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Active Control of a Chaotic Fractional Order Economic System

Haci Mehmet Baskonus ^{1,*}, Toufik Mekkaoui ², Zakia Hammouch ² and Hasan Bulut ³

¹ Department of Computer Engineering, Faculty of Engineering, University of Tunceli, 62100 Tunceli, Turkey

² E3MI Group, Department of Mathematics, Faculty of Sciences and Techniques of Errachidia, Moulay Ismail University, 52000 Meknes, Morocco; E-Mails: toufik_mekkaoui@yahoo.fr (T.M.); hammouch.zakia@gmail.com (Z.H.)

³ Department of Mathematics, Faculty of Science, Firat University, 23100 Elazig, Turkey; E-Mail: hbulut@firat.edu.tr

* Author to whom correspondence should be addressed; E-Mail: hmbaskonus@gmail.com; Tel.: +90-428-213-17-94.

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Abstract: In this paper, a fractional order economic system is studied. An active control technique is applied to control chaos in this system. The stabilization of equilibria is obtained by both theoretical analysis and the simulation result. The numerical simulations, via the improved Adams–Bashforth algorithm, show the effectiveness of the proposed controller.

Keywords: fractional-order differential equations (FDEs); chaos; economic system; active control

MSC classifications: 34H10; 26A33; 65P20

1. Introduction

Fractional calculus has 300-year history. However, applications of fractional calculus in physics and engineering have just begun. Many systems are known to display fractional order dynamics, such as viscoelastic systems, dielectric polarization and electromagnetic waves [1–6]. In recent years, the emergence of effective methods in differentiation and integration of non-integer order equations makes fractional order systems more and more attractive for the systems control community [7–10].

More recently, there has been a new trend to investigate the control and the dynamic behavior of fractional order chaotic systems. It has been shown that nonlinear chaotic systems may keep their chaotic behavior when their models become fractional [11–13].

In this paper, the aim is to control a chaotic fractional-order economic system, using a nonlinear active control method.

This paper is organized as follows: Some preliminaries about fractional calculus, the stability criterion and the numerical algorithm are given in Section 2. The fractional order economic system and its dynamical behavior are described in Section 3. The active control method and the numerical simulations are presented in Section 4. Concluding remarks are drawn in Section 5.

2. Preliminary Tools

2.1. Fractional Calculus

Historical introductions on fractional-order differential equations (FDEs) can be found in [3–6,14]. Commonly-used definitions for fractional derivatives are due to Riemann–Liouville and Caputo [15]. In what follows, Caputo derivatives are considered, taking the advantage that this allows for traditional initial and boundary conditions to be included in the formulation of the considered problem.

Definition 1. A real function $f(x)$, $x > 0$, is said to be in the space C_μ , $\mu \in \mathbb{R}$ if there exists a real number $\lambda > \mu$, such that $f(x) = x^\lambda g(x)$, where $g(x) \in C[0, \infty)$, and it is said to be in the space C_μ^m if and only if $f^{(m)} \in C_\mu$ for $m \in \mathbb{N}$.

Definition 2. The Riemann–Liouville fractional integral operator of order α of a real function $f(x) \in C_\mu$, $\mu \geq -1$, is defined as:

$$J^\alpha f(x) = \frac{1}{\Gamma(\alpha)} \int_0^x (x-t)^{\alpha-1} f(t) dt, \quad \alpha > 0, x > 0, \quad (1)$$

and $J^0 f(x) = f(x)$. The operators J^α have some properties, for $\alpha, \beta \geq 0$ and $\xi \geq -1$:

- $J^\alpha J^\beta f(x) = J^{\alpha+\beta} f(x)$,
- $J^\alpha J^\beta f(x) = J^\beta J^\alpha f(x)$,
- $J^\alpha x^\xi = \frac{\Gamma(\xi+1)}{\Gamma(\alpha+\xi+1)} x^{\alpha+\xi}$.

Definition 3. The Caputo fractional derivative D^α of a function $f(x)$ of any real number α , such that $m-1 < \alpha \leq m$, $m \in \mathbb{N}$, for $x > 0$ and $f \in C_{-1}^m$ in terms of J^α , is:

$$D^\alpha f(x) = \frac{1}{\Gamma(m-\alpha)} \int_0^x (x-t)^{m-\alpha-1} f^{(m)}(t) dt \quad (2)$$

and has the following properties for $m-1 < \alpha \leq m$, $m \in \mathbb{N}$, $\mu \geq -1$ and $f \in C_\mu^m$:

- $D^\alpha J^\alpha f(x) = f(x)$,
- $J^\alpha D^\alpha f(x) = f(x) - \sum_{k=0}^{m-1} f^{(k)}(0^+) \frac{x^k}{k!}$, for $x > 0$.

2.2. Stability Criterion

In order to investigate the dynamics and to control the chaotic behavior of a fractional order dynamic system:

$$D_t^\alpha X(t) = F(X(t)), \quad (3)$$

where $X(t) = (x_1, x_2, \dots, x_n)^T \in \mathbb{R}^n$, $t > t_0$, $t \in [0, T]$, $\alpha \in (0, 1)$ and $F : T \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ is continuous in X . We will need the following indispensable stability theorem (see Figure 1).

Theorem 1 (See [16]). *For a given commensurate fractional order system (3), the equilibria can be obtained by calculating $F(X) = 0$. These equilibrium points are locally-asymptotically stable if all of the eigenvalues λ of the Jacobian matrix $J = \frac{\partial F}{\partial X}$ at the equilibrium points satisfy:*

$$|\arg(\lambda)| > \frac{\pi}{2}\alpha. \quad (4)$$

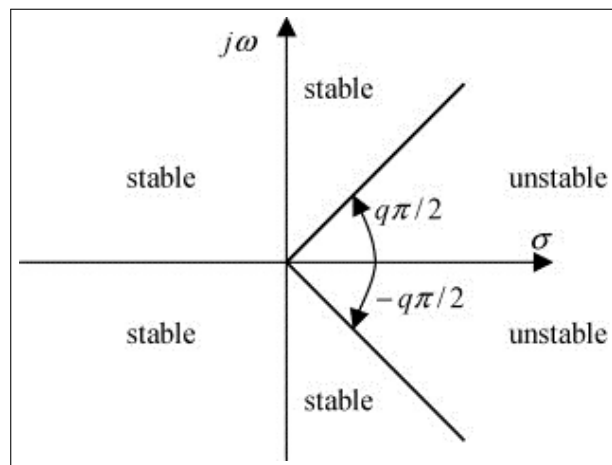


Figure 1. Stability region of the fractional order system (3).

2.3. The Adams–Bashforth–Moulton Algorithm

We recall here the improved version of Adams–Bashforth–Moulton algorithm [17] for the fractional-order systems. Consider the fractional order initial value problem:

$$\begin{cases} D_t^\alpha x = f(x(t)) & 0 \leq t \leq T, \\ x^{(k)}(0) = x_0^{(k)}, & k = 0, 1, \dots, m-1. \end{cases} \quad (5)$$

It is equivalent to the Volterra integral equation:

$$x(t) = \sum_{k=0}^{[\alpha]-1} x_0^{(k)} \frac{t^k}{k!} + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} f(s, x(s)) ds. \quad (6)$$

Diethelm *et al.* have given a predictor-corrector scheme (see [17]), based on the Adams–Bashforth–Moulton algorithm, to integrate Equation (6). By applying this scheme to the fractional order system (5), and setting:

$$h = \frac{T}{N}, \quad t_n = nh, \quad n = 0, 1, \dots, N,$$

Equation (6) can be discretized as follows:

$$x_h(t_{n+1}) = \sum_{k=0}^{[\alpha]-1} x_0^{(k)} \frac{t^k}{k!} + \frac{h^\alpha}{\Gamma(\alpha+2)} f(t_{n+1}, x_h^p(t_{n+1})) + \frac{h^\alpha}{\Gamma(\alpha+2)} \sum_{j=0}^n a_{j,n+1} f(t_j, x_h(t_j)), \quad (7)$$

where:

$$a_{j,n+1} = \begin{cases} n^{\alpha+1} - (n-\alpha)(n+1)^\alpha, & j=0, \\ (n-j+2)^{\alpha+1} + (n-j)^{\alpha+1} - 2(n-j+1)^{\alpha+1}, & 1 \leq j \leq n, \\ 1, & j=n+1, \end{cases} \quad (8)$$

and the predictor is given by:

$$x_h^p(t_{n+1}) = \sum_{k=0}^{[\alpha]-1} x_0^{(k)} \frac{t^k}{k!} + \frac{1}{\Gamma(\alpha)} \sum_{j=0}^n b_{j,n+1} f(t_j, x_h(t_j)), \quad (9)$$

where $b_{j,n+1} = \frac{h^\alpha}{\alpha} ((n+1)-j)^\alpha - (n-j)^\alpha$. The error estimate of the above scheme is:

$$\max_{j=0,1,\dots,N} \{|x(t_j) - x_h(t_j)|\} = O(h^p),$$

in which $p = \min(2, 1 + \alpha)$.

3. A Fractional Order Economic System

We consider a 3D system of fractional order autonomous differential equations; this system can be interpreted as an idealized macroeconomic model with foreign capital investments [18]. It can be described by:

$$\begin{cases} D^\alpha x = my + px(d - y^2), \\ D^\alpha y = -x + cz, \\ D^\alpha z = sx - ry. \end{cases} \quad (10)$$

where $\alpha \in (0, 1]$ and the state variables, x , y and z , are the savings of households, the gross domestic product (GDP) and the foreign capital inflow, respectively. Furthermore, the fractional derivation is considered with respect to time. Positive parameters represent corresponding ratios: m is the marginal propensity to saving, p is the ratio of capitalized profit, d is the value of the potential GDP, c is the output/capital ratio, s is the capital inflow/savings ratio and r is the debt refund/output ratio.

3.1. Dynamical Behavior

When $m = 0.02$, $p = 0.4$, $c = 50$, $d = 1$, $r = 0.1$ and $s = 10$. The system (10) has three real equilibria $E_0(0, 0, 0)$, $E_1(0.024, 2.4, 4.8 \times 10^{-4})$ and $E_2(-0.024, -2.4, -4.8 \times 10^{-4})$.

At the equilibrium point E_0 , the Jacobian matrix of System (10) is given by:

$$J|_{E_0} = \begin{pmatrix} pd & m & 0 \\ -1 & 0 & c \\ s & -r & 0 \end{pmatrix},$$

The eigenvalues of above matrix are given by:

$$\lambda_1 = 1.6761839, \quad \lambda_2 = -0.6380920 + 2.5984529i \quad \text{and} \quad \lambda_3 = -0.6380920 - 2.5984529i.$$

Hence, the equilibrium point E_0 is unstable. At the equilibrium point E_1 and E_2 , the Jacobian matrix of System (10) is given by:

$$J|_{E_{1,2}} = \begin{pmatrix} pd - 5.76p & m - 0.115p & 0 \\ -1 & 0 & c \\ s & -r & 0 \end{pmatrix},$$

The eigenvalues of the above matrix are given by:

$$\lambda_1 = -2.8852598, \quad \lambda_2 = 0.4906299 + 2.7503585i \quad \text{and} \quad \lambda_3 = 0.4906299 - 2.7503585i.$$

Here, λ_1 is a negative real number and λ_2 and λ_3 are a pair of complex conjugate eigenvalues with positive real parts. Therefore, the equilibrium points E_1 and E_2 are unstable. According to Theorem (4), System (10) exhibits chaotic behavior for $\alpha \geq \alpha_{min} = 0.8876170531$. We stress here that the case $\alpha = 1$ was studied in [18].

3.2. Numerical Simulations

In order to confirm the chaotic behavior of System (10), numerical simulations were conducted for $\alpha = 0.9$ and the selected initial conditions $(x_0, y_0, z_0) = (0.05, 0.1, 0.02)$. The time histories of the state variables, x , y and z , are graphically presented in Figure 2, and the phase diagrams are shown in Figure 3, while the chaotic attractor is plotted in Figure 4.

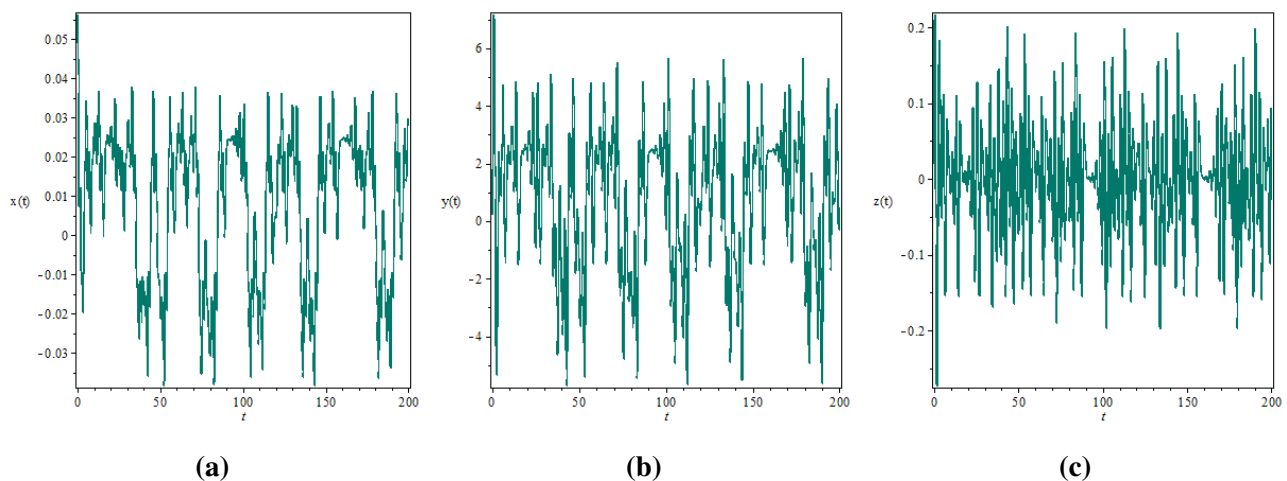


Figure 2. The time histories of variables (a) $x(t)$, (b) $y(t)$ and (c) $z(t)$ for $\alpha = 0.9$.

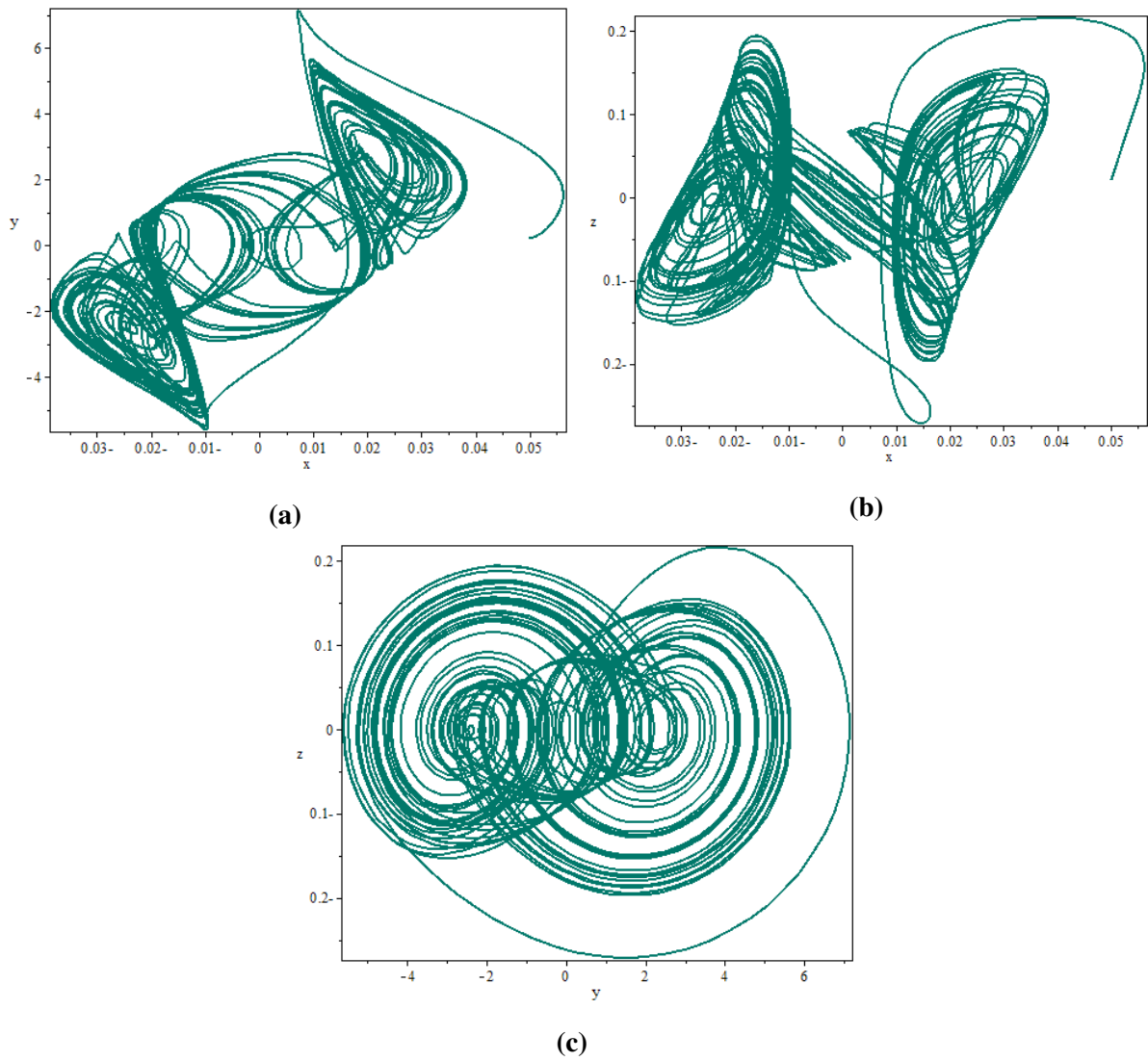


Figure 3. Phase portraits: (a) $x - y$, (b) $x - z$ and (c) $y - z$ for System (10) when $\alpha = 0.9$.

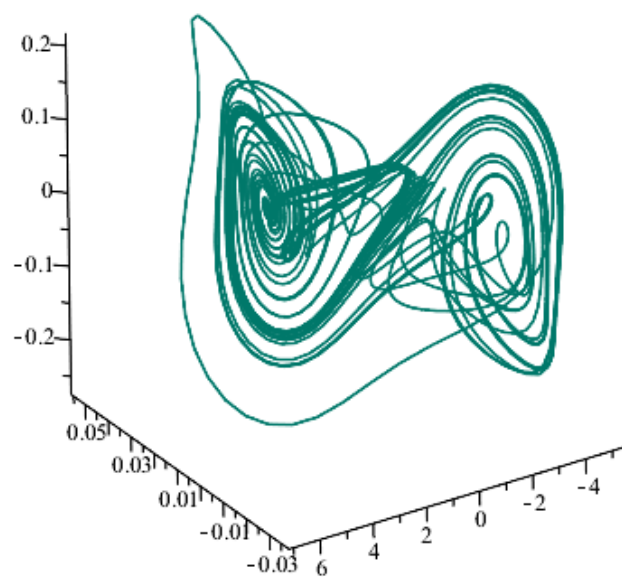


Figure 4. Chaotic attractor xyz for System (10) when $\alpha = 0.9$.

4. Active Control of the Fractional Order Chaotic System

In this section, we investigate the problem of chaos control of the fractional chaotic System (10). In order to control it towards equilibrium points E_0 , E_1 and E_2 , as in [19], we assume that the controlled fractional order autonomous system is given by:

$$\begin{cases} D^\alpha x = my + px(d - y^2) + U_1, \\ D^\alpha y = -x + cz + U_2, \\ D^\alpha z = sx - ry + U_3. \end{cases} \quad (11)$$

where $U_j(t)$ ($j = 1, 2, 3$) are external active control inputs, which will be suitably-determined later. We prove the following result:

Theorem 2. *Starting from any initial condition, an equilibrium point E_i of system (11) is asymptotically stable when the controller U_j , $j = 1, 2, 3$, is active, for $\alpha \geq \alpha_{min}$.*

Proof. As a Lyapunov candidate function associated with System (11), we consider the quadratic function defined by:

$$V(t, (X(t) - E_i)) = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2, \quad (12)$$

where $X = (x, y, z)^T$ and $E_i = (x_i, y_i, z_i)^T$ is an equilibrium point. Note that V is a positive-definite function on \mathbb{R}^3 . From system (11), we have:

$$D^\alpha V(t, (X(t) - E_i)) = -2V(t, (X(t) - E_i)) < 0. \quad (13)$$

According to the Lyapunov theory, the equilibrium point E_i is asymptotically stable. \square

To stabilize the chaotic orbits in (10) to its equilibrium E_0 (respectively, E_1 or E_2), we need to add the following active controllers:

- For E_0 :

$$\begin{cases} U_1 := -1.4x + 0.98y + 0.4xy^2, \\ U_2 := -y - 49.9z, \\ U_3 := -10x - z. \end{cases} \quad (14)$$

- For E_1 :

$$\begin{cases} U_1 = 0.904x + 1.02608y - 0.002304 + 0.4xy^2 + 1.92xy + 0.0096y^2, \\ U_2 = -y - 49.9z, \\ U_3 = -10x - z. \end{cases} \quad (15)$$

- For E_2 :

$$\begin{cases} U_1 = 0.904x + 1.02608y + 0.002304 + 0.4xy^2 - 1.92xy - 0.0096y^2, \\ U_2 = -y - 49.9z, \\ U_3 = -10x - z. \end{cases} \quad (16)$$

Taking into account the above-described controllers, the equilibria E_0 , E_1 and E_2 are stabilized, and then, the chaos is controlled in system (10).

Now, we implement the improved Adams–Bashforth algorithm for numerical simulations (for $t \in [0, 100]$ and $t \in [0, 300]$). The unstable point E_0 has been stabilized, as shown in Figures 5–7. We remark that the behaviors of $x(t)$, $y(t)$ and $z(t)$ start as chaotic; then, when the control is activated at $t = 40$, the equilibrium point is rapidly stabilized. The equilibria E_1 and E_2 are stabilized in an analogous way (see Figures 8–13).

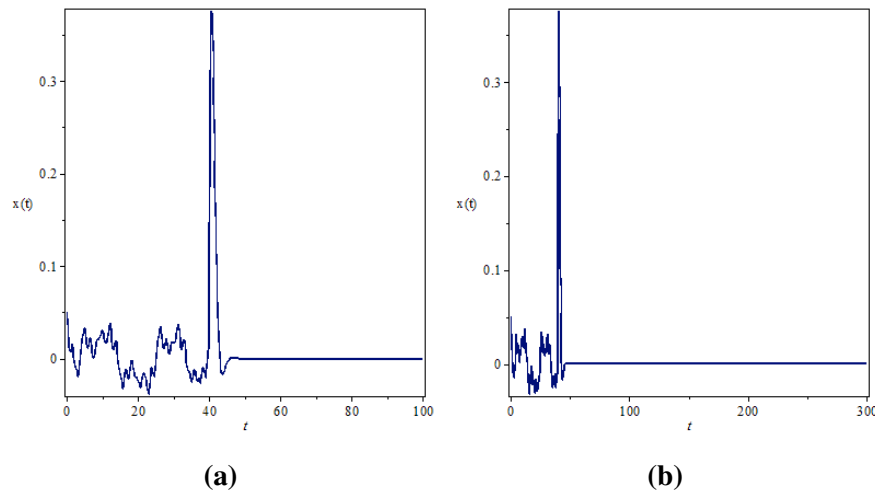


Figure 5. Time histories of System (11) for x signal at the equilibrium E_0 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

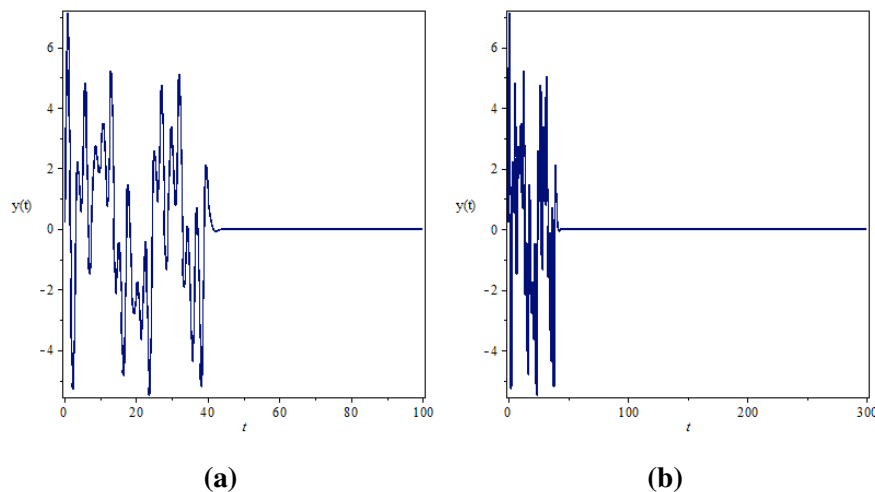


Figure 6. Time histories of system (11) for y signal at the equilibrium E_0 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

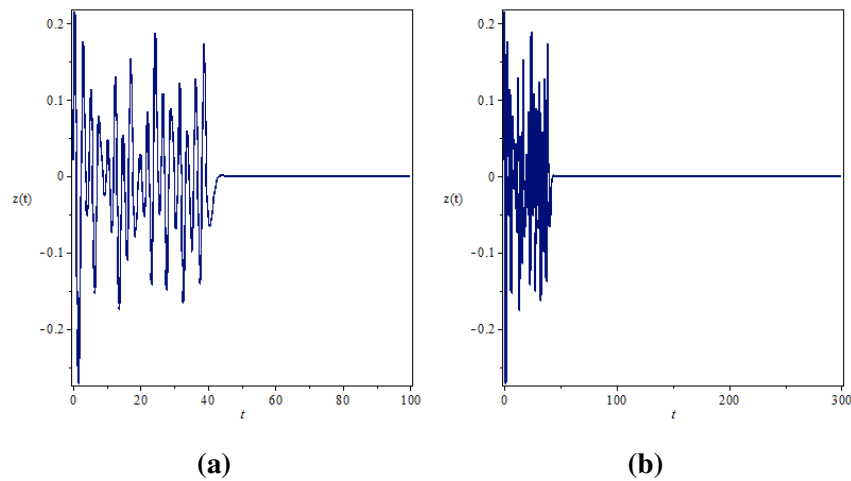


Figure 7. Time histories of System (11) for z signal at the equilibrium E_0 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

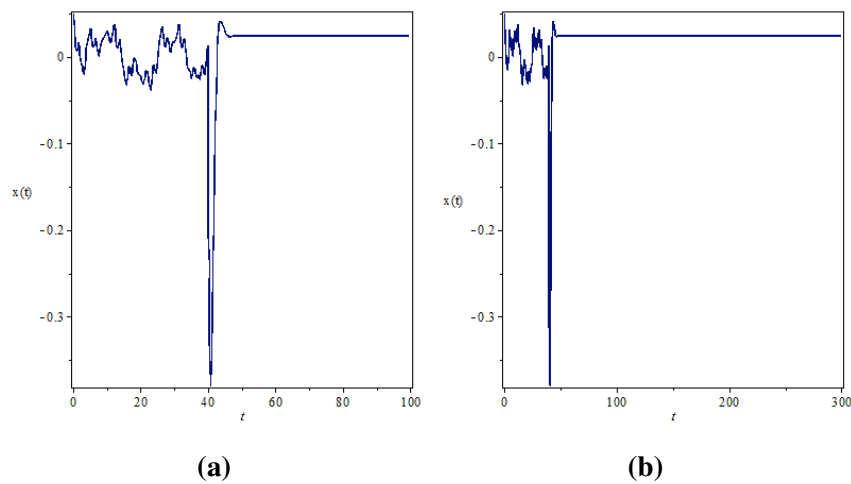


Figure 8. Time histories of System (11) for x signal at the equilibrium E_1 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

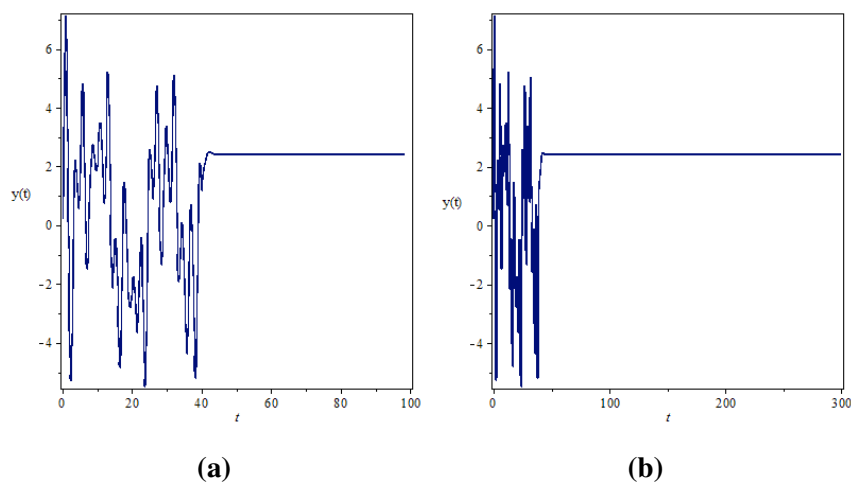


Figure 9. Time histories of System (11) for y signal at the equilibrium E_1 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

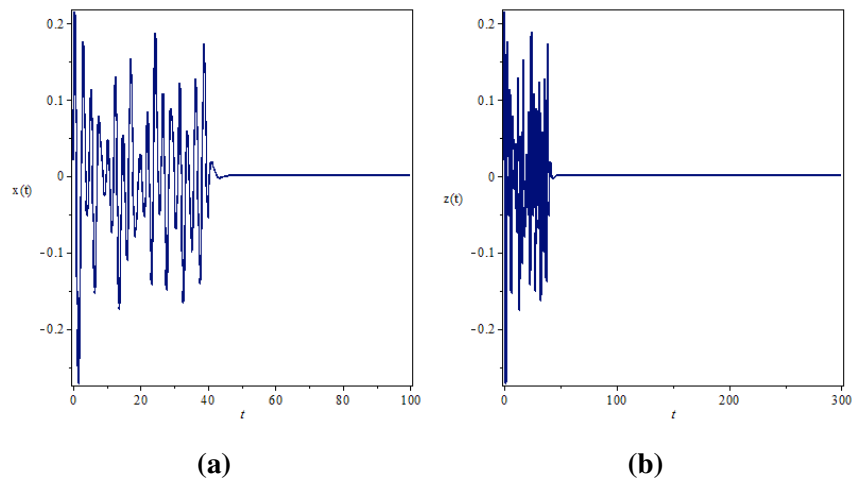


Figure 10. Time histories of System (11) for z signal at the equilibrium E_1 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

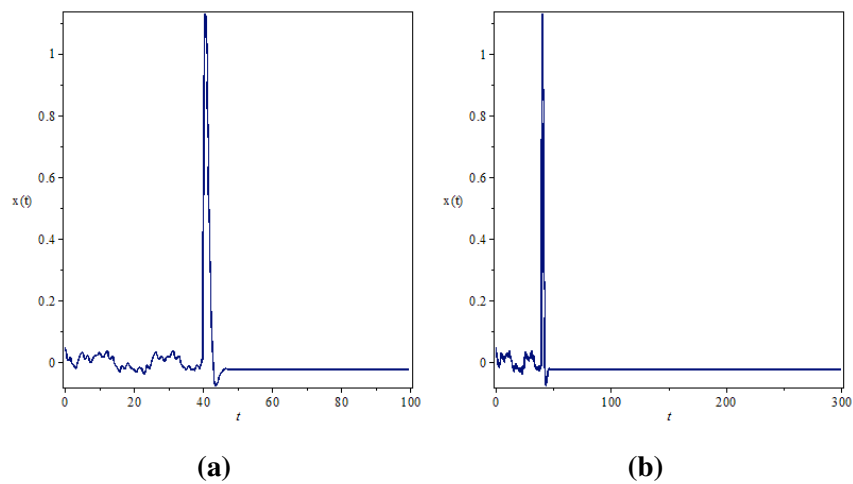


Figure 11. Time histories of System (11) for x signal at the equilibrium E_2 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

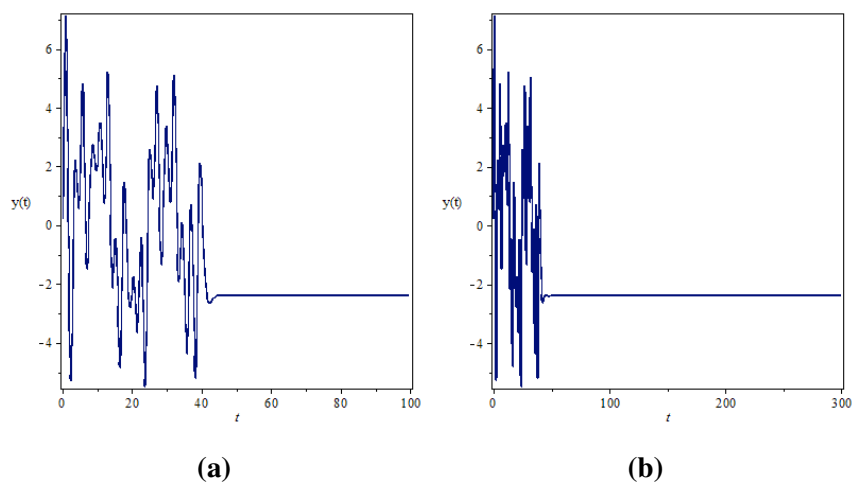


Figure 12. Time histories of System (11) for y signal at the equilibrium E_2 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

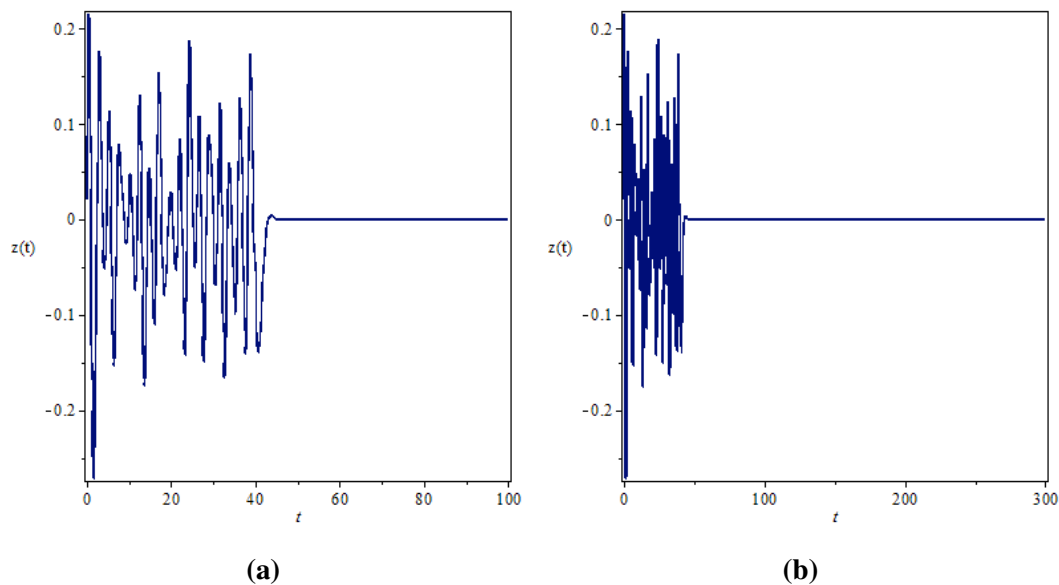


Figure 13. Time histories of System (11) for z signal at the equilibrium E_2 with $\alpha = 0.9$: (a) $t_{max} = 100$, (b) $t_{max} = 300$.

5. Conclusion

In this paper, chaos control of a fractional-order chaotic economic system is studied. Furthermore, we have studied the local stability of the equilibria using the Matignon stability condition. Analytical conditions for nonlinear active control have been implemented. Simulation results have illustrated the effectiveness of the proposed control method.

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Author Contributions

Zakia Hammouch designed the research, Toufik Mekkaoui performed the numerical experiment, Hacı Mehmet Baskonus and Hasan Bulut analysed the data. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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