Design and Research of a Two Level Fuzzy PID Electronic Control System for Automotive Semi-Active Suspension

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Abstract. In response to the problem of outdated traditional PID control performance and excessively single control parameters in automotive suspension, a two level fuzzy PID control system for automotive semi-active suspension is proposed. The system has two control loops: the first level control loop is PID control, and the second level control loop is fuzzy control. The second level control loop fully utilizes the motion state of unsprung mass that affects the comprehensive performance of the suspension to achieve fine adjustments to the PID controller control parameters in the first level control loop, making the PID controller control parameters more suitable for adjusting suspension performance after hierarchical adjustment, thereby achieving the goal of improving ride comfort. The analysis data shows that the control performance of the two level fuzzy PID control system is significantly better than that of the PID control system, and the comprehensive performance of the suspension and ride comfort has been significantly improved.

Keywords: semi-active suspension; PID control; suspension performance.

1. Introduction

Automotive suspension can be divided into passive suspensions and active suspensions based on their ability to adjust stiffness and damping forces. Passive suspensions are suspensions where both stiffness and damping forces are not adjustable. These suspensions have low overall performance， but its application range is relatively wide [1-3]. Active suspension can also be divided into fully active suspension and semi-active suspension based on whether the stiffness and damping force are adjustable at the same time. The semi-active suspension has a relatively simple structure, relatively low manufacturing cost, and good comprehensive performance, which is widely used in high-end vehicles [4,5].

The control method and system of semi-active suspension directly affect the comprehensive performance of the suspension and have a decisive role in ride comfort. The optimization control of semi-active suspension has become a research hotspot in recent years. Li et al. [6] proposed a semi-active suspension control method based on state feedback and preview feedforward, which solves the problems of weak anti road interference ability of state feedback control and poor applicability of preview feedback control based on fixed time delay. The analysis results show that compared with passive suspension, in terms of vertical acceleration, pitch angle acceleration There has been a significant improvement in roll angle acceleration. Lin proposed an improved ADD control strategy for semi-active suspension. The improved acceleration damping control strategy retains the optimization effect of the acceleration damping control strategy on the acceleration of the spring mass, solving the problem of chattering caused by the switch type control strategy [7]. Liu used a three-layer feedforward network structure to design a BP neural network PID adaptive controller for vibration control of suspension system smoothness. The results showed that the BP neural network PID adaptive control of semi-active suspension has stronger robustness and adaptability [8]. Li proposed a linear quadratic Gaussian control system based on gravity search algorithm, which takes various performance indicators of the suspension as the objective function and uses gravity search algorithm to optimize the weighting matrix coefficients. This method solves the problem of difficult determination of the weighting matrix coefficients in traditional linear quadratic Gaussian controllers. The results show that: The vehicle magnetorheological semi-active suspension based on GSA-LQG control has better comfort and safety performance [9]. Ge proposed a type of energy fed magnetorheological damper structure and designed a corresponding semi-active suspension fuzzy sliding mode control strategy. Based on a hybrid canopy damping control system, a sliding mode variable structure controller was designed to optimize the suspension damping performance and energy fed performance [10]. Li proposed a composite control strategy for semi-active suspension based on switch functions, using the least squares method based on Levenberg Marquardt optimization algorithm to identify the parameters of the adjustable sigmoid model, which improved the comprehensive vibration isolation performance of vehicles equipped with magnetorheological semi-active suspension under complex road conditions [11].

Numerous scholars have proposed various control methods for semi-active suspension, but the current control methods are all single parameter control, which only optimizes the suspension performance using a certain parameter and does not fully consider other key parameters that affect the overall performance of the suspension. As a result, the suspension performance cannot be fundamentally improved. Based on this issue, a two level fuzzy PID control system for automotive semi-active suspension was proposed in this paper, which utilizes two control loops and two influencing factors to adjust the control parameters of the PID controller at multiple levels. This method achieves the goal of improving the overall performance of the suspension.

2. A Simplified Model of a Vehicle with Semi-active Suspension System

Due to the excessive complexity of the overall structure of the vehicle, it is necessary to simplify the vehicle structure when analysing the suspension system. The simplified vehicle model containing a semi-active suspension system is shown in Fig. 1. In Fig.1, m_b is the sprung mass, m_w is the unsprung mass, F_u is the damping force output by the suspension, k is the suspension spring stiffness, k_t is the tire stiffness, z_b, z_w, and z_r are the sprung mass displacement, unsprung mass displacement, and road relative displacement, respectively.

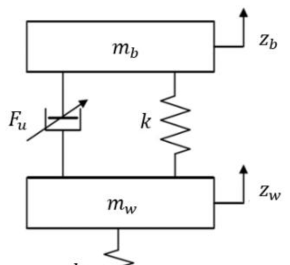


Fig. 1 A simplified model of a vehicle with semi-active suspension system

The mathematical expression of this model is:

$$\begin{cases} m_b\ddot{z}_b + k(z_b - z_w) + F_u = 0 \\ m_w\ddot{z}_w - k(z_b - z_w) + k_t(z_w - z_r) - F_u = 0 \end{cases} \tag{1}$$

The expression of the suspension mentioned above cannot clearly express the direct relationship between various factors and the overall performance of the vehicle. Therefore, matrix processing is required for the expression, and the processed state space model can be expressed as:

$$\begin{cases} \dot{X} = AX + BU + EW \\ Y = CX + DU \end{cases} \tag{2}$$

X is the input variable matrix; Y is the output variable matrix; A, B, C, D, and E are all coefficient matrices; U and W are relational matrices, which can be represented as:

$$A=\begin{pmatrix} 0 & -\frac{k}{m_b} & 0 & \frac{k}{m_b} & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{k}{m_w} & 0 & -\frac{k+k_t}{m_w} & \frac{k_t}{m_w} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix};\quad B=\begin{pmatrix} -\frac{1}{m_b} \\ 0 \\ \frac{1}{m_w} \\ 0 \\ 0 \end{pmatrix};\quad C=\begin{pmatrix} 0 & -\frac{k}{m_b} & 0 & -\frac{k}{m_b} & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{pmatrix};\quad D=\begin{pmatrix} -\frac{1}{m_b} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix};\quad E=\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

3. Design of a two level fuzzy PID control system for semi-active suspension of automobiles

The traditional control method of suspension is passive control, which means that the damping and stiffness of the suspension are not adjustable, which makes the overall performance of the suspension relatively poor. The comprehensive performance of the suspension system under PID control has significantly improved compared to passive control, but the PID control system structure is too simple and the input variables are relatively single, making it fundamentally difficult to achieve significant breakthroughs in control performance. A two level fuzzy PID control system was designed based on the PID control system, as shown in Fig.2. In Fig. 2, r is the set sprung mass acceleration, e_r is the sprung mass acceleration error, Δe is the rate of change in the acceleration error of the sprung mass. g is the set unsprung mass acceleration, Δe_g is the rate of change in acceleration error of unsprung mass.

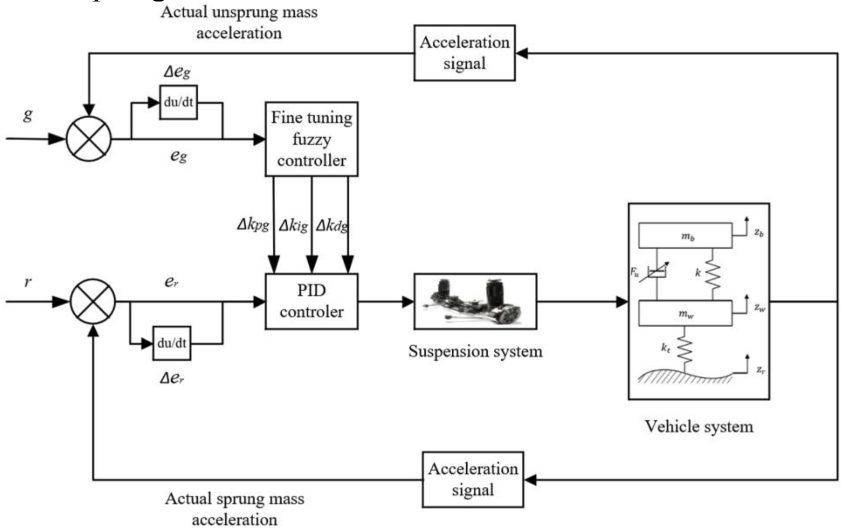


Fig. 2 The two level fuzzy PID control system

The control system is divided into two control loops. The first level control loop is a PID control loop. The input variables of this control loop are the spung acceleration error value and its rate of change, and the output variables are the semi-active suspension damping force. This loop is used to directly control the comprehensive performance of the suspension. Due to the relationship between the unsprung mass and the sprung mass, the motion state of the unsprung mass will also affect the motion state of the sprung mass, thereby affecting the overall performance of the suspension. Therefore, the second level control circuit takes into account the motion state of the unsprung mass, and uses a fuzzy controller as a bridge connecting the unsprung mass and the first level control circuit, This enables the use of unsprung mass motion states to trace the control parameters of the PID controller and fine tune the overall performance of the suspension, achieving multiple adjustments of the PID controller control parameters and suspension performance. The input variables of the fuzzy controller in the second level control loop are the unsprung mass acceleration error value and its rate of change, and the output variables are the fine tuning of the PID controller control parameters Δk_{pg}, Δk_{ig} and Δk_{dg}. The fuzzy controller control rules are shown in Tab. 1.

Table 1. Control rules

g	Δe_g						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/PS/NB	NS/NS/NB	ZO/ZO/NM	ZO/ZO/PM
NM	PB/NM/ZO	PB/NB/NS	PM/NS/NB	PS/PS/NM	NS/ZO/NM	ZO/PS/NS	NS/ZO/ZO
NS	PM/NM/ZO	PM/NM/NM	PS/NS/NM	PS/ZO/NM	PS/ZO/NS	NS/PS/NS	NS/PS/ZO
ZO	PS/NM/ZO	PS/NS/NM	PS/NS/NS	ZO/ZO/NS	ZO/PS/NS	NM/PS/ZO	NM/PS/ZO
PS	PS/NM/PM	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	PS/ZO/ZO	NM/PM/ZO	NM/PM/PM
PM	PS/NM/PB	ZO/ZO/PS	NS/ZO/PS	NS/PS/ZO	PM/PS/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/PS/PM	NM/PM/PM	NM/PM/PS	PM/PM/PS	NB/PB/PM	NB/PB/PB

PID controller control parameters k_p, k_i and k_d adjusted by two control loops can be expressed as follows:

$$\begin{cases} k_p = k_{p_0} + \Delta k_{pg} \\ k_i = k_{i_0} + \Delta k_{ig} \\ k_d = k_{d_0} + \Delta k_{ig} \end{cases} \tag{3}$$

K_{p0}, k_{i0} and k_{d0} are the initial control parameters of the PID controller.

After the control parameters are transmitted to the semi-active suspension, the semi-active suspension can adjust the output damping force based on the control parameters, thereby achieving adjustment of suspension performance. The output damping force of the semi-active suspension can be expressed as:

$$F_u = k_p e + k_i \int_0^t e\,dt + k_d \frac{de}{dt} \tag{4}$$

4. Comparative analysis of control performance

This article compares and analyzes the comprehensive performance of suspension under PID control and two level fuzzy PID control, and selects common C-level road surface as the road input excitation of the control system. The excitation signal of C-level road surface is shown in Fig. 3.

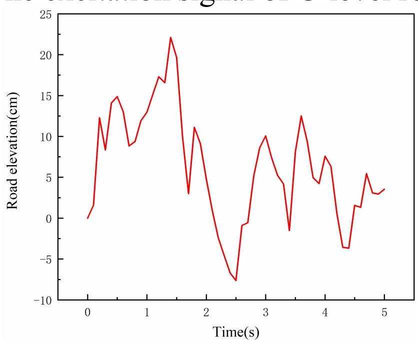
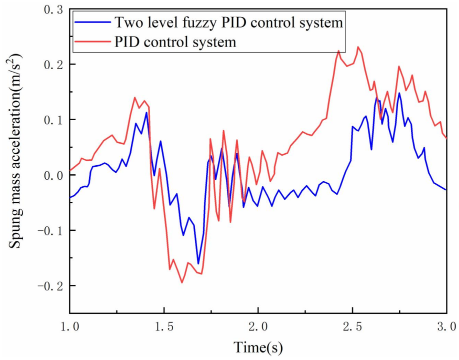


Fig. 3 The excitation signal of C-level road surface

Selecting the suspension spung mass acceleration and dynamic load as the evaluation parameters for suspension performance, the spung mass acceleration and dynamic load conditions under the two control systems are shown in Fig. 4 and Fig. 5.



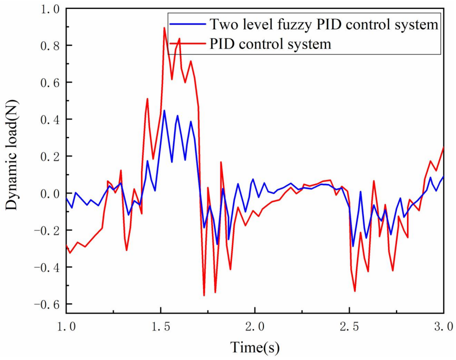


Fig. 4 Spung mass acceleration Fig. 5 Dynamic load

As shown in Fig. 4 and Fig. 5, the suspension sprung mass acceleration of the two level fuzzy PID control system has decreased by 19.53% compared to the PID control system. The suspension sprung mass acceleration peak of the two level fuzzy PID control system is significantly lower than that of the PID control system, and the curve changes relatively smoothly, meaning that the sprung mass acceleration is more uniform and the degree of mutation is small. The dynamic load of the two level fuzzy PID control system is 13.29% lower than that of the PID control system. The dynamic load peak of the two level fuzzy PID control system is significantly lower than that of the PID control system. The spung mass acceleration and dynamic load are significantly improved. The comprehensive performance of the suspension is significantly improved, and the ride comfort is greatly improved. The above data prove the correctness and progressiveness of the control system proposed in this paper.

5. Summary

In this paper, a two level fuzzy PID control system for semi-active suspension of automobiles is proposed. The control system has two control loops. The first level control loop uses the difference between the actual dynamic parameters of the vehicle and the ideal parameters for PID adjustment, while the second level control loop uses a fuzzy controller to take into account the motion characteristics of the unsprung mass that affect the overall performance of the suspension. By utilizing the motion characteristics of unspring masses, minor adjustments are made to the PID controller control parameters to achieve multi level adjustment of the suspension output damping force, thereby improving the overall performance of the suspension. Comparing the control performance of the two level fuzzy PID control system with that of the traditional PID control system, it can be seen that the acceleration and dynamic load of the sprung mass of the two level fuzzy PID control system have been significantly improved, the comprehensive performance of the suspension has been significantly improved, and the ride comfort has been greatly improved, which also proves the correctness and progressiveness of the proposed control system.

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