Al-Qadisiyah Journal of Pure Science

Volume 27 | Number 1 Article 22

4-7-2022

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## Recommended Citation

Rahman, Zain-Aldeen S.A.; Jasim, Basil H.; and Alhamdawee, Ehsan (2022) "Secure Communication Scheme Based on a New 3-D Jerk Chaotic System," *Al-Qadisiyah Journal of Pure Science*: Vol. 27: No. 1, Article 22.
DOI: 10.29350/qjps.2022.27.2.1453
Available at: https://qjps.researchcommons.org/home/vol27/iss1/22

Al-Qadisiyah Journal of Pure Science Vol.(27 ) Issue ( 1) (2022) comp.pp. 33-47

QJPS
Al-Qadisiyah Journal of Pure Science

Al-Qadisiyah Journal of Pure Science

ISSN(Printed): 1997-2490 ISSN(Online): 2411-3514

DOI: /10.29350/jops.

http://qu.edu.iq/journalsc/index.php/JOPS

# Secure Communication Scheme Based on a New 3-D Jerk Chaotic System

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***Article History***

Received on:28/9/2021
Revised on: 30/2/2022
Accepted on: 26/4/2022
*Nonlinear Dynamics, Chaos, Jerk, Synchronization, Secure communication*

**DOI:** https://doi.org/10.29350/jops. 2022.27. 1.1453

**ABSTRACT**

Chaos theory plays a significant role in the engineering fields and especially in the security of data transmission in communication systems. In this paper, a new 3-D jerk chaotic system has been suggested. The fundamental dynamical properties, including the fixed points, chaotic attractors, bifurcation diagrams, and Lyapunov exponents are investigated. In communication systems, data security and the implementation of designed transceivers of secure communication scheme can be considered the main challenge for applying such systems. In this work, a 3-D new jerk chaotic scheme has been proposed to be used in data encryption of communication systems. The proposed jerk chaotic system is used for constructing identical transceivers of communication scheme that is presented by a master (transmitter) and a slave (receiver). In the master end, a useful information beam is encrypted through a chaotic signal. On the other hand, in the slave side, the original information beam is retrieved from the mutual transmitted beam by a chaotic synchronization mechanism. The communication scheme transceivers are synchronized by an adaptive observer synchronization mechanism. Finally, the system is tested and evaluated on a stream of binary information that is encrypted in the transmitter and recovered in the receiver. The results show that our proposal cryptosystem has good performance in term of securing transmitted data.

## 1. Introduction

In the last years, the chaotic arrangements have established a significant attention in different research fields as it can be applied for various fields such as securing communication systems, neural networks, information processing, industrial automation, power systems, and signal generators. In fact, the information signal in the transmitter of communication systems can

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be encrypted through the chaotic signals where it is difficult to be recovered unless the receiver has the same chaotic signal generated by the transmitter side [18]. The first chaotic attractor with 3-D autonomous system was found by Lorenz in 1963 [32]. Chaoticity phenomena can take place in independent ordinary differential systems equations with minimum three variables and term(s) cause the nonlinearities [19]. Thus, researchers gave significant attentions for building secure communication schemes based on the chaos theory and chaotic circuits. Sprott determined the functional form for 3-D dynamical systems, which show a chaos. Jerk equation achieves a nonlinear function that can be implemented with an electronic circuit for generating chaotic signals [11]. In 1996, Gottlieb noted some of chaotic systems can be rewritten as a single 3rd order differential equation system presented by jerk function [12]. Generally jerk system that reaches the chaoticity can be styled as following [3].

$$\dddot{x} = J\,(\ddot{x}, \dot{x}, x) \tag{1.1}$$

Where J refers to the jerk that presents a derivation scalar of the variable x. According to Newtonian system, $\dot{x}$ presents the displacement of velocity, $\ddot{x}$ is the acceleration, and $\dddot{x}$ is the jerk. The jerk functions define many occurrences in engineering and dynamics such as electronic circuits, mechanical alternators, and biological schemes [20]. A synchronization mechanism in chaotic systems plays the key role in the secure communication schemes [5]. It occurs between identical chaotic systems where one presents a master and the driven presents a slave [35]. The master system adapts the slave system by the transmitted signals. In 1983, Yamada and Fujisaka, study the first subject of the chaotic synchronization [28]. Impulsive control, Active control, adaptive control, sliding mode control, and passive control are some of the control approaches that have been developed for controlling and synchronizing chaotic systems. In this article an adaptive observer method was employed for synchronizing two chaotic systems. These two systems on present the master and the other presents the slave [2]. Whereas, the adaptive observer synchronization technique has a number of advantages including a good transient performance, quick dynamics responses and a technique that is resistant to disturbances, and parameter changes, and initial conditions [36].

In addition, as an application for the proposed system and its synchronization, a secure communication mechanism is offered. In recent years, a number of chaotic-based secure communication methods have been developed. The major ways for utilizing chaotic signals in secure communications include chaotic masking, chaotic shift keying, inclusion, and parameter modulation [24]. The chaotic masking technique was used in this study. MATLAB Simulink was used to test and determine the obtained results.

The organization of this paper is as follows: Related works have been introduced in section 2, in section 3, we describe the proposed 3-D new jerk chaotic system and we analyze the proposed chaotic jerk system for determining its equilibrium point, corresponding eigenvalues, and chaotic attractors. The dynamical analyses including bifurcation diagrams and Lyapunov exponents have been investigated in section 4. In section 5, we propose the synchronization mechanism of two identical for the designed chaotic system and calculate the synchronization error and matching between the master and slave signals. In section 6, we test the proposed chaotic system and the synchronization method on a stream of binary numbers. In section 7, the conclusions of this paper are presented.

## 2. Related Work

In recent years, many new private communication schemes depend on the management of chaos systems have been established. Jun Mou et. al. [26] simulated a private communication system based on an adaptive observer synchronization mechanism. Mauricio Z. D.et. al. [8] modified the Chua oscillator and they applied it in a secure communication system. Ali Durdu et. al. [9] introduced a PC synchronization for secure communication system. S. Vaidyanathan and Christos K. Volos [34] suggested an adaptive back stepping control for a novel jerk system. Vaidyanathan S. et. al. in 2018 introduced a sound encryption scheme based a simple chaotic circuit [33], and many similar chaotic systems are investigated and used in encryption systems as in [4].

The objective of this paper is to design a new chaotic system using numerical method that used for designing a secure communication scheme. In the proposed communication scheme, an adaptive observer controller is used for synchronization between the transceivers of designed secure communication system with a new 3-D proposed jerk system. The contributions of this work include designing a new 3-D chaotic jerk system for securing transmitted data in communication system, simplicity realization of the electronic circuit of the designed system, and high accuracy of recovering signals in the receiver side.

## 3. New 3-D Jerk Chaotic System Analysis

Despite the fact that many novel chaotic systems have been presented in recent years, developing, discovering, and analyzing new chaotic systems is still beneficial to the subject of chaos in theoretical and practical fields. This fact is stated in several specialized papers, some of which are cited in the article's sources [13,22,23,37]. This is due to the fact that some chaotic applications, such as secure communication, necessitate the ongoing development of new systems.

This section describes the proposed five terms 3-D new jerk system that has two terms ($yx^2$ and xy) that cause the nonlinearities. The system is generated by a simple 3-D dynamics system and described by the following equation.

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= z \\ \dot{z} &= ax + by - cyx^2 - dz + kxy \end{aligned} \tag{3.1}$$

Where x, y, and z are the states of system; a, b, c, d, and k are positive constant parameters of the suggested system. The proposed system demonstrates a conventional chaotic performance with parameter standards of a = 3, b = 6, c = 1.5, d = 1.2, and k = 1.3. These parameters are determined for achieving a good performance of the chaos based on the obtained chaotic attractors Lyapunov exponents and the bifurcation diagrams of the proposed system. The most significant dynamics of the chaos schemes are the fixed points [14]. Equilibrium points for the proposed system are determined by resolving the system in equation (2) as in equation (3.2).

$$\begin{aligned} \dot{x} &= y = 0 \\ \dot{y} &= z = 0 \\ \dot{Z} &= -ax + by - cyx^2 - dz + kxy = 0 \end{aligned} \tag{3.2}$$

Therefore, the proposed system has a single equilibrium point at the origin (x*, y*, z*) = (0, 0, 0) i,e. $E_0(0, 0, 0)$ Usually, the number of equilibrium points of any system are not necessarily equal to the system order (number of system equations) [27]. For testing the stability type of the offered system in equation (3.1) at this equilibrium points, we derive Jacobian matrix which be expressed as following.

$$J = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\mathrm{a} - 2\mathrm{cyx} + \mathrm{ky} & b - \mathrm{cx}^2 + kx & -d \end{bmatrix} \tag{3.3}$$

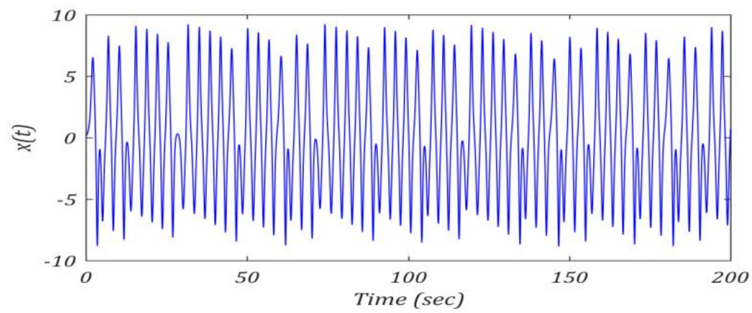
Then, the eigenvalues corresponding to the fixed-point of the proposed system can be obtained according to:

$$\left| J(E_{0,}) - \lambda \right| = 0 \tag{3.4}$$

Therefore, the eigenvalues of $E_0$ are obtained as; $\lambda_1 = -2.9210$, $\lambda_{2,3} = -0.8605 \pm j0.5353$. So, $E_0$ is a saddle focus equilibrium point, which responsible for exciting the attractors, where the chaotic behavior can be excited by a saddle focus equilibrium point(s) as stated in [25]. To determine numerical simulation results, the parameter values are chosen as mentioned above with initial state is selected $(x_0, y_0, z_0) = (0.1, 0.4, 0)$. The state variables of the new chaotic system described by equation (3.1) are plotted with respect to the time as displayed in **Figure 3.1**. While, **Figure 3.2** demonstrates the system chaotic attractor of suggested chaotic scheme in 2-D and 3-D visions.

## 4. Dynamical Behavior of The System

Bifurcation diagrams and Lyapunov exponents are the two basic dynamical tools for investigating the dynamical behaviors of nonlinear systems in general. The bifurcation diagrams and Lyapunov exponents are numerically explored in this part using MATLAB.

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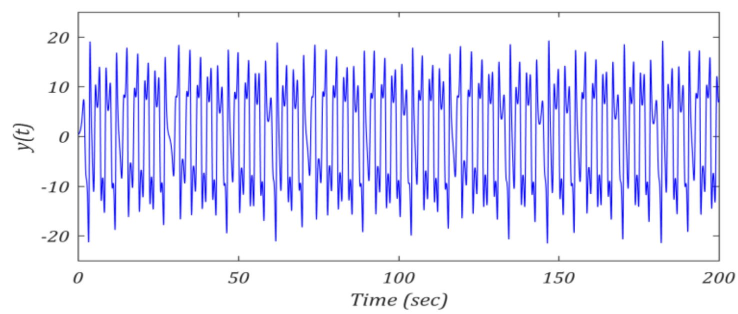


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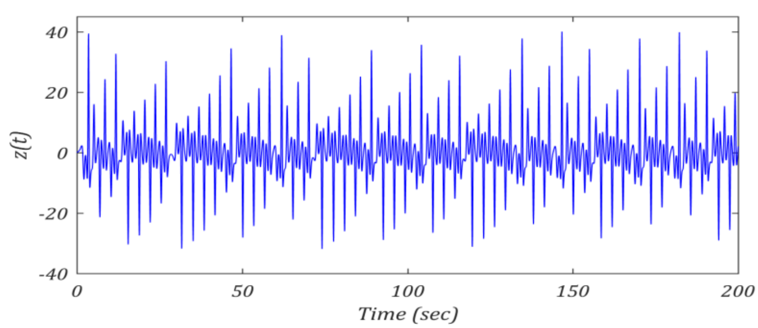



(c)

**Figure 3.1:** The time series trajectories representation of the proposed system; (a) x(t), (b) y(t), and (c) z(t).

### 4.1. Bifurcation Diagrams

Bifurcation diagrams are commonly tool used to depict chaotic behavior [10]. The nonlinear characteristics of the suggested system have been established using bifurcation diagrams. **Figure 4.1** shows the system's behavior in response to changes in the value of parameter b. Where the other system parameters are selected as a = 3, c = 1.5, d = 1.2, and k = 1.3, with initial conditions $(x_0, y_0, z_0) = (0.1, 0.4, 0)$. The suggested system validates the normal chaotic performance for the parameter b in the range of b ≥ 4.88, as seen in the bifurcation diagram.

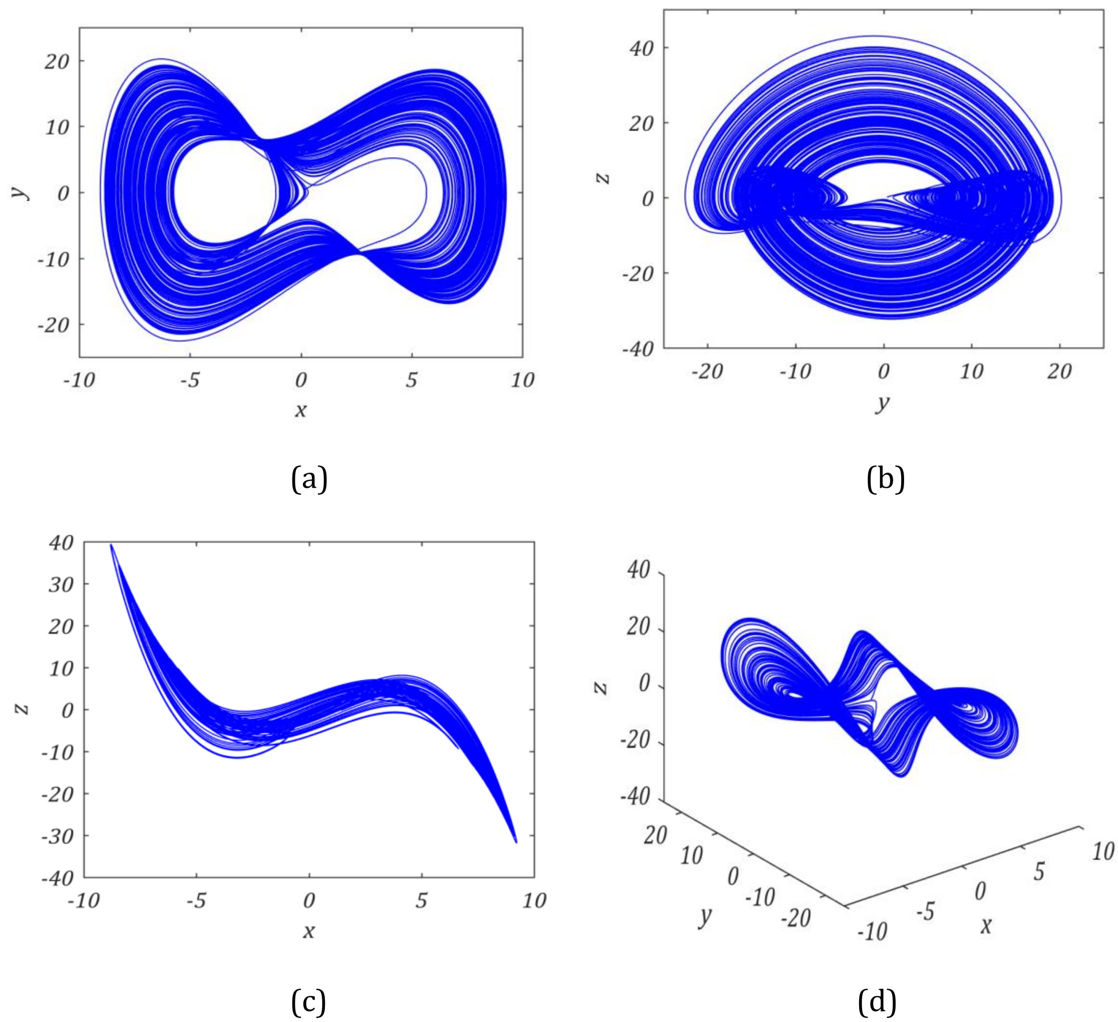



**Figure 3.2:** The proposed system chaotic attractor; (a) x-y phase portrait, (b) y-z phase portrait, (c) x-z phase portrait, and (d) 3-D (x-y-z) chaotic attractor arrangement.

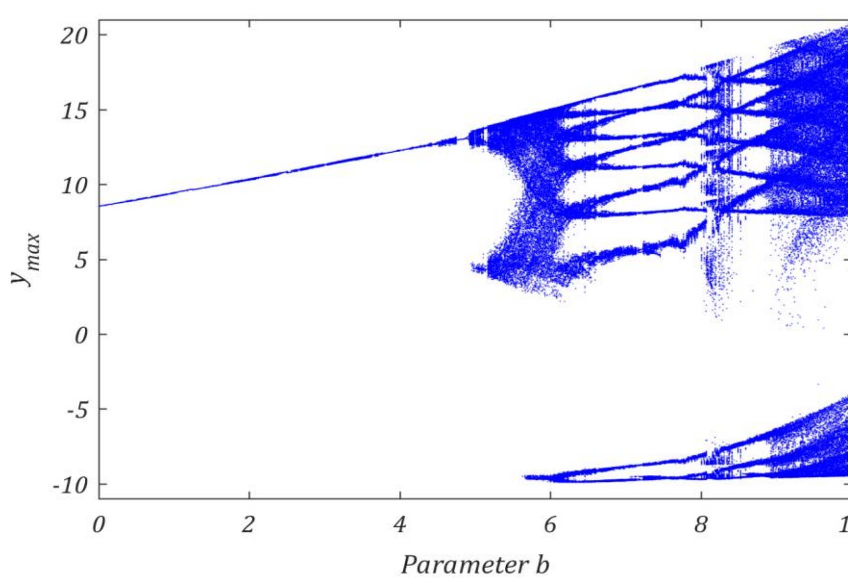



**Figure 4.1**: Bifurcation diagram of the new system corresponding to parameter b.

### 4.2. Lyapunov Exponents

The nonlinear characteristics of the proposed system have been proved by the Lyapunov exponent. The Lyapunov exponents of the proposed system have been calculated and verified as a chaotic behavior of the proposed system. A positive Lyapunov exponent is an indicator of chaos.

The system can be classified as a chaotic system if it has at least one positive Lyapunov exponent [21]. The Lyapunov exponents are determined as Le1 = 0.5089, Le2 = -0.4063, and Le3 = -1.1027. As Lyapunov determined, the proposed jerk system exhibits chaotic phenomena. **Figure 4.2** depicts the Lyapunov exponents of the proposed system with the same selected parameter and initial conditions as mentioned above in the bifurcation diagram, where the parameter b was chosen to be equal 6. The Lyapunov exponents have been found by using Alan wolf algorithm [1].

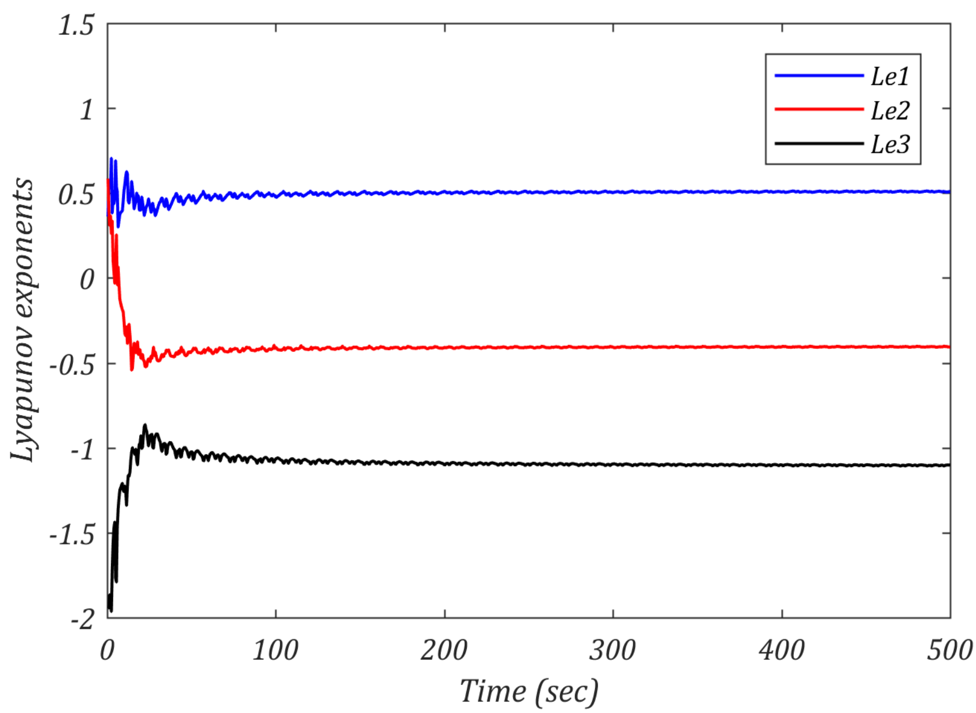



**Figure 4.2**: Lyapunov exponents of the proposed jerk chaotic system

### 5. The Synchronization Strategy

The chaos synchronization technique is based on the notion that two chaotic systems might evolve on different attractors, but when they are synchronized, they start on various attractors and then follow a same course. In other words, synchronization can be described as the mechanism that are used for achieving the closeness of the frequencies between different periodic oscillating signals [6]. These signals generated by two systems: one presents the master of the system and the other presents slave that responses to the master. Chaos control and synchronization strategies are two major ways to use chaos in practice [31]. Because secure communication systems rely heavily on synchronization between transceivers, chaotic synchronization has gotten a lot of attention [15]. As noted in the introduction section, researchers have introduced a variety of chaos management and synchronization strategies. In this work, an adaptive observer control method is used for synchronizing between the master side and the slave side of the chaotic system.

The master and the slave are presented by the following equations (5.1) and (5.2) respectively:

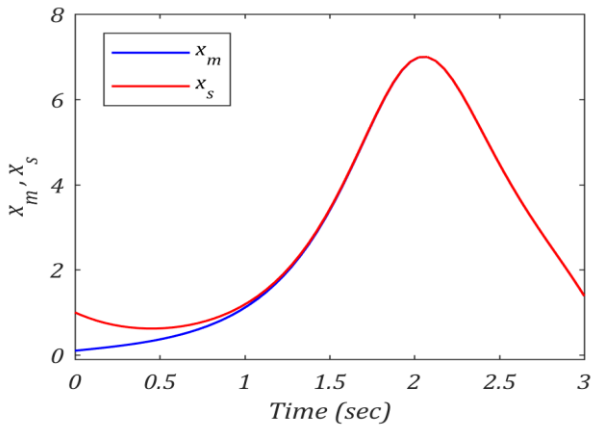
$$\begin{aligned} \dot{x}_m &= y_m \\ \dot{y}_m &= z_m \\ \dot{z}_m &= ax_m + by_m - cy_m x_m^2 - dz_m + kx_m y_m \end{aligned} \tag{5.1}$$

$$\begin{aligned} \dot{x}_s &= y_s + u_x \\ \dot{y}_s &= z_s + u_y \\ \dot{z}_s &= ax_s + by_s - cy_s x_s^2 - dz_s + kx_s y_s + u_z \end{aligned} \tag{5.2}$$

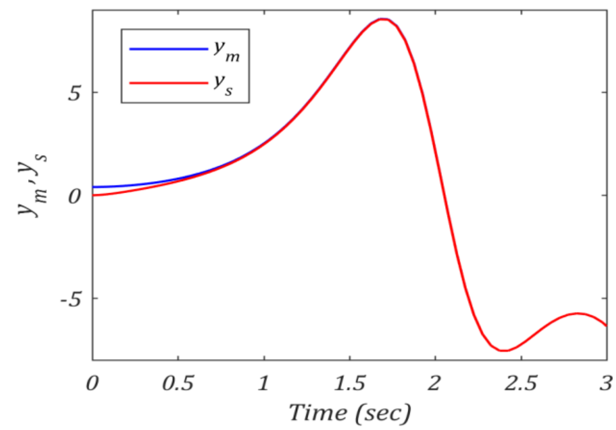
Where $u_{(x,\,y,\,z)} = -ke_{(x,\,y,\,z)}$ in equation (5.2) presents the controller (control signals) [7], $K \in R^{nxn}$ is a gain matrix and $e_{(x,y,z)}$ is the synchronization error and can be calculated as follows.

$$\begin{aligned} e_x &= x_s - x_m \\ e_y &= y_s - y_m \\ e_z &= z_s - z_m \end{aligned} \tag{5.3}$$

Therefore, here we suggest the slave is identical to the master. The eigenvalues of the gain matrix ($k_{(x,y,z)}$ ) of the control must be negative ($\lambda_i < 0$, i present the eigenvalue number), that achieves the error state vectors exponentially converge to zero. Practically, the gain matrix is chosen to be ($k_x$= 2, $k_y$ = 2.2, and $k_z$= 0.9) that achieves a stable closed loop system based on Lyapunov stability theory [17]. With the master and slave parameters (a = 3, b=6, c = 1.5, d = 1.2, and k = 1.3) and the initial states for master and slave are set (x(0) , y(0) , z(0)) = (0.1, 0.4, 0) and (x(0) , y(0), z(0)) = (1, 0, -1) respectively. The trajectories (state variables) of the master and the slave are synchronized as illustrated in **Figure 5.1**. **Figure 5.2** shows the synchronization error of states. **Figure 5.3** shows the 3-D phase portrait projections for master-slave synchronization, where the synchronization process was simulated for only 5 seconds.




(a)

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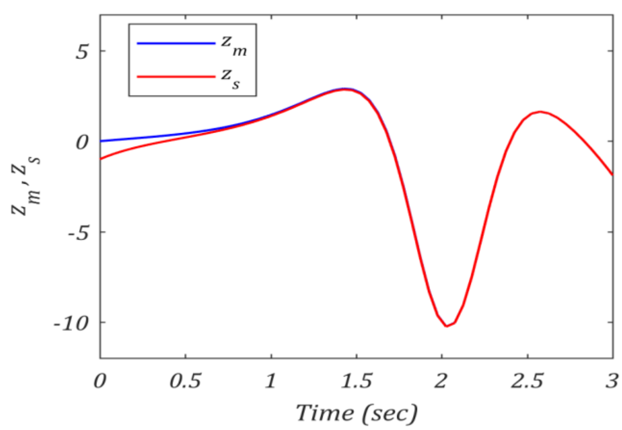


(c)

**Figure 5.1**: The states synchronization; (a) $(x_m(t), x_s(t))$, (b) $(y_m(t), y_s(t))$, and (c) $(z_m(t), z_s(t))$

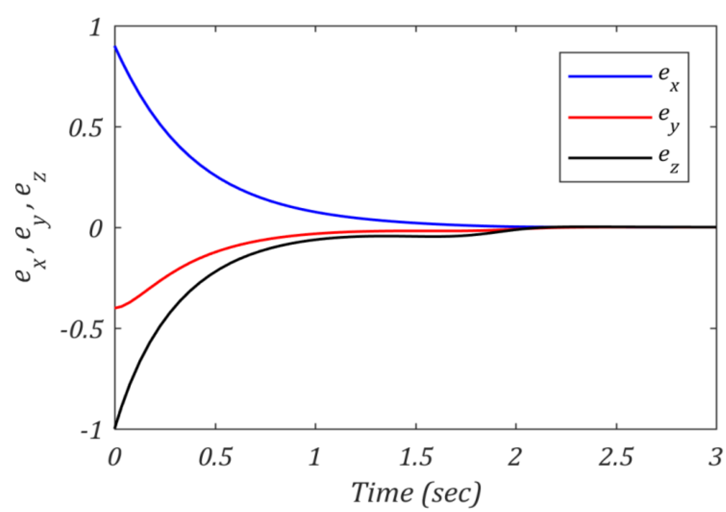


**Figure 5.2**: The synchronization errors.

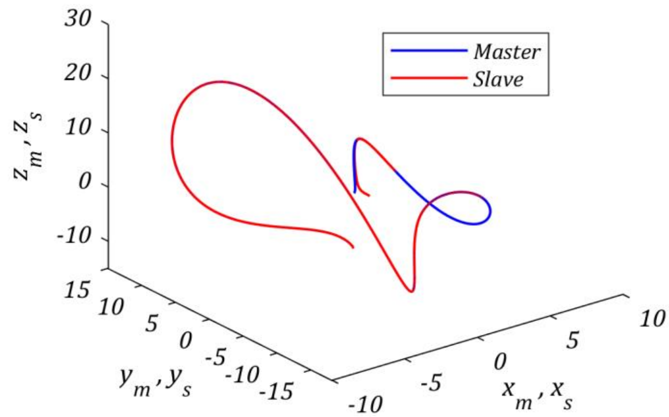


**Figure 5.3**: Synchronization performance, master and its slave response in 3-D phase portrait.

**Figure 5.1** confirms the slave trajectories aligned with the equivalent master trajectories. Also, **Figure 5.2** approves the synchronization errors $e_x$, $e_y$, and $e_z$ are rapidly approaching zero with respect to time (about 2.2 sec). These results show the efficiency and good performance of the employed synchronization mechanism.

## 6. Application in Secure Communication

The feasibility of using the proposed jerk chaotic systems in real-world applications is discussed in this section. Because chaotic signals have a broadband spectrum, they are well suited for use in secure communication and cryptosystem fields. In secure communication setups, the above-mentioned adaptive observer synchronization mechanism is used. The chaotic masking technique has the benefit of being simple and straightforward to use in electronic circuits [29]. In this work, the proposed chaotic system is applied in secured communications. The proposed communication scheme with an adaptive observer synchronization is depicted in **Figure 6.1**.

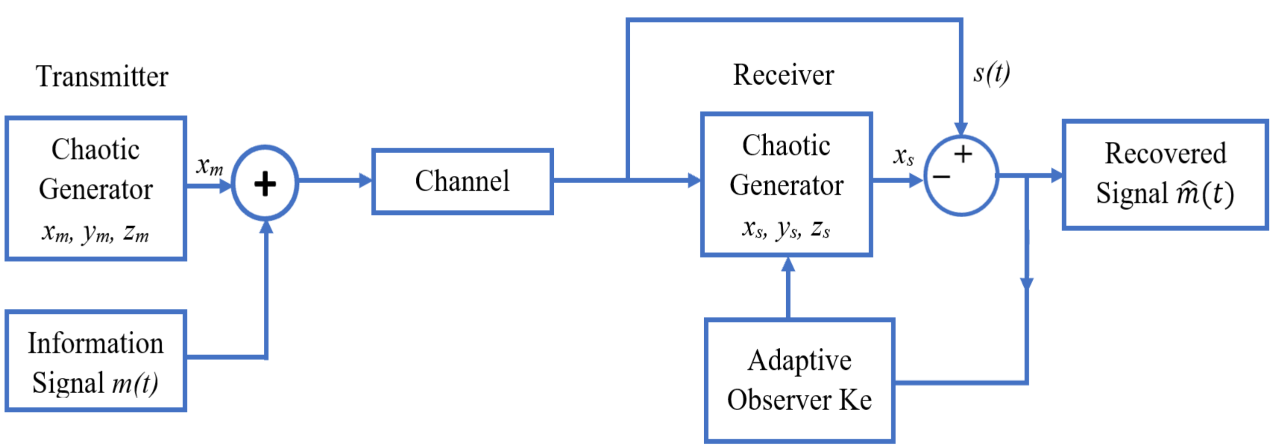


**Figure 6.1:** The utilized secure communication structure with adaptive observer synchronization mechanism

In the **Figure 6.1**, the master and slave present transmitter and receiver of the communication system, respectivelly. Adding an information signal to a chaotic signal at the transmitter (master) side produce an encrypted signals that will be send to the receiver, wher the chaotic masking technique has been emoloyed. Thanks for using chaos synchronization technique to retrieve the original information signals at the receiver side. The receiver must generate a chaotic signal similar the chaotic signal which has been generated at the transmitter side. The receiver recovers the information beam after removing the unrequired chaotic signal from the total received encrypted signal. The original signal's amplitude must be very small in relation to the chaotic signal; otherwise, synchronization would be broken, and the chaotic signal will be unable to hide the encrypted signal spectrum. In this work, information's beam m(t) is encoded by output of chaotic signal $y_m$ in the master side as in equation (6.1). Here, the information signal is a stream of binary numbers generated by Bernoulli binary generator in MATLAB Simulink. Where the binary strean have been scaled by a facor equal to 0.01. Therefore, the transmitted s(t) through a noiseless channel is get as.

$$s(t) = y_m(t) + m(t) \tag{6.1}$$

The required information recovered in the receiver side can be obtained as.

$$\hat{m}(t) = s(t) - y_s(t) \tag{6.1}$$

**Figure 6.2** shows information's beam m(t), transmitted (encoded) beam s(t), recovered beam $\hat{m}(t)$, and the transmission error ( $\hat{m}(t)$ =– r(t)).

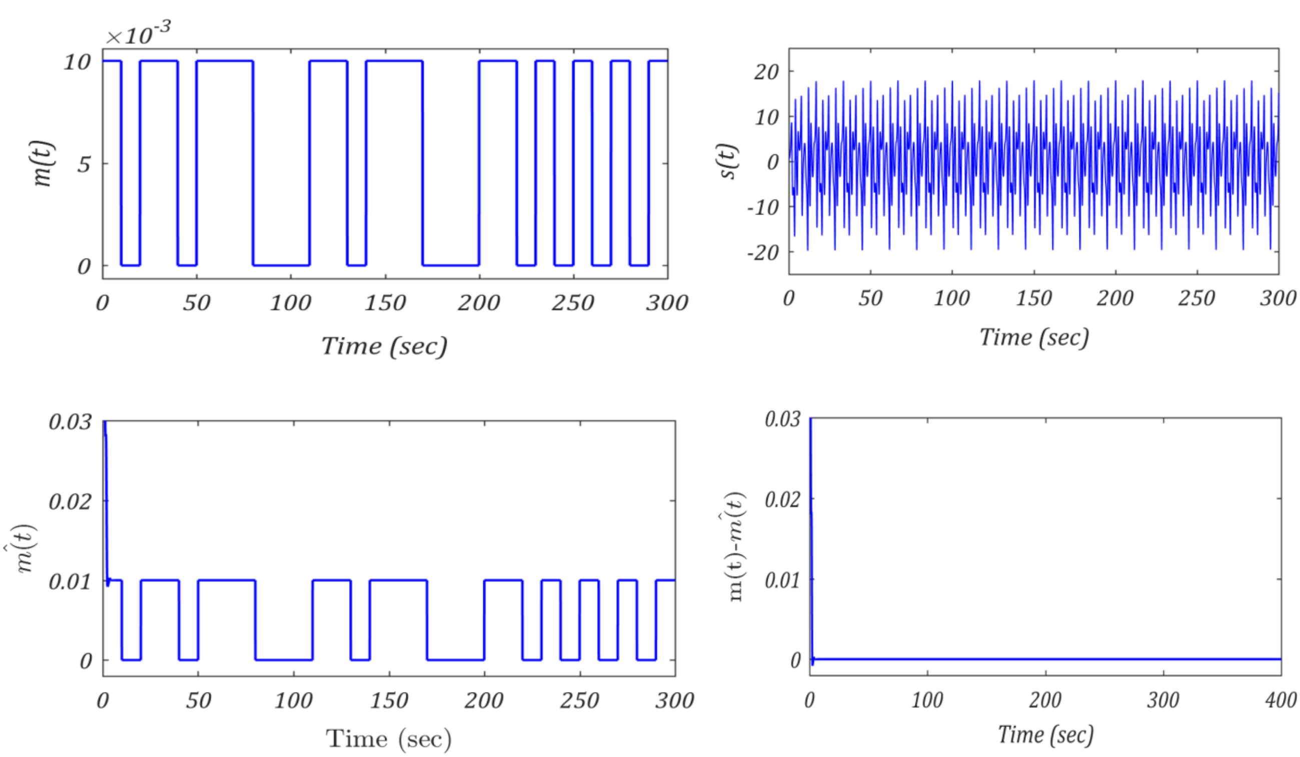


**Figure 6.2:** The signals of the employed secure communication system

From the numerical simulation results of the proposed synchronization mechanism, we can see the rapid matching between the transmitter and receiver signals. The matching time of these signals is very small up to 2.5 sec where this time amount is considered good in synchronization mechanisms of chaotic systems [30]. In other word, the required time such that the synchronization error between the transmitted and received signal converges to zero is 2.5 sec only. Also, in the transmitting and receiving signals, we notice that when the information beam is encrypted by the generated chaotic signal, the transmitted signal is random and complex. In the receiver side, when the chaotic signal subtracted from the transmitted signal, the information beam is recovered with a high accuracy.

## 7. Conclusions

In this article, a 3-D new jerk chaotic system has been presented. The dynamics of the system that proofs the nonlinearity and chaoticity phenomena have been achieved as noticed by the chaotic attractors, bifurcation diagrams, and Lyapunov exponents. Then, an adaptive observer synchronization control of two chaotic systems have been utlized for ensuring the slave trajectories tracked and matched the corresponding mastery trajectories. Furthermore, the system is applied for designing a secure communication scheme based on the employed adaptive observer synchronization technique. Our system analysis was done by using theoretical analysis and simulations via Matlab-Simulink. An information beam presented by a stream of binary numbers randomly generated was encoded and recovered by the designed communication scheme. The developed synchronization technique's efficacy and practicability, as well as its applicability in secure communication. According to the obtained results of this investigation, the proposed jerk chaotic system is simple to be implemented and suitable to be used in secure communication and cryptosystems. Also, the designed communication system exhibits high security in recovering the transmitted signals.

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