Research Article

Sliding Mode Control of the Vehicle Speed System Based on LMIs

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Due to the nonlinear characteristics of the vehicle speed system, its stability is difficult to control. This paper analyzes the stability and traceability of the vehicle speed system under nonlinear characteristics. A sliding mode control method of the nonlinear system state observation based on linear matrix inequalities (LMIs) is proposed. In the proposed control method, Lyapunov function is used as the control function to track the position and speed of the vehicle speed system in real time. In the design process of the controller, the successive scaling method (SSM) is designed to improve the tracking accuracy. The simulation results demonstrate that the sliding mode control can effectively track the position of the vehicle speed system, which has better stability and traceability for the nonlinear vehicle speed system.

1. Introduction

The stability of the system has always been a key issue in the design of control systems, and its application range is extremely wide. For example, the consistency of multiagent systems and the improvement of power systems are closely related to stability issues [1–5]. In the research of nonlinear systems such as aircrafts, inverted pendulums, and time-varying state-delay systems, some scholars have also conducted in-depth studies on their stability. In [6], the stability of the aircraft is closely related to its performance. In this research, the uncertainty and instability of the aircraft are studied. In [7], the stable tracking for the inverted pendulum system was studied. Due to external interference or certain uncertain factors, it is easy to lose its stability for inverted pendulum systems, so its stability must be ensured. Sliding mode control can be used to control the stability of the system. In [8], a sliding mode control method was proposed to improve the stability of time-varying state-delay systems. However, it is only suitable for small input delay systems. In fact, the study of sliding mode control is based on the dynamic performance of the system itself, such as stability and robustness. Therefore, researchers have begun to pay attention to the research based on sliding mode control and have obtained more and more research results [9–14].

Robust control methods are also widely used in system stability control. In most cases, the robust control problem can be transformed into the problem of solving linear matrix inequalities. For example, linear matrix inequalities are used by some scholars to study underactuated systems [15, 16]. They designed the observer and improved the robustness of the observer through the coupling method. When the interference is added to the controller, the system cannot maintain the original robustness and stability. In this case, we can also consider using appropriate nonlinear characteristics and reasonable Lyapunov functions to improve the robustness and stability. In short, the application of research based on robust control in real life is significant. In many cases, we can also use other methods to solve the uncertainty of the system. For example, adaptive fuzzy neural network control can be used to solve the uncertainty of the system [17]. In [18], a new adaptive interleaved reinforcement learning algorithm was proposed for nonlinear systems with matching or mismatching uncertainties. It transforms the robust control problem into the optimal control problem of the nominal system and improves the robustness of the system. In [19], coprime decomposition of composite operators was used to solve the robust stability of nonlinear systems with multiple uncertainties. In [20], a multilevel discrete fracture model was presented to guarantee a robust

and efficient solution for naturally fractured reservoir simulation. In [21], the input-output dynamic stability of networked physical systems was studied. The given networked physical systems are transformed into logical networks with the same robustness. The robustness of networked physical systems is analyzed, and the design method is applied to the robustness analysis of infinite bus systems.

In the control system, the accuracy and robustness of the system are equally important. In order to improve the accuracy of the system, some scholars have studied different control methods to control different systems. A methodology for the synthesis of time-varying static output-feedback gains, capable of stabilising continuous-time linear time-varying systems, was proposed in [22]. In [23], the state feedback nonlinear model predictive control law was approximated offline by the smooth function of the state. This method can improve the accuracy of the system by setting some characteristic parameters. In [24], a new adaptive output feedback control method was proposed to solve the problem of “explosion of complexity” in the case of all state constrained regions based on backstepping. In [25], the control method of the nonlinear system with unknown time-varying disturbance and uncertainty was proposed, which makes the system asymptotically stable in the presence of bounded input and improves the accuracy of the system. In addition, some scholars have designed corresponding control methods to solve the oscillation problem in the system. A method combining empirical mode decomposition with decomposition mode evaluation was proposed in [26]. The method extends the signal preprocessing to improve the robustness and computational efficiency of the system. In [27], an active vibration control technology of the DC motor under harmonic mechanical load torque was introduced. The proposed method can accurately determine the parameters of unknown harmonic vibration. In [28], the problem of linear optimal estimation was studied for discrete and continuous systems with multiple state delays. The linear optimal estimation of the state is obtained by directly calculating the optimal gain, which greatly saves the amount of calculation and increases the accuracy of calculation.

In order to optimize the performance of the system, some researchers have applied different control methods to the converter, the load of the power system, centrifugal compressor, Genesio’s chaotic system, and Chua’s circuit system. For example, in [29], a simple and systematic approach was presented to design a second-order sliding mode controller for buck converters. The proposed twisting method presents an improvement in steady-state error and settling time of output voltage during load changes. In [30], the load frequency control for power systems with communication delays was studied. The proposed method solves the problem of load disturbance and improves the performance of the system. In [31], a new robust predictive controller was proposed, which used the linear matrix inequality (LMI) tool to improve computation time and complexity. The problem of surge in the centrifugal compressor is solved. In [10], a second-order fast terminal sliding mode control technique based on LMIs was studied. Using this method, a robust chattering-free control scheme was

proposed, and the parameters of the controller were given in the form of LMIs. The control structure is independent of the order of the model, and the simulation results in Genesio’s chaotic system and Chua’s circuit system verify the effectiveness of the scheme. Under these control methods, the corresponding system performance has been improved.

From the above examples, it is not difficult to find that the essence of the research problem is around the robustness and stability of each system. Different controllers can obtain different control effects. Although the aforementioned methods have improved the stability and robustness of the system, most methods do not solve the tracking accuracy problem of the system well, and most strategies are relatively complicated and deserve further investigation.

Inspired by the above discussions, this paper studies the nonlinear characteristics of the vehicle speed system. Roughly, there are three aspects of contributions in this paper:

- (i) For the stability control of the vehicle speed system, a sliding mode control method based on the LMI nonlinear state observer is proposed, and the detailed design is given.
- (ii) In order to improve the tracking accuracy of the system, the successive scaling method (SSM) is proposed in this paper. In the design of the sliding mode controller, the SSM method is used to make the closed-loop system achieve exponential convergence.
- (iii) In the process of solving the gain value of the observer, we obtained the condition of the observer gain value by constructing an inequality and reducing the number of variables.

The rest of the paper is arranged as follows. Some preliminaries and observers’ descriptions are presented in Section 2. The main results and derivations of correlation are presented in Section 3. The simulation results and analysis are verified in Section 4. Conclusion is given in Section 5.

2. Preliminaries

Consider the vehicle speed system model:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = u + h, \\ y = kx_1, \end{cases} \quad (1)$$

where $x = [x_1 \ x_2]^T$, x is the state vector, u is the control input, let $u = g\varphi$, and g is a coefficient related to vehicle weight, φ represents traction or braking force, h represents the disturbance of the vehicle speed system, y is the system output, and k represents the scale factor of the vehicle position. x_1 and x_2 are the position and speed of the vehicle speed system, respectively. At this time, the practical problem can be transformed into the observer-related problem. Let x_1 follow x_t , and let x_2 follow $\dot{x}_t$ [32–35].

The state equation of system (1) is

$$\begin{cases} \dot{x} = Ax + B_1u + B_2h, \\ y = Cx, \end{cases} \quad (2)$$

where

$$\begin{aligned} A &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \\ B_1 &= [0 \ 1]^T, \\ B_2 &= [0 \ 1]^T, \\ C &= [k \ 0]. \end{aligned} \quad (3)$$

A is the system matrix; B_1 is the control matrix; B_2 is the disturbance correlation matrix; C is the output matrix, where $x = [x_1 \ x_2]^T$, u is the control input, and the designed state observer is

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_1u + B_2h + L(y - \hat{y}), \\ \hat{y} = C\hat{x}. \end{cases} \quad (4)$$

Then,

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + L_1(y - \hat{y}), \\ \dot{\hat{x}}_2 = u + h + L_2(y - \hat{y}), \\ \hat{y} = k\hat{x}_1, \end{cases} \quad (5)$$

where $\hat{x} = [\hat{x}_1 \ \hat{x}_2]^T$, $L = [L_1 \ L_2]$, L denotes the observed gain.

If $\tilde{x} = x - \hat{x}$, the following can be obtained:

$$\begin{aligned} \dot{\tilde{x}} &= \dot{x} - \dot{\hat{x}} \\ &= Ax + B_1u + B_2h - A\hat{x} - B_1u - B_2h - L(y - \hat{y}) \\ &= (A - LC)\tilde{x}. \end{aligned} \quad (6)$$

Define Lyapunov function:

$$V_1 = \tilde{x}^T S \tilde{x}, \quad (7)$$

where $S^T = S$, even $S > 0$.

The following form can be acquired:

$$\begin{aligned} \dot{V}_1 &= \dot{\tilde{x}}^T S \tilde{x} + \tilde{x}^T S \dot{\tilde{x}} \\ &= [(A - LC)\tilde{x}]^T S \tilde{x} + \tilde{x}^T S [(A - LC)\tilde{x}] \\ &= \tilde{x}^T (A - LC)^T S \tilde{x} + \tilde{x}^T S (A - LC) \tilde{x} \\ &= \tilde{x}^T [(A - LC)^T S + S(A - LC)] \tilde{x}. \end{aligned} \quad (8)$$

Then let $A = (A - LC)^T S + S(A - LC)$.

Take $A + \rho I < 0$, $\rho > 0$; then

$$\dot{V}_1 = \tilde{x}^T A \tilde{x} < -\rho \tilde{x}^T \tilde{x}. \quad (9)$$

that is,

$$(A - LC)^T S + S(A - LC) + \rho I < 0. \quad (10)$$

Let $Q = SL$; we have the first LMI as follows:

$$(SA - QC + [SA - QC]^T) + \rho I < 0. \quad (11)$$

We define λ_m as the maximum eigenvalue of A .

$$\begin{aligned} \dot{V}_1 &< -\rho \tilde{x}^T \tilde{x} \\ &< -\frac{\rho}{\lambda_m} \tilde{x}^T A \tilde{x} = \gamma \tilde{x}^T A \tilde{x} \leq \gamma V_1, \end{aligned} \quad (12)$$

where $\gamma = -\rho/\lambda_m$.

The solution of inequality $\dot{V}_1 < -\gamma V_1$ is $V_1(t) < e^{-\gamma t} V_1(0)$, then V_1 converges to 0 exponentially, and the closed-loop system is exponentially convergent, t . The convergence rate of the system depends on γ .

We know the second LMI is

$$S > 0. \quad (13)$$

It follows that

$$L = S^{-1}Q. \quad (14)$$

3. Main Results

In the current section, we select its control law under the premise of sliding mode function and take the control function as Lyapunov function for the vehicle speed system. The successive scaling method is used. Let the observer track the ideal, and we analyze the errors between the actual and the ideal.

Design the sliding mode function:

$$s = ge + \dot{e}. \quad (15)$$

For any $g > 0$, $e = x_t - x_1$, and $\dot{e} = \dot{x}_t - \dot{x}_1$.

Taking the control law of vehicle speed system as

$$\varphi = \frac{1}{g} \ddot{x}_t + \eta \hat{s} + \dot{\hat{e}}, \quad (\eta > 0), \quad (16)$$

where $\hat{s} = g\hat{e} + \dot{\hat{e}}$, and $\hat{e} = x_t - \hat{x}_1$, $\dot{\hat{e}} = \dot{x}_t - \dot{\hat{x}}_1$.

Taking the control Lyapunov function as

$$V_2 = \frac{1}{3} s^3, \quad (17)$$

due to $\ddot{e} = \ddot{x}_t - \ddot{x}_1 = \ddot{x}_t - g\varphi + h$.

$$\dot{s} = g\dot{e} + \ddot{e} = g\dot{e} + \ddot{x}_t - g\varphi + h. \quad (18)$$

Define $\dot{\hat{e}} = \dot{e} - \dot{\hat{e}}$ and $\dot{\hat{x}}_1 = \dot{x}_1 - \dot{\hat{x}}_1$; the following can be obtained:

$$\begin{aligned} \dot{s} &= g\dot{e} + \ddot{x}_t - g\left(\frac{1}{g}\ddot{x}_t + \eta\hat{s} + \dot{\hat{e}}\right) - h \\ &= g\dot{\hat{e}} - g\eta\hat{s} - h \\ &= g(-\eta s + \eta\hat{s}) + g\dot{\hat{e}} - h \\ &= -g\eta s + g\eta(-g\tilde{x}_1 - \dot{\hat{x}}_1) + g(-\dot{\hat{x}}) - h. \end{aligned} \quad (19)$$

In this,

$$\begin{aligned}\tilde{x}_2 &= x_2 - \hat{x}_2, \\ \tilde{e} &= e - \hat{e} = -x_1 + \hat{x}_1 = -\tilde{x}_1,\end{aligned}\quad (20)$$

$$\begin{aligned}\dot{\tilde{e}} &= \dot{e} - \dot{\hat{e}} = \dot{x}_t - \dot{\hat{x}}_1 - (\dot{x}_t - \dot{\hat{x}}_1) = -(\dot{x}_1 - \dot{\hat{x}}_1) = -\dot{\tilde{x}}_1, \\ &= -\dot{\tilde{x}}_1,\end{aligned}\quad (21)$$

$$\begin{aligned}\tilde{s} &= s - \hat{s} = ge + \dot{e} - (g\hat{e} + \dot{\hat{e}}) = g\tilde{e} + \dot{\tilde{e}} = -g\tilde{x}_1 - \dot{\tilde{x}}_1. \\ &= -g\tilde{x}_1 - \dot{\tilde{x}}_1.\end{aligned}\quad (22)$$

Then, there is

$$\begin{aligned}\dot{V}_2 &= s^2 [-g\eta s + g\eta(-g\tilde{x}_1 - \dot{\tilde{x}}_1) + g(-\dot{\tilde{x}}_1) - h] \\ &= -(g\eta s^3 + s^2 h) + s^2 [-g^2\eta\tilde{x}_1 + (-g\eta - g)\dot{\tilde{x}}_1] \\ &= -(g\eta s^3 + s^2 h) + k_1 s^2 \tilde{x}_1 + k_2 s^2 \dot{\tilde{x}}_1.\end{aligned}\quad (23)$$

In this, $k_1 = -g^2\eta$ and $k_2 = -g\eta - g$. According to the properties of the inequality,

$$\begin{aligned}k_1 s^2 \tilde{x}_1 &\leq \frac{1}{2}s^4 + \frac{1}{2}k_1^2 \tilde{x}_1^2, \\ k_2 s^2 \dot{\tilde{x}}_1 &\leq \frac{1}{2}s^4 + \frac{1}{2}k_2^2 \dot{\tilde{x}}_1^2.\end{aligned}\quad (24)$$

Let $s^4 < as^3$, the value of a is determined by s . Then, we can derive

$$\begin{aligned}\dot{V}_2 &\leq -(g\eta s^3 + s^2 h) + \frac{1}{2}s^4 + \frac{1}{2}k_1^2 \tilde{x}_1^2 + \frac{1}{2}s^4 + \frac{1}{2}k_2^2 \dot{\tilde{x}}_1^2 \\ &\leq -(g\eta s^3) + s^4 + \frac{1}{2}k_1^2 \tilde{x}_1^2 + \frac{1}{2}k_2^2 \dot{\tilde{x}}_1^2 \\ &\leq (-g\eta + a)s^3 + \eta_2 \tilde{x}^T \tilde{x} \\ &\leq -\eta_1 V_2 + \eta_2 \tilde{x}^T \tilde{x}.\end{aligned}\quad (25)$$

It follows that

$$\begin{aligned}\dot{\tilde{x}}_1^2 &= (\dot{x}_1 - \dot{\hat{x}}_1)^2 \\ &\leq (x_2 - \hat{x}_2 - L_1 C \tilde{x}_1)^2 \\ &= (\tilde{x}_2 - L_1 C \tilde{x}_1)^2 \\ &= \tilde{x}_2^2 - 2L_1 \tilde{x}_1 C \tilde{x}_2 + L_1^2 C^1 \tilde{x}_1^2 \\ &\leq \tilde{x}_2^2 + L_1^2 C^2 \tilde{x}_1^2 + L_1 C \tilde{x}_1^2 + L_1 C \tilde{x}_2^2 \\ &= (1 + L_1 C) \tilde{x}_2^2 + (L_1^2 C + L_1) C \tilde{x}_1^2, \\ \frac{1}{2}k_1^2 \tilde{x}_1^2 + \frac{1}{2}k_2^2 \dot{\tilde{x}}_1^2 &\leq \frac{1}{2}k_1^2 \tilde{x}_1^2 + \frac{1}{2}k_2^2 [(1 + L_1 C) \tilde{x}_2^2 + (L_1^2 C + L_1) C \tilde{x}_1^2] \\ &= \left[\frac{1}{2}k_1^2 + \frac{1}{2}k_2^2 (L_1^2 C + L_1) C \right] \tilde{x}_1^2 + \frac{1}{2}k_2^2 (1 + L_1 C) \tilde{x}_2^2,\end{aligned}\quad (26)$$

Where

$$\eta_2 = \max\{(1/2)k_1^2 + (1/2)k_2^2 (L_1^2 C + L_1) C, (1/2)k_2^2 (1 + L_1 C)\}$$

and $\eta_1 = 3(g\eta - a)$.

The Lyapunov function of the vehicle speed system is

$$V = V_1 + V_2, \quad (27)$$

where $V_1 = \tilde{x}^T S \tilde{x}$.

It can be seen from (13) that

$$\begin{aligned}\dot{V} &= \dot{V}_1 + \dot{V}_2 < -\rho \tilde{x}^T \tilde{x} + \eta_2 \tilde{x}^T \tilde{x} - \eta_1 V_2 \\ &= -\eta_1 V_2 - (\rho - \eta_2) \tilde{x}^T \tilde{x}.\end{aligned}\quad (28)$$

For $\rho > \eta_2$, we can gain

$$-(\rho - \eta_2) \tilde{x}^T \tilde{x} < -\frac{\rho - \eta_2}{\lambda_m} \tilde{x}^T A \tilde{x} = -b \tilde{x}^T A \tilde{x} < -b V_1. \quad (29)$$

λ_m , where $b = (\rho - \eta_2)/\lambda_m$, $\rho > \eta_2$. And Then

$$\dot{V} \leq -\eta_1 V_2 - b V_1 \leq -\tau (V_1 + V_2) = -\tau V, \quad (30)$$

where $\tau = \min\{\eta_1, b\}$.

The solution of inequality $\dot{V} \leq -\tau V$ is $V(t) \leq e^{-\tau t}$, then the exponential form of $V(t)$ converges to 0. When $t \rightarrow \infty$, $s \rightarrow 0$, $\tilde{x} \rightarrow 0$, the system satisfies the exponential convergence condition, then the vehicle speed system is also exponentially convergent. The convergence rate of the system depends on η_1, b .

The so-called SSM is a method of applying the related principles of inequality scaling to obtain the desired result. Specifically, we first set reasonable equations (15) and (16), and (24) is established according to the related principle of inequality, and then we appropriately scale V_2 on the basis of (24) to obtain a form related to (17). Finally, combine V_1 and V_2 to get (30); it can be concluded that the closed-loop system is exponentially convergent from (30).

4. Simulation

Take (2) as the controlled object and (4) as the observer, and the initial state value of the observer is $\hat{x}(0) = [0 \ 0]^T$. The initial state of the controlled object is $x(0) = [0.5 \ 0]^T$. By solving LMIs (11) and (13), we obtain the observation gain value $L = [0.9678 \ 1.3179]^T$. In the present study, it is set that $\alpha = 29$, and $x1p \rightarrow x1, x2p \rightarrow x2$. The simulation results are shown in Figures 1 and 2.

The vehicle speed system is simulated under given conditions. The controlled object is (1), and the initial state is set as $x(0) = [0.5 \ 0]^T$. The observer is (5), and the initial state of the observer is set as $\hat{x}(0) = [0 \ 0]^T$. Equation (16) is the controller, and $g = 10, \eta = 4.0$. The position instruction takes $x_t = \cos(t)$. We obtain the observation gain value L by solving inequalities. The simulation results are shown in Figures 3–5.

In Figure 1(a), the tracking effect is poor in the first 2 seconds, and the tracking effect has a higher degree of approximation after 2 seconds. In Figure 1(b), the tracking effect is gradually improved after 5 seconds.

In Figure 2(a), the error gets smaller in the first 10 seconds. The error goes almost to 0 after 10 seconds. In

FIGURE 1: State observation results.

FIGURE 2: State observation error.

Figure 2(b), the error gradually stabilizes and is near 0. It can be seen that the system has a good tracking effect.

In Figure 3(a), it can be seen that the position tracking error is relatively large in the first 4.3 seconds, and in the subsequent time, the position tracking has achieved good results. In Figure 3(b), for the speeding tracking, the margin of error is large in the first 2.6 seconds, which drops from 5.7 to 0.1, and the error tends to 0 after 2.6 seconds, and the effect of speed tracking becomes better.

In Figure 4(a), for x_1 estimation error, the error range goes from 0.5 to -0.223 in the first 7.9 seconds. It goes from -0.223 to -0.011 , and the error is about -0.01 after

7.9 seconds. In Figure 4(b), for the estimation error of x_2 , the error has a relatively large change in the first 7.52 seconds. After 7.52 seconds, the error gradually stabilizes.

As shown in Figure 5, the control input has a relatively large change in the first 2.3 seconds, and its amplitude reaches 78. The control input tends to be stable gradually after 2.3 seconds.

The simulation results demonstrate that the degree of coincidence was gradually improved. In a word, the vehicle speed system has obtained stable control, and the position and speed have good tracking effects.

FIGURE 3: Position and speed tracking.

FIGURE 4: Estimation error of x_1 and x_2 .

FIGURE 5: Control input.

5. Conclusion

To conclude, the vehicle speed system in actual operation has strong nonlinearity. For low-speed motion, a simple controller can achieve better control effect, but for high-speed motion, a simple controller is difficult to obtain good control effect. Therefore, a more appropriate controller should be used. In such a case, a sliding mode control method based on LMIs is proposed to improve the stability and traceability of the vehicle speed system. In this process, the SSM is designed to improve the accuracy of the controller. Therefore, the accuracy of system tracking is ensured. In the meanwhile, the observer gain matrix algorithm is designed in the study of sliding mode control of the nonlinear system, and the obtained observer gain matrix ensures the stable operation of the system. According to simulation results, the proposed method shows a good control effect on the vehicle speed system.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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