptive Filter

LMS adaptive filter algorithm was advanced by B. Widow. Quadratic index can reach minimum by adjusting filter's weight coefficients. LMS adaptive algorithm changes the weight coefficient according to negative gradient of single sample mean square. The implementation of the LMS adaptive algorithm can be seen in fig. 2.

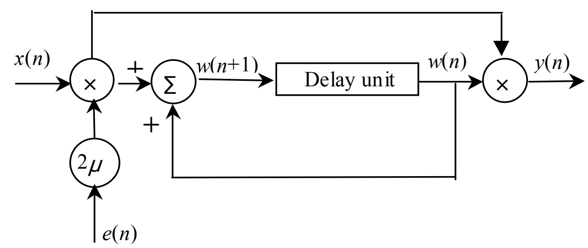

Fig. 2 Block diagram to LMS adaptive filter

Let input vector is

$$X^T(n)=[x(n), x(n-1), \cdots\cdots, x(n-L+1)]$$

Weight vector is

$$W^T=[w_1, , w_2 \cdots\cdots, w_L]$$

Where L is the length of filter, input vector $X(n)$ is composed by present samples and sample delay signals before. So output of adaptive transverse filter is

$$y(n) = \sum_{j=1}^{L} w_j x(n-j+1) = W^T X(n) \qquad (4)$$

In addition, error signal $e(n)$ is used to adjust weight vector, supposing

$$e(n)=d(n)\, y(n) \qquad (5)$$

Where d(n) is acceleration respondent signal of sprung mass.

C. Design of Intelligent Controller with Fuzzy Rectification Factor

LMS adaptive filter algorithm is applied in the design of intelligent controller with the rectification factor, it can improve defects caused by that the fixed rectification factor can't adapt to the variation input, also it can reduce human's effect in the process of adjusting the rectification factor by the math functions. The algorithm adopts LMS adaptive method to adjust the rectification factor. It can make the variation of the rectification factor be affected by the input.

The structure of the intelligent controller of active suspension system can be seen in fig.3. The acceleration and its rate of vehicle vibration can be regarded as the inputs of the fuzzy controller; the control force of the active suspension is the output. In the fuzzy control rules with rectification factor, the rectification factor can be achieved by the LMS adaptive method. LMS adaptive block has two inputs. One is the road excitation signal. The other one is the acceleration signal of sprung mass, it also is used as the error channel signal of the LMS adaptive block at the same time.

According to the actual condition, the rectification factor can be continuously adjusted in order to follow the control process in time. If the rectification factor can be adjusted according to the sprung mass acceleration of the suspension system, the LMS adaptive fuzzy control will be an effective method in practice.

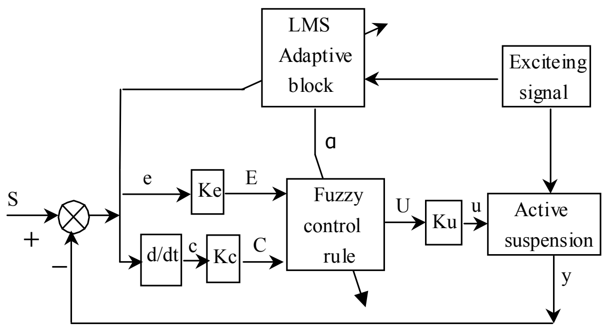

Fig. 3 Intelligent controller of active suspension

Assuming that the sprung mass acceleration and its rate are the input linguistic variable, the active control force is the output linguistic variable. All these linguistic variables are defined as

NB (negative big), NS (negative small), ZO (zero), PS (positive small), PB (positive big).

Define the values in the every quantization field as follows:

NB = –2, NS = –1, ZO = 0, PS = 1, PB = 2

According to the analytic formula (3), the fuzzy control list of output force directly is obtained.

IV. Simulative Study

In order to evaluate the riding comfort and handling safety of active suspension system, the dynamic deflection of the suspension system and the dynamic tyre load should be considered, except that the acceleration of sprung mass is considered as an important index. Accordingly, in the process of simulation, the performances above are regarded as evaluation indexes.

Under the road random signal, PSD curves of evaluation indexes of active suspension systems are shown in fig. 4 - fig.9.

A. Sprung mass Acceleration

For two-degree-of-freedom suspension system, the intelligent control with fuzzy rectification factor can decline the acceleration of sprung mass effectively in resonance frequency band, even more obviously in the lower frequency, and its PSD is reduced to 5%, as shown in fig. 4 - fig. 5.

B. Dynamic Tyre Load

In index curve of dynamic tyre load, the intelligent control with fuzzy rectification factor only decline the performance index by 20% in the resonance band of high frequency. It proves that the dynamic tyre load can meet the request for handling safety under random road excitation.

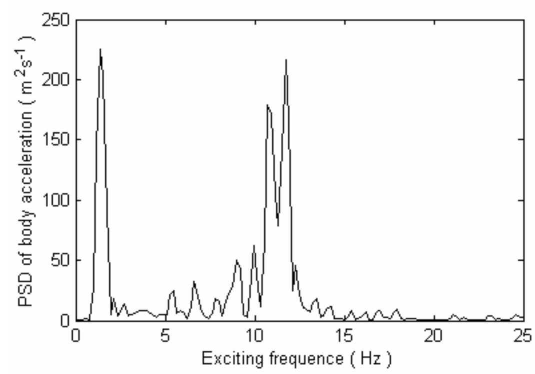

Fig. 4 Sprung mass acceleration PSD of passive suspension

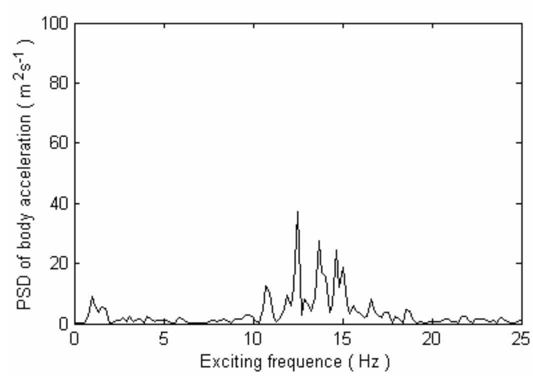

Fig. 5 Sprung mass acceleration PSD of intelligent control suspension with fuzzy rectification factor

C. Dynamic Deflection of Suspension System

The dynamic deflection PSD of suspension system is shown in fig. 8 – fig. 9, under the intelligent control with fuzzy rectification factor, the peak value of dynamic deflection PSD is reduced obviously in low frequency resonance band. The handing safety of vehicle system is improved obviously.

Under random road stimulation, the mean square roots of suspension system indexes are shown in table 1.

V. Conclusion

The handling safety and riding comfort of vehicle are regarded as control aims, and the intelligent control with fuzzy rectification factor is brought up. Contrasting with common fuzzy algorithm, the intelligent control with fuzzy rectification factor is no membership function choice of fuzzy subset for input and output of controller. It is fitter for active control of suspension system.

The rectification factor is adjusted online according to LMS adaptive filter algorithm. The factor can be influenced by exciting signal and controlled signal, so the intelligent control with fuzzy rectification factor has adaptive ability. For the sprung mass acceleration, the dynamic tyre load and the dynamic deflection of suspension system, the simulation results show that the intelligent control algorithm has obvious effect on the vibration control of suspension system.

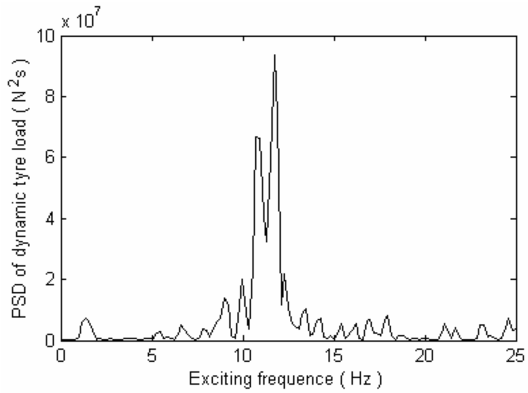

Fig. 6 Dynamic tyre load PSD of passive suspension

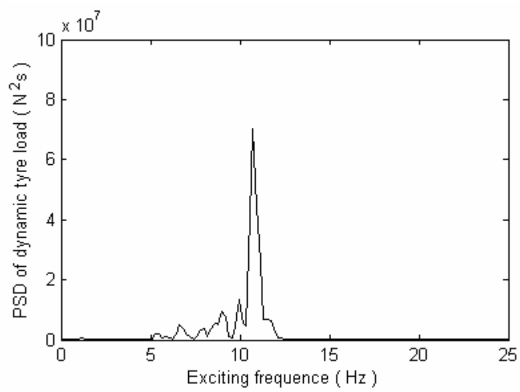

Fig. 7 Dynamic tyre load PSD of intelligent control suspension with fuzzy rectification factor

ACKNOWLEDGMENT

The correspondence author is Qingmei Yang. This work is supported by the science and technology development program of Beijing municipal commission of education.

REFERENCES

[1] Y. M. Chang, Z. H. Cheng, D. F. Jin, " Control of Vehicle suspension damp," *Automotive Engineering,* vol.12, pp. 58-64, Jun. 1990.

[2] Qiang Yu, "Continuous fuzzy control of active suspension system," *Automotive Technology*, pp. 9-12, Jan. 1999.

[3] Wang Qingfeng, Yang Botao, Tu Huagang. Hybrid fuzzy control for electro-hydraulic active damping suspension. *Chinese Journal of Mechanical Engineering (English Edition)*, 2002, 15 (3): 228-232.

[4] X. B. Fang, W. W. Chen, L. Wu, "Fuzzzy control technology and the application to vehicle semi-active suspension," *Chinese J. Mechanical Engineering,* vol. 35, pp. 98-100, Jun. 1999.

[5] Sun Julu, "Application of self-adjusting fuzzy controller in a vector controlled induction motor drive," *IPEMC'2000,* Beijing, China, 1996, pp. 1197-1201.

[6] Gao X. D. et al, "Application of fuzzy logic controller in the seam tracking of arc-welding robot," *IECON'97, the 23rd Annu. Int. Conf. the IEEE Industrial Electronics Society*, New Orlean, Louisiana, 1997, pp. 1367-1372.

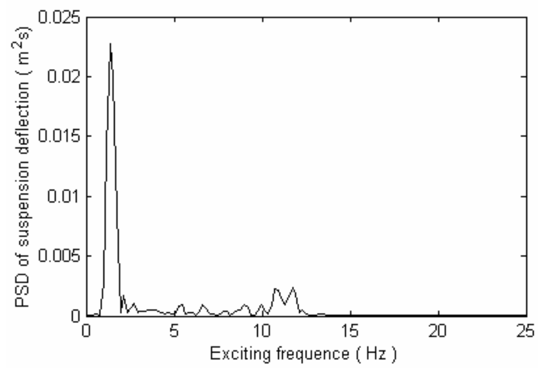

Fig. 8 Dynamic deflection PSD of passive suspension

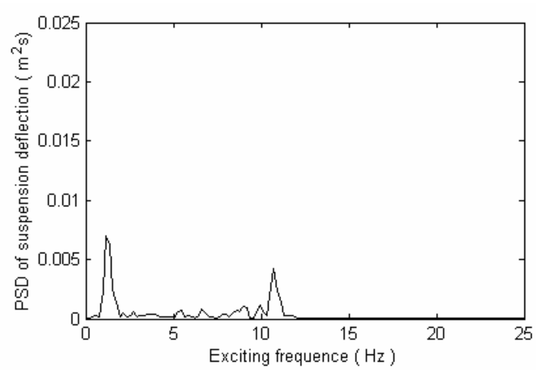

Fig. 9 Dynamic deflection PSD of intelligent control suspension with fuzzy rectification factor

TABLE I. MEAN SQUARE ROOTS OF SUSPENSION SYSTEM"S PERFORMANCE INDEXESS (PSD)

Performance Indexes	**Sprung mass Acceleration m^2s^{-1}**	**Dynamic Tyre Load KN^2s**	**Suspension Deflection mm^2s**
Passive Suspension	35.27	11.28	2200
Intelligent Control Suspension	1.33	6.22	1300

[7] Huang Shiuh, Lin Chiangwei. Application of a fuzzy enhance adaptive control on active suspension system. *International Journal of Computer Applications in Technology*, 2004, 20 (4): 152-160..

[8] Sun Julu, Application of self-adjusting fuzzy controller in a vector controlled induction motor drive, *IPEMC'*2000, Beijing, China, 1996, 1197-1201.

[9] Gao X. D. et al, Application of fuzzy logic controller in the seam tracking of arc-welding robot, IECON'97, the 23rd *Annu. Int. Conf. the IEEE Industrial Electronics Society*, New Orlean, Louisiana,1997, 1367-1372.

[10] Deshpande S, Mehta S, Jazar G. Optimization of secondary suspension of piecewise linear vibration isolation systems. *International Journal of Mechanical Sciences*, vol.48, no.4, 341-377, 2006

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