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# ROBUST ADAPTIVE SLIDING MODE CONTROLLER FOR SEMI-ACTIVE VEHICLE SUSPENSION SYSTEM

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Abstract. *For the tracking control problem of vehicle suspension, a robust design method of adaptive sliding mode control is derived in this paper. The influence of parameter uncertainties and external disturbances on the system performance can be reduced and system robustness can be improved. The adaptive sliding mode controller is designed so that the practical system can track the state of the reference model. The asymptotically stability of the adaptive sliding mode control system is proved based on the Lyapunov stability theory. Numerical simulations demonstrate the effectiveness of the proposed adaptive sliding mode control for semi-active vehicle suspension.*
**Keywords:** Adaptive sliding mode control, Vehicle suspension, Reference model, Lyapunov stability

1. **Introduction.** The performance of vehicle suspension is typically evaluated by its handling safety and riding comfort. The current vehicles can only offer a compromise between these two properties by providing spring and damping coefficients with fixed rates. Among them, semi-active suspension control systems have wide application prospects in the future. Compared with active suspension system, the advantages of the semi-active suspension system are simple, economical, safe and a small power demand. Therefore, semi-active suspension system has been researched for a long time.

A variety of control algorithms have been proposed for semi-active suspension. From skyhook, LQG and fuzzy control strategies have been studied. Karnopp et al. [1] first proposed a skyhook control algorithm for a vehicle suspension system and demonstrated that this system can improve performance over a passive system when applied to a single-degree-of-freedom system. Dyke et al. [2] applied a clipped-optimal control strategy (LQG) based on acceleration feedback. The performance of LQG or LQR controllers is dependent upon the choice of weighting matrices for the vector of regulated responses and control forces. Fang and Chen [3] applied a fuzzy control strategy to a 4-DOF vehicle model and developed a useful control strategy.

As we know, vehicle is a complicated vibration system which needs to be simplified in order to build its dynamic model. However, simplified model is not exact. Otherwise, the variation in load, the nonlinear of spring and damper, the wear of tires as well as the pressure variation in tires could generate parameters variations in systems and cause model uncertainties. In order to reach a high robustness against model parameter uncertainty and road disturbance, robust control schemes should be adopted. Various robust control strategies have been proposed including sliding mode control [4], $H_\infty$ control, adaptive control [5] and so on.

The sliding mode control was first proposed by Utkin [6]. Dan [7] presented the application of sliding mode control to stabilize an electromagnetic suspension system with experimental results. Young [8] developed a sliding mode controller for robot manipulators. Sam et al. [9] presented a class of proportional and integral sliding mode control with application to active suspension system. Yagiz et al. [10] developed a backstepping controller for the vehicle suspension system. Priyandoko et al. [11] used skyhook and adaptive neuro active force control for the vehicle active suspension of a quarter car model. Yagiz et al. [12] applied fuzzy sliding mode control for the active vehicle. Huang et al. [13] proposed an adaptive sliding controller with self-tuning fuzzy compensation for vehicle suspension control. Cao et al. [14] reviewed recent intelligent control approaches such as fuzzy inference systems, neural networks and genetic algorithms for active suspension systems. Adaptive laws to estimate the upper bound of uncertainties are developed in [15-17]. Robust adaptive sliding mode control for triaxial MEMS gyroscope and adaptive feedforward control with discrete time sliding mode compensator for flexible structure were presented in [18,19] respectively. Jiang et al. [20] proposed robust adaptive integral variable structure attitude controller with application to flexible spacecraft. The information of the upper bound of the uncertainties and disturbance must be known in advance in the previous research related to active suspension system. In this paper, this limitation is removed and an adaptive control algorithm is derived to estimate the upper bound of the uncertainties and disturbance based on the methodologies [15-17].

In this paper, a sliding mode control combined with adaptive control based on Lyapunov stability theory for the vehicle suspension in the presence of the model uncertainties and external disturbances is proposed. A convergence analysis of adaptive sliding mode control is given in detail. The innovation of the paper is that an adaptive sliding mode controller to estimate the unknown upper bound of model uncertainties and external disturbances in the vehicle suspension is proposed. According to the literature review, all the previous research papers regarding to the control of vehicle suspension did not adopt adaptive sliding mode scheme. This paper introduced the adaptive sliding mode control that could identify unknown upper bound of model uncertainties and external disturbances using adaptive model reference controller. The novelty of the adaptive design is that adaptive control is incorporated into the sliding mode control to improve the adaptation and robustness of the semi-active vehicle suspension system. The proposed method could provide higher adaptation ability than standard sliding mode control systems. The simulation will show that the suspension system using adaptive sliding mode controller is more stable and accurate than standard and non-adaptive sliding mode controller.

The paper is organized as follows. In Section 2, the dynamic model of semi-active vehicle suspension model is derived. In Section 3, the adaptive sliding mode controller is developed to achieve the state tracking objectives and estimate the unknown upper bound of model uncertainties and external disturbances. In Section 4, simulation results are presented to verify the proposed adaptive sliding mode control. Conclusion is provided in Section 5.

## 2. **Vehicle Suspension System Model.** 

In this paper, the 1/4 vehicle model of two-degree-of-freedom is adopted, as shown in Figure 1.

The dynamic differential equations of suspension system are set up as follows:

$$\begin{cases} m_s\ddot{z}_s = -k_s(z_s - z_t) - f_d \\ m_t\ddot{z}_t = k_s(z_s - z_t) - k_t(z_t - z_0) + f_d \end{cases} \tag{1}$$

where $m_s$ and $m_t$ are the sprung mass and the unsprung mass of the system, $k_s$ is the suspension rigidity, $k_t$ is the tyre rigidity, $C$ is the suspension damper, $z_s$ and $z_t$ are the displacements of the sprung mass and the unsprung mass. $z_0$ represents the road displacements. Let $x_1 = z_s - z_t$, $x_2 = z_t - z_0$, $x_3 = \dot{z}_s$, $x_4 = \dot{z}_t$, $X = [x_1, x_2, x_3, x_4]^T$. The state space equation in matrix is given by:

$$\dot{X} = AX + Bu + Cw \tag{2}$$

where $A = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\dfrac{k_s}{m_s} & 0 & 0 & 0 \\ \dfrac{k_s}{m_t} & -\dfrac{k_t}{m_t} & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 & -\dfrac{1}{m_s} & \dfrac{1}{m_t} \end{bmatrix}^T$, $C = \begin{bmatrix} 0 & -1 & 0 & 0 \end{bmatrix}^T$, $w = \dot{z}_0$.

For the purpose of model reference, the suspension system with the skyhook damper is used as the reference model, as shown in Figure 2.

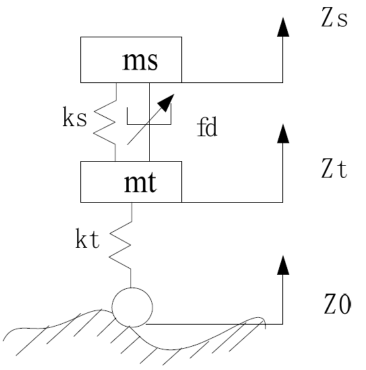


FIGURE 1. Vehicle dynamic model with 1/4 body

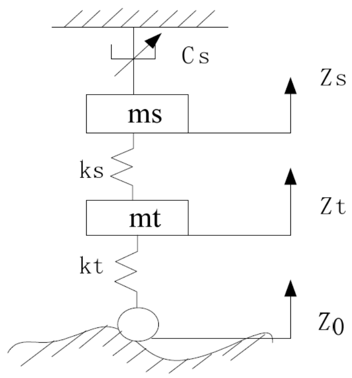


FIGURE 2. Skyhook damper model

The dynamic differential equations are set up as follows:

$$\begin{cases} m_s\ddot{z}_s = -k_s(z_s - z_t) - f_{dr} \\ m_t\ddot{z}_t = k_s(z_s - z_t) - k_t(z_t - z_0) \end{cases} \tag{3}$$

$$f_{dr} = \begin{cases} C_s\dot{z}_s & \dot{z}_s(\dot{z}_s - \dot{z}_t) > 0 \\ 0 & \dot{z}_s(\dot{z}_s - \dot{z}_t) \le 0. \end{cases} \tag{4}$$

Rewriting the reference model in state-space equation:

$$\dot{X}_m = A_m X_m + B_m f_{dr} + C_m w \tag{5}$$

where $X_m = [z_s - z_t, z_t - z_0, \dot{z}_s, \dot{z}_t]^T$, $A_m = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\dfrac{k_s}{m_s} & 0 & 0 & 0 \\ \dfrac{k_s}{m_t} & -\dfrac{k_t}{m_t} & 0 & 0 \end{bmatrix}$,

$B_m = \begin{bmatrix} 0 & 0 & -\dfrac{1}{m_s} & 0 \end{bmatrix}^T$, $C_m = \begin{bmatrix} 0 & -1 & 0 & 0 \end{bmatrix}^T$, $w = \dot{z}_0$.

3. **Adaptive Sliding Mode Control Design.** Consider the system in (2) with parameter uncertainties and external disturbances, and (2) can be rewritten as follows:

$$\dot{X} = (A + \Delta A)X + Bf_d + C\xi + f(t) \tag{6}$$

where $\Delta A$ is the unknown parameter uncertainties of the matrix $A$, $f(t)$ is uncertain external disturbances or unknown non-linearity of the system.

To ensure the achievement of model reference's objective, we make the following assumptions:

Assumption 1 (matching condition): There exist unknown matrix functions of appropriate dimensions $D(t)$ and $G(t)$ such that

$$f(t) = BG(t), \quad \Delta A(t) = BD(t) \tag{7}$$

Under the assumption of matching condition, (6) can be rewritten as follows:

$$\begin{aligned} \dot{X} &= AX + Bf_d + C\xi + \Delta AX + f(t) \\ &= AX + Bf_d + C\xi + BDX + BG \\ &= AX + Bf_d + C\xi + Bf_m \end{aligned} \tag{8}$$

where $Bf_m$ represents the lumped matched parameter uncertainties and external disturbances, which is given by

$$f_m = DX + G \tag{9}$$

Assumption 2 (bounded condition): There exist unknown positive constants $\bar{\alpha}_1$ and $\bar{\alpha}_2$ such that

$$\|f_m\| \le \bar{\alpha}_1 + \bar{\alpha}_2 \|X\|. \tag{10}$$

Define the tracking error as follows:

$$e = X - X_m \tag{11}$$

Then its derivative is

$$\dot{e} = A_m e + (A - A_m)X + Bf_d + B_m f_{dr} + Bf_m \tag{12}$$

Define the sliding surface as follows:

$$S = \lambda e \tag{13}$$

where $\lambda$ is a constant matrix.

The derivative of the sliding surface is

$$\dot{S} = \lambda\dot{e} = \lambda A_m e + \lambda(A - A_m)X + \lambda Bf_d + \lambda B_m f_{dr} + \lambda Bf_m. \tag{14}$$

The equivalent control of can be obtained as:

$$f_{deq} = -(\lambda B)^{-1}\lambda A_m e - (\lambda B)^{-1}\lambda(A - A_m)X - (\lambda B)^{-1}\lambda B_m f_{dr}. \tag{15}$$

We consider the following sliding mode control law

$$\begin{aligned} f_d &= f_n + f_{deq} + f_s \\ &= -K(\lambda B)^{-1}S - (\lambda B)^{-1}\lambda A_m e - (\lambda B)^{-1}\lambda(A - A_m)X \\ &\quad - (\lambda B)^{-1}\lambda B_m f_{dr} - \frac{B^T\lambda^T S}{\|B^T\lambda^T S\|}\rho \end{aligned} \tag{16}$$

where $K$ is a positive constant, $\rho = \alpha_1 + \alpha_2 \|X\|$ is adaptive estimation of the upper bound of $f_m$, $\alpha_1$ and $\alpha_2$ are estimation value of $\bar{\alpha}_1$ and $\bar{\alpha}_2$ respectively, $f_s = -\dfrac{B^T\lambda^T S}{\|B^T\lambda^T S\|}\rho$ is the sliding mode term representing the non-linear feedback control for suppressing the effect of the uncertainty.

Substituting (16) into (14), $\dot{S}$ becomes

$$\dot{S} = -KS + \lambda B f_m - \rho\lambda B \frac{B^T\lambda^T S}{\|B^T\lambda^T S\|} \tag{17}$$

Define a Lyapunov function as follows:

$$V = \frac{1}{2}S^T S + \frac{1}{2}c_1\tilde{\alpha}_1^2 + \frac{1}{2}c_2\tilde{\alpha}_2^2 \tag{18}$$

where $\tilde{\alpha}_1 = \alpha_1 - \bar{\alpha}_1$, $\tilde{\alpha}_2 = \alpha_2 - \bar{\alpha}_2$.

Differentiating (18) with respect to time yields

$$\begin{aligned}
\dot{V} &= S^T\dot{S} + c_1\tilde{\alpha}_1\dot{\tilde{\alpha}}_1 + c_2\tilde{\alpha}_2\dot{\tilde{\alpha}}_2 \\
&= S^T\left(-KS + \lambda B f_m - \rho\lambda B\frac{B^T\lambda^T S}{\|B^T\lambda^T S\|}\right) + c_1\tilde{\alpha}_1\dot{\tilde{\alpha}}_1 + c_2\tilde{\alpha}_2\dot{\tilde{\alpha}}_2 \\
&= -KS^T S + S^T\lambda B f_m - \rho S^T\lambda B\frac{B^T\lambda^T S}{\|B^T\lambda^T S\|} + c_1\tilde{\alpha}_1\dot{\tilde{\alpha}}_1 + c_2\tilde{\alpha}_2\dot{\tilde{\alpha}}_2 \\
&= -KS^T S + S^T\lambda B f_m - \rho\left\|B^T\lambda^T S\right\| + c_1\tilde{\alpha}_1\dot{\tilde{\alpha}}_1 + c_2\tilde{\alpha}_2\dot{\tilde{\alpha}}_2 \\
&= -KS^T\mathrm{S} + S^T\lambda B f_m - (\alpha_1 + \alpha_2\|X\|)\left\|B^T\lambda^T S\right\| + c_1(\alpha_1 - \overline{\alpha}_1)\dot{\tilde{\alpha}}_1 + c_2(\alpha_2 - \overline{\alpha}_2)\dot{\tilde{\alpha}}_2 \\
&\le -KS^T S + \left\|B^T\lambda^T S\right\|\|f_m\| - (\alpha_1 + \alpha_2\|X\|)\left\|B^T\lambda^T S\right\| \\
&\quad + c_1(\alpha_1 - \overline{\alpha}_1)\dot{\tilde{\alpha}}_1 + c_2(\alpha_2 - \overline{\alpha}_2)\dot{\tilde{\alpha}}_2 \\
&\le -KS^T S + \left\|B^T\lambda^T S\right\|(\overline{\alpha}_1 + \overline{\alpha}_2\|X\|) - (\alpha_1 + \alpha_2\|X\|)\left\|B^T\lambda^T S\right\| \\
&\quad + c_1(\alpha_1 - \overline{\alpha}_1)\dot{\tilde{\alpha}}_1 + c_2(\alpha_2 - \overline{\alpha}_2)\dot{\tilde{\alpha}}_2 \\
&= -KS^T S - (\alpha_1 - \overline{\alpha}_1)(\left\|B^T\lambda^T S\right\| - c_1\dot{\tilde{\alpha}}_1) - (\alpha_2 - \overline{\alpha}_2)(\left\|B^T\lambda^T S\right\|\|X\| - c_2\dot{\tilde{\alpha}}_2)
\end{aligned} \tag{19}$$

To make $\dot{V} \le 0$, we choose the adaptive laws for the upper bound as follows:

$$\begin{cases} \dot{\tilde{\alpha}}_1 = \dfrac{1}{c_1}\left\|B^T\lambda^T S\right\| \\ \dot{\tilde{\alpha}}_2 = \dfrac{1}{c_2}\left\|B^T\lambda^T S\right\|\|X\| \end{cases} \tag{20}$$

Substituting the adaptive laws (20) into (19), results in

$$\dot{V} \le -KS^T S \le 0. \tag{21}$$

This implies that $\dot{V}$ is negative semi-definite function.

Furthermore, we have

$$\int_0^t \dot{V}(\tau)d\tau = V(t) - V(0) \le -\int_0^t KS(\tau)^T S(\tau)d\tau \tag{22}$$

that is

$$V(t) + \int_0^t KS(\tau)^T S(\tau)d\tau \le V(0). \tag{23}$$

Since $V(0)$ is bounded and $V(t)$ is non-increasing bounded function, therefore,

$$\lim_{t\to\infty}\int_0^t KS(\tau)^T S(\tau)d\tau < \infty \tag{24}$$

According to Barbalat lemma, it can be concluded that $\lim_{t\to\infty} KS(\tau)^T S(\tau)d\tau = 0$, which means $\lim_{t\to\infty} S(t) = 0$ and also $\lim_{t\to\infty} e(t) = 0$.

**Remark 3.1.** *In order to eliminate chattering, the discontinuous control component $f_s$ in (16) can be replaced by a smooth sliding mode component to yield*

$$f_s = \frac{B^T \lambda^T S}{\|B^T \lambda^T S\| + \varepsilon} \rho \tag{25}$$

*where $\varepsilon > 0$ is a small constant. This creates a small boundary layer around the switching surface in which the trajectory will remain. Therefore, the chattering problem can be reduced.*

**Remark 3.2.** *Sometimes $S$ will not be equal to zero all the time if the continuous approximation for the sliding mode law is used, therefore the adaptive gain will slowly increase boundlessly. This will decrease the tracking accuracy of control system. The dead-zone techniques can be used to remove this implementation problem. To eliminate the problem of integral wind-up in the adaptation of the upper bound of the unknown disturbance, the adaptive laws are modified as*

$$\begin{cases} \dot{\tilde{\alpha}}_1 = \dfrac{1}{c_1} \left( -\varphi_1 \tilde{\alpha}_1 + \left\| B^T \lambda^T S \right\| \right) \\ \dot{\tilde{\alpha}}_2 = \dfrac{1}{c_2} \left( -\varphi_2 \tilde{\alpha}_2 + \left\| B^T \lambda^T S \right\| \|X\| \right) \end{cases} \tag{26}$$

*where $\varphi_1$ and $\varphi_{21}$ are constants.*

4. **Simulation Study.** According to the proposed control method, the simulation is performed using MATALB/Simulink. We choose the following parameters: $m_s = 500kg$, $m_t = 50kg$, $k_s = 16800N/m$, $k_t = 168000N/m$, $C_s = 3550N \cdot s/m$, $\lambda = \begin{bmatrix} -10 & 10 & -10 & 1 \end{bmatrix}$, $c_1 = 20$, $c_2 = 20$, $\varphi_1 = 10$, $\varphi_2 = 10$.

In this paper, we choose Grade C road as random input reflecting different amplitudes of road input, the irregular road coefficients is $G_0 = 256 \times 10^{-6} m^2$, the variance of road excitation signal is $n_0 = 0.1$ and velocity is $v = 20m/s$. The random road input is shown in Figure 3. This is to simulate a stabilized road with $1cm \times 1cm$ pebbles.

Considering the riding comfort, the body acceleration is an important evaluation target in this research. The body acceleration response is shown in Figure 4. It can be seen that the controlled system can effectively track the reference system after a few time and the acceleration tracking error between the controlled system and referenced system is driven into a very small bounded region. It can be concluded that the proposed adaptive sliding mode controller is effective to reduce the acceleration error. In addition to considering the handing safety, dynamic tyre load and dynamic deflection of suspension system are also analyzed as shown in Figures 5 and 6, respectively, clearly demonstrating that the controlled system will follow the desired reference model.

The behavior of tracking error $e$ and the sliding surface $S$ are shown in Figures 7 and 8. It can be seen that tracking error and sliding surface are converge to zero asymptotically. Figure 9 shows the adaptation of the upper bound of the disturbance's magnitude. It is shown that the upper bound parameters $\alpha_1$ and $\alpha_2$ converge to constant values. Figure 10 shows the curve of the discontinuous control component $f_s$, where chattering phenomenon exists. When we add a small constant proposed in Remark 3.1, the chattering can be reduced. Therefore, we get a smooth sliding mode component $f_s$, as shown in Figure 11. That is to say, proposed controller can significantly improve the ride quality.

In the simulation, the system ability of rejecting external disturbances and parameter variations is also studied. Variances of sprung mass and stiffness coefficients were examined to check the adaptation capability.

First, in order to investigate the adaptability and robustness of the model parameters, the system will be charged 20% decline in the sprung mass, spring stiffness increased by 10%, that is $m_s = 400kg$, $k_s = 18480N/m$. Figure 12 shows the body acceleration response for the variable parameters. It can be seen that parameter variations do not affect the performance of the controller, the actual controlled system still can track the reference model and the tracking error is always maintained at a very small range. It indicates that the adaptive sliding mode control system has good adaptability and robustness.

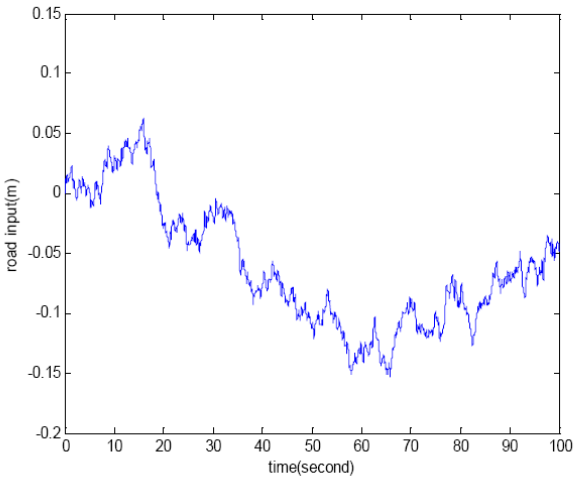


FIGURE 3. Random road input

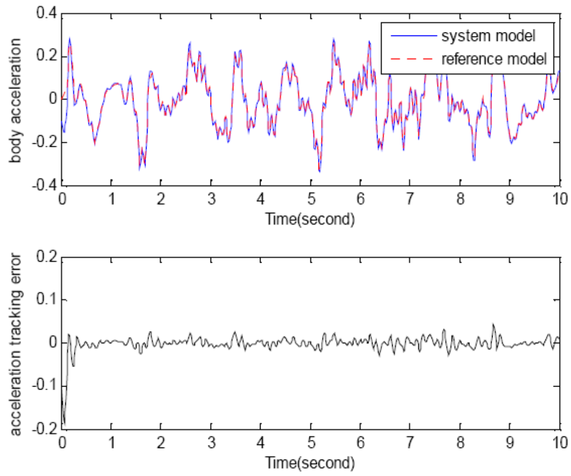


FIGURE 4. Body acceleration

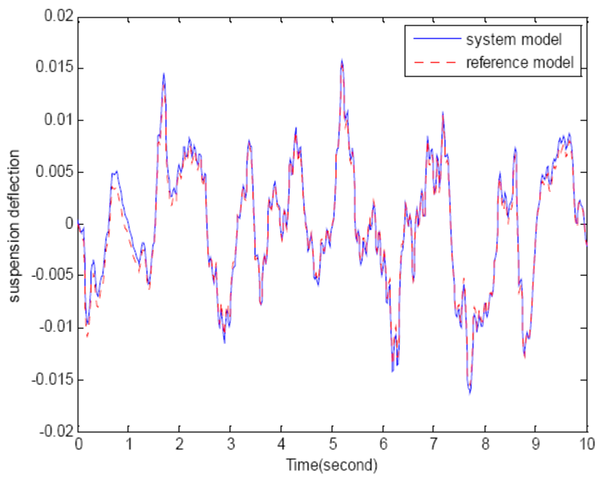


FIGURE 5. Suspension dynamic deflection

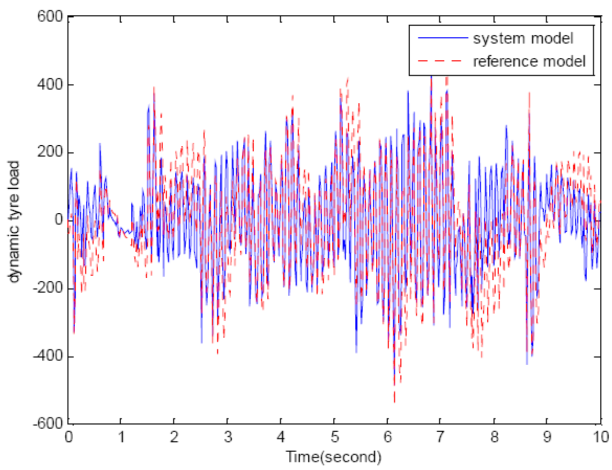


FIGURE 6. Dynamic tyre load

Then, we consider the external disturbance $f(t) = 100\sin(wt)$, which will simulate the driving condition of sinusoidal bump road. Figure 13 shows the body acceleration of the adaptive sliding mode controlled suspension system, non-adaptive sliding mode control suspension and the passive suspension system. For comparison, they are plotted in one figure. In this figure, compared with passive suspension, the body acceleration in both the adaptive sliding mode and non-adaptive sliding mode controllers is greatly reduced, which indicates that the ride comfort has been significantly improved. By comparing the

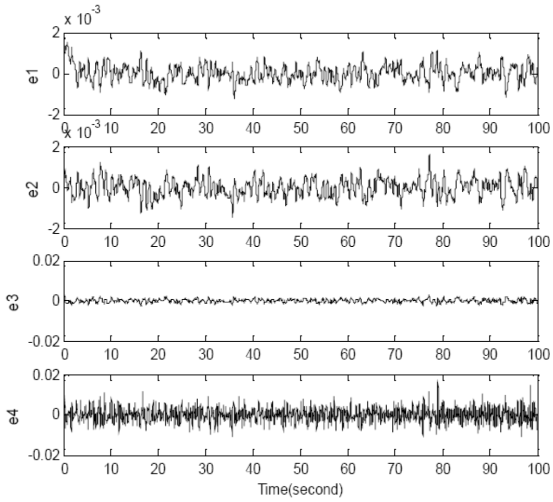


FIGURE 7. Tracking error $e(t)$

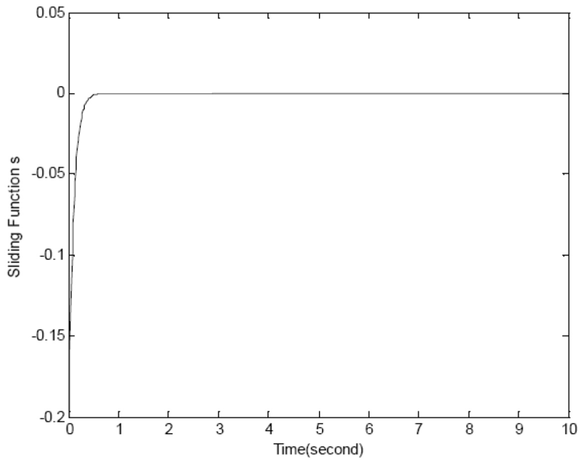


FIGURE 8. Sliding surface $S(t)$

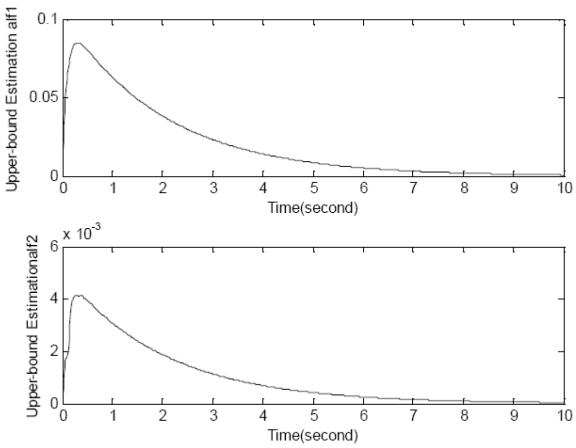


FIGURE 9. Adaptation of upper bound of disturbance

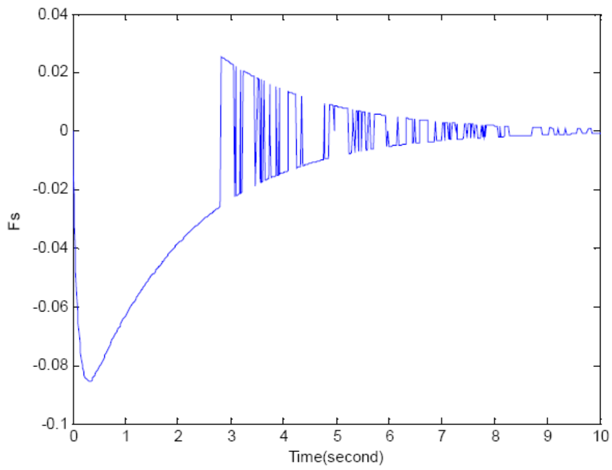


FIGURE 10. Control signal $f_s$ with chattering

tracking error, which is the adaptive sliding mode controller and sliding mode controller between the reference model, we can see that the adaptive sliding mode control method has stronger disturbance rejecting ability than standard sliding mode control. It can be observed that the proposed method is effective in achieving the design objective.

**Remark 4.1.** *Although the simulation results demonstrated the good adaptation performance with the proposed adaptive sliding mode controller, more realistic driving conditions should be implemented to improve the potential of practical application. Therefore, it is necessary to evaluate the driving conditions to simulate the practical road surface from the perspective of practical application which seems to be the future research works.*

5. **Conclusions.** In this paper, to deal with the parameter uncertainties of the vehicle suspension, an adaptive sliding mode controller was successfully designed based on sliding mode and Lyapunov stability theory. The proposed control method could reduce the body acceleration to a large extent by adjusting the adjustable gain of parameter estimation to

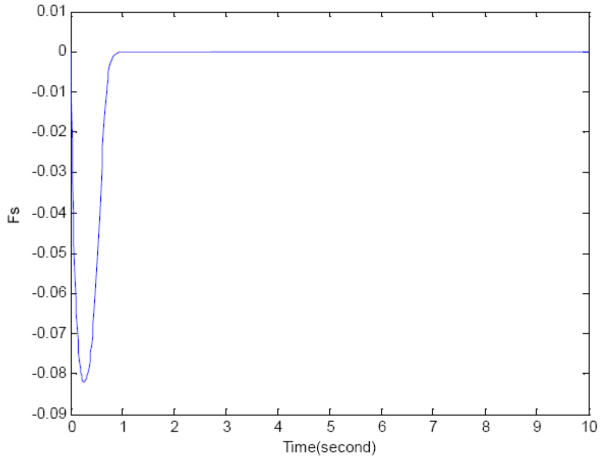


FIGURE 11. Control signal $f_s$ with smooth sliding mode control force

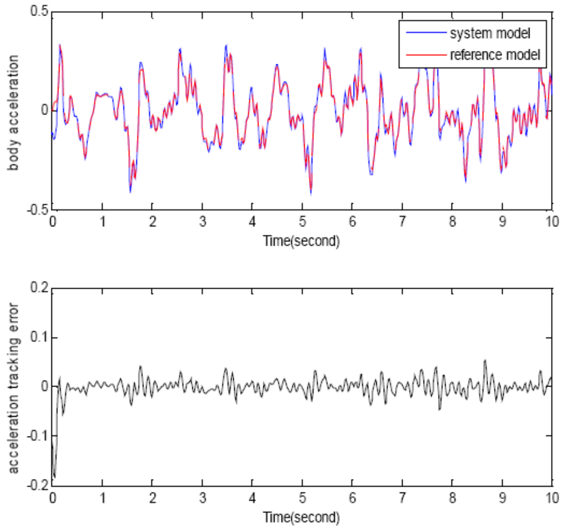


FIGURE 12. Body acceleration response (variable parameters

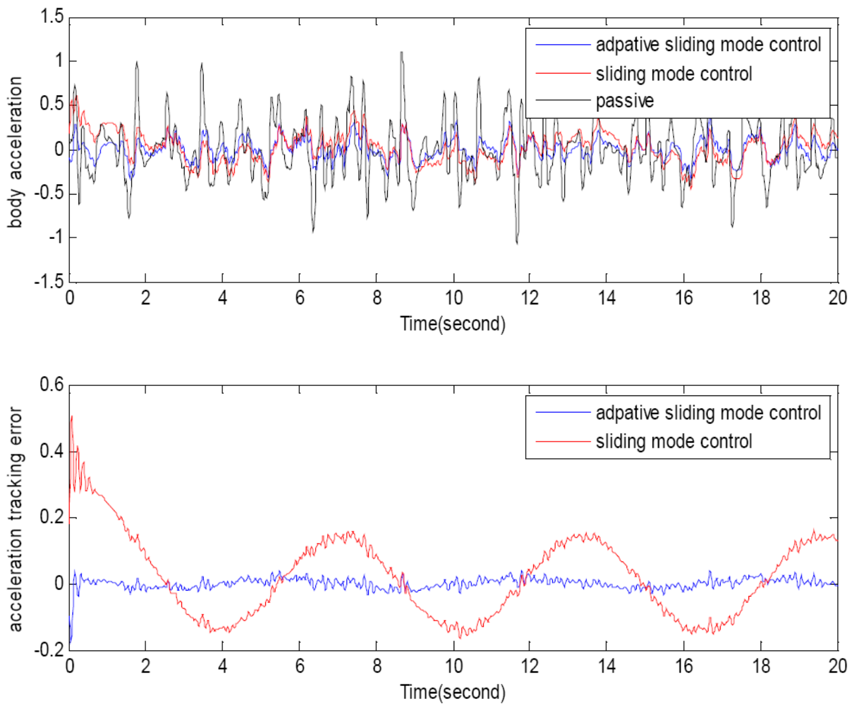


FIGURE 13. Comparison for body acceleration

estimate the unknown upper bound of the uncertainties. It has good dynamic response and tracking performance. Besides, the adaptive algorithm is simple, easy to achieve and has good adaptability and robustness against the parameter variations and external disturbances. Furthermore, a smooth version of the adaptive sliding mode controller is used to reduce the control chattering. Simulation results show that the adaptive sliding mode control is more effective than the standard non-adaptive sliding mode control in the presence of model uncertainties and external disturbances.

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