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Feedback Control and Synchronization of a Structurally-Complex Toroidal Chaotic System

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ABSTRACT

Hybrid feedback control and synchronization of a structurally complex chaotic system with toroidal morphology is presented in this paper. The Deng's toroidal chaotic attractor is three-coupled differential equations which consist of 34 terms including 24 nonlinear terms which produced a highly complex and densely folded chaotic attractors. Firstly, a linear feedback controller satisfying the Hurwitz constraints was designed to regulate the state dynamics to some equilibrium points at the origin. Secondly, a hybrid feedback controller made up of both linear and nonlinear parts was designed to globally synchronize identical Deng's toroidal systems based on appropriate selection of feedback coupling coefficients. Matlab software simulations of the modelled systems shows that the designed linear controller effectively stabilized the state dynamics with comparably small feedback strength while the hybrid controller also synchronized completely, the exponentially divergent trajectories of the coupled systems with small feedback coefficient in transient time.

Keywords: *Chaos, feedback control, synchronization, toroidal chaotic system*

1. INTRODUCTION

Chaos has continued to be a rallying research field due to the increasing applications of its dynamics in theoretical research and practical engineering and non-engineering designs. As a nonlinear phenomenon, chaos is a distinguishing characteristic of dynamic systems that are highly sensitive to structural and state perturbations. A slight change in the system's algebraic frame or initial condition can lead to an unpredictable future state. While much attention has been devoted to the study and application of chaos in engineering systems such as in secure communication [1], radar systems [2] and power system control [3], recently, new frontiers have been uncovered in many non-engineering sciences such as medicine [4], finance [5] and food science [6] among others. During the past two decades, several chaotic systems have been evolved and been analyzed, control and synchronized. These include the Lu-Chen-Cheng [7], Rabinovich [8], Sundarapandian-Pelivan [9], Bullard dynamo [10], Yu-Wang [11] among others. Methods of control have included feedback control [12], sliding mode control [13] and fuzzy control [14]. Synchronization has received significant attention in the literature due to its prime application in secure communication and different methods such as adaptive synchronization [15], hybrid projective synchronization [16], and impulsive synchronization [17] have been applied to synchronize chaos. In this paper, the controllability and synchronizability of a toroidal system which evolves a highly complex and densely folded attractor is studied. Although this system has been evolved over two decades ago [18], a review of literature on this system shows that attention has not been given to understand the system by researchers, in spite its rich dynamics and possibility of applications to secure communications. This therefore justifies our interest in its control and synchronization.

2. THE DENG'S TOROIDAL CHAOTIC SYSTEM

The algebraic structure of the Deng's toroidal chaotic system [18] consists of a three-coupled differential equation having 34 terms including 24 nonlinear terms in its simplified form. The canonical form of the equation is expressed as follows:

$$
\begin{aligned}
\dot{x} &= z(\lambda x - \mu y) + (2-z)\left[\alpha x\left(1 - \frac{x^2+y^2}{R^2}\right) - \beta y\right] \\
\dot{y} &= z(\mu x - \lambda y) + (2-z)\left[\alpha y\left(1 - \frac{x^2+y^2}{R^2}\right) + \beta x\right] \\
\dot{z} &= \frac{1}{\varepsilon}\left[\begin{array}{l} z((2-z)(a(z-2)^2+b) - dx)(z+ \\ m(x^2+y^2) - \eta) - \varepsilon c(z-1) \end{array}\right]
\end{aligned}
\tag{1}
$$

Where $a, b, c, d, m, \eta, R, \sigma, \beta, \varepsilon, \lambda, \mu$ are control parameters. By expanding (1), the coefficient of each variable produces the lengthy equations given in (2).

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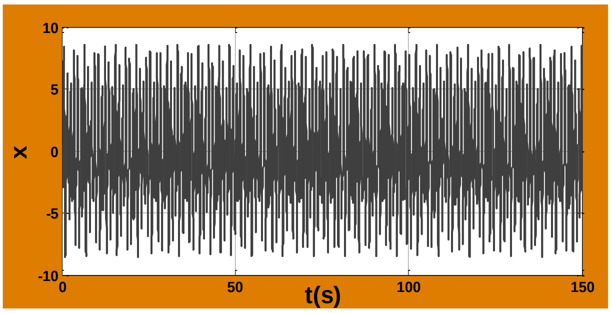
$$\dot{x} = 2\sigma x - 2\beta y + (\lambda - \sigma)xz + (\beta - \mu)yz + \frac{\sigma}{R^2}(-2x^3 - 2xy^2 + x^3 z + xy^2 z)$$

$$\dot{y} = 2\beta x + 2\sigma y + (\mu - \beta)xz + (\lambda - \sigma)yz + \frac{\sigma}{R^2}(-2y^2 - 2x^2 y + x^2 yz + y^3 z)$$

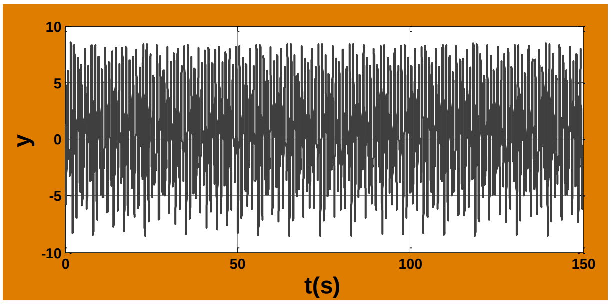
$$\dot{z} = -\frac{a}{\varepsilon}z^5 + \frac{a}{\varepsilon}(6+\eta)z^4 - \frac{1}{\varepsilon}(6a - 12a - b)z^3 + \frac{1}{\varepsilon}(12a\eta + b\eta + 8a + 2b)z^2 - \ldots$$

$$-\left(\frac{\eta}{\varepsilon}(8a+2b)+c\right)z - \frac{am}{\varepsilon}(x^2z^4 + y^2z^4) + \frac{6am}{\varepsilon}(x^2z^3 + y^2z^3) - \frac{m}{\varepsilon}(12a+b)(x^2z^2 + y^2z^2) + \frac{m}{\varepsilon}(8a+2b)(x^2 z + y^2 z) - \frac{dm}{\varepsilon}(x^2 z + xy^2 z) + \frac{d\eta}{\varepsilon}xz - xz^2 + 1 \tag{2}$$

For the values of the following constants:
$a = 3, b = 0.8, c = 1, d = 0.1, m = 0.05, \eta = 3.312, R = 10,$
$\sigma = 2.8, \beta = 5, \varepsilon = 0.1, \lambda = -2, \mu = 1$
the toroidal system is chaotic and evolves the trajectories in Fig.1.



(a)



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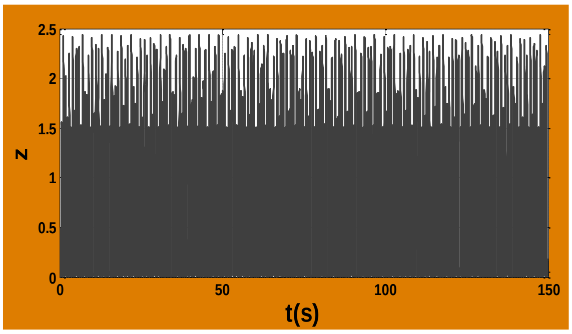

(c)

Fig. 2. State trajectories of the Toroidal system

In order to analyze the zero equilibrium of the open loop system (1), we let $E_0(0,0,0)$ be a zero equilibrium point of the system (1). By linearizing (1), the Jacobian matrix at $E_0(0,0,0)$ is of the form

$$J\big|_{E_0(0,0,0)} = \begin{bmatrix} 2\sigma & -2\beta & 0 \\ 2\beta & 2\sigma & 0 \\ 0 & 0 & -\frac{\eta}{\varepsilon}(8a+2b) - c \end{bmatrix}$$

Eq. (3) produces the polynomial

$$\lambda^3 + \left(\frac{\eta}{\varepsilon}(8a+2b) + c - 4\sigma\right)\lambda^2 + \left(4(\sigma^2 + \beta^2 - \sigma c) - \frac{4\sigma\eta}{\varepsilon}(8a+2b)\right)\lambda + \frac{4\eta}{\varepsilon}(8a+2b)(\sigma^2+\beta^2) + 4c(\sigma^2+\beta^2) \tag{4}$$

The roots of the characteristic equation for the polynomial in (3) are

$$\lambda_1 = -8.4887, \lambda_2 = 0.056 + 0.1i, \ \lambda_3 = 0.056 - 0.1i$$

λ_1 is a negative number. λ_2 and λ_3 is a pair of conjugate characteristic values with positive real parts. Thus, we conclude that the zero equilibrium is a saddle-focus point which is unstable. According to the Routh-Hurwitz stability principle [19], the system (2) is asymptotically stable if and only if the roots of the equation are negative. To satisfy these criteria, (4) must meet the following conditions

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i. $\frac{\eta}{\varepsilon}(8a+2b)+c-4\sigma>0$

ii. $4(\sigma^2+\beta^2-\sigma c)-\frac{4\sigma\eta}{\varepsilon}(8a+2b)>0$

iii. $\left(\frac{\eta}{\varepsilon}(8a+2b)+c-4\sigma\right)\begin{pmatrix}4(\sigma^2+\beta^2-\sigma c)-\dots\\-\frac{4\sigma\eta}{\varepsilon}(8a+2b)\end{pmatrix}$

$$>\frac{4\eta}{\varepsilon}(8a+2b)(\sigma^2+\beta^2)+4c(\sigma^2+\beta^2) \tag{5}$$

3. LINEAR FEEDBACK CONTROLLER DESIGN

$$\begin{aligned}
\dot{x} &= 5.6x-10y-4.8xz+4yz-0.056x^3\\
&\quad -0.056xy^2+0.028x^3z+0.028xy^2z+u_1\\
\dot{y} &= 5.6x+10y-4xz-4.8yz-0.056y^3\\
&\quad -0.056x^2y+0.028x^2yz+0.028y^3z+u_2\\
\dot{z} &= -30z^5+279.36z^4-964.16z^3+1474.816z^2\\
&\quad -848.872z+9(x^2z^3+y^2z^3)-18.4(x^2z^2+y^2z^2)\\
&\quad +12.8(x^2z+y^2z)-0.05(x^3z+xy^2z)\\
&\quad -1.5(x^2z^4+y^2z^4)-xz^2+3.312xz+1+u_3
\end{aligned} \tag{6}$$

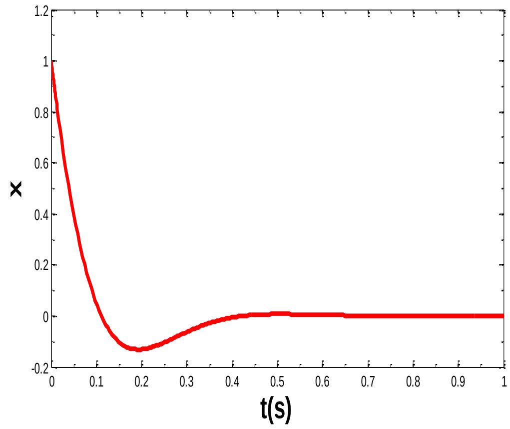
Where $u_1=\Phi_1 x, u_2=\Phi_2 y, u_3=\Phi_3 z,$ are control inputs to be derived and Φ_1,Φ_2,Φ_3 are feedback coefficients of the feedback controllers. By linearizing (6) at equilibrium point $E_0(0,0,0)$, the Jacobian matrix is easily obtained as

$$\begin{aligned}
&\lambda^3+\left(837.672+\Phi_1+\Phi_2+\Phi_3\right)\lambda^2\\
&\quad -(9376.0064+5.6\Phi_1+5.6\Phi_2+\\
&\quad 11.2\Phi_3-848.872\Phi_1-848.872\Phi_2\\
&\quad -\Phi_1\Phi_2-\Phi_1\Phi_3-\Phi_2\Phi_3)\lambda+507.8259\\
&\quad -4753.6832\Phi_1-4753.6832\Phi_1\\
&\quad +131.36\Phi_3+848.872\Phi_1\Phi_2\\
&\quad -5.6\Phi_1\Phi_3-5.6\Phi_2\Phi_3+\Phi_1\Phi_2\Phi_3\\
&=\lambda^3-\xi\lambda^2+\varphi\lambda+\Theta
\end{aligned} \tag{7}$$

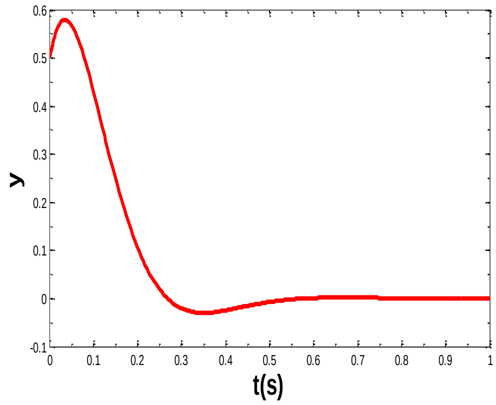
For (7) to be Hurwitz, the conditions in (5) must be satisfied i.e. $\xi>0, \varphi>0, \xi\varphi>\Theta$. Therefore, the feedback coefficient must be appropriately chosen for the roots of the characteristic equation to have negative real parts.

4. SIMULATION RESULTS

The system (6) was simulated with MATLAB/SIMULINK for the initial conditions $x(0), y(0)\, z(0)=[0.5, 0.5, 0.5]$ and feedback gains $\Phi_1(0)=\Phi_2(0)=\Phi_3(0)=15$. The results are given in the following figures.



(a)



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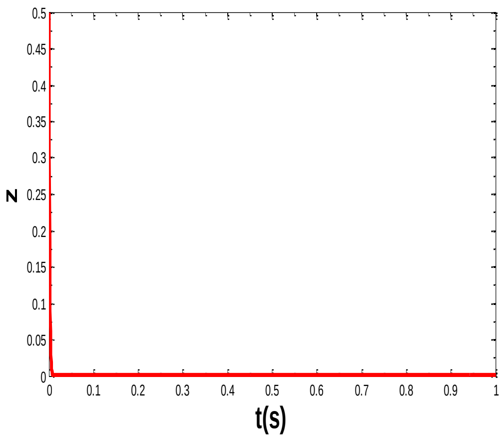

(c)

Fig.3. Time series evolution of the controlled trajectories

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5. IDENTICAL SYNCHRONIZATION VIA HYBRID FEEDBACK CONTROL

(i) Feedback controller design

In hybrid feedback synchronization [20] , a complement of linear and nonlinear controllers are used to couple two divergent state dynamics of identical or non-identical chaotic systems to achieved complete synchrony or anti-synchrony. Consider a drive system of the form

$$\Xi x_d + \Delta \Pi(x_d) \tag{8}$$

Where $x_d \in \mathbb{R}^n$ is the state vector, $\Xi \in \mathbb{R}^{n\times n}$ is the system matrix, $\Delta \in \mathbb{R}^{n\times n}$ is a constant matrix and $\Pi(x_d): \mathbb{R}^n \to \mathbb{R}^n$ is a nonlinear vector function. If a response system to be synchronized with (8) is given by

$$\Gamma y_r + \Delta[\Pi(y_r) + F_{LN}(x,y,z)] \tag{9}$$

$F_{LN}(x,y,z)$ is a hybrid controller to be designed and $y_r \in \mathbb{R}^n$ is the state vector of the response system . Let $F_{LN}(x,y,z) = u_L + u_N$ where

$$u_L = \Phi(y_r - x_d) \tag{10}$$

$$u_N = \Pi(y_r) - \Pi(x_d) \tag{11}$$

.

are respectively, the linear and nonlinear controller subsystems of the hybrid control law. For identical synchronization $\Xi = \Gamma$. The synchronization error system is then modelled to conform to the following algebraic structure

$$\dot{e} = (\Gamma - \Delta\Phi)e \tag{12}$$

Where

$$\begin{aligned} e &= (e_1, e_2, e_3)^T = (y_r - x_d)^T \\ &= (e_1 = \hat{x} - x, e_2 = \hat{y} - y, e_3 = \hat{z} - z)^T \end{aligned} \tag{13}$$

is the synchronization error and the feedback matrix $\Phi = diag(\Phi_{11}, \Phi_{22}, \Phi_{33})^T$ equal to

$$\Phi = \begin{bmatrix} \Phi_1 & 0 & 0 \\ 0 & \Phi_2 & 0 \\ 0 & 0 & \Phi_3 \end{bmatrix} \tag{14}$$

If the matrix $\Gamma - \Delta\Phi$ is Hurwitz, i.e. all the eigenvalues of the matrix have negative real part, then the sufficient condition for synchronization is satisfied and the error system (12) will be asymptotically stable [19]. We denote the state vectors of the drive and response systems as $x_d = (x,y,z)^T, y_r = (\hat{x}, \hat{y}, \hat{z})^T$.

(ii) Synchronization of identical Deng's Toroidal system via hybrid feedback control

The system (1) can be rewritten in contracted form as follows

$$\begin{aligned} \dot{x} &= 5.6x - 10y + f_x \\ \dot{y} &= 5.6x + 10y + f_y \\ \dot{z} &= -848.872z + f_z \end{aligned} \tag{15}$$

Where f_x, f_y, f_z are the nonlinear functions associated with the state variables $\dot{x}, \dot{y}, \dot{z}$.

$$\begin{aligned} f_x &= -4.8xz + 4yz - 0.056x^3 - 0.056xy^2 \\ &\quad + 0.028x^3z + 0.028xy^2z \end{aligned}$$

$$\begin{aligned} f_y &= -4xz - 4.8yz - 0.056y^3 - 0.056x^2y \\ &\quad + 0.028x^2yz + 0.028y^3z \end{aligned}$$

$$\begin{aligned} f_z &= -30z^5 + 279.36z^4 - 964.16z^3 \\ &\quad + 1474.816z^2 + 9(x^2z^3 + y^2z^3) \\ &\quad - 18.4(x^2z^2 + y^2z^2) + 12.8(x^2z + y^2z) \\ &\quad - 0.05(x^3z + xy^2z) - 1.5(x^2z^4 + y^2z^4) \\ &\quad - xz^2 + 3.312xz + 1 \end{aligned} \tag{16}$$

The system (15) can be written in the form of (9) as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} 5.6 & -10 & 0 \\ 10 & 5.6 & 0 \\ 0 & 0 & -848.872 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \tag{17}$$

By comparing (17) with (9), we can deduce that

$$\Xi = \Gamma = \begin{bmatrix} 5.6 & -10 & 0 \\ 10 & 5.6 & 0 \\ 0 & 0 & -848.872 \end{bmatrix} \tag{18}$$

$$\Delta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } \Pi = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \tag{19}$$

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Thus, the matrix

$$\Gamma - \Delta\Phi = \begin{bmatrix} 5.6-\Phi_1 & -10 & 0 \\ 10 & 5.6-\Phi_2 & 0 \\ 0 & 0 & -848.872-\Phi_3 \end{bmatrix} \quad (20)$$

The characteristic equation of (16) becomes

$$\lambda^3 - \xi\lambda^2 + \varphi\lambda + \Theta \quad (21)$$

It can be seen that (21) is the same with (7). Thus, the Hurwitz constraints are not satisfied. To satisfy the Hurwitz criteria, $\xi > 0, \varphi > 0, \xi\varphi > \Theta$, the feedback gains must be chosen such that $\Phi_1 > 0, \Phi_2 > 0, \Phi_3 > 0$.
From (9)-(11), the hybrid controllers have the following structures

$$u_N = \begin{bmatrix} f_{\hat{x}} - f_x \\ f_{\hat{y}} - f_y \\ f_{\hat{z}} - f_z \end{bmatrix}$$

$$u_L = \Phi(y_r - x_d)^T = \begin{bmatrix} \Phi_1(\hat{x}-x) \\ \Phi_2(\hat{y}-y) \\ \Phi_3(\hat{z}-z) \end{bmatrix} \quad (22)$$

Where $f_{\hat{x}}, f_{\hat{y}}, f_{\hat{z}}$ are nonlinear function vectors associated with the response system (drive and response system are identical in this study). By using the system matrices (18) and (19) together with the hybrid controllers in (22), the controlled response system (9) can be transformed to the following matrix form (note that for identical synchronization, $\Xi = \Gamma$.

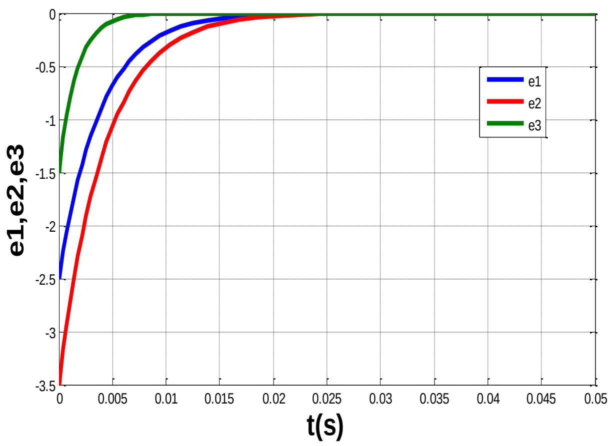
$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{\hat{y}} \\ \dot{\hat{z}} \end{bmatrix} = \begin{bmatrix} 5.6 & -10 & 0 \\ 10 & 5.6 & 0 \\ 0 & 0 & -848.872 \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_{\hat{x}} - f_x \\ f_{\hat{y}} - f_y \\ f_{\hat{z}} - f_z \end{bmatrix} + \begin{bmatrix} \Phi_1 & 0 & 0 \\ 0 & \Phi_2 & 0 \\ 0 & 0 & \Phi_3 \end{bmatrix} \begin{bmatrix} (\hat{x}-x) \\ (\hat{y}-y) \\ (\hat{z}-z) \end{bmatrix} \quad (23)$$

The matrix equation (23) can be further reduced to the algebraic form given as

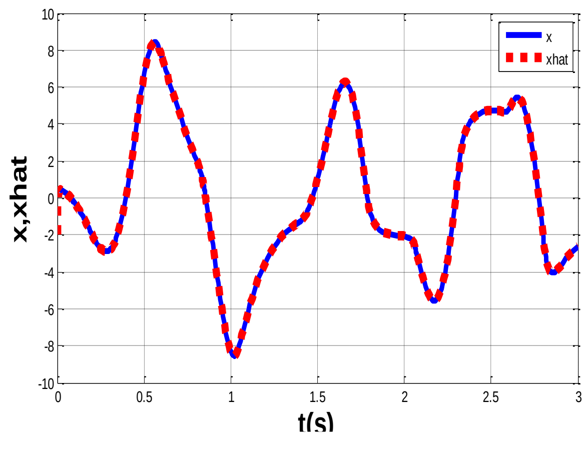
$$\begin{aligned} \dot{\hat{x}} &= 5.6\hat{x} - 10\hat{y} + f_x - \Phi_1(\hat{x}-x) \\ \dot{\hat{y}} &= 5.6\hat{x} + 10\hat{y} + f_y - \Phi_2(\hat{y}-y) \\ \dot{\hat{z}} &= -848.872\hat{z} + f_z - \Phi_3(\hat{z}-z) \end{aligned} \quad (24)$$

6. SIMULATION RESULTS

The system (15) and response system (23) were simulated with MATLAB/SIMULINK for the following initial conditions $x(0), y(0)\, z(0) = [0.5, 0.5, 0.5]$ and $\hat{x}(0), \hat{y}(0)\, \hat{z}(0) = [-2, -3, -1]$. The initial condition for error system becomes $e_1(0), e_2(0), e_3(0) = [-2.5, -3.5, -1.5]$. The feedback coefficients were chosen as $\Phi_1(0) = \Phi_2(0) = \Phi_3(0) = 10$. The following figures show the results.



(a)
Fig. 4. Asymptotic convergence of the error state dynamics e1,e2,e3



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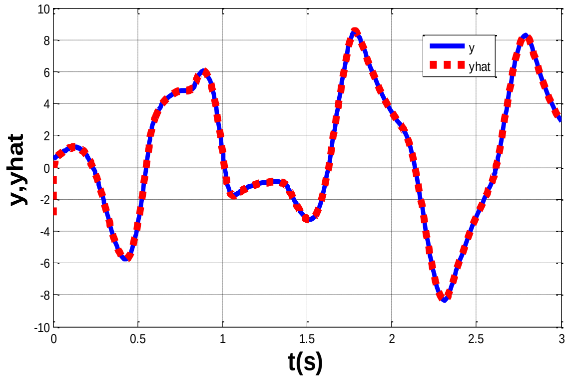

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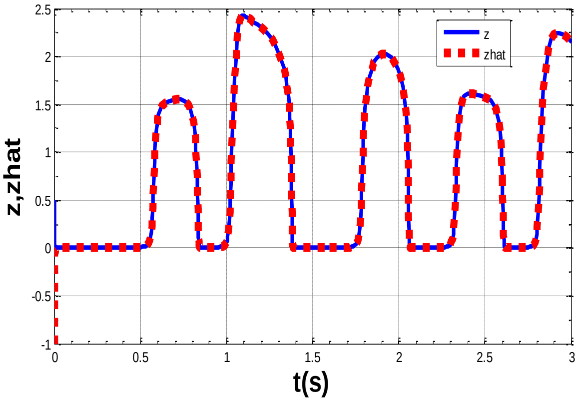

(c)

Fig.5 (a) -(c). Dynamics of the synchronized systems in 2D space

7. CONCLUSION

The control and identical synchronization of a structural-complex toroidal chaotic system has been reported in this paper. Due to the high number of nonlinear terms in the algebraic structure of this system, the evolved attractor has very dense unstable periodic orbits. A linear feedback controller was designed to control trajectories of the controlled system and a hybrid blend of linear and nonlinear controllers were designed to synchronize the identical system. Numerical simulation results shows that the controllers asymptotically stabilized the dynamics in transient time and equally synchronized the trajectories of the coupled system. Thus the controller design and synthesis methods have been confirmed to be effective. The controllability and synchronizability of this system implies that the system has potentials of applications in modelling of engineering and non-engineering systems. It can also be used as a potential chaotic carrier in secure communications systems.

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