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Design of a New Chaotic System with Sine Function: Dynamic Analysis and Offset Boosting Control

Rameshbabu Ramar *,[1]
*Department of Electronics and Communication Engineering, VSB Engineering College, Tamilnadu, India.

ABSTRACT A new chaotic system is presented in this research work.The proposed system has three nonlinear terms and one sine term which improves the complexity of the system. The basic properties of new system such as Lyapunov exponent, equilibrium point and stability are analyzed in detail. The dynamic analysis is conducted using classic tools such as bifurcation diagram and Lyapunov exponent plot to verify the chaotic nature in the proposed system. The changes in the states of the system is verified using bifurcation diagram and Lyapunov exponent plot. The proposed system presents some special features such as two wing attractors, forward and reverse periodic doubling bifurcation, and dc offset boosting control. The dc offset boosting behavior can be used to diagnosis the multistability behaviour in the dynamical system and to reduce the number of components in the communication system. This special feature converts the bipolar signal in to unipolar signal which can be used in many engineering applications. The theoretical study and the simulation results show that the proposed system has wealthy chaotic behaviour itself. Furthermore, the adaptive sysnchronization of identical new system is achieved for the application of secure communication system.

KEYWORDS
Chaotic system
Sine function
Dynamic analysis
Offset boosting
Adaptive synchronization

INTRODUCTION

Since Lorenz discovered a chaotic system in 1963, the generation of chaotic system becomes hot research topic due to their complex behaviour such as unpredictability, variation due to initial conditions etc. The chaotic systems have wide range of applications in crypto systems (Zia *et al.* 2022; El-Latif *et al.* 2022; Lin *et al.* 2022), secure communication (Kumar and Singh 2022; Zhou and Tan 2019) mobile robots (Nwachioma and Pérez-Cruz 2021; Cetina-Denis *et al.* 2022), Circuit applications (Lai *et al.* 2021; Wang *et al.* 2015), IOT applications (Li *et al.* 2022a; Trujillo-Toledo *et al.* 2021) etc. Due to these applications, recently many researchers introduced new 3D chaotic systems (Veeman *et al.* 2022; Hu *et al.* 2022a; Ablay 2022; Ramakrishnan *et al.* 2022).

The traditional chaotic system has low degree of complexity and it leads to the limitation of usage of chaotic system to solve some practical problems. The complex dynamic behaviour of chaotic system is required for various engineering applications such as image encryption, voice encryption, DCSK, particle motion and secure communication etc. Therefore, the construction of chaotic system using trigonometry function is hot research topic and many researchers proposed chaotic systems based on product trigonometric function (Yu and Yu 2020; Yu and Gong 2022; Sriram *et al.* 2023), hyperbolic sine (Liu *et al.* 2018; Mobayen *et al.* 2020; Hu *et al.* 2022b; Joshi and Ranjan 2020), hyperbolic cosine (Signing *et al.* 2019; Signing and Kengne 2018), cosine function (Yan *et al.* 2022) and tangent and cotangent (Guo and Liang 2021).

Recently, many researchers introduced sine function based chaotic systems for example, Zhou *et al.* (2021) proposed a new autonomous chaotic system with sine function and analysed coexisting nested multiple attractors behaviour for different initial conditions. Kuate and Fotsin (2020) described a new five term chaotic system with one sine nonlinearity term which produces one scroll and double scroll attractor and also analysed its coexisting attractor using dc offset boosting method. Yang *et al.* (2021) presented a sine chaotic system which generates multi - scroll attractors and observed both homogeneous and heterogeneous multi stability in the proposed system. Hua *et al.* (2018) introduced a one-dimensional sine chaotification model (SCM) and improved the complexity of three existing systems. Bao *et al.* (2020) proposed a 2D sine map and investigated initials – boosted coexisting attractors in the proposed system. Sahoo and Roy (2022) introduced a new technique to generate multi wing attractors from two wing

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[1]rrameshbabu15@gmail.com (**Corresponding author**)

existing chaotic attractors. The proposed technique uses a nonlinear function with sine term to generate multi wing attractors from existing Lu and Chen system. Volos *et al.* (2021) proposed a dynamical system with sine function and observed hidden attractors in the proposed system.

In the past few decades, the chaos synchronization has great attention since it can be used to solve many issues in secure communication system. Recently, various adaptive synchronization scheme Rahman and Jasim (2022); Roldán-Caballero *et al.* (2023); Pal *et al.* (2022); Li *et al.* (2022b) have been developed for the application of secure communication system.

This motivates me in this study to construct another trigonometry function based chaotic system. The proposed system presents offset boosting control property which means the position of the attractor can be easily controlled by adding a controller with any one of the state signals of the system. The offset boosting control method can also be used to identify the multistability of the dynamical system.

The proposed system has the following features:

- The proposed system produces two wing attractors.
- The proposed system is constructed using sine term which presents complex behaviour.
- The system presents both forward and reverse periodic doubling bifurcation.
- It presents dc offset boosting property that is the attractor of proposed system is position controllable.

INTRODUCTION OF SINE FUNCTION BASED NEW CHAOTIC SYSTEM

In 2017, Lai *et al.* (2017) introduced a new chaotic system as given in Equation. (1).

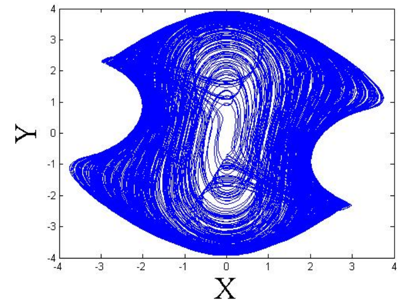
$$\begin{aligned} \dot{x} &= ax - yz \\ \dot{y} &= -by + xz \\ \dot{z} &= xyz - cz + d \end{aligned} \tag{1}$$

where, (a, b, c, d)=$(4, 9, 4, 4)$. The Lyapunov exponents of the system (1) are calculated as $l_1 = 1.7729$, $l_2 = 0$, $l_3 = -7.5549$. The Lyapunov dimension is $D_L = 2.2334$. The system (1) presents one scroll attractors. In this paper, the new chaotic system is designed by replacing the term y by $sin(x)$ in second equation and the term xyz by xy in third equation of system (1). The new system (2) produces two scroll attractors while the old system (1) produces one scroll attractor and infinitely many shifted attractors.

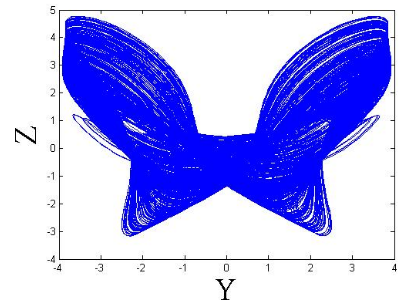
Thus, the new chaotic system with sine term can be modelled as in Equation. (2).

$$\begin{aligned} \dot{x} &= ax - kyz \\ \dot{y} &= bsinx + xz \\ \dot{z} &= gxy - cz + d \end{aligned} \tag{2}$$

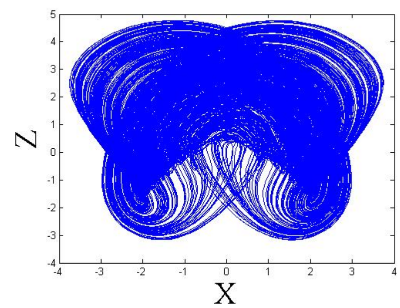
Here x, y, and z are the signal variables of new system (2) and a,b,c,d,g and k are the positive and non-zero parameters. The system (2) has the parameter values as, $a = 1.5$, $b = 10$, $c = 4$, $d = 2$, $g = 4$ and $k = 2$.



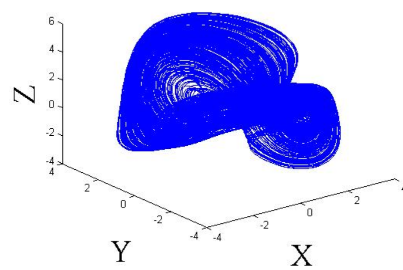
(a) xy plane



(b) yz plane



(c) xz plane

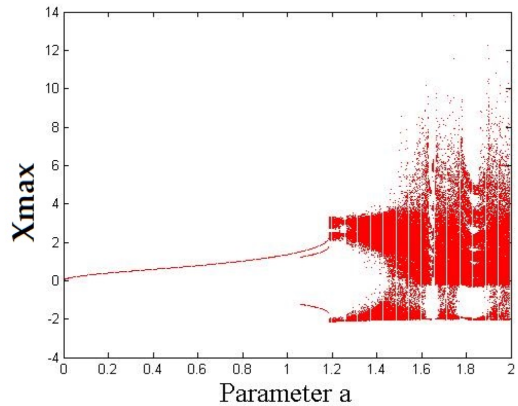


(d) xyz plane

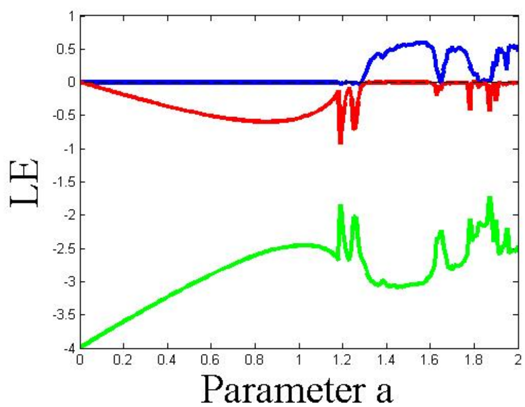
Figure 1 The two wing attractors of new chaotic system with sine term.

BASIC INFORMATION ABOUT THE NEW CHAOTIC SYSTEM WITH SINE TERM

In this section, the basic information about the proposed chaotic system such as, Lyapunov exponents, dissipative, equilibrium points, stability and the sensitivity to the initial conditions are discussed in detail.



(a) Bifurcation diagram



(b) Lyapunoov exponent spectrum

Figure 2 (a) Bifurcation diagram (b) Lyapunov exponent spectrum of system (2) under parameter a with initial condition $(-1, 0, 1)$.

Lyapunov Exponents (LE) are calculated numerically using Wolf algorithm and MATLAB with the initial conditions $(-1, 0, 1)$ and simulation time 10000 sec. The system (2) has Lyapunov exponent value as, (LE_1, LE_2, LE_3)= $(0.561522, 0, -3.061664)$. Since, the proposed system satisfies the conditions that $LE_1 > 0$,$LE_2 = 0$ and $LE_3 < 0$, it is found that the system (2) has the chaotic behaviour itself.

Lyapunov dimension (D_L) of system (2) can be calculated using (3) as,

$$D_L = 2 + \frac{LE_1 + LE_2}{|LE_3|} = 2.183 \tag{3}$$

which indicates that the system (2) has fractional dimension. The dissipative nature of the system (2) can be verified using (4) as,

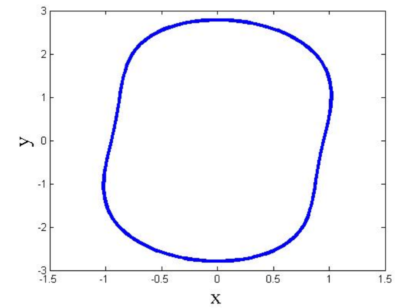
$$\nabla V = \frac{\partial V}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial V}{\partial z} = a - c = -2.5 \tag{4}$$

The dissipative nature of the dynamic system can also be verified by adding all their Lyapunov exponent values as (5),

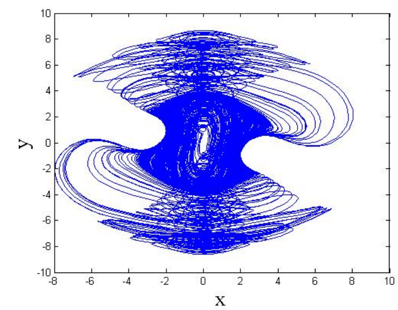
$$LE_T = LE_1 + LE_2 + LE_3 = -2.5 \tag{5}$$

The negative values of LE_T indicates that the proposed system (2) is dissipative.

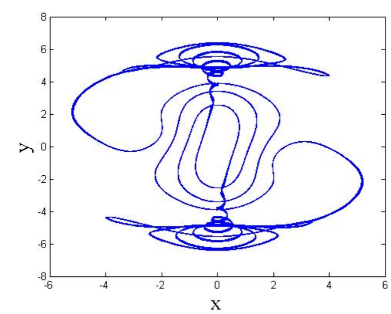
The equilibrium (E) points are calculated by letting $\dot{x}$=$\dot{y}$=$\dot{z}$=0 in the proposed system (2) and by solving those equations. Thus the system (2) can be written as in (6) and the solution of (6) gives the equilibrium point as, $E = (0, 0, 0.5)$.



(a) $a = 0.8$



(b) $a = 1.6$



(c) $a = 1.8$

Figure 3 Various periodic and chaotic attractors of system (2) under the parameter $a\epsilon[0, 2]$.

$$\begin{aligned} ax - kyz &= 0 \\ bsinx + xz &= 0 \\ gxy - cz + d &= 0 \end{aligned} \tag{6}$$

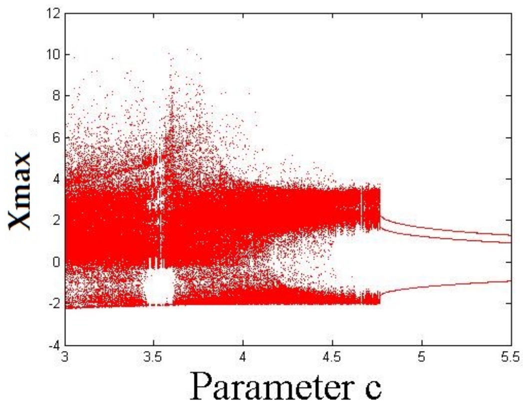
Now, Jacobian Matrix (J) of the system (2) can be written as in (7),

$$J = \begin{vmatrix} a & -kz & -ky \\ z + bcosx & 0 & x \\ gy & gx & -c \end{vmatrix} \tag{7}$$

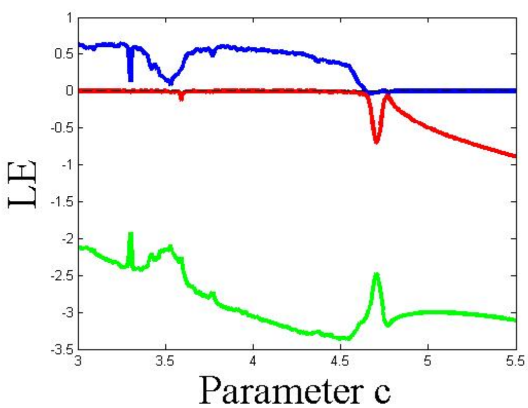
By substituting the equilibrium point (E) and the corresponding parameter values in (7),

$$J(E) = \begin{vmatrix} 1.5 & -1 & 0 \\ 10.5 & 0 & 0 \\ 0 & 0 & -4 \end{vmatrix} \quad (8)$$

The eigen values (λ) can be calculated from (8) as $\lambda_{1,2} = 0.75 \pm j3.152$, $\lambda_3 = -4$ which indicates that the equilibrium point (E) is saddle which is always unstable. The attractors of proposed system (2) in 2D and 3D plane are displayed in Figure 1.



(a) Bifurcation diagram

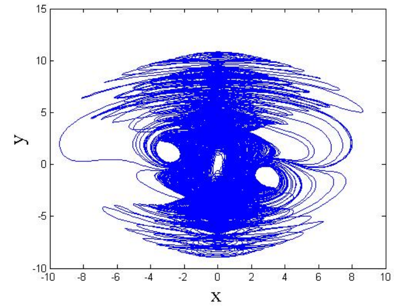


(b) Lyapunoov exponent spectrum

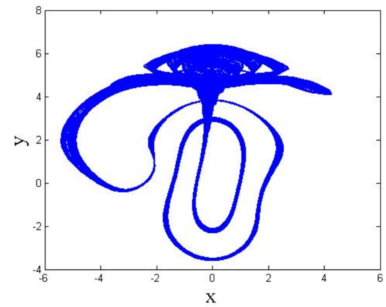
Figure 4 (a) Bifurcation diagram (b) Lyapunov exponent spectrum of system (2) under parameter c with initial condition $(-1, 0, 1)$.

DYNAMIC ANALYSIS OF NEW CHAOTIC SYSTEM WITH SINE FUNCTION

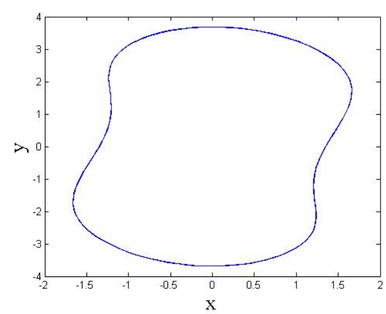
In this section, the bifurcation diagram and Lyapunov spectrum are investigated in order to prove the rich dynamics in the new system. Both plots can be obtained by varying any one of the system parameters and keeping remaining parameters with constant values. The state of the chaotic system may change from periodic to chaotic or chaotic to period depends on the system parameter values. This change in the states can be observed using bifurcation diagram and Lyapunov exponent spectrum plot under various



(a) $c = 3$



(b) $c = 3.5$



(c) $c = 5$

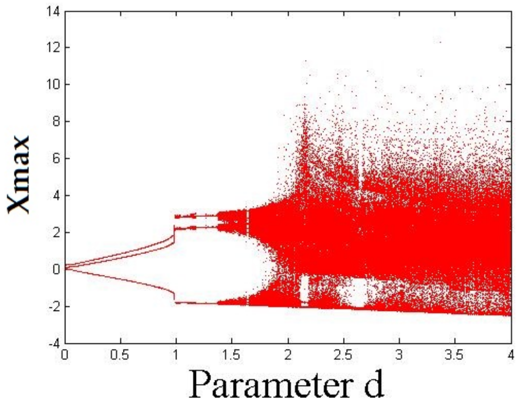
Figure 5 Various periodic and chaotic attractors of system (2) under the parameter $c\epsilon[3, 5.5]$.

system parameters. In Lyapunov exponent spectrum, the positive Lyapunov exponents region indicates the chaotic attractor and other regions indicate the periodic attractor. The LE_1, LE_2 and LE_3 are represented using blue, red and green colours respectively.

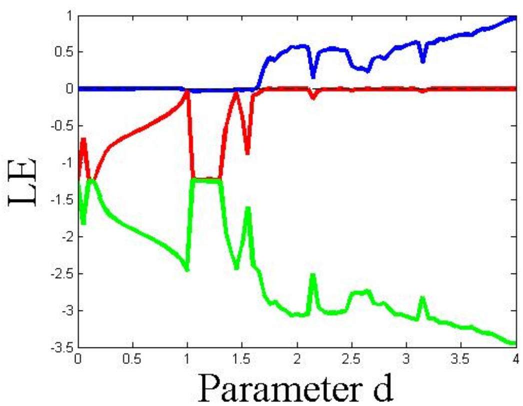
Figure 2 shows the bifurcation diagram and corresponding Lyapunov exponents spectrum for parameter a in the region $a\epsilon[0, 2]$ and indicates that the system has periodic attractor up to $a = 1.3$ and chaotic attractor for the region $a\epsilon[1.4, 1.6]$. Figure 3 represents the periodic and chaotic attractors of system (2) under the parameter $a\epsilon[0, 2]$ and (b, c, d, g, k)=$(10, 4, 2, 4, 2)$.

Figure 4 shows the bifurcation diagram and Lyapunov exponent spectrum for the parameter c in the region $c\epsilon[3, 5.5]$. The state of the system is changed from chaotic to periodic beyond $c = 4.5$ when the parameter value is increased. Figure 5 represents some of the periodic and chaotic attractors of system (2) under the parameter $c\epsilon[3, 5.5]$ and (a, b, d, g, k)=$(1.5, 10, 2, 4, 2)$.

Figure 6 shows the bifurcation diagram and Lyapunov exponent spectrum for another parameter d in the region $d\epsilon[0, 4]$ and also shows that the system has chaotic flow beyond $d = 1.75$. Figure 7 represents the periodic and chaotic attractors of system (2) under the parameter $d\epsilon[0,4]$ and (a,b,c,g,k)=$(1.5,10,4,4,2)$.



(a) Bifurcation diagram



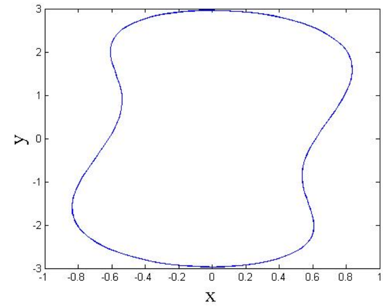
(b) Lyapunoov exponent spectrum

Figure 6 (a) Bifurcation diagram (b) Lyapunov exponent spectrum of system (2) under parameter d with initial condition $(-1,0,1)$.

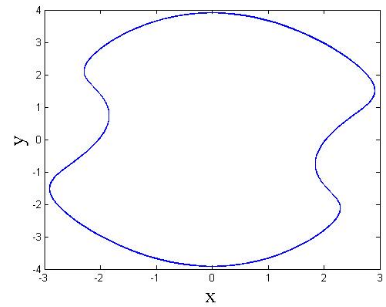
Figure 8 shows the bifurcation diagram and Lyapunov exponent spectrum for the parameter g in the region $g\epsilon[3,5.5]$. Figure8 indicates that the system has chaotic attractors in the region $g\epsilon[3,4.2]$ and then periodic attractors. It is evident from Figures 6 and 8 that the proposed system experiences both forward and reverses periodic doubling behaviour. Figure 9 represents the periodic and chaotic attractors of system (2) under the parameter $g\epsilon[2,6]$ and (a,b,c,d,k)=$(1.5,10,4,2,2)$.

OFFSET BOOSTING CONTROL

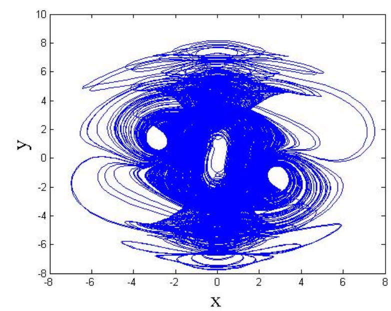
Offset boosting control Chunbiao *et al.* (2021); Ma *et al.* (2021); Wen *et al.* (2021) is the important property of chaotic system which is used to find the multistability of the system. It is observed in the system (2) when we introduce the offset booster m in the state signal y as given in Equation. (9). When the value of the booster m is varied, the proposed attractor becomes bipolar to unipolar as shown in Figure 10. Figures (10a - 10b) show the offset boosted attractor of system (2) in xy and yz plane for $m = -10$ (Red), $m = 0$ (Blue) and $m = 10$ (Green) respectively. Figure 10c represents the Lyapunov exponent plot of system (9) in the region $m\epsilon[-20,20]$. Figure 10c also represents that the system (9) has constant Lyapunov exponent in the specified region and the offset



(a) $d = 0.5$



(b) $d = 1.4$

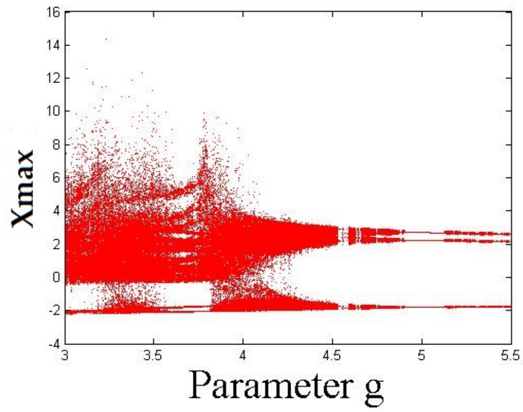


(c) $d = 3.5$

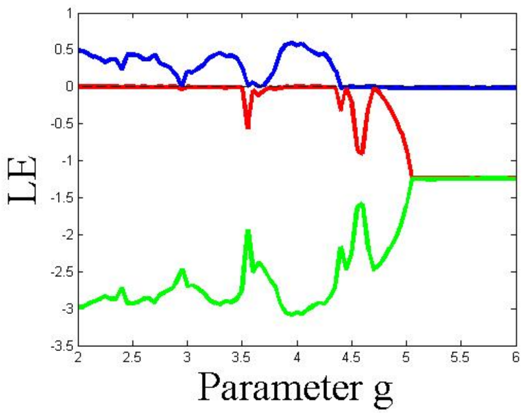
Figure 7 Various periodic and chaotic attractors of system (2) under the parameters $d\epsilon[0,4]$.

booster m does not modify the chaotic behavior of the proposed system (2).

$$\begin{aligned} \dot{x} &= ax - k(y+m)z \\ \dot{y} &= bsinx + xz \\ \dot{z} &= gx(y+m) - cz + d \end{aligned} \tag{9}$$

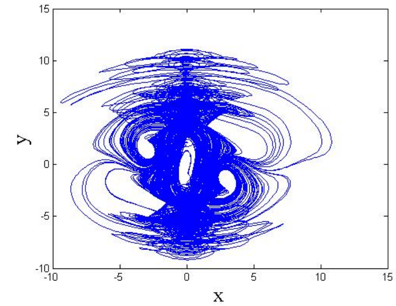


(a) Bifurcation diagram

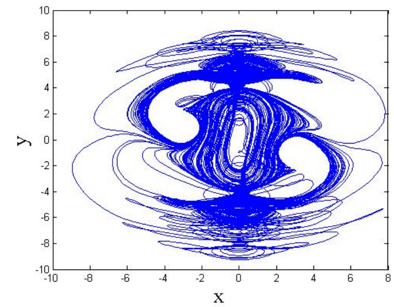


(b) Lyapunoov exponent spectrum

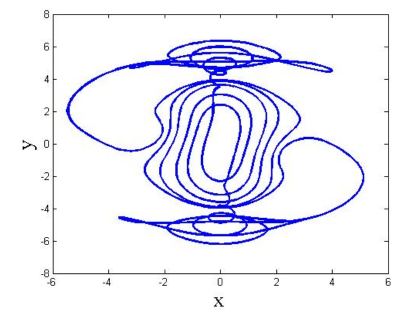
Figure 8 (a) Bifurcation diagram (b) Lyapunov exponent spectrum of system (2) under parameter g with initial condition $(-1, 0, 1)$.



(a) $g = 2.5$



(b) $g = 3.5$



(c) $g = 3.6$

Figure 9 Various periodic and chaotic attractors of system (2) under the parameter $g\epsilon[2, 6]$.

ADAPTIVE SYNCHRONIZATION

In this section, the adaptive synchronization between the proposed system is achieved using nonlinear feedback control methodology and master - slave scheme. The adaptive synchronization results are verified using Lyapunov stability theorem. The master and slave systems are considered as in (10) and (11) respectively.

$$\begin{aligned} \dot{x}_1 &= ax_1 - ky_1z_1 \\ \dot{y}_1 &= bsinx_1 + x_1z_1 \\ \dot{z}_1 &= gx_1y_1 - cz_1 + d \end{aligned} \tag{10}$$

$$\begin{aligned} \dot{x}_2 &= ax_2 - ky_2z_2 + u_x \\ \dot{y}_2 &= bsinx_2 + x_2z_2 + u_y \\ \dot{z}_2 &= gx_2y_2 - cz_2 + d + u_z \end{aligned} \tag{11}$$

Here x_1, y_1, z_1 are the signal variables of master system, x_2, y_2, z_2 are the signal variables of slave system, u_x, u_y and u_z are the adaptive controllers to be designed. The adaptive synchronization errors can be written as, e_x=$x_2 - x_1$, e_y=$y_2 - y_1$ and e_z=$z_2 - z_1$. By simple calculation, the adaptive controllers and the estimates of error dynamics can be obtained as given in (12) and (13) repectively.

$$\begin{aligned} u_x &= -\hat{a}e_x - \hat{k}(y_1z_1 - y_2z_2) - k_xe_x \\ u_y &= -\hat{b}(sinx_2 - sinx_1) - x_2z_2 + x_1z_1 - k_ye_y \\ u_z &= -\hat{g}(x_2y_2 - x_1y_1) + \hat{c}e_z - k_ze_z \end{aligned} \tag{12}$$

$$\begin{aligned} \dot{e_x} &= e_ae_x + e_k[y_1z_1 - y_2z_2] - k_xe_x \\ \dot{e_y} &= e_b[sinx_2 - sinx_1] - k_ye_y \\ \dot{e_z} &= e_g[x_2y_2 - x_1y_1] - e_ce_z - k_ze_z \end{aligned} \tag{13}$$

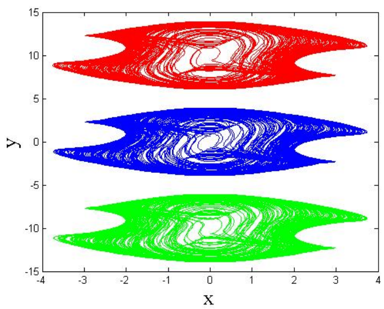
Here, $e_a = a - \hat{a}$, $e_b = b - \hat{b}$, $e_c = c - \hat{c}$, $e_g = g - \hat{g}$, $e_k = k - \hat{k}$ are the parameter errors, $\hat{a}$, $\hat{b}$, $\hat{c}$, $\hat{g}$ and $\hat{k}$ are the estimates of unknown parameters a, b, c, g and k respectively and k_x, k_y and k_z are the gains of the controllers.

Now, consider Lyapunov stability function as given in (14),

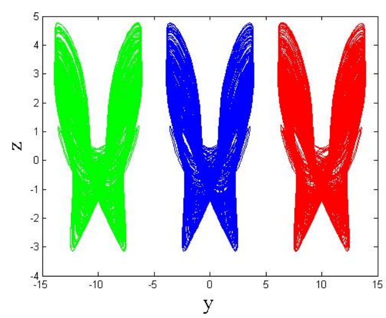
$$\begin{aligned}\dot{V} &= e_x\dot{e_x} + e_y\dot{e_y} + e_z\dot{e_z} + e_a\dot{e_a} + e_b\dot{e_b} + e_c\dot{e_c} + e_g\dot{e_g} + e_k\dot{e_k} \\ &= e_a[(e_x)^2 - \dot{\hat{a}}] + e_k[e_x(y_1z_1 - y_2z_2) - \dot{\hat{k}}] + \\ & e_b[e_y(sinx_2 - sinx_1) - \dot{\hat{b}}] + e_g[e_z(x_2y_2 - x_1y_1) - \dot{\hat{g}}] + \\ & e_c[-(e_z)^2 - \dot{\hat{c}}] - [k_x(e_x)^2 + k_y(e_y)^2 + k_z(e_z)^2] \end{aligned} \quad (14)$$

The Eqn. (14) is a negative function when $\dot{\hat{a}}$=$(e_x)^2$, $\dot{\hat{b}} = e_y(sinx_2 - sinx_1)$, $\dot{\hat{c}}$=$-(e_z)^2$, $\dot{\hat{k}}$=$e_x(y_1z_1 - y_2z_2)$ and $\dot{\hat{g}}$=$e_z(x_2y_2 - x_1y_1)$. The negative value of (14) represents that the system (2) is globally synchronized and the synchronization errors are globally bounded.

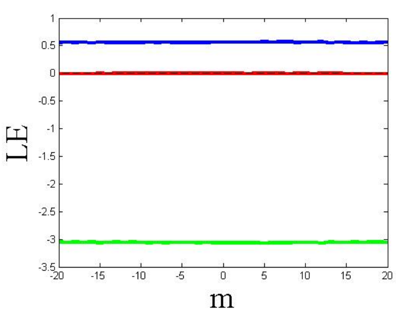
The results obtained for adaptive synchronization are verified using MATLAB software with the assumptions that the initial conditions for master and slave systems are $(-1, 0, 1)$ and $(1, -1, 1)$ respectively and gain of the controllers are $k_{x,y,z}$=0.8. Figure 11 shows the synchronization results obtained in this work. The state signals are synchronized after the time period $t = 11sec$ and hence the error signals reach zero after the time period $t = 11sec$.



(a) xy plane

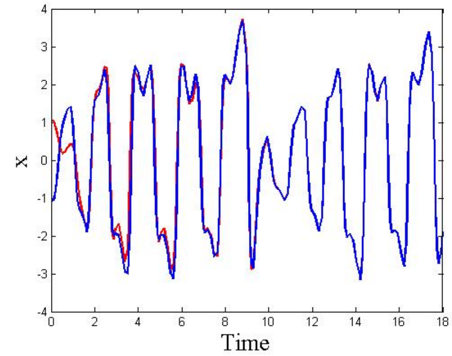


(b) yz plane

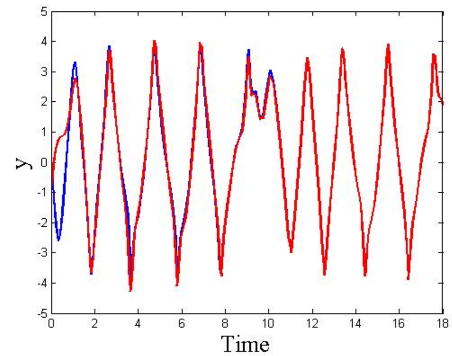


(c) Lyapunov exponent plot

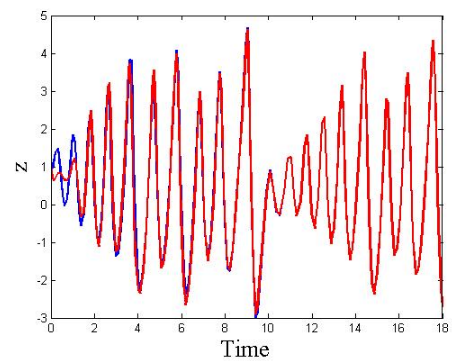
Figure 10 (a-b) Offset boosted attractors of system (2) with initial condition $(-1, 0, 1)$, (c) Lyapunov exponent plot of system (9).



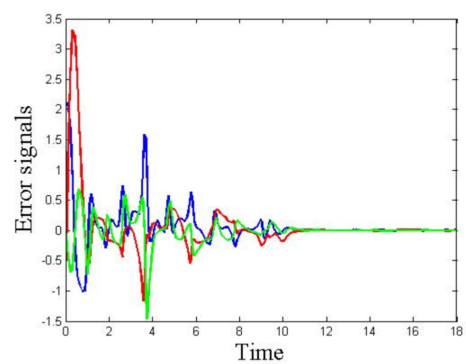
(a) Synchronized x signal



(b) Synchronized y signal



(c) Synchronized z signal



(d) Synchronized error signal

Figure 11 (a-c) Synchronized state variables of master (Blue) and slave (Red) system, (d) Synchronized error signals e_x (Blue), e_y (Red) and e_z (Green).

CONCLUSION

A new chaotic system with two wing attractor is developed. The proposed system satifies the basic conditions required to be a chaotic such as unstable equilibrium point and atleast one positive Lyapunov value. The chaotic nature in the proposed system is also verified using the bifurcation diagram, Lyapunov exponent plot and attractor diagram. The offset boosting control behavior of the new system is verified by means of attractor diagram and Lyapunov exponent plot. The offset boosted system has constant Lyapunov exponent values which means that the system maintain its chaotic nature for the various values of booster parameter. The adaptive controllers are designed for the adaptive synchronization of proposed system using feedback control method. All the state signal of proposed system can be synchronized and the synchronization errors become zero after the small time period. Due to these properties, the proposed system has complex dynamic behaviour, infinitely multiple attractors which can be used in many engineering applications.

Availability of data and material

Not applicable.

Conflicts of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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