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THE DESIGN OF ADAPTIVE FUZZY CONTROLLER FOR ACTIVE SUSPENSION SYSTEM

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Abstract

In order to solve the control problem of active suspension, improve the ride comfort, three degree freedom of 1/4 vehicle active suspension system dynamics model with the driver's model was established, and the variable universe adaptive fuzzy controller based on fuzzy inference applied to the active suspension system was designed. The universe size of the system fuzzy controller can be adjusted automatically according to system deviation, the fuzzy control accuracy can be improved effectively. Through the comparison of passive suspension, the active suspension applied variable universe adaptive fuzzy controller, the acceleration of body and seat can be reduced substantially, and the riding comfort and the running smoothness can be improved effectively.

Keywords: active suspension, variable universe, adaptive, fuzzy controller, riding comfort.

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1. Introduction

The suspension system is an important assembly of vehicles, which can isolate the shock and vibration from the ground. And its performance is an important influence factor of vehicle ride comfort and operation stability [1]. The traditional passive suspension is composed of spring and damper, only designed for a certain kind of road, so its performance can not change with the road change. The full active suspension adopt an actuator to replace the spring and damper, which can adapt to the complex working condition, but it will consume huge energy [2]. And there is a another form active suspension, the actuator combined with the spring and damper, which has low energy consumption, so it will has a broad prospect in application. In this paper, we mainly conduct a deep study of this active suspension.

A good control strategy is the key technology of active suspension, such as the LQG control, which has been developed relatively mature in linear control field, through determine the index weighting coefficient, system state variables and control variables weighted matrix, provides some design space for the designer [3]. But the determination of index weighting coefficient always depend on trial method or designer's experience [4-6], cannot meet the requirements of engineering. The suspension system has strong nonlinear characteristic, and for nonlinear systems, fuzzy control shows the advantages of good robustness and model independent, but the fuzzy control also has the problem of low precision and depend on the experience to determine the fuzzy rules. So [7] designed the parameters self-adjustment fuzzy controller for active suspension system, the performance is better then that of LQG control. But the parameter self-adjustment function model and the shape parameter still need to be determined by experience.

So the variable universe fuzzy control can be applied in the suspension control system, such as applied the function model to described the contraction-expansion factor [8, 9], but the choice of function model always with more difficulty and the accuracy of the function model also difficult to ensure. So [10, 11] applied fuzzy rules to describe the contraction-expansion factor was more flexible, the control accuracy and adaptive ability can be improved. Therefore, in view of the above situation, we proposed active suspension variable universe adaptive fuzzy control, the contraction-expansion factor can be determined by fuzzy control rules, and the driver model be added to test the control effect.

2. The Suspension Model and Road Model

1/4 vehicle model of active suspension with driver model is shown in Figure 1.

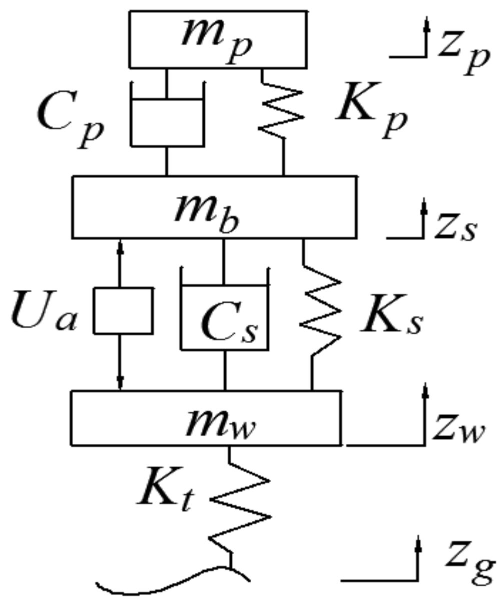


Figure 1. 1/4 vehicle model of active suspension.

In Figure 1, m_p is the driver and seat mess; K_p is the stiffness of seat; C_p is the damping of seat; m_b is the sprung mess; K_s is the stiffness of suspension; C_s is the damping of suspension; U_a is the control force of actuator; m_w is the unsprung mass; K_t is the stiffness of tire; z_s is the displacement of sprung mess; z_p is the displacement of seat; z_s is the displacement of sprung mess; z_w is the displacement of unsprung mess; and z_g is road input displacement.

The dynamic differential equation of system can be established as follow:

$$m_p\ddot{z}_p = -K_p(z_p - z_s) - C_p(\dot{z}_p - \dot{z}_s), \tag{1}$$

$$m_b\ddot{z}_s = -K_s(z_s - z_w) - C_s(\dot{z}_s - \dot{z}_w) - U_a - m_p\ddot{z}_p, \tag{2}$$

$$m_w\ddot{z}_w = K_s(z_s - z_w) + C_s(\dot{z}_s - \dot{z}_w) - K_t(z_w - z_g) + U_a. \tag{3}$$

The first-order filtering white noise can be used as the road input

$$\dot{z}_g(t) = -2\pi f_0 z_g(t) + 2\pi\sqrt{G_0 u_c}\,w(t), \tag{4}$$

where f_0/Hz is the lower cut-off frequency; $G_0/(\mathrm{m}^3\mathrm{cycle}^{-1})$ is the road roughness coefficient; u_c is the vehicle speed; w is the Gauss white noise distribution, the mean value is 0 and the noise intensity is 1.

The state vector can be defined as

$$\boldsymbol{X} = \begin{bmatrix}\dot{z}_p & \dot{z}_s & \dot{z}_w & z_p & z_s & z_w & z_g\end{bmatrix}^T.$$

And the output vector can be defined as

$$\boldsymbol{Y} = \begin{bmatrix}\ddot{z}_p & \ddot{z}_s & z_p - z_s & z_s - z_w & z_w - z_g\end{bmatrix}^T.$$

According to the Equations (1)-(4), the system state-space equation can be described by Equation (5)

$$\begin{cases}\dot{\boldsymbol{X}}(t) = \boldsymbol{AX}(t) + \boldsymbol{BU}(t) + \boldsymbol{FW}(t), \\ \boldsymbol{Y}(t) = \boldsymbol{CX}(t) + \boldsymbol{DU}(t),\end{cases} \tag{5}$$

where $\boldsymbol{A}$ is the state matrix, $\boldsymbol{B}$ and $\boldsymbol{F}$ is the input matrix, $\boldsymbol{C}$ is the output matrix, $\boldsymbol{D}$ is the transfer matrix, $\boldsymbol{U} = U_a$ is the control force of actuator, $\boldsymbol{W} = w(t)$ is the Gauss white noise input of road model.

3. The Design of Variable Universe Fuzzy Controller

3.1. Variable universe theory

Fuzzy controller is actually the interpolated controller, the control accuracy will be increased along with the increase of fuzzy rules, but it will bring some difficulties to summarize the rules by expert knowledge, and the steady-state error of system can also be increased [12]. Therefore, the variable universe method can be introduced to the fuzzy control, and the universe size can be adjusted by the system error on the premise of the rules are the same. Which is the universe will be expanded when the system error increased, equal to reduce the rules; and the universe will be shrunk when the system error reduced, equal to increase the rules. So the control accuracy will be increased by this method.

When the vehicle in the complex road, the common fuzzy controller cannot meet the expectation, the variable universe fuzzy control can adaptive adjust the input and output variable according to the driving condition, reflect the good control effect.

The initial universe of input and output variables can be defined as Equations (6) and (7)

$$X(x_i) = [-E,\ E], \tag{6}$$

$$Y(y_j) = [-U,\ U], \tag{7}$$

where $x_i = (i = 1, 2, \cdots, n)$ is the input error and $y_j = (j = 1, 2, \cdots, m)$ is the output error.

And the universe $X(x_i)$ and $Y(y_j)$ contraction and expansion can be described by Equations (8) and (9)

$$\alpha(x_i)X(x_i) = [-\alpha(x_i)E,\ \alpha(x_i)E], \tag{8}$$

$$\beta(y_j)Y(y_j) = [-\beta(y_j)U,\ \beta(y_j)U], \tag{9}$$

where contraction-expansion factor $\alpha(x_i)$ and $\beta(y_j)$ are the continuous function of input error $x_i = (i = 1, 2, \cdots, n)$ and the output error $y_j = (j = 1, 2, \cdots, m)$.

And the universe variable can be described by Figure 2.

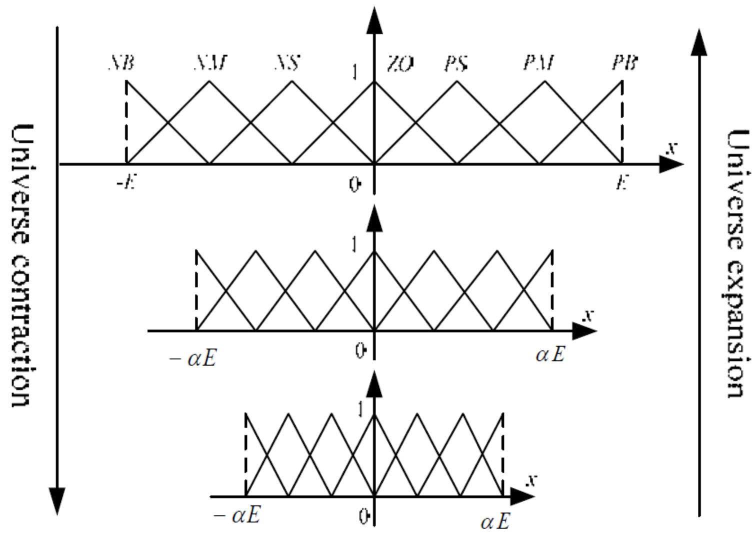


Figure 2. The situation of the universe variables.

3.2. Variable universe fuzzy control based on fuzzy inference

The contraction-expansion factor can be defined by function model or fuzzy rules. But the former have not a standard determine method, need a large number experiment to determine. And the variable universe fuzzy control based on fuzzy inference can avoid universe repeated adjustment, improved the convergence speed of the system [13]. The diagram of variable universe fuzzy control based on fuzzy inference is shown in Figure 3.

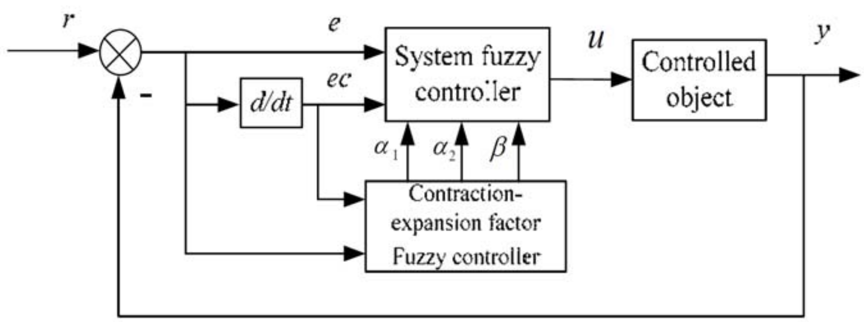


Figure 3. The diagram of variable universe fuzzy control.

In Figure 3, the system fuzzy controller can be designed according to the conventional fuzzy controller with double input and single output. The basic universe of $e(t)$ and $\Delta e(t)$ should be determined by the actual amount of feedback, the initial universe of $e(t)$ and $\Delta e(t)$ can be selected as $[-1, 1]$ and $[-4, 4]$, and the universe can be partitioned into 7 fuzzy subset: [NB, NM, NS, Z, PS, PM, PB]. The output is the control force, and fuzzy universe can be selected as $[-6, 6]$, and the universe can be partitioned into 7 fuzzy subset: [NB, NM, NS, Z, PS, PM, PB].

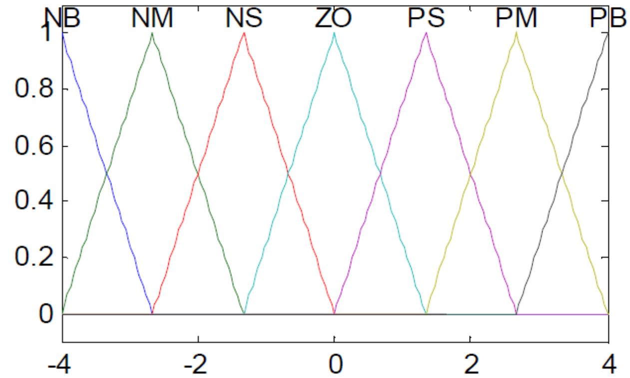
The design principles of control rules can be divided into three points:

(1) When $e(t)$ and $\Delta e(t)$ have the same sign, the larger control variable should be adopted.

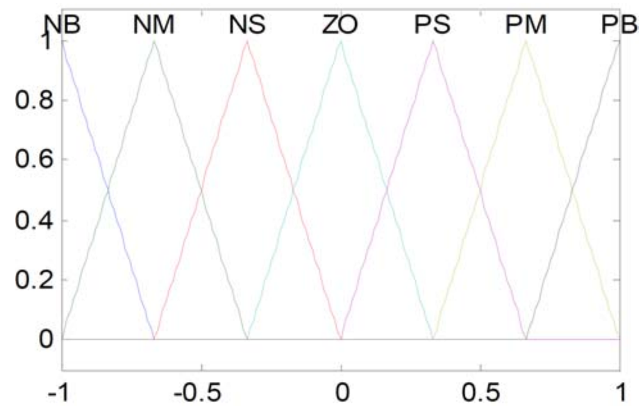
(2) When the sign of $e(t)$ and $\Delta e(t)$ different, the system should adopt smaller control variable.

(3) When the variable of $\Delta e(t)$ is small, the choice of control variable should prevent overshoot. From these principles, the fuzzy control rule of system fuzzy controller can be determined.

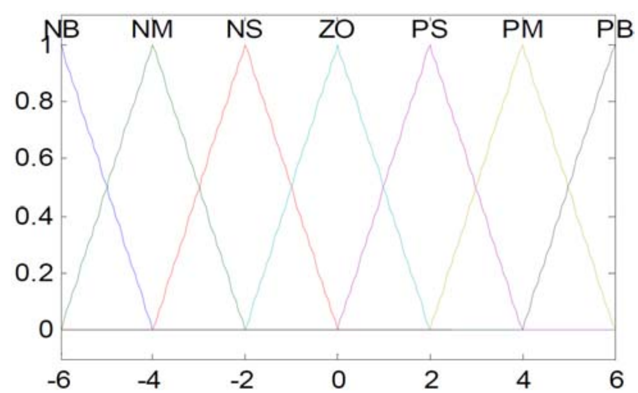
The triangular membership function can be adopted as membership function of input and output can take, and the defuzzification can take the centroid method. So we can get the fuzzy control rules. And the membership function and the output surface of system fuzzy control rules is shown in Figures 4 and 5, respectively.



(a) The membership function of $\Delta e(t)$.



(b) The membership function of $e(t)$.



(c) The membership function of output.

Figure 4. Input and output membership function of system fuzzy controller.

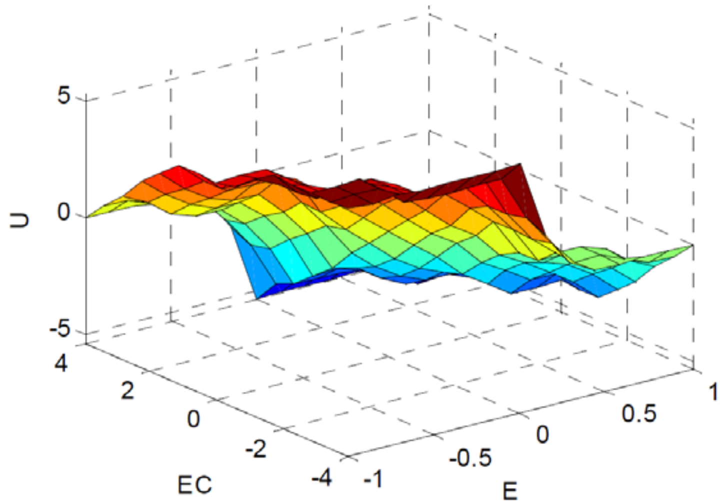


Figure 5. Output surface of system fuzzy control rules.

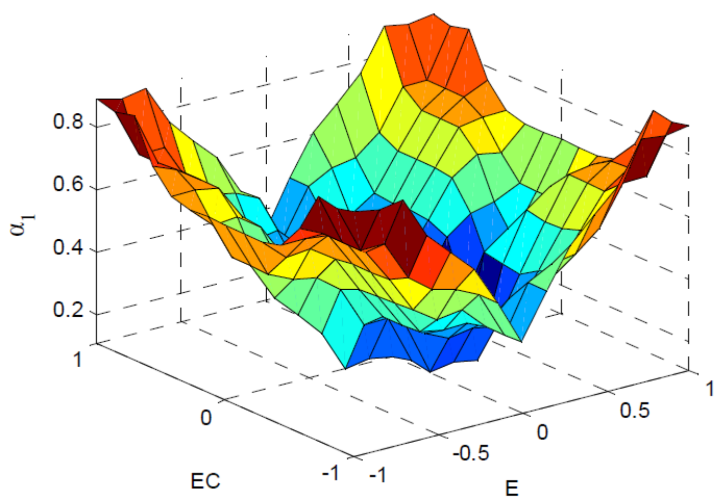
The contraction-expansion factor fuzzy controller is a two input and three output fuzzy controller, according to the system input $e(t)$ and $\Delta e(t)$, output three contraction-expansion factor to adjust input and output universe. Therefore, the key to realize variable universe fuzzy control is the design of contraction-expansion factor fuzzy controller. We can define that $\alpha_1(x)$ and $\alpha_2(x)$ as the input universe contraction-expansion factor, and $\beta(y)$ as the output universe contraction-expansion factor. The design principle of control rules can be that:

(1) When $e(t)$ or $\Delta e(t)$ is large, in order to reduce the system error, α_1 and α_2 should take a large value. That is, the universe expansion is equivalent reduce rules, the control process is accelerated, and the value of β is basically invariant.

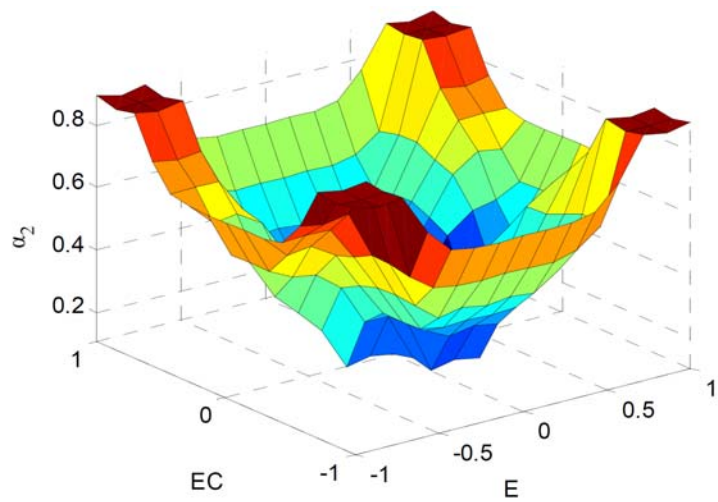
(2) When $e(t)$ or $\Delta e(t)$ is small, α_1 and α_2 should take a small value. The universe contraction is equivalent add rules, increase the sensitivity of the system, and the value of β should be reduced.

The initial universe of $\alpha_1, \alpha_2,$ and β can be take as $[0, 1]$. The universe of α_1 and α_2 can be partitioned into 4 fuzzy subset: [Z, S, M, B].

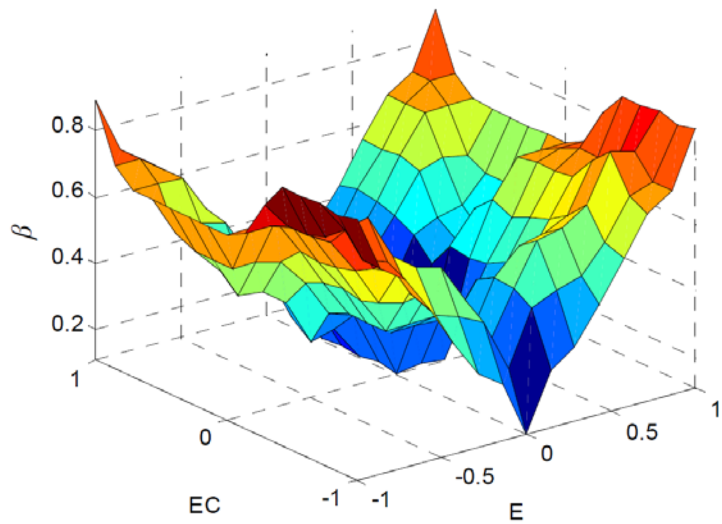
α_1, α_2, and β have the same control rules, and the corresponding peak point can be [0, 1/2, 2/3, 1]. The triangular membership function can be adopted as membership function of input and output can take, and the defuzzification can take the centroid method. From the control rules, we can get the contraction-expansion factor fuzzy controller output surface, as is shown in Figure 6.



(a) The fuzzy rules output surface of α_1.



(b) The fuzzy rules output surface of α_2.



(c) The fuzzy rules output surface of β.

Figure 6. The fuzzy rules output surface of three contraction-expansion factor.

The body vertical acceleration and velocity as the input of controller, and the output of the controller is the control force of actuator.

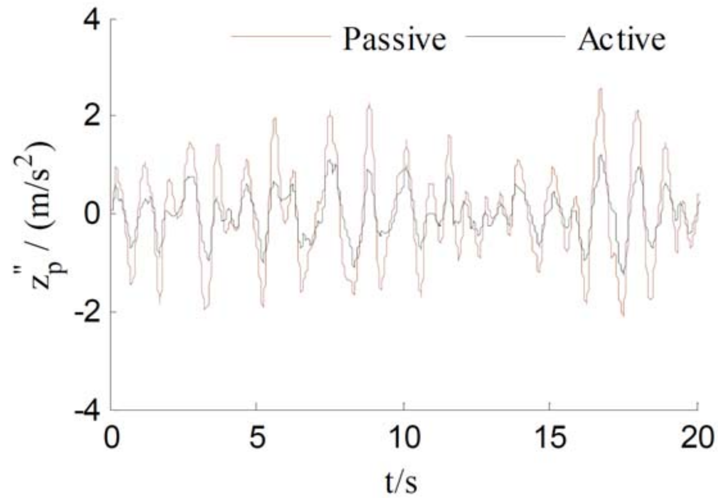
4. Simulation Analysis of System

A type of vehicle can be as the study object, and the parameters value is shown in Table 1.

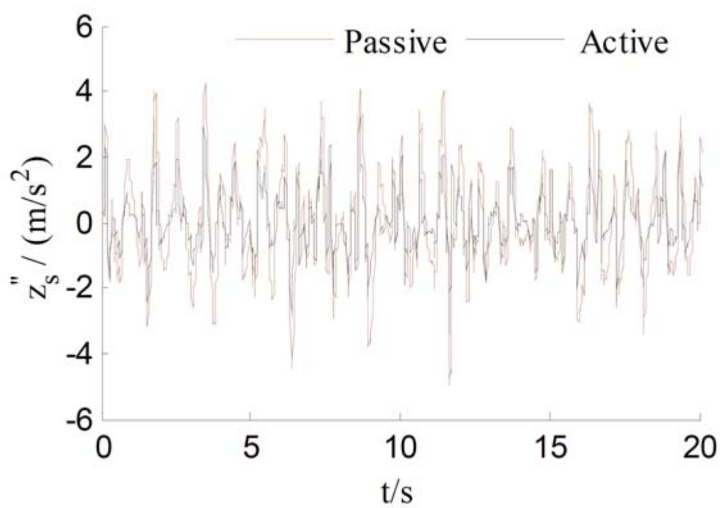
Table 1. Numerical parameters of vehicle

Symbol	Value	Symbol	Value
m_b/kg	320	$K_p/(\mathrm{N} \cdot \mathrm{m}^{-1})$	1800
m_p/kg	100	$K_t/(\mathrm{N} \cdot \mathrm{m}^{-1})$	200000
m_w/kg	40	$C_p/(\mathrm{N} \cdot \mathrm{s} \cdot \mathrm{m}^{-1})$	264
$K_s/(\mathrm{N} \cdot \mathrm{m}^{-1})$	20000	$C_s/(\mathrm{N} \cdot \mathrm{s} \cdot \mathrm{m}^{-1})$	1100

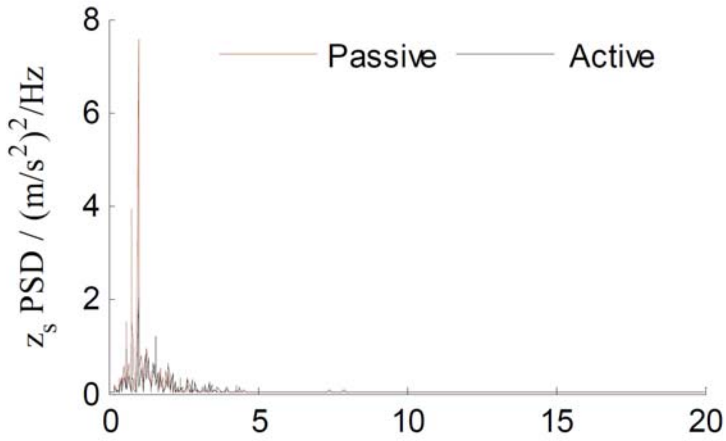
According to the complex of the working road, we define u_c = 20m/s, $G_0 = 5 \times 10^{-6} \mathrm{m}^3$/cycle, and $f_0 = 0.1$Hz. Through the simulation analysis in Matlab/Simulink, the performance comparison of active suspension and passive suspension can be shown in Figure 7.



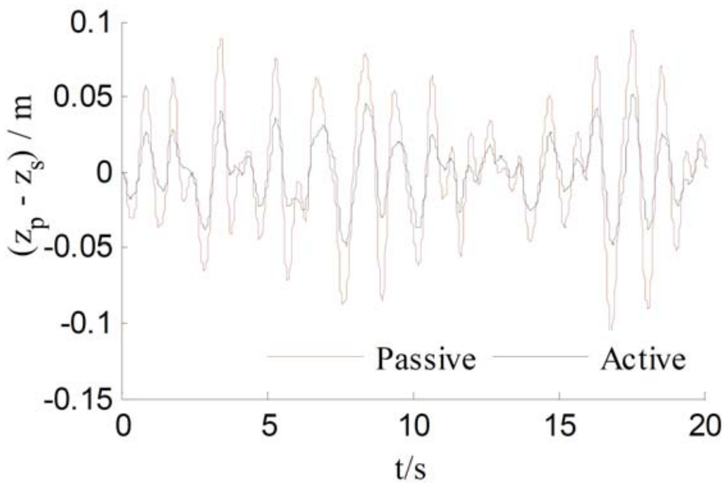
(a) The seat acceleration.



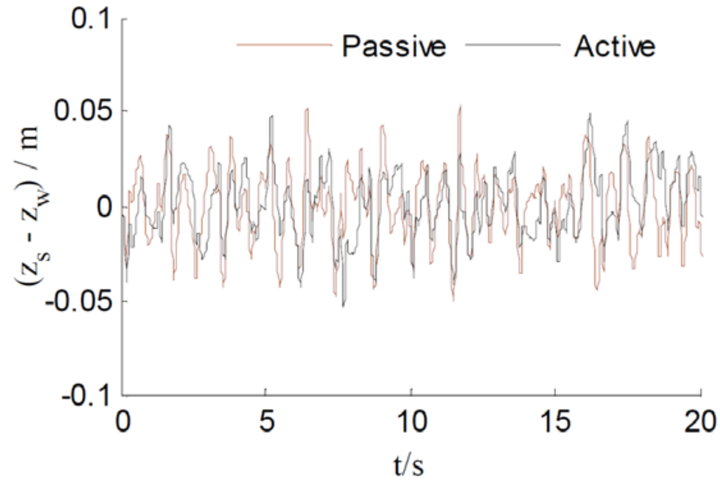
(b) The body acceleration.



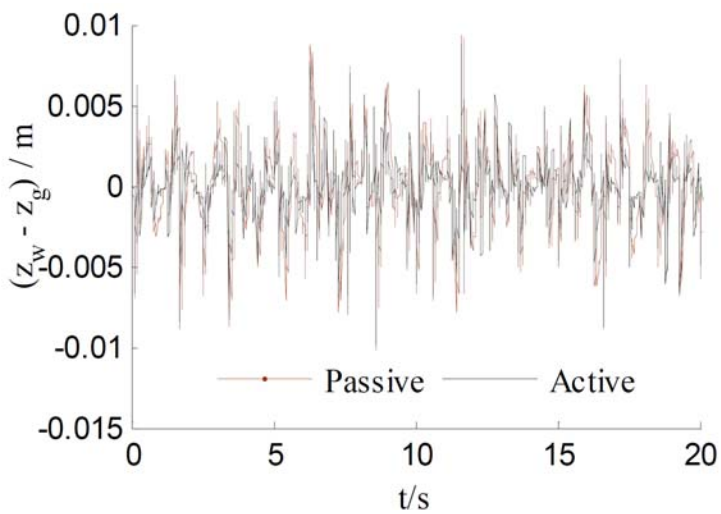
(c) The body acceleration PSD.



(d) The seat displacement.



(e) The suspension displacement.



(f) The tire displacement.

Figure 7. The performance comparison of two suspension.

From Figure 4, we can find that the peak value of seat and body acceleration of active suspension reduced when compared of the passive suspension. And the seat displacement, suspension displacement, and tire displacement of active suspension also reduced.

The comparison of each performance root mean square value of passive suspension and active suspension can be shown in Table 2.

Table 2. The comparison of performance root mean square value

Performance classification	Passive suspension	Active suspension	Performance improvement
$\ddot{z}_p(\text{m/s}^2)$	0.911	0.440	51.7%
$\ddot{z}_s(\text{m/s}^2)$	1.595	0.902	43.4%
$(z_p - z_s)(\text{cm})$	3.76	1.87	50.3%
$(z_s - z_w)(\text{cm})$	1.96	1.73	11.7%
$(z_w - z_g)(\text{mm})$	2.89	2.18	24.6%

It can be seen from the date in Table 2, the performance indicators of active suspension system have reached the minimum value, the suspension performance has been greatly improved.

5. Conclusion

From the analysis of simulation, all aspects of performance of active suspension have been generally improved than the passive suspension, especially in the body acceleration and seat acceleration. The ride comfort and running smoothness has been greatly improved. The variable universe adaptive fuzzy control based on fuzzy inference can meet the control requirements of active suspension system.

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