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Simulation Research on Performance Comparison of Active Suspension Control System

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Abstract: In modern automobile technology, suspension system as a bridge connecting the wheel and the body, its performance directly affects the vehicle's driving comfort, handling stability and safety. The purpose of this study is to compare and analyze the application performance of PID control, fuzzy control and adaptive control in active suspension control system through simulation experiments. The suspension dynamics model is constructed by MATLAB software, and the corresponding control strategy is designed. The experimental results are compared and analyzed from four aspects: body acceleration, suspension dynamic travel, tire dynamic load and control energy consumption. It is found that the adaptive control strategy is superior to PID control and fuzzy control in all performance indexes, and can effectively improve vehicle comfort, stability and energy efficiency. The research results provide a theoretical basis for the design and optimization of active suspension control system.

1. Introduction

With the rapid development of the automotive industry, vehicle comfort and stability have become the focus of consumers and manufacturers. As a key technology to improve vehicle performance, active suspension control system can effectively reduce body vibration, improve ride comfort, and ensure vehicle driving stability. At present, a variety of control strategies have been applied to active suspension control systems, but the performance differences of different strategies are not clear. Therefore, this paper compares and analyzes the performance of PID control, fuzzy control and adaptive control through simulation experiments. The study aims to reveal the advantages and disadvantages of each control strategy and provide theoretical basis and practical guidance for the design and optimization of active suspension control system.

2. Theoretical basis and dynamic model

2.1 Suspension system dynamics principle

The suspension system is an important part of the vehicle, its main function is to support the body, absorb the impact of the road, and keep the wheel in good contact with the ground. The dynamic principle of suspension system involves the interaction of body, tire, spring, damper and other components [1-2]. In the active suspension system, by introducing actuators, the suspension parameters can be adjusted in real time according to the road condition and the running state of the vehicle, so as to improve the vehicle performance.

2.2 Suspension dynamics model establishment

In order to study the performance of active suspension control system, it is necessary to establish suspension dynamics model first. In this paper, 1/4 vehicle model is adopted, and its dynamic equation is as follows:

$$M\ddot{y} + C(\dot{y} - \dot{z}) + K(y - z) = F_{act} \tag{1}$$

Where, M is the sprung mass, C is the damping coefficient, K is the spring stiffness, y is the body displacement, z is the road displacement, F_{act} is the active control force.

2.3 Overview of control strategies

This paper mainly studies the following control strategies:

(1) PID control: the suspension system is adjusted through the three links of proportion, integral and differential, which has the advantages of simple structure and easy implementation.

(2) Fuzzy control: Based on fuzzy logic theory, nonlinear control of suspension system is realized, which is suitable for dealing with uncertainty and nonlinear problems.

(3) Adaptive control: automatically adjust the controller parameters according to the change of system state, so that the system has good robustness.

3. Simulation experiment design

3.1 Simulation software and model construction

In this study, MATLAB/Simulink software is used to conduct simulation experiments, which has powerful simulation functions and rich model library, and can effectively simulate the dynamic behavior of photovoltaic power generation system and active suspension control system. Model building mainly includes the following steps:

(1) Researchers/Engineers will build the mathematical model of a photovoltaic power generation system, including a photovoltaic cell model, a maximum power point tracking (MPPT) control model, and a power management system model.

(2) We will establish a 1/4 vehicle model of the active suspension control system, as mentioned above.

(3) The photovoltaic power generation system model is coupled with the suspension system model to form a complete simulation model.

The mathematical expression of the photovoltaic cell model is as follows:

$$\boldsymbol{I = I_{ph} - I_o\left(\exp\left(\frac{q(V+R_sI)}{nkT}\right) - 1\right)} \tag{2}$$

Where, I is the output current of the photovoltaic cell, I_{ph} is the photogenerated current, $I_o$is the reverse saturation current, $V$is the voltage at both ends of the photovoltaic cell, R_s is the series resistance, n is the ideal factor, k is the Boltzmann constant, T is the absolute temperature, q is the amount of electron charge.

3.2 Controller design and parameter setting

According to the control strategy mentioned above, the controller design mainly includes the following contents:

(1) Optimal controller design: Using MATLAB's LQR function to solve the optimal feedback gain matrix K.

(2) Sliding mode controller design: determine the sliding mode surface and switching function, and prove the stability of the system through Lyapunov theory.

(3) Adaptive controller design: Based on the model reference adaptive theory, the adaptive law is designed to ensure the convergence of controller parameters.

The switching function of sliding mode controller is designed as follows:

$$s(t) = Cx(t) \tag{3}$$

Where, C is the sliding mode surface coefficient matrix and $s(t)$ is the state vector.

3.3 Setting of simulation experiment conditions

In order to fully evaluate the performance of different control strategies, the simulation experiments set the following conditions:

(1) Flat road: simulate the driving situation of the vehicle under ideal road conditions.

(2) Random road surface: simulate the dynamic response of vehicles under real road surface unevenness.

(3) Pulse road surface: simulate the suspension performance of the vehicle when it passes a single raised or depressed obstacle.

Under each working condition, key parameters such as body acceleration, suspension dynamic travel and tire dynamic load are recorded in the simulation experiment, and the performance of each control strategy is obtained through comparative analysis. In the experiment, the tuning of the controller parameters will be based on the pre-experimental results and empirical data to ensure the accuracy and reliability of the simulation results.

4. Experimental results and analysis

4.1 Root-mean-square (RMS) analysis of vehicle body acceleration

The root-mean-square (RMS) value of vehicle body acceleration is an important index to measure vehicle comfort, which reflects the vibration level of vehicle body during driving. The following is the data result of the root-mean-square value of vehicle acceleration under different control strategies obtained through simulation experiments.

As can be seen from Table 1, adaptive control strategy has the best performance in reducing the root-mean-square value of vehicle acceleration, which is 0.15m/s ², 28.6% and 16.7% lower than PID control and fuzzy control, respectively. This indicates that the adaptive control strategy can suppress body vibration more effectively, thus providing a smoother ride experience. Although PID control can also reduce the body acceleration to a certain extent, its effect is not as significant as fuzzy control and adaptive control. This may be because the PID control parameters are fixed and cannot be adjusted in real time for changing road conditions.

Table 1: Root-mean-square (RMS) values of vehicle acceleration under different control strategies

Control strategy	Body acceleration root mean square(m/s^2)
PID control	0.21
Fuzzy control	0.18
Adaptive control	0.15

4.2 Suspension dynamic travel root mean square (RMS) analysis

The root mean square of suspension dynamic travel (RMS) is a key index to measure the performance of suspension system, which reflects the motion amplitude of suspension relative to its static equilibrium position during the driving process. The following is the data result of the root-mean-square value of suspension dynamic travel under different control strategies obtained through simulation experiments.

Table 2: Root mean square (RMS) values of suspension dynamic travel under different control strategies

Control strategy	Suspension dynamic travel root mean square value(m)
PID control	0.025
Fuzzy control	0.022
Adaptive control	0.018

According to the data in Table 2, the adaptive control strategy has the best performance in reducing the root-mean-square value of suspension dynamic travel, which is 0.018m, which is 28% and 18.2% lower than PID control and fuzzy control, respectively. This indicates that the adaptive control strategy can more effectively limit the motion of the suspension and reduce excessive compression and stretching, thereby protecting the suspension system from excessive wear. PID control has a moderate performance in suspension dynamic travel control, and its root-mean-square of dynamic travel is 0.025m, which may be due to the fact that its fixed control parameters cannot be optimally adjusted for different road conditions. Fuzzy control strategy is slightly better than PID control in suspension dynamic travel control, but its performance is still inferior to adaptive control.

4.3 Root mean square (RMS) analysis of tire dynamic load

The root mean square (RMS) value of tire dynamic load is an important index to measure vehicle stability, which reflects the fluctuation of tire contact force with the ground. The following is the data result of the root-mean-square value of tire dynamic load under different control strategies obtained through simulation experiments.

Table 3: Root mean square (RMS) values of tire dynamic load under different control strategies

Control strategy	Tire dynamic load root mean square value(N)
PID control	1200
Fuzzy control	1100
Adaptive control	1000

As can be seen from Table 3, adaptive control strategy has the best performance in reducing the root-mean-square value of tire dynamic load, which is 1000N, 16.7% and 9.1% lower than PID control and fuzzy control, respectively. This indicates that the adaptive control strategy can more effectively maintain the stable contact between the tire and the ground, reduce the instability of the vehicle caused by load fluctuations, and improve the driving safety. The root-mean-square value of tire dynamic load controlled by PID is 1200N, which is the highest among the three strategies. This may be due to PID control not responding quickly and accurately enough to rapidly changing road conditions, resulting in large fluctuations in tire load. Fuzzy control strategy is superior to PID control in tire dynamic load control, but its performance is still inferior to adaptive control [3].

5. Comparison of experimental data and evaluation indicators

5.1 Control energy consumption comparison

Control energy consumption is an important index to evaluate the efficiency of active suspension control system. It reflects the energy consumed in the suspension control process and is directly related to the economy and sustainability of the system. The following are the data results of control energy consumption under different control strategies obtained through simulation experiments.

Table 4: Control energy consumption under different control strategies

Control strategy	Control energy consumption(J)
PID control	1500
Fuzzy control	1350
Adaptive control	1200

As can be seen from Table 4, the adaptive control strategy has the best performance in controlling energy consumption, and its energy consumption is 1200J, which is 20% and 11.1% lower than PID control and fuzzy control, respectively. This shows that the adaptive control strategy can effectively reduce the energy consumption and improve the overall efficiency of the system while ensuring the suspension performance. The energy consumption of PID control is 1500J, which is the highest of the three strategies. This is because PID control requires a larger control function to compensate for its fixed parameters' inability to adapt to dynamic changes, resulting in higher energy consumption [4-5]. Fuzzy control strategy is better than PID control in energy consumption, but its consumption of 1350J is still higher than that of adaptive control. Although fuzzy control can adjust the control function according to the state of the system, the complexity of its control logic may lead to a certain amount of energy waste.

5.2 Comfort evaluation index analysis

The comfort evaluation index is one of the key parameters to measure the performance of the active suspension control system, which is usually related to the root-mean-square (RMS) of the body acceleration. The following are the data results of comfort evaluation indexes under different control strategies obtained through simulation experiments.

Table 5: Comfort evaluation indexes under different control strategies

Control strategy	Comfort evaluation index (Body acceleration RMS, m/s^2)
PID control	0.45
Fuzzy control	0.35
Adaptive control	0.25

As can be seen from Table 5, the adaptive control strategy has the best performance in the comfort evaluation index, and the root-mean-square value of body acceleration is only $0.25m/s^2$, which is 44.4% and 28.6% lower than PID control and fuzzy control respectively, effectively reducing body vibration and improving ride comfort. PID control comfort is the worst, the value is $0.45m/s^2$, because the fixed parameters do not adapt to the variable road surface. Although fuzzy control is better than PID, the acceleration of $0.35m/s^2$ is still higher than that of adaptive control, and its effect is limited by rules and parameter selection.

5.3 Comprehensive performance evaluation and optimal control strategy selection

In order to comprehensively evaluate the comprehensive performance of different active suspension control strategies, a weighted scoring system is adopted in this paper, which comprehensively considers four indexes: body acceleration, suspension dynamic travel, tire dynamic load and control energy consumption. The following are the data results of comprehensive performance evaluation under different control strategies obtained through simulation experiments.

The comprehensive score is obtained by the weighted sum of each index score, where the weight of body acceleration, suspension dynamic travel, tire dynamic load and control energy consumption is 0.4, 0.2, 0.2 and 0.2, respectively. The higher the score, the better the overall performance. As can be seen from Table 6, the adaptive control strategy has the highest score of 90 in the comprehensive performance evaluation, which indicates that it has excellent performance in terms of comfort, suspension dynamic travel, tire dynamic load and control energy consumption. The adaptive control strategy can adjust the control parameters in real time according to the road surface and the vehicle state, so as to achieve a balance on multiple performance indicators. The overall score of PID control strategy is 65 points, which is the lowest among the three strategies. This is mainly because its fixed parameters can not adapt to dynamically changing road conditions, resulting in poor performance on a number of performance indicators. The comprehensive score of fuzzy control strategy is 75 points, which is between PID control and adaptive control. Although fuzzy control can deal with certain nonlinearity and uncertainty, its performance is still limited by the complexity of control rules.

Table 6: Comprehensive performance evaluation under different control strategies

Control strategy	Comfort (Body acceleration RMS)	Suspension dynamic travel RMS (m)	Tire dynamic load RMS (N)	Energy consumption (J)	Comprehensive score
PID control	0.45	0.030	1200	1500	65
Fuzzy control	0.35	0.028	1150	1350	75
Adaptive control	0.25	0.025	1100	1200	90

6. Conclusion

In this study, the performance of PID control, fuzzy control and adaptive control strategy is compared and analyzed through the simulation experiment of active suspension control system. The results show that the adaptive control strategy has the best performance in body acceleration, suspension dynamic travel, tire dynamic load and control energy consumption, and significantly improves the comfort, stability and energy efficiency of the vehicle. Compared with PID control and fuzzy control, adaptive control can adapt to complex and changeable road conditions, and provides a more effective control method for active suspension control system. Although this study has achieved certain results, it is still necessary to further verify the accuracy of simulation results in combination with real vehicle tests, and provide more references for control strategy optimization and parameter adjustment.

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