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Abstract

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Robust Adaptive Sliding Mode PI Control for Active Vehicle Seat Suspension Systems

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Abstract: In this paper, a robust adaptive sliding mode proportional integral control (RASMPIC) method is proposed for an active vehicle seat suspension system, where the driver's mass is supposed as an unknown parameter with boundaries. A dynamic active seat suspension system is established at first. Then a sliding mode controller (SMC) is designed to achieve the required ride comfort performance based on the driver's mass estimated by utilizing an adaptive law where a projecting adaptive algorithm is used to prevent the estimated parameters from surpassing their boundaries to enhance the robustness of the seat suspension system. Also, a proportional and integral (PI) control for driver's acceleration is added into the controller as RASMPIC for the stabilization of the proposed suspension system. In simulations, sinusoidal vibrations are used to test the controllers and the results show the RASMPIC has a better control performance to reduce driver's acceleration and improve the driving comfort than SMC and RASMC.

Key Words: SMC, RASMC, RASMPIC, active seat suspension, vibration, ride comfort

1 INTRODUCTION

Vehicle vibrations, caused by uneven road surfaces, can damage not only vehicles and cargos but also the health of drivers or passengers [1]. A suspension system is one of the important parts of the vehicles, which can protect vehicles and cargos from damage and improve driver's comfort [2]. In the past decades, a lot of research has been done to improve the performance of the vehicle suspensions [3]. However, heavy vehicle drivers, such as truck, SUV, crane, agricultural vehicle drivers, still suffer a lot from vehicle vibrations [4]. Therefore, seat suspensions are necessary for those heavy vehicles to improve the driving comfort [5].

There are generally three main types of seat suspensions: passive, semi-active and active suspensions [6]. Passive seat suspensions are the simplest and cheapest, because they only contain springs and dampers, but fixed parameters make them only suitable for certain road disturbances [7]. Most of the passive seat suspension research focuses on the optimization of damping coefficients and spring stiffness without external inputs [8]. Semi-active seat suspensions are one kind of controllable suspension systems, which are able to adjust coefficients of dampers according to road surface conditions and vehicle body posture perceived by sensors, in order to improve smooth and stable driving performance of vehicles [9]. Semi-active seat suspensions have simple structures, low

cost and good performance, but output forces of controllable dampers are in most time nonlinear and constrained [10]. Generally speaking, active seat suspensions have the best performance among the three types of seat suspensions, because an additional control force device (actuator) can make suspension systems always stay in optimum vibration reduction state [11]. There have been many control methods used to improve driving comfort for active seat suspension systems, such as robust control [12], fuzzy control [13], sliding mode control [14], adaptive control [15, 16], neural network control [17], etc.

Since 1950s, adaptive control was invented to deal with uncertain or unknown parameters problems in some control systems [18], which can modify its own characteristics to adapt the dynamics of the plant and disturbance's variability. An adaptive tracking control method is proposed in [15] to deal with the nonlinearity in a bioinspired dynamics-based suspension system. Another adaptive tracking control method is proposed in [16] to adapt parameter uncertainties and the effects from non-ideal actuator (with dead-zone and hysteresis) for active suspension systems.

Sliding mode control (SMC) is a series of variable structure controllers [19], which can deal with some problems like uncertain system parameters and external disturbance because of its robust characteristics. A recursive derivative nonsingular higher order terminal sliding mode method is proposed in [14] based on a highgain observer to estimate the nonlinear system states for an active suspension system to cope with external disturbance, system nonlinearities and uncertainties. A high order sliding mode controller is designed for active vehicle suspension systems based on super twisting algorithm to attenuate chattering for the

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suspension stable control with parameter variation and external disturbance in [20].

Because both adaptive control and sliding mode control have the ability to deal with the uncertainties of the systems and external disturbance, they are often combined together to obtain the advantages of these two control methods and get better control performance [19, 21-23]. An adaptive sliding mode controller is designed in [19] for Markov jump nonlinear systems to cope with actuator faults, nonlinearity of the system and external disturbance. An adaptive sliding mode control scheme is proposed in [21] together with the pole-placement control and the time-delay estimation technique to achieve a tracking control for robot manipulators. An adaptive robust sliding mode controller is designed in [22] to achieve position tracking control for induction motor. An adaptive sliding mode controller is designed in [23] together with T-S fuzzy approach for a nonlinear half-vehicle active suspension model to deal with the varying sprung and unsprung mass and the unknown actuator nonlinearity. However, to the authors' best knowledge, the combination of adaptive control and sliding mode control haven't been applied into an active seat suspension system, which greatly activates the authors' motivation to introduce the adaptive sliding mode control into a vehicle seat suspension system.

Different masses from different drivers and dynamic driving gesture of drivers may affect the real suspension control mass, which can also bring some uncertainties for the active seat suspension system to make the vibration control more difficult. In this paper, both the uncertainties of the driver's mass and external disturbance are taken into consideration. A model reference adaptive law is designed to estimate the driver's mass, so it is unnecessary to weigh drivers before sitting on the seat. Then the adaptive sliding mode controller is constructed to guarantee that the states of the active seat suspension system can reach the sliding mode surface and stay stable. To avoid the estimated value of the driver's mass becoming too large to make the input force of the actuator beyond its maximum value, a projection function is used here to enhance the robustness of the controlled active vehicle seat suspension system. Then, we can obtain the robust adaptive sliding mode controller (RASMC) for the seat suspension system.

The sliding surface is designed by driver's displacement and velocity, so the major control objective of RASMC is to reduce the absolute displacement of drivers. However, the value of driver's acceleration is the main factor to influence the driving comfort. Because of the characteristics of the seat suspension system, a small dynamic variable value of the displacement can't guarantee a small value of the acceleration. In fact, there often exist some spiking responses of the acceleration when the active seat suspension meets some disturbance like a sinusoidal function because the RASMC focuses on reducing the displacement of drivers. To deal with this problem, a proportional and integral (PI) control for the acceleration can be added into the controller. An acceleration sensor can measure a driver's acceleration at real time, so the PI control for the acceleration is available for practical use.

The main contributions of this paper can be listed as follows:

- Driver's mass is not necessary to know in advance, which can be estimated through the adaptive law.
- A PI control for driver's acceleration is added into the controller for vibration control, which greatly helps to reduce driver's acceleration and improve the driving comfort.
- The PI controller also helps to smooth the input force, which is easier to output the control force for actuators.

The content of this paper is organized as follows. Section 2 will introduce the active suspension system and some standards for the vibration isolation. The robust adaptive sliding mode PI controller (RASMPIC) will be designed and the proof of the stability of the seat suspension system with RASMPIC is given in Section 3. Section 4 will show some simulation results to illustrate the outstanding control performance of the proposed control methods for vibration control. The conclusion will be given in Section 5.

2 SEAT SUSPENSION MODEL AND CONTROL OBJECTIVE

2.1 Seat suspension model

Fig 1. Active seat suspension model.

A simplified active seat suspension model is shown in Fig. 1. According to Newton's second law, the dynamic active seat suspension model can be described as

$$m\ddot{z}_s + c(\dot{z}_s - \dot{z}_v) + k(z_s - z_v) = u \quad (1)$$

where m is the unknown mass of a drive and the seat; k is the stiffness of the seat suspension; c is the damping coefficient of the seat suspension; z_s and z_v are the displacements of the suspension upper and base, respectively; $\dot{z}_s$ and $\dot{z}_v$ are the velocities of the suspension upper and base, respectively; u is the control input.

When defining $x = z_s$, $d = kz_v + c\dot{z}_v$, equation (1) can be rewritten as

$$m\ddot{x} + c\dot{x} + kx - d = u \quad (2)$$

where x is regarded as state variable and d as a general disturbance. The following Assumptions are used for the following proof.

Assumption 1: The disturbance d is bounded for a stable system as

$$|d| \leq D \quad (3)$$

Assumption 2: The upper and lower bound of the uncertain parameter m can be defined as

$$m \in \Omega \triangleq \{\theta: 0 < m_{\min} \leq m \leq m_{\max}\} \quad (4)$$

where $m_{\min}$ and $m_{\max}$ are the minimum and maximum value of the unknown driver's mass.

3 ROBUST ADAPTIVE SLIDING MODE PI CONTROL

In this section, both the robust adaptive sliding mode controller (RASMC) and the robust adaptive sliding mode PI controller (RASMPIC) are designed for the active vehicle seat suspension system. Sliding mode control is chosen as a main control method to reduce the driver's acceleration in this paper, because it has many advantages such as a fast response, less sensitive to parameters change and disturbance, no need to identify system online, simple physical implementation and easy to combine with other algorithms. However, the main control objective of the sliding mode control is to reduce the displacement value, because the sliding surface is designed by driver's displacement and velocity in this paper. Hence, it can do well for position tracking but not for acceleration reduction, because a small value of the acceleration can't be guaranteed by a small dynamic variable value of the displacement due to the seat suspension's own characteristics. In fact, when the controlled suspension system faces some disturbances (like a sinusoidal function), the performance of the acceleration of drivers often meets some spiking responses. It not only enlarges the acceleration value at a fast speed, but also makes the controller value change fast, which is not very easy to implement for the actuator. To deal with this problem, the driver's acceleration signal is also used to construct a controller. This controller can deal with the acceleration reduction directly, so it can eliminate the spiking response of the driver's acceleration. Additionally, an adaptive law is applied to estimate the unknown driver's mass for the seat suspension system, which makes it easy to control it because there is no need to weigh drivers every time.

Here we define a new sliding mode surface as

$$s = \dot{x} + c_s x \quad (5)$$

where $c_s > 0$.

Firstly, the robust adaptive sliding mode controller is designed for the active vehicle seat suspension system and a Lyapunov candidate is chosen as

$$V_1 = \frac{1}{2} \left[m s^2 + \frac{1}{\gamma} \tilde{m}^2 \right] \quad (6)$$

where $\tilde{m} = \hat{m} - m$ is the parameter estimation error and $\gamma > 0$ is a large constant.

Then the derivate of V_1 can be calculated as

$$\begin{aligned} \dot{V}_1 &= m s \dot{s} + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \\ &= s(m\ddot{x} + m c_s \dot{x}) + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \\ &= s(-c\dot{x} - kx + u + d + m c_s \dot{x}) + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \end{aligned} \quad (7)$$

Here the sliding mode controller can be chosen as

$$u = c\dot{x} + kx - \hat{m} c_s \dot{x} - k_s s - \sigma \text{sgn}(s) \quad (8)$$

where $k_s > 0$ and $\sigma > D$.

Substituting the controller (8) into equation (7), we have

$$\dot{V}_1 = -\tilde{m} c_s \dot{x} s - k_s s^2 - \sigma |s| + d s + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \quad (9)$$

Here we choose the adaptive law as

$$\dot{\hat{m}} = \gamma c_s \dot{x} s \quad (10)$$

where $\gamma > 0$ controls the adaption speed, so we have

$$\dot{V}_1 = -k_s s^2 - \sigma |s| + d s \leq -k_s s^2 \leq 0 \quad (11)$$

Therefore, it is clear to show that s converges to zero when $t \rightarrow \infty$ and the convergence rate of this suspension system depends on the value of k_s , so the stability of the active seat suspension system is guaranteed.

To reduce the oscillation of the input signal, the sign function in the control law can be replaced by a saturation function. Then the robust adaptive sliding mode controller (RASMC) can be rewritten as

$$u = c\dot{x} + kx - \hat{m} c_s \dot{x} - k_s s - \sigma \text{sat}(s) \quad (12)$$

where

$$\text{sat}(s) = \begin{cases} 1 & s > \Delta \\ k_t s & |s| \leq \Delta, k_t = \frac{1}{\Delta} \\ -1 & s < -\Delta \end{cases} \quad (13)$$

and Δ is a small positive number, which is the boundary layer of the saturation function.

Because of the existence of external disturbance, the estimated mass value $\hat{m}$ is not very easy to converge to its true value m . There often exists some oscillation of the estimated mass value, which easily causes the value of the input controller beyond its limited power. To deal with this problem, preventing $\hat{m}$ from getting too large or too small, the adaptive law should be designed to make $\hat{m} \in [m_{\min}, m_{\max}]$. A projecting adaptive algorithm can be adapted to bound the estimated driver's mass and strengthen the robustness of the seat suspension system, so the adaptive law (10) can be modified as follows:

$$\begin{aligned} \dot{\hat{m}} &= \text{Proj}_{\hat{m}}(\gamma c_s \dot{x} s) \\ \text{Proj}_{\hat{m}}(\cdot) &= \begin{cases} 0 & \text{if } \hat{m} \geq m_{\max} \text{ and } \cdot > 0 \\ 0 & \text{if } \hat{m} \leq m_{\min} \text{ and } \cdot < 0 \\ \cdot & \text{otherwise} \end{cases} \end{aligned} \quad (14)$$

When $\hat{m}$ surpasses the maximum value and tends to keep increasing as $\hat{m} > 0$, set $\hat{m}$ invariant as $\dot{\hat{m}} = 0$. Similarly, when $\hat{m}$ surpasses the minimum value and tends to keep decreasing as $\hat{m} < 0$, set $\hat{m}$ invariant as $\dot{\hat{m}} = 0$. Therefore, this projecting algorithm can bound $\hat{m} \in [m_{\min}, m_{\max}]$ and guarantee $-\tilde{m} c_s \dot{x} s + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \leq 0$, so $\dot{V}_1 \leq 0$ can be guaranteed.

To deal with the spiking responses of the acceleration, a PI control for the acceleration can be added into the RASMC (12). A new Lyapunov functional candidate can be designed as

$$V_2 = V_1 + k_p s^2 \quad (15)$$

where $k_p > 0$ is a proportionality coefficient. Then the derivate of V_2 can be calculated as

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + k_p s \dot{s} \\ &= s(-c\dot{x} - kx + u + d \\ &\quad + m c_s \dot{x} + k_p \ddot{x} + k_p c_s \dot{x}) + \frac{1}{\gamma} \tilde{m} \dot{\tilde{m}} \end{aligned} \quad (16)$$

Here we also choose the saturation function (13) to replace the sign function and the projecting adaptive algorithm (14), so the RASMPIC can be chosen as

$$u = c\dot{x} + kx - \hat{m} c_s \dot{x} - k_s s - \sigma \text{sat}(s) - k_p \ddot{x} - k_p c_s \dot{x} \quad (17)$$

where k_p and $k_p c_s$ can be regarded as the proportional and integral parameters of the PI controller for the acceleration.

Fig 2. Block diagram of the ARSMPIC scheme

Substituting the RASMPIC (17) and the projecting adaptive algorithm (14) into (16), we have

$$\dot{V}_2 = -k_s s^2 - \sigma |s| + ds \leq -k_s s^2 \leq 0 \quad (18)$$

The inequality (18) is similar with the inequality (9), so s converges to zero when $t \rightarrow \infty$. Therefore, the active vehicle seat suspension system with the RASMPIC (17) is stable and the convergence rate depends on the value of k_s . The proposed RASMPIC scheme in (17) is illustrated in block diagram of Fig 2. Compared with conventional sliding mode control, the proposed RASMPIC (17) adds an equivalent proportional and integral (PI) controller $-k_p \ddot{x} - k_p c_s \dot{x}$ of the driver's acceleration signal from the active seat suspension. This PI control part of the acceleration in the controller directly aims at reducing the acceleration value, so it can help to deal with the spiking response of the acceleration and get better vibration control performance.

4 SIMULATION RESULTS

In this section, some simulation results of the proposed control methods for the active seat suspension system are shown, which will show the good control performance of the proposed control methods.

The active vehicle seat suspension system parameters and the model reference system parameters are shown in Table 1. The initial value of $\hat{m}$ is chosen as 50kg. The adaption speed depends on the adaption gain. The larger adaption gain is, the faster the estimated $\hat{m}$ converges to the true mass value m , but too large adaption gain value easily cause a big oscillation of the estimated mass value $\hat{m}$. To get a good trade off, we choose an adaption gain value as $\gamma = 10^6$.

Table 1: The suspension system and the controller parameters

$m(\text{kg})$	$k_s(\text{N/m})$	$c_s(\text{Ns/m})$	$m_{\min}(\text{kg})$	$m_{\max}(\text{kg})$
80	4600	500	75	85
D	c	k	k_p	-
80	60	100	500	-

From Figure 3 and 4, we can see that both the RASMPIC and RASMC can reduce the displacement and velocity of the driver. But both the displacement and velocity of the seat suspension system with the controller RASMPIC are less than the seat suspension system with the controller RASMC.

To show the advantage of the RASMPIC for the active vehicle seat suspension system to reduce the driver's acceleration, we compare it with sliding mode control, RASMC and uncontrolled system. For sliding mode control, if we don't know the true mass value and use the false mass value to the sliding mode controller, it is easy to make the system become divergent.

Fig 3. The displacement comparison of the seat suspension system with sinusoidal vibration

Fig 4. The velocity comparison of the seat suspension system with sinusoidal vibration

Fig 5. The acceleration comparison of the seat suspension system with sinusoidal vibration

Fig 6. The driver's mass estimation comparison

Fig 7. The output value of the controllers RASMPIC (17) and RASMC (12) with sinusoidal vibration disturbance

Therefore, we have to suppose the true mass value is known, so the sliding mode controller is $u = c\dot{x} + kx - mc_s\dot{x} - k_s s - \sigma \text{sat}(s)$, where $c_s = 60$, $k_s = 100$, $\sigma = 100$. The driver's acceleration response performance of different control methods for the seat suspension system is shown in Fig 5. Here it is clear to see that the proposed RASMPIC method has the best control performance to reduce the driver's acceleration, which can greatly improve the driving comfort. Especially for the acceleration, the RASMC can reduce it compared with uncontrolled seat suspension system, but there are some spiking responses, which greatly influence the driving comfort. There is no spiking response in the acceleration performance of the seat suspension system with the RASMPIC, and the peak value of the acceleration is reduced a lot, so the RASMPIC has better control performance than RASMC.

Fig 6 shows that both the RASMPIC and RASMC can estimate the mass value and bound this value in a limited area, but RASMC has a faster estimation speed than RASMPIC. Fig 7 shows the real time value of the controllers RASMPIC and RASMC. Here we can see that the peak values of the two controllers are similar, but the trajectory of RASMPIC is much smoother than RASMC, so it is easier to achieve for the electric motor which provides the input force.

5 CONCLUSION

In this paper, the vibration control for the active vehicle seat suspension systems is considered. Firstly, based on an active seat suspension model with an unknown driver's mass, the robust adaptive sliding mode controller is designed. The adaptive law is used to estimate the driver's mass. The sliding mode controller deals with the external disturbance and guarantees the stability of the suspension system. A projection law is applied to restrain the value of the estimated driver's mass, which strengthen the robustness of the proposed control system. Then the adaptive robust sliding mode PI controller is constructed to reduce the vibration for the seat suspension system. The PI control part helps to reduce the value of the driver's acceleration effectively. Simulation results show that ARSMPIC has the best vibration control performance to reduce the driver's displacement and acceleration among the three controllers, which greatly improves driving comfort. The experiment of the proposed control methods will be considered as our future research work.

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