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Dynamics and Control of Tokamak System with Symmetric and Magnetically Confined Plasma

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Abstract: One of the most developed of the modern magnetic fusion concepts is the Tokamak. In respect of their symmetry properties, toroidal magnetically confined plasmas have much in common with the Taylor-Couette flow. This research work analyzes the dynamics of the Tokamak system with symmetric and magnetically confined plasma studied by Arter (2009). Then this work discusses the adaptive control of the Tokamak chaotic system with unknown system parameters. The main result is established using Lyapunov stability theory. MATLAB plots have been shown to illustrate all the main results discussed on the Tokamak chaotic system with symmetric and magnetically confined plasma.
Keywords: Tokamak, magnetic fusion, plasma, symmetric system, chaotic system, adaptive control, etc.

Introduction

One of the most developed modern magnetic fusion concepts is the Tokamak [1]. After 40 years of research, a great amount is known about Tokamak behaviour. However, a complete understanding of some of the most prominent phenomena has not yet been achieved. For example, diagnosing the behaviour of some aspects of extremely hot plasma is still a very challenging problem for the experimenter. The most intensively studied configuration most analogous to toroidal plasma devices is the Taylor-Couette experiment [2]. In this work, we analyze the dynamics of the Tokamak system with rotationally symmetric and magnetically confined plasma studied by Arter [1].

A dynamical system is called *chaotic,* the system variables should contain some nonlinear terms and the system must satisfy three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [3-4]. The first known chaotic system was discovered by Lorenz in 1963 [5]. Subsequently, Rössler discovered a 3-D chaotic chemical reaction system in 1976 [6].

The classical chaotic systems were followed by the finding of many 3-D chaotic systems such as Arneodo system [7], Sprott systems [8], Chen system [9], Lü-Chen system [10], Cai system [11], Tigan system [12], etc. Many new chaotic systems have been also discovered in the recent years such as Sampath system [13], Sundarapandian systems [14-15], Vaidyanathan systems [16-35], Pehlivan system [36], Pham system [37], etc.

Chaos theory has very useful applications in many fields of science and engineering such as oscillators [38], lasers [39-40], biology [41-42], chemical reactions [43-45], neural networks [46-47], robotics [48-49], electrical circuits [50], etc.

This paper describes the modelling and properties of the Tokamak chaotic system with rotationally symmetric and magnetically confined plasma [1]. This paper also derives new results of adaptive feedback controller design for the Tokamak chaotic system using Lyapunov stability theory [51].

In control theory, active control method is used when the system parameters are available for measurement [52-68]. Adaptive control is a popular control technique used for stabilizing systems when the system parameters are unknown [69-82]. There are also other popular methods available for control and synchronization of systems such as backstepping control method [83-88], sliding mode control method [89-100], etc.

Recently, chaos theory is found to have applications in many areas such as chemistry [101], biology [102], memristors [103-105], electrical circuits [106], etc.

Tokamak system with symmetric and magnetically confined plasma:

The mathematical model for the Tokamak system with rotationally symmetric and magnetically confined plasma [1] is given the 3-D dynamics

$$\begin{cases} \dot{x} = y \\ \dot{y} = x - x^3 \\ \dot{z} = a - bz^2 - x^2 \end{cases} \quad (1)$$

In (1), x, y, z are the states of the Tokamak system and a, b are constant system parameters.

In [1], Arter (2009) showed that the Tokamak system (1) shows dissipative chaotic behaviour, when we take the system parameter values as

$$a = 1, \quad b = 0.001 \quad (2)$$

For numerical simulations, we take the initial conditions as $x(0) = 0.01$, $y(0) = 0.01$ and $z(0) = 0.01$.

For the parameter values (2) and the chosen initial conditions, the Lyapunov exponents of the Tokamak system (1) are numerically determined as

$$L_1 = 0.0228, \quad L_2 = 0, \quad L_3 = -0.0701. \quad (3)$$

Also, the Lyapunov dimension of the Tokamak chaotic system (1) is determined as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} = 2 + \frac{0.0228 + 0}{0.0701} = 2.3252 \quad (4)$$

Figure 1 shows the 3-D phase portrait of the strange chaotic attractor of the Tokamak system (1).

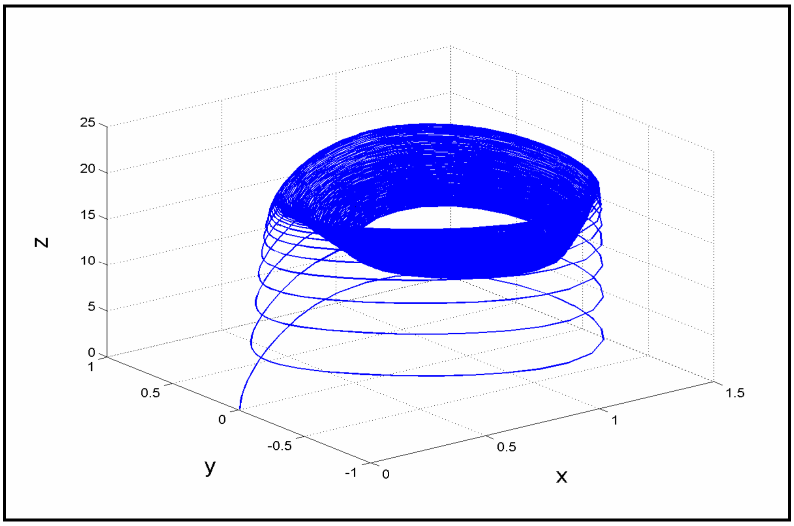

Figure 1. Strange chaotic attractor of the Tokamak system

Adaptive control of the Tokamak chaotic system

In this section, we use adaptive control method to design an adaptive feedback control law for stabilizing the Tokamak chaotic system with symmetric and magnetically confined plasma.

Thus, we consider the controlled Tokamak system given by the 3-D dynamics

$$\begin{cases} \dot{x} = y + u_x \\ \dot{y} = x - x^3 + u_y \\ \dot{z} = a - bz^2 - x^2 + u_z \end{cases} \tag{5}$$

In (5), x, y, z are the states and u_x, u_y, u_z are the adaptive feedback controls to be found using estimates of the unknown parameters a, b of the system (2).

We consider the adaptive controller defined by

$$\begin{cases} u_x = -y - k_x x \\ u_y = -x + x^3 - k_y y \\ u_z = -\hat{a}(t) + \hat{b}(t)z^2 + x^2 - k_z z \end{cases} \tag{6}$$

where k_x, k_y, k_z are positive constants and $\hat{a}(t), \hat{b}(t)$ are estimates of the unknown parameters $a, b,$ respectively.

Substituting (6) into (5), we get the closed-loop control system given by

$$\begin{cases} \dot{x} = -k_x x \\ \dot{y} = -k_y y \\ \dot{z} = [a - \hat{a}(t)] - [b - \hat{b}(t)]z^2 - k_z z \end{cases} \tag{7}$$

We define parameter estimation errors as follows:

$$\begin{cases} e_a = a - \hat{a}(t) \\ e_b = b - \hat{b}(t) \end{cases} \tag{8}$$

Using (8), we can simplify the error dynamics (7) as follows.

$$\begin{cases} \dot{x} = -k_x x \\ \dot{y} = -k_y y \\ \dot{z} = e_a - e_b z^2 - k_z z \end{cases} \tag{9}$$

Differentiating the parameter estimation errors (8) with respect to time, we get

$$\begin{cases} \dot{e}_a = -\dot{\hat{a}}(t) \\ \dot{e}_b = -\dot{\hat{b}}(t) \end{cases} \tag{10}$$

Next, we consider the candidate Lyapunov function given by

$$V(x, y, z, e_a, e_b) = \frac{1}{2}\left(x^2 + y^2 + z^2 + e_a^2 + e_b^2\right) \tag{11}$$

Differentiating V along the trajectories of (9) and (10), we obtain

$$\dot{V} = -k_x x^2 - k_y y^2 - k_z z^2 + e_a[z - \dot{\hat{a}}(t)] + e_b[-z^3 - \dot{\hat{b}}(t)] \tag{12}$$

In view of (12), we take the parameter estimates as follows:

$$\begin{cases} \dot{\hat{a}} = z \\ \dot{\hat{b}} = -z^3 \end{cases} \tag{13}$$

Theorem 1. *The Tokamak chaotic system (5) with symmetric and magnetically confined plasma is globally and exponentially stabilized for all initial values* $(x(0), y(0), z(0)) \in R^3$ *by the adaptive control law (6) and parameter update law (13), where* k_x, k_y, k_z *are positive gain constants.*

Proof. The quadratic Lyapunov function V defined by Eq. (11) is a positive definite function on R^5. Substituting the parameter update law (13) into (12), the time-derivative of V is obtained as

$$\dot{V} = -k_x x^2 - k_y y^2 - k_z z^2, \qquad (14)$$

which is a negative semi-definite function on R^5.

Thus, by Lyapunov stability theory [51], we conclude that $X(t) = \left[x(t), y(t), z(t)\right] \to 0$ exponentially as $t \to \infty$ for all initial conditions $e(0) \in R^2$. This completes the proof. ■

Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the systems of differential equations given by (5) and (13).

We take the gain constants as $k_x = k_y = k_z = 10$.
We take the initial conditions of the Tokamark system (5) as $X(0) = [10.1, \ 3.2, \ 20.7]$.
We take the system parameters as in the chaotic case, *i.e.* $a = 1$ and $b = 0.001$.
Also, we take the initial conditions of the parameter estimates as $\hat{a}(0) = 7.2$ and $\hat{b}(0) = 9.5$.

Figure 2 shows the time-history of the exponential convergence of the states $x(t), y(t), z(t)$ to zero.

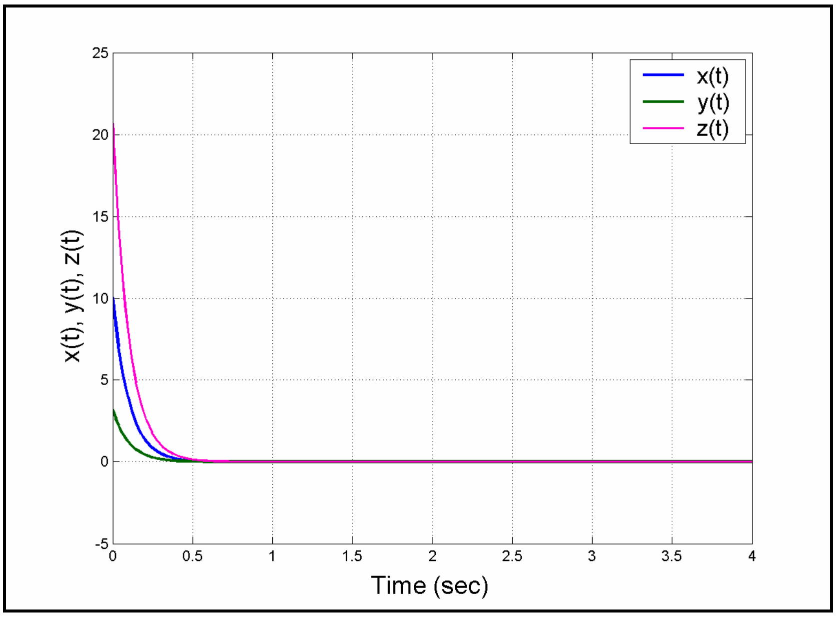

Figure 2. Time-history of the controlled states $x(t), y(t), z(t)$

Conclusions

In this paper, new results have been derived for the analysis and adaptive control of the Tokamak chaotic system with rotationally symmetric and magnetically confined plasma. We analyzed the dynamics and qualitative properites of the Tokamak system with symmetric and magnetically confined plasma studied by Arter (2009). Then we derived new results for the adaptive control of the Tokamak chaotic system with unknown system parameters. The main result was established using Lyapunov stability theory.

MATLAB plots were depicted to illustrate all the main results discussed on the Tokamak chaotic system with symmetric and magnetically confined plasma.

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