Global Chaos Regulation of a Symmetric Nonlinear Gyro System via Integral Sliding Mode Control

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Abstract: Chaos theory has a lot of applications in science and engineering. Gyros are an important class of nonlinear control systems and they have attributes of great utility to navigational, aeronautical and space engineering. In this research work, we first describe the dynamics of a symmetric nonlinear gyro system with linear and cubic damping discovered by Chen (2002). Chen’s gyro system is a two-dimensional, non-autonomous, chaotic system and it has important applications. Next, new results are obtained for the global chaos regulation of the Chen’s gyro system. MATLAB plots have been shown to illustrate the phase portraits of Chen’s gyro system and the global chaos regulation of Chen’s gyro system via integral sliding mode control.

Keywords: Chaos, chaotic systems, gyro system, symmetrical system, gyroscope, navigational engineering, aeronautical engineering, sliding mode control, chaos regulation, chaos control, stability.

1. Introduction

A dynamical system is called chaotic if it satisfies the three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [1-4]. Chaos theory has a lot of applications in science and engineering [5]. Chaos theory has applications in dynamo systems [6-12], memristors [13-16], nonlinear oscillators [17-30], Tokamak systems [31-32], finance system [33], cellular neural networks [34-39], chemical reactors [40-50], neurology [51-58], population biology systems [59-67], etc.

Gyros are an important class of nonlinear control systems and they have attributes of great utility to navigational, aeronautical and space engineering. In this research work, we first describe the dynamics of a symmetric nonlinear gyro system with linear and cubic damping discovered by Chen ([68], 2002). Chen’s gyro system is a two-dimensional, non-autonomous, chaotic system and it has important applications.

This paper also derives new results for the global chaos regulation of Chen’s symmetric gyro system via integral sliding mode control method. Sliding mode control is a popular control technique used in the control and synchronization of chaotic systems [69-73]. MATLAB plots are shown to illustrate the phase portraits and global chaos regulation of Chen’s symmetric nonlinear gyro system.

2. Chen’s symmetric nonlinear chaotic gyro system

In 2002, Chen discovered a symmetric nonlinear gyro system [68], which is described as
\[
\ddot{\theta} + \alpha^2 \frac{(1-\cos\theta)^2}{\sin^3 \theta} - \beta \sin \theta + c_1 \dot{\theta} + c_2 \dot{\theta}^3 = f \sin(\omega t) \sin \theta
\]  

(1)

where \( f \sin(\omega t) \) represents a parametric excitation, \( c_1 \dot{\theta} \) and \( c_2 \dot{\theta}^3 \) are linear and cubic damping terms, respectively, and \( \alpha^2 \frac{(1-\cos\theta)^2}{\sin^3 \theta} \) is a nonlinear term.

To simplify the notations in (1), we define

\[
g(\theta) = -\alpha^2 \frac{(1-\cos\theta)^2}{\sin^3 \theta} \quad \text{and} \quad F(t) = f \sin(\omega t)
\]

(2)

We define phase variables as

\[
x_1 = \theta, \; x_2 = \dot{\theta}
\]

(3)

In other words, \( x_1 \) and \( x_2 \) are the angular displacement and angular velocity, respectively, of Chen’s symmetric nonlinear gyro system.

Using (2) and (3), we can represent Chen’s symmetric nonlinear gyro system (1) in state space form as

\[
\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= g(x_1) - c_1 x_2 - c_2 x_1^2 + (\beta + F(t)) \sin(x_1)
\end{aligned}
\]

(4)

The gyro dynamics (4) was studied by Chen [190] and it was shown that the gyro system (4) is chaotic for the parameter values

\[
\alpha^2 = 100, \; \beta = 1, \; c_1 = 0.5, \; c_2 = 0.05, \; f = 35.5, \; \omega = 2
\]

(5)

For numerical simulations, we take the initial conditions

\[
x_1(0) = 0.2, \; x_2(0) = 0.2
\]

(6)

The 2-D phase portrait of the strange chaotic attractor of Chen’s symmetric gyro system (2) is depicted in Figure 1.

![Figure 1. The 2-D phase portrait of Chen’s chaotic gyro system](attachment:image.png)

3. Global chaos regulation of the symmetric nonlinear chaotic gyro system

In this section, we use integral sliding mode control method [74] to regulate the states of Chen’s symmetric nonlinear gyro system. We use Lyapunov stability theory [75] to prove the main result derived in this
Thus, we consider the symmetric nonlinear chaotic gyro dynamics given by

\[
\begin{aligned}
\dot{x}_1 &= x_2 + u_1 \\
\dot{x}_2 &= g(x_1) - c_1 x_2 - c_2 x_2^3 + (\beta + F(t)) \sin(x_1) + u_2
\end{aligned}
\]  

(7)

In (7), \(x_1, x_2\) are the states of Chen’s symmetric nonlinear chaotic gyro system. The design goal is to find controls \(u_1, u_2\) so that the system states \(x_1(t), x_2(t)\) are regulated to the constant reference values (set-point controls) \(\alpha_1, \alpha_2\), respectively.

Thus, the regulation errors are defined by

\[
\begin{aligned}
\epsilon_1(t) &= x_1(t) - \alpha_1 \\
\epsilon_2(t) &= x_2(t) - \alpha_2
\end{aligned}
\]  

(8)

The error dynamics is obtained as

\[
\dot{\epsilon}_1 = x_2 + u_1 \\
\dot{\epsilon}_2 = g(x_1) - c_1 x_2 - c_2 x_2^3 + (\beta + F(t)) \sin(x_1) + u_2
\]  

(9)

Based on the sliding mode control theory [19], the integral sliding surface of each error variable is defined as follows:

\[
\begin{aligned}
s_1 &= \left[ \frac{d}{dt} + \lambda_1 \right] \int_0^t \epsilon_1(\tau) d\tau + \epsilon_1 + \lambda_1 \int_0^t \dot{\epsilon}_1(\tau) d\tau \\
s_2 &= \left[ \frac{d}{dt} + \lambda_2 \right] \int_0^t \epsilon_2(\tau) d\tau + \epsilon_2 + \lambda_2 \int_0^t \dot{\epsilon}_2(\tau) d\tau
\end{aligned}
\]  

(10)

The derivative of each equation in (10) yields

\[
\begin{aligned}
\dot{s}_1 &= \dot{\epsilon}_1 + \dot{\lambda}_1 \epsilon_1 \\
\dot{s}_2 &= \dot{\epsilon}_2 + \dot{\lambda}_2 \epsilon_2
\end{aligned}
\]  

(11)

The Hurwitz condition is satisfied if \(\lambda_1, \lambda_2\) are positive constants.

Based on the exponential reaching law [74], we set

\[
\begin{aligned}
\dot{s}_1 &= -\eta_1 \text{sgn}(s_1) - k_1 s_1 \\
\dot{s}_2 &= -\eta_2 \text{sgn}(s_2) - k_2 s_2
\end{aligned}
\]  

(12)

Comparing equations (11) and (12), we get

\[
\begin{aligned}
\dot{\epsilon}_1 + \lambda_1 \epsilon_1 &= -\eta_1 \text{sgn}(s_1) - k_1 s_1 \\
\dot{\epsilon}_2 + \lambda_2 \epsilon_2 &= -\eta_2 \text{sgn}(s_2) - k_2 s_2
\end{aligned}
\]  

(13)

Using Eq. (9), we can rewrite Eq. (13) as follows:

\[
\begin{aligned}
\dot{x}_2 + u_1 + \lambda_1 \epsilon_1 &= -\eta_1 \text{sgn}(s_1) - k_1 s_1 \\
g(x_1) - c_1 x_2 - c_2 x_2^3 + (\beta + F(t)) \sin(x_1) + u_2 + \lambda_2 \epsilon_2 &= -\eta_2 \text{sgn}(s_2) - k_2 s_2
\end{aligned}
\]  

(14)

From Eq. (14), the control laws are obtained as follows:

\[
\begin{aligned}
u_1 &= -x_2 - \lambda_1 \epsilon_1 - \eta_1 \text{sgn}(s_1) - k_1 s_1 \\
u_2 &= -g(x_1) + c_1 x_2 + c_2 x_2^3 - (\beta + F(t)) \sin(x_1) - \lambda_2 \epsilon_2 - \eta_2 \text{sgn}(s_2) - k_2 s_2
\end{aligned}
\]  

(15)

Next, we state and prove the main result of this section.

**Theorem 1.** The states \(x_1, x_2\) of Chen’s symmetric nonlinear chaotic gyro system (7) are regulated to track the
constant reference signals $\alpha_1, \alpha_2$, respectively as $t \to \infty$ for all initial conditions $(x_1(0), x_2(0)) \in \mathbb{R}^2$ by the integral sliding mode control law (15), where the constants $\lambda_1, \lambda_2, \eta_1, \eta_2, k_1, k_2$ are all positive.

**Proof.** This result is proved using Lyapunov stability theory [75].

We consider the following quadratic Lyapunov function

$$V(s_1, s_2) = \frac{1}{2} (s_1^2 + s_2^2),$$

(16)

where $s_1, s_2$ are as defined in (10).

The time-derivative of $V$ is obtained as

$$\dot{V} = s_1 \dot{s}_1 + s_2 \dot{s}_2$$

(17)

Substituting from Eq. (12) into (17), we get

$$\dot{V} = s_1[-\eta_1 \text{sgn}(s_1) - k_1 s_1] + s_2[-\eta_2 \text{sgn}(s_2) - k_2 s_2]$$

(18)

Simplifying Eq. (18), we obtain

$$\dot{V} = -\eta_1 |s_1|^2 k_1 - \eta_2 |s_2|^2 k_2$$

(19)

Since $k_1, k_2 > 0$ and $\eta_1, \eta_2 > 0$, it follows from (19) that $\dot{V}$ is a negative definite function.

Thus, by Lyapunov stability theory [75], it follows that $(s_1, s_2) \to (0, 0)$ as $t \to \infty$.

Hence, it is immediate that $(e_1, e_2) \to (0, 0)$ as $t \to \infty$.

This completes the proof. ■

4. Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the system of differential equations (7) when the integral sliding mode controller (15) is implemented.

The parameter values of Chen’s symmetric nonlinear gyro system (7) are taken as in the chaotic case, viz.

$$\alpha^2 = 100, \quad \beta = 1, \quad c_1 = 0.5, \quad c_2 = 0.05, \quad f = 35.5, \quad \omega = 2$$

(20)

We take the sliding constants as

$$\lambda_1 = \lambda_2 = 0.1, \quad \eta_1 = \eta_2 = 0.1, \quad k_1 = k_2 = 20$$

(21)

We take the initial conditions of Chen’s symmetric nonlinear gyro system as

$$x_1(0) = 7.5, \quad x_2(0) = 9.8$$

(22)

We take the constant reference signals as $\alpha_1 = 1$ and $\alpha_2 = 2$.

Figure 2 shows the output regulation of the states $x_1(t), x_2(t)$. Figure 3 shows the time-history of the output regulation errors $e_1(t), e_2(t)$. 


In this paper, we first described the dynamics of a symmetric nonlinear gyro system with linear and cubic damping discovered by Chen (2002). Chen’s gyro system is a two-dimensional, non-autonomous, chaotic system and it has important applications. Next, new results were derived for the global chaos regulation of the Chen’s gyro system. MATLAB plots have been shown to illustrate the phase portraits of Chen’s gyro system and the global chaos regulation of Chen’s gyro system via integral sliding mode control.

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