Hindawi
Journal of Mathematics
Volume 2021, Article ID 6646941, 7 pages
https://doi.org/10.1155/2021/6646941

*Research Article*

# Nonsingular Terminal Sliding Mode Control of Uncertain Chaotic Gyroscope System Based on Disturbance Observer

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Received 3 November 2020; Revised 23 November 2020; Accepted 20 December 2020; Published 4 January 2021

Academic Editor: Ahmed Mostafa Khalil



Based on disturbance observer, this paper develops a nonsingular terminal sliding mode control method for uncertain chaotic gyroscope system. Firstly, fuzzy logic system (FLS) is used to estimate the unknown function; then disturbance observer (DOB) is constructed to estimate the mixed disturbance, which consists of the fuzzy estimation error, external disturbance, and dead-zone input error. Subsequently, by using a nonsingular terminal sliding mode function, the control method proposed in this paper can achieve the sliding mode variable approaching a small neighborhood of zero and reduce chattering phenomenon of the tracking error and controller. Finally, comparative simulation results confirm the effectiveness of the method proposed in this paper.

## 1. Introduction

As an important sensor in navigation system, gyroscope was first used in ship navigation. With the development of science and technology, up to now, it has been widely used in aviation, aerospace, missile, automobile, and other related fields [1–4] requiring orientation and balance. However, the gyro system often exhibits chaotic phenomenon, which will damage its applications. In recent years, more and more attention has been paid to the control of the chaotic behavior of the gyroscope, for example, OGY control [5], linear feedback control [6], adaptive control [7, 8], and sliding mode control [9–22]. Among these methods, sliding mode control (SMC) is widely used because of its simple structure, fast response, and strong robustness to disturbance and unmodeled dynamics. However, due to the demand for new industrial applications and technological progress, some problems related to SMC are still the current research directions, such as disturbance elimination, selection of sliding mode surface, and integration with other control methods. For the gyro system, Moghani et al. [14] added fuzzy control based on the research of [13], using fuzzy inference engine to eliminate the discontinuity of the sign function of the SMC system at the arrival stage, which improved the performance of the system. Fazlyab et al. [15] studied a hybrid intelligent controller for vibratory gyroscopes in single-axis MEMS. An additional interval type-2 fuzzy SMC is used to minimize the effect of noise. Fang et al. [17] derived an $H_\infty$ control strategy based on Lyapunov function to achieve ideal attenuation of various external disturbances in MEMS gyroscope. Aiming at the trajectory tracking problem of an under-driven two-degrees-of-freedom control moment gyroscope, in order to increase the robustness, a controller, which was based on an adaptive neural network to compensate for unknown dynamics, was designed in [19]. Then, for this type of system, in addition to using the adaptive neural network algorithm in [19], Montoya-Chirez et al. [20] also proposed an adaptive model regressor scheme. Zhang et al. [21] studied the SMC with compound learning of the MEMS gyroscope, gave a series-parallel estimation model, and constructed the filter error to design the weights updating law of neural networks. By using prescribed performance control method, Xiang et al. [22] achieved the synchronization of two uncertain gyro systems.

However, although the control objective can be guaranteed by aforementioned control methods, the system uncertainties cannot be estimated accurately. In this paper, a novel control method is proposed to overcome this problem. The disturbance observation and fuzzy estimation parameters are integrated into the nonsingular terminal SMC

(NTSMC), so that the controlled system can achieve finite time stability quickly and effectively. The main contributions of this paper are as follows: (1) The proposed control method can quickly stabilize the tracking error. (2) The mixed disturbance can be accurately estimated by proposed FLSs and DOB. (3) The proposed control method can avoid singular problem and chattering phenomena can also be reduced.

The organizational structure of this paper is as follows. In Section 2, the problem of a class of chaotic gyroscope systems is presented. The design and stability analysis of the control method are investigated in Section 3. In Section 4, comparative simulation results show the superiority of the proposed method. A short conclusion is given in Section 5.

## 2. System Descriptions and Problem Formulations

In this paper, a symmetrical gyroscope system with linear damping installed on a vibrating base is considered. The motion equation of the gyroscope system is given by the angle $\xi$ as

$$\ddot{\xi} + A^2\frac{(1-\cos\xi)^2}{\sin^3\xi} - B\sin\xi + C\dot{\xi} + D\dot{\xi}^3 = F\sin\omega t\sin\xi, \tag{1}$$

where $F\sin\omega t$ represents a parametric excitation, $C\dot{\xi}$ is linear damping term, $D\dot{\xi}^3$ is nonlinear damping term, and $A^2((1-\cos\xi)^2/\sin^3\xi) - B\sin\xi$ is a nonlinear resilience force. Choosing parameters as $A^2 = 100, B = 1, C = 0.5, D = 0.05, F = 35.7, \omega = 2$ and states initial values of $\xi(0) = -1, \dot{\xi}(0) = 1$, the gyroscope system display chaotic behavior can be seen in Figure 1.

Define $x_1 = \xi, x_2 = \dot{\xi}$, and $x = [x_1, x_2]^T$; then the controlled gyroscope system (1) can be described as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f(t,x) + d(t) + \chi(u(t)), \end{cases} \tag{2}$$

where $f(t,x) = -A^2[(1-\cos(x_1))^2/\sin^3(x_1)] + B\sin(x_1) - Cx_2 - Dx_2^3 + F\sin(\omega t)\sin(x_1)$, $d(t)$ is an external disturbance, and $\chi(u(t))$ is the control input, which is affected by the dead zone. Similar to literature [22], $\chi(u(t)) = \beta u(t) + \sigma(u(t))$, and

$$\sigma(u(t)) = \begin{cases} -\beta a_1, & \text{if } u(t) < a_1, \\ -\beta u(t), & \text{if } a_1 \le u(t) \le a_2, \\ -\beta a_2, & \text{if } u(t) > a_2, \end{cases} \tag{3}$$

where $\beta, a_1, a_2$ are design parameters. Clearly, $\sigma(u(t))$ is bounded. Meanwhile, we give the following assumptions.

*Assumption 1.* The nonlinear function $f(t,x)$ is unknown and bounded.

*Assumption 2.* The external disturbance $d(t)$ and its derivative are unknown and bounded.

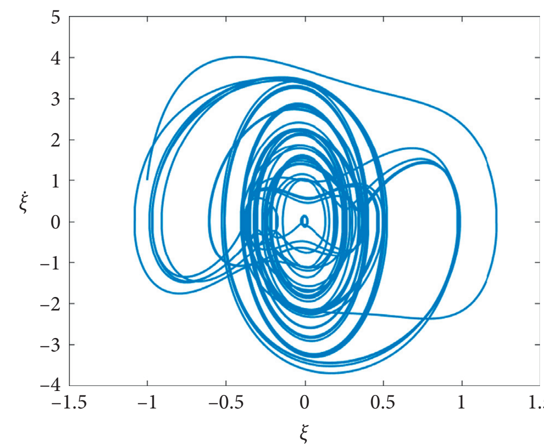


Figure 1: Phase plane trajectory of gyroscope system.

In this paper, the unknown function $f(t,x)$ is estimated by using the fuzzy logic system; for the relevant principles, please see [23, 24]. The goal of this paper is to design a nonsingular fuzzy terminal sliding mode control method so that $x_1$ can track a reference signal $x_d$, where the reference signal $x_d$ and its second derivative $\ddot{x}_d$ are continuous and bounded.

## 3. Control Design and Stability Analysis

Let $e_1 = x_1 - x_d$; one has

$$\begin{cases} \dot{e}_1 = e_2, \\ \dot{e}_2 = \dot{x}_2 - x_d = f(t,x) - x_d + d(t) + \beta u(t) + \sigma(u(t)), \end{cases} \tag{4}$$

and define $F(t,x) = \lambda f(t,x)$, by using fuzzy logic system, which can be expressed as

$$\left\{ F(t,x) = \eta^{*T}\varpi_F(x) + \rho(x), \right. \tag{5}$$

where $\lambda > 0$ is design parameter, $\eta^*$ is the optimal approximation vector, $\varpi_F(x)$ is the basis function vector, $\rho(x)$ is a fuzzy estimation error, and, according to [23], $\rho(x)$ is bounded.

From the relation between $F(t,x)$ and $f(t,x)$, one gets

$$\begin{aligned} f(t,x) &= \lambda^{-1}F(t,x) = \lambda^{-1}\left[\eta^{*T}\omega_F(x) + \rho(x)\right], \\ &= \lambda^{-1}\tilde{\eta}^T\omega_F(x) + \lambda^{-1}\hat{\eta}^T\omega_F(x) + \lambda^{-1}\rho(x), \end{aligned} \tag{6}$$

and let $\tilde{\eta} = \eta^* - \hat{\eta}$, where $\hat{\eta}$ is an estimate of $\eta^*$. Then equation (4) can be written as

$$\begin{cases} \dot{e}_1 = e_2, \\ \dot{e}_2 = \lambda^{-1}\tilde{\eta}^T\omega_F(x) + \lambda^{-1}\hat{\eta}^T\omega_F(x) - \ddot{x}_d + \bar{d}(t) + \beta u(t), \end{cases} \tag{7}$$

where $\bar{d}(t) = \lambda^{-1}\rho(x) + d(t) + \sigma(u(t))$ (we denote $\bar{d}(t)$ as mixed disturbance). It is easy to know that $|\bar{d}(t)|$ is bounded; that is, $|\bar{d}(t)| \le d^{\max}$, $d^{\max}$ is an unknown positive constant.

Define the following terminal sliding mode as

$$s = e_2 + \varsigma e_1 + e_1^{\tau}, \tag{8}$$

where $0 < \tau = q/p < 1$, $q$ and $p$ are positive odd constants, and $\varsigma$ is positive constant.

*Remark 1.* Compared with the traditional sliding mode in [12], the terminal sliding mode in (8) can achieve a fast approach speed for $e_1$; and, to avoid the singularity problem, we define $\tau e_1^{\tau-1} e_2$ as follows:

$$\tau e_1^{\tau-1} e_2 = \begin{cases} \tau e_1^{\tau-1} e_2, & \text{for } e_1 \neq 0, e_2 \neq 0, \\ \tau \varepsilon_1^{\tau-1} e_2, & \text{for } e_1 = 0, e_2 \neq 0, \\ 0, & \text{for } e_1 = 0, e_2 = 0, \end{cases} \tag{9}$$

where $\epsilon_1$ is a small positive number.Taking derivative of $s$, one has

$$\begin{aligned} \dot{s} &= \dot{e}_2 + \varsigma \dot{e}_1 + \tau e_1^{\tau-1} \dot{e}_1, \\ &= \lambda^{-1} \tilde{\eta}^T \varpi_F(x) + \lambda^{-1} \hat{\eta}^T \varpi_F(x) - \ddot{x}_d + \bar{d}(t) \\ &\quad + \beta u(t) + \varsigma e_2 + \tau e_1^{\tau-1} e_2. \end{aligned} \tag{10}$$

According to (10), the control method is designed as

$$u = u_1 + u_2 + u_3, \tag{11}$$

with

$$\begin{aligned} u_1 &= \frac{1}{\beta}\left[\ddot{x}_d - \varsigma e_2 - \tau e_1^{\tau-1} e_2\right], \\ u_2 &= \frac{1}{\beta}\left[-\hat{\bar{d}}(t) - \lambda^{-1}\hat{\eta}^T \varpi_F(x)\right], \\ u_3 &= \frac{1}{\beta}\left[-l_1 s - l_2 |s|^a \operatorname{sign}(s)\right], \end{aligned} \tag{12}$$

where $\hat{\bar{d}}$ is the estimate of $\bar{d}$, $l_1$ and $l_2$ are positive design parameters, and $0 < a < 1$.

Let $\tilde{\bar{d}} = \bar{d} - \hat{\bar{d}}$. From equations (10)–(12), one gets

$$\dot{s} = -l_1 s - l_2 |s|^a \operatorname{sign}(s) + \tilde{\bar{d}} + \lambda^{-1} \tilde{\eta}^T \varpi_F(x). \tag{13}$$

For fuzzy estimation parameter $\tilde{\eta}$, the adaptive law is given as

$$\dot{\hat{\eta}} = k_1\left(s \lambda^{-1} \varpi_F(x) - k_2 \hat{\eta}\right), \tag{14}$$

where $k_1$ and $k_2$ are positive design parameters.

Then, we construct the following disturbance observer:

$$\begin{cases} \hat{\bar{d}} = m(e_2 - z), \\ \dot{z} = \lambda^{-1}\hat{\eta}^T \varpi_F(x) + \beta u(t) + \hat{\bar{d}} - x_d - m^{-1} s, \end{cases} \tag{15}$$

where $m$ is a positive design parameter.

From the disturbance observation error $\tilde{\bar{d}} = \bar{d} - \hat{\bar{d}}$ and equation (15), we can get

$$\begin{aligned} \dot{\tilde{\bar{d}}} &= \dot{\bar{d}} - \dot{\hat{\bar{d}}} = \dot{\bar{d}} - m(\dot{e}_2 - \dot{z}), \\ &= \dot{\bar{d}} - m\left(\tilde{\bar{d}} + t\lambda^{-1} n \tilde{\eta}^T q \varpi_F h(x)_+ x m^{-1} 7 s\right). \end{aligned} \tag{16}$$

From the above analysis, we obtain the following theorem.

**Theorem 1.** *Consider the uncertain chaotic gyroscope system (1), which satisfies Assumptions 1 and 2; the parameter adaptation law (14), disturbance observer (15), and terminal sliding mode controller (11) can guarantee that all of closed-loop signals $s, \tilde{\eta}, \tilde{\bar{d}}$ are bounded, and the sliding mode variable $s$ converges to small neighborhood of zero in finite time.*

*Proof.* Consider the Lyapunov function candidate as

$$V = \frac{1}{2}\left[s^2 + \tilde{\bar{d}}^2 + \frac{1}{k_1}\tilde{\eta}^T \tilde{\eta}\right]. \tag{17}$$

We have

$$\begin{aligned} s\dot{s} &= s\left[-l_1 s - l_2 |s|^a \operatorname{sign}(s) + \tilde{\bar{d}} + \lambda^{-1}\tilde{\eta}^T \varpi_F(x)\right], \\ &= -l_1 s^2 - l_2 |s|^{a+1} + s\tilde{\bar{d}} + s\lambda^{-1}\tilde{\eta}^T \varpi_F(x), \\ \tilde{\bar{d}}\dot{\tilde{\bar{d}}} &= \tilde{\bar{d}}\dot{\bar{d}} - \tilde{\bar{d}} m \lambda^{-1} \tilde{\eta}^T \varpi_F(x) - m\tilde{\bar{d}}^2 - \tilde{\bar{d}} s, \\ \frac{1}{k_1}\tilde{\eta}^T \dot{\tilde{\eta}} &= \frac{1}{k_1}\tilde{\eta}^T (-\dot{\hat{\eta}}) = -\frac{1}{k_1}\tilde{\eta}^T \left[k_1\left(s\lambda^{-1}\varpi_F(x)\right) - k_2 \hat{\eta}\right], \\ &= -\lambda^{-1} s \tilde{\eta}^T \varpi_F(x) + k_2 \tilde{\eta}^T \hat{\eta}. \end{aligned} \tag{18}$$

Therefore, $\dot{V}$ can be expressed as

$$\begin{aligned} \dot{V} &= s\dot{s} + \tilde{\bar{d}}\dot{\tilde{\bar{d}}} + \frac{1}{k_1}\tilde{\eta}^T \dot{\tilde{\eta}} \\ &= -l_1 s^2 - l_2 |s|^{a+1} + s\tilde{\bar{d}} + s\lambda^{-1}\tilde{\eta}^T \varpi_F(x) + \tilde{\bar{d}}\dot{\bar{d}} \\ &\quad - m\lambda^{-1}\tilde{\bar{d}}\tilde{\eta}^T \varpi_F(x) \\ &\quad - m\tilde{\bar{d}}^2 - \tilde{\bar{d}} s - \lambda^{-1} s\tilde{\eta}^T \varpi_F(x) + k_2 \tilde{\eta}^T \hat{\eta} \\ &= -l_1 s^2 - l_2 |s|^{a+1} + \tilde{\bar{d}}\dot{\bar{d}} - m\lambda^{-1}\tilde{\bar{d}}\tilde{\eta}^T \varpi_F(x) \\ &\quad - m\tilde{\bar{d}}^2 + k_2 \tilde{\eta}^T \hat{\eta}. \end{aligned} \tag{19}$$

The following inequalities hold:

$$\begin{aligned} \tilde{\bar{d}}\dot{\bar{d}} &\le \frac{1}{2}\tilde{\bar{d}}^2 + \frac{1}{2}\dot{\bar{d}}^2, \\ -m\lambda^{-1}\tilde{\bar{d}}\tilde{\eta}^T \varpi_F(x) &\le m\lambda^{-1}\left(\frac{1}{2}\tilde{\eta}^T \tilde{\eta} + \frac{1}{2}\Upsilon^2 \tilde{\bar{d}}^2\right), \\ k_2 \tilde{\eta}^T \hat{\eta} = k_2 \tilde{\eta}^T (\eta^* - \tilde{\eta}) &\le -\frac{k_2}{2}\tilde{\eta}^T \tilde{\eta} + \frac{k_2}{2}\eta^{*T}\eta^*, \end{aligned} \tag{20}$$

where $\|\varpi_F(x)\| \le \Upsilon$.

Therefore, substituting (20) into (19), one obtains

$$\begin{aligned}\dot{V} \le & -l_1 s^2 - l_2|s|^{a+1} + \frac{1}{2}\tilde{\tilde{d}}^2 + \frac{1}{2}\dot{d}^2 - m\tilde{\tilde{d}}^2 \\ & + m\lambda^{-1}\left(\frac{1}{2}\tilde{\eta}^T\tilde{\eta} + \frac{1}{2}\Upsilon^2\tilde{\tilde{d}}^2\right) \\ & -\frac{k_2}{2}\tilde{\eta}^T\tilde{\eta} + \frac{k_2}{2}\eta^{*T}\eta^* = -l_1 s^2 - l_2|s|^{a+1} - k_d\tilde{\tilde{d}}^2 - k_\eta\|\tilde{\eta}\|^2 + p_0,\end{aligned} \tag{21}$$

where $k_d = m - (1/2) - (1/2)m\lambda^{-1}\Upsilon^2, k_\eta = (k_2/2) - (1/2)m\lambda^{-1}, p_0 = (1/2)\dot{d}^2 + (k_2/2)\eta^{*T}\eta^*$.

By selecting parameters $m, \lambda$, and $k_2$ such that $k_d > 0, k_\eta > 0$, one has

$$\dot{V} \le -c_1 V + p_0, \tag{22}$$

where $c_1 = \min\{2l_1, 2k_d, 2k_\eta\}$.

From (22), one gets

$$0 \le V \le \frac{p_0}{c_1} + \left[V(0) - \frac{p_0}{c_1}\right]e^{-c_1 t}. \tag{23}$$

It is known that $V \longrightarrow (p_0/c_1)$, as $t \longrightarrow \infty$. Then all the signals involved in (17) are bounded. Let $\theta = \tilde{\tilde{d}} + \lambda^{-1}\tilde{\eta}^T\varpi_F(x)$.

Then (13) can be written as

$$\dot{s} = -l_1 s - l_2|s|^a \operatorname{sign}(s) + \theta. \tag{24}$$

Because $\tilde{\tilde{d}}$ and $\tilde{\eta}$ are bounded, there exists an unknown constant $R$ such that $|\theta| \le R$.

If $s$ is not zero, rewrite (24) as

$$\dot{s} = -\left(l_1 - \frac{\theta}{s}\right)s - l_2|s|^a \operatorname{sign}(s). \tag{25}$$

Let $l_1 = (R/|s|) + r_1$, and let $\tilde{V} = (1/2)s^2$; then we have

$$\dot{\tilde{V}} = s\dot{s} \le -r_1 s^2 - l_2|s|^{a+1} = -2r_1\tilde{V} - 2l_2\tilde{V}^{(a+1/2)}. \tag{26}$$

As we all know, $s$ will converge to the regions $\Omega = \{|s|: |s| \le (R/l_1 - r_1)\}$ in finite time. □

*Remark 2.* Reference [12] used sliding mode control method to achieve the synchronization of a class of chaotic systems. However, in [12], just assuming that the disturbance is bounded and through the sign function to eliminate the influence of the external disturbance, the controller can make the state enter the sliding mode surface which is designed, but it will produce a large jitter phenomenon. Moreover, the method cannot understand the influence of the external disturbance and unknown function on the system, so the disturbance observer is designed in this paper. On the one hand, it targets accurately estimating the mixed disturbance, which is composed of the dead-zone input error, fuzzy estimation error, and the external disturbance. On the other hand, compared with the traditional control method, the control effect will be further improved and the jitter phenomenon will be reduced. Therefore, this paper can be regarded as a further study of [12].

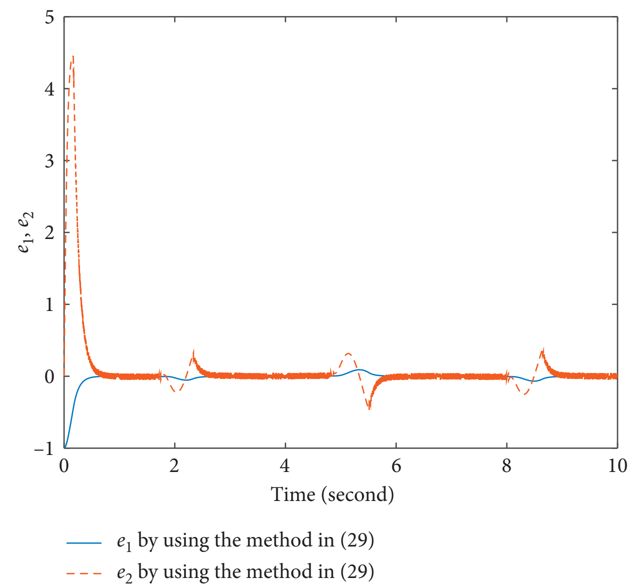


Figure 2: Trajectories of $e_1$ and $e_2$ by using the method in (27).

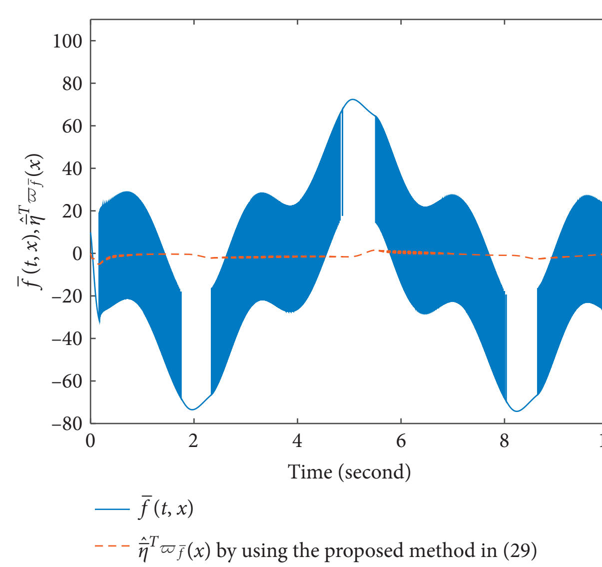


Figure 3: Trajectories of $\bar{f}(t,x)$ and $\hat{\tilde{\eta}}^T\varpi_{\bar{f}}(x)$ by using the method in (27).

## 4. Numerical Simulations

In this section, the parameters of the chaotic system are selected as $A^2 = 100, B = 1, C = 0.5, D = 0.05, F = 35.7, \omega = 2$, with initial values of $\xi(0) = -1, \dot{\xi}(0) = 1$ and reference signal $x_d = \sin(t)$. For comparison with the proposed method in (11), the traditional control method combining linear sliding mode and fuzzy logic system is designed as follows:

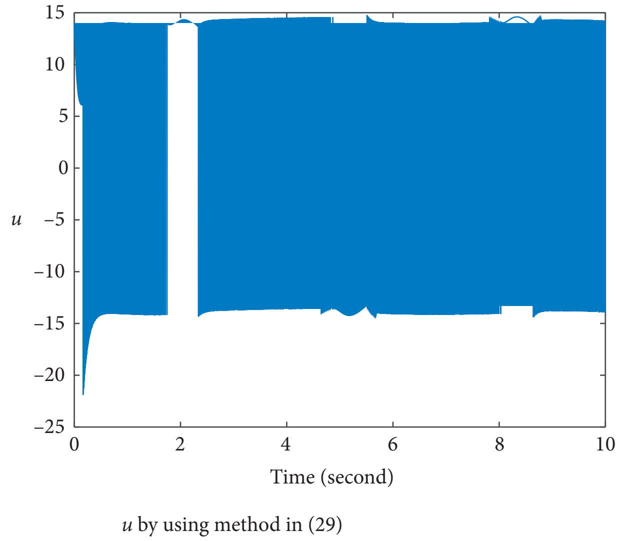


FIGURE 4: Trajectory of $u$ by using the method in (27).

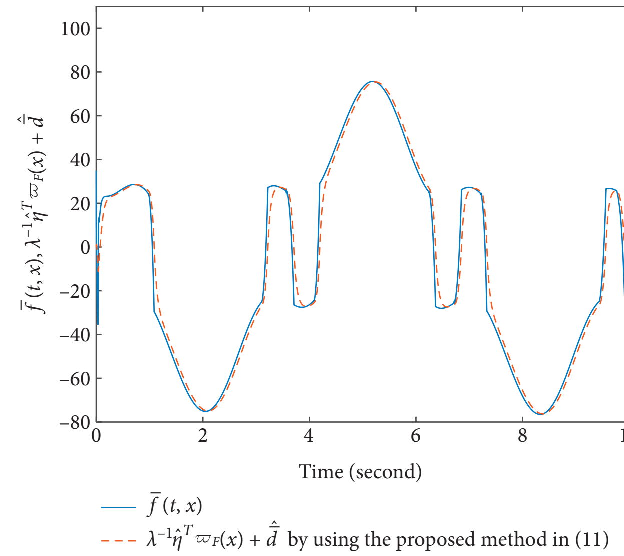


FIGURE 6: Trajectories of $\bar{f}(t,x)$ and $\lambda^{-1}\hat{\eta}^T\varpi_F(x) + \hat{\bar{d}}(t)$ by using the proposed method in (11).

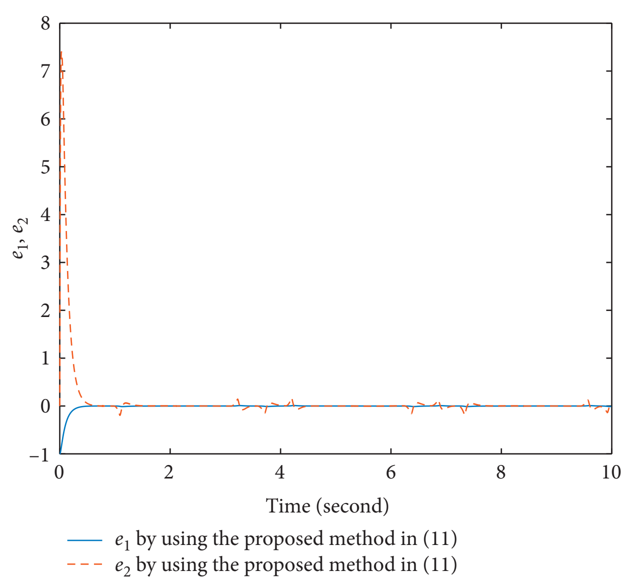


FIGURE 5: Trajectories of $e_1$ and $e_2$ by using the proposed method in (11).

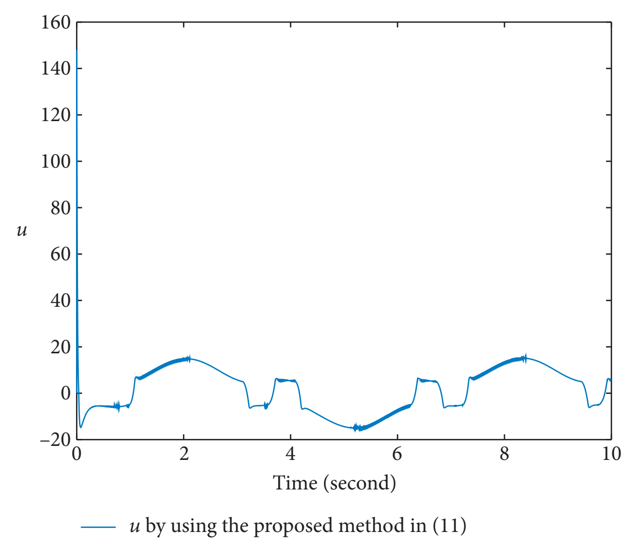


FIGURE 7: Trajectory of $u$ by using the proposed method in (11).

$$\bar{s} = e_2 + \varsigma e_1,$$

$$u = \frac{1}{\beta}\left[-\hat{\bar{\eta}}^T \varpi_{\bar{f}}(x) + \ddot{x}_d - \varsigma e_2 - \bar{\gamma}\operatorname{sign}(\bar{s})\right], \qquad (27)$$

$$\dot{\hat{\bar{\eta}}} = k_1\left(\bar{s}\varpi_{\bar{f}} t(x) n - q k_2 h \hat{\bar{\eta}}\right),$$

where $\hat{\bar{\eta}}^T\varpi_{\bar{f}}(x)$ is the fuzzy estimation of $f(t,x) + d(t) + \sigma(u(t))$, and $d(t) = \cos((3/5)t)$. Define five Gaussian membership functions centered at $-5, -2.5, 0, 2.5, 5$ with a variance equal to 1.2. The initial value of $\hat{\bar{\eta}}(0) = 0$, and other parameters are selected as $\bar{\gamma} = 70, k_1 = 30, k_2 = 0.5, \varsigma = 10, \beta = a_1 = a_2 = 5$. By using the method in (27), the corresponding simulation results are shown in Figures 2–4.

It can be seen from Figure 2 that the tracking error $e_1$ and its derivative $e_2$ approach the neighborhood of zero, but the chattering phenomenon of $e_2$ is obvious. Figure 3 exhibits that the fuzzy estimation $\hat{\bar{\eta}}^T\varpi_{\bar{f}}(x)$ cannot effectively estimate the unknown function $\bar{f}(t,x)$ and Figure 4 shows that the controller $u$ has chattering phenomenon. Under the same parameters and initial values of the method in (27), the other parameters and initial values are selected as $m = 20, \lambda = 5, \tau = (3/5)$ and $\epsilon_1 = 0.05, z(0) = 0$ for the proposed method in (11), and the simulation results of the proposed method in (11) are shown in Figures 5–7.

Obviously, compared with Figure 2, the control effect of $e_1$ and its derivative $e_2$ is improved in Figure 5, and the chattering phenomenon is also reduced. From Figure 6, we can find that the estimation effect of the proposed method in (11) for $\bar{f}(t,x)$ is more better than that of the method in

(27), and the chattering phenomenon of controller $u$ is also reduced in Figure 7. The above simulation results confirm that the method proposed in (11) in this paper is more effective.

## 5. Conclusion

In this paper, a terminal sliding mode control method is proposed for uncertain chaotic gyroscope system; based on disturbance observer and FLSs, the mixed disturbance can be estimated accurately. By using a nonsingular terminal sliding mode function, the proposed control method can achieve the sliding mode variable approaching a small neighborhood of zero. Then, the boundedness of all closed-loop signals is proved according to Lyapunov theory. Compared with the traditional sliding mode control method, simulation results verify that the method proposed in this paper has better control performance.

## Data Availability

All datasets generated for this study are included in the manuscript.

## Conflicts of Interest

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

## Acknowledgments

The authors gratefully acknowledge the support of the Natural Science Foundation of Anhui Province project (2008085MF200) and the Natural Science Research Projects in Anhui Universities (KJ2019ZD48 and KJ2019A0695).

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