



Article

Simple Electric Circuit with Memory Under Λ -Fractional Calculus

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Abstract

A simple electric circuit with memory is discussed, adopting global analysis through fractional analysis. The already presented Fractional analysis with Caputo derivatives, although widely used, fails to satisfy the prerequisites of Differential Topology for a derivative. Hence, they are unable to formulate differential analysis, especially differential geometry. However, the Λ -fractional derivatives can be created for any positive order. In the present analysis, the Λ -fractional analysis is also applied to fractional orders γ with $0 < \gamma$. Although extension of γ is presented for $1 < \gamma < 2$, there is no restriction for extending the present analysis to any $0 < \gamma$.

Keywords: electric system; memristor; chaotic response; Λ -fractional analysis; Λ -fractional derivative; fractional Λ -space; γ -fractional order

1. Introduction

The study of the dynamics of electrical circuits within the context of fractional calculus has attracted considerable scientific interest in recent years. This is especially true for electrical circuits containing elements with “memory” properties that exhibit chaotic behavior. Such an autonomous circuit, consisting of a “memory” element defined as a memristor, was proposed by Muthuswamy and Chua [1] and Chua [2,3], and was also studied by Z. Chen et al. [4], who explored its chaotic characteristics. The fractional response of that system has been described by Sene [5], who adopts fractional calculus with Caputo derivatives. Fractional calculus has helped in the global analysis of various phenomena in engineering, physics, and beyond. Since engineering and physics, especially at micro- or nanoscale dimensions, demand global analysis, the fractional calculus method is one of the best mathematical tools. Eringen [6], in his book on the micro- and nano-behavior of materials, states that the balance laws are considered for the whole body rather than locally, as is common. Since conventional differential calculus is a tool for local analysis, fractional calculus is a tool for global analysis, serving micro- and nanoscale theories in engineering and physics. Leibniz [7], Liouville [8], Riemann [9], and others were highly interested in fractional integrals and derivatives. Machado et al. [10] have presented the various historical steps of fractional calculus. The importance of fractional calculus in describing specific phenomena in control theory, economics, engineering,

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mechanics, biomechanics, physics, etc., has also been highlighted by Baleanu [11] and Atanackovic [12]. Information about fractional calculus can be found in various books, including those on applications. There exists a large collection of phenomena in mechanics [13–15], physics [16,17], etc., that cannot be described by local mathematical calculus. Although fractional calculus arose from the need to mathematically express the non-locality of viscoelastic phenomena, its use has been extended to various areas of physics, especially in micro- and nanophysics. In fact, the stress and strain fields around singularities, such as the crack tips and dislocations, exhibit non-local non-linearities that necessitate a fractional differential approach.

It is pointed out further that relations between fractional orders and fractal dimensions have already been established [18–21]. Contrary to the conventional strain, Truesdell [22] proposed a strain with strong non-locality, as proposed by Lazopoulos [23] (fractional strain). Nevertheless, the well-known fractional derivatives do not satisfy the prerequisites of Differential Topology, as Chillingworth [24] demands.

a. Linearity

$$D(af(x) + bg(x)) = aDf(x) + bDg(x) \quad (1)$$

b. Leibniz rule

$$D(f(x) \cdot g(x)) = Df(x) \cdot g(x) + f(x) \cdot Dg(x) \quad (2)$$

c. Chain rule

$$D(g(f))(x) = Dg(f(x)) \cdot Df(x) \quad (3)$$

Hence, the use of fractional derivatives was not mathematically established. Lazopoulos [25] introduced the Λ -fractional analysis, proposing the fractional Λ -derivative along with the Λ -fractional space. That derivative satisfies the prerequisites of Differential Topology. Lazopoulos [26–28] and others have applied Λ -fractional analysis, proposing a non-local procedure to various problems in mechanics, physics, economics, etc.

Geometry and physics are analyzed in the conventional sense in the Λ -space. In fact, almost the whole analysis is performed in the Λ -fractional space, where the rules of the common analysis are valid, and the results are transferred to the real initial space from the Λ -fractional space. As it has already been stated, the dynamics of electrical circuits has already been studied within the context of fractional calculus by Muthuswamy and Chua [1], Chen [4] and Sene [5] who studied the fractional order system into the Caputo sense. Due to the handicap of the Caputo derivative, to generate geometry, the fractional order memristor system is studied in the context of the Λ -fractional derivative, which is the unique fractional derivative conforming to the prerequisites of Differential Topology. In the present work, Λ -fractional differential analysis, similar to the Laplace transform, is formulated. The fractional derivatives exhibit the specific property of being local in the Λ -fractional space, whereas they are non-local in the initial space, where they are transferred. The present analysis is limited to presenting solutions for fractional-order systems without studying the chaotic aspects of the problem. Nevertheless, the interested reader has all the necessary tools for studying the stability and chaotic aspects of the present problem.

2. Summary of Fractional Calculus

Fractional calculus has recently been studied in pure mathematics and is necessary in physics, engineering, and economics, among other fields. There are many varied fractional derivatives serving specific purposes. Nevertheless, their common characteristic is their non-locality, contrary to the locality of the conventional ones. Information on

fractional analysis and its applications may be found in the classical books by Samko et al. [14], Podlubny [15], and Oldham et al. [16].

For a function $f(x)$, its n -fold integral is expressed by

$${}_a I_x^n f(x) = \frac{1}{(n-1)!} \int_a^x (x-s)^{n-1} f(s) ds, \quad x > 0, n \in \mathbb{N} \quad (4)$$

The γ -multiple integral of Leibniz with $0 < \gamma < 1$ is defined by

$${}_a I_x^\gamma f(x) = \frac{1}{\Gamma(\gamma)} \int_a^x \frac{f(s)}{(x-s)^{1-\gamma}} ds \quad (5)$$

with $\Gamma(\gamma)$ Euler's Gamma function.

Further, the left Riemann–Liouville (R-L) derivatives are defined by

$${}^{RL}_a D_x^\gamma f(x) = \frac{d}{dx} ({}_a I_x^{1-\gamma} f(x)) = \frac{1}{\Gamma(1-\gamma)} \frac{d}{dx} \int_a^x \frac{f(s)}{(x-s)^\gamma} ds. \quad (6)$$

Let us point out that the right fractional integrals and derivatives, as defined by Podlubny [9], are similarly defined.

The Λ -fractional derivative (Λ -FD) has been introduced as

$${}^\Lambda_a D_x^\gamma f(x) = \frac{{}^{RL}_a D_x^\gamma f(x)}{{}^{RL}_a D_x^\gamma x} \quad (7)$$

Considering the definition of the fractional derivative, Equation (6), the Λ -FD is expressed by

$${}^\Lambda_a D_x^\gamma f(x) = \frac{\frac{d}{dx} {}_a I_x^{1-\gamma} f(x)}{\frac{d}{dx} {}_a I_x^{1-\gamma} x} = \frac{d {}_a I_x^{1-\gamma} f(x)}{d {}_a I_x^{1-\gamma} x} \quad (8)$$

The Λ -FD is defined as a conventional derivative in the fractional space $(X, F(X))$, where $X = {}_a I_x^{1-\gamma} x$ and $F(X) = {}_a I_x^{1-\gamma} f(x)$. In the Λ -fractional space $(X, F(X))$, the differential geometry follows the conventional rules, where the derivative

$${}^\Lambda_a D_x^\gamma f(x) = \frac{dF(X)}{dX} \quad (9)$$

Further, the relation

$${}^{RL}_a D_x^{1-\gamma} ({}_a I_x^{1-\gamma} f(x)) = f(x) \quad (10)$$

transfers the various results from the fractional Λ -space into the initial one, the real space. Results are only accepted in real space. In fact, Λ -fractional analysis is a transformation closely related to the Laplace transform. Furthermore, Equation (10) is similar to the well-known inverse Laplace transformation.

3. A Simple Electric Circuit with Memory Under Λ -Fractional Calculus

As it has been pointed out, Chen [4] explored the chaotic characteristics of a memristor proposed by Chua [1].

A layout of this circuit is shown in the diagram below, Figure 1.

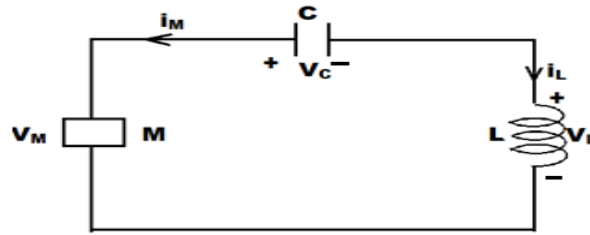


Figure 1. The electric circuit proposed by Muthuswamy and Chua with a quadratic memristance function R .

In 1971, Leon Chua noticed the need for a new fundamental circuit element besides resistors, capacitors, and inductors [3]. Chua justified the existence of a missing element on the grounds of symmetry. Suppose we consider the six possible combinations of the four basic circuit variables: electric charge q , current I , voltage V , and flux φ . According to Ohm's law ($V = IR$), resistors relate voltage to current in capacitors. Further, inductors connect current to flux ($\varphi = LI$) and electric charge to voltage ($q = CV$). The relationship, not covered by any of the conventional circuit elements, is the connection between electric charge and flux. This is the sixth possible relation.

Chua also claimed the existence of a fourth fundamental circuit element, connecting the charge to the flux. He named it a memristor, with units of resistance (Ω) short for 'memory resistor'. Chua and Kang in 1976 extended the theory of memristors, introducing a class of nonlinear dynamic systems, the memristive systems [3]. A passive two-terminal device with variable resistance, the memristive device is similar to a memristor.

The equations connecting voltage and current across the capacitance (C) and inductance (L) are

$$\frac{dV_c}{dt} = \frac{1}{C} \cdot i_L, V_L = L \cdot \frac{di_L}{dt} \quad (11)$$

Applying Kirchhoff's law for the voltages across the circuit, we have

$$V_L + V_C = V_M \quad (12)$$

The voltage across the memristor is

$$V_M = R(z) \cdot (-i_L). \quad (13)$$

Hence, the following equation is used:

$$\frac{di_L}{dt} = -\frac{1}{L} (V_C + R(z) \cdot i_L), \quad (14)$$

where z denotes an internal variable of the specific memristive model. Considering a quadratic function for the memristor $R(z) = \beta(z^2 - 1)$, the latter equation is written as

$$\frac{di_L}{dt} = -\frac{1}{L} (V_C + \beta(z^2 - 1) \cdot i_L) \quad (15)$$

The third differential equation of our system refers to the internal variable z , written as follows:

$$\frac{dz}{dt} = (z - 1) \cdot i_L - \alpha \cdot z \quad (16)$$

If we let $V_C = X(T)$, $i_L = Y(T)$, $z = Z(T)$, and $t = T$, we end up with the following system of equations:

$$\frac{dX}{dT} = \frac{1}{C} \cdot Y \quad (17a)$$

$$\frac{dY}{dT} = -\frac{1}{L} \cdot [X + \beta(Z^2 - 1) \cdot Y] \quad (17b)$$

$$\frac{dZ}{dT} = (Z - 1) \cdot Y - \alpha \cdot Z. \quad (17c)$$

The corresponding system of equations in fractional form is expressed by

$${}^{RL}_a D_t^\gamma x = \frac{1}{c} y \quad (18a)$$

$${}^{RL}_a D_t^\gamma y = -\frac{1}{L} [x + \beta(z^2 - 1)y] \quad (18b)$$

$${}^{RL}_a D_t^\gamma z = (z - 1)y - \alpha z \quad (18c)$$

Based on the methodology of Λ -fractional calculus, we solve this system in Λ -space and transform the solutions $X(T)$, $Y(T)$, and $Z(T)$ to the corresponding real-space solutions $x(t)$, $y(t)$, and $z(t)$. The constant values proposed in the article are $C = 1$, $L = 3$, $\beta = 1.5$, and $\alpha = 0.6$. The initial conditions used are $X(0) = 0.1$, $Y(0) = 0$, $Z(0) = 0.1$.

Based on the methodology of Λ -fractional calculus, this system is solved in Λ -space, and the solutions $X(T)$, $Y(T)$, and $Z(T)$ are transformed to the corresponding real-space solutions $x(t)$, $y(t)$, and $z(t)$ —the system of Equation (17a–c) has been numerically solved for the specific values of the parameters $\alpha = 0.6$ and $\beta = 1.5$ (Figure 2, 3). As already pointed out, the system is solved in the Λ -space using the conventional method.

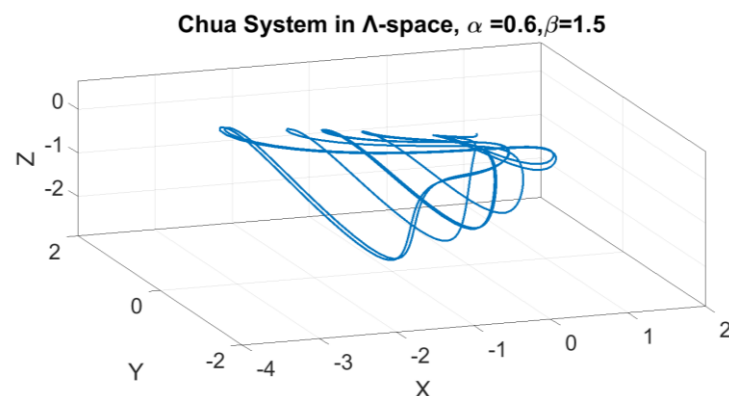


Figure 2. The 3D solution to the system in the Λ -fractional space for $\alpha = 0.6$ and $\beta = 1.5$.

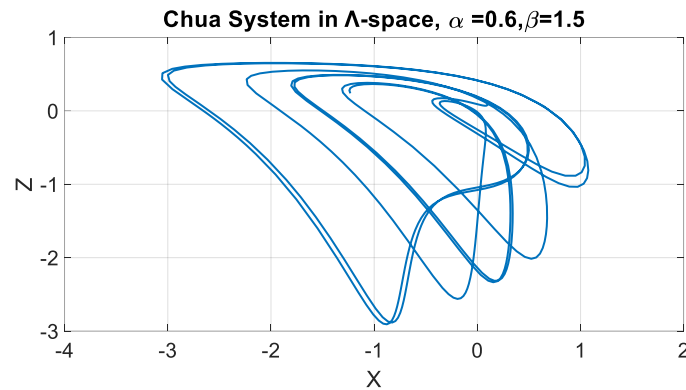


Figure 3. The x–z projection of the solution to the system in the Λ -fractional space for $\alpha = 0.6$ and $\beta = 1.5$.

Further, the projection of the solution to the system, Equation (19), for the same values of the parameters α and β onto the plane X, Y of the Λ -space is presented in Figure 4.

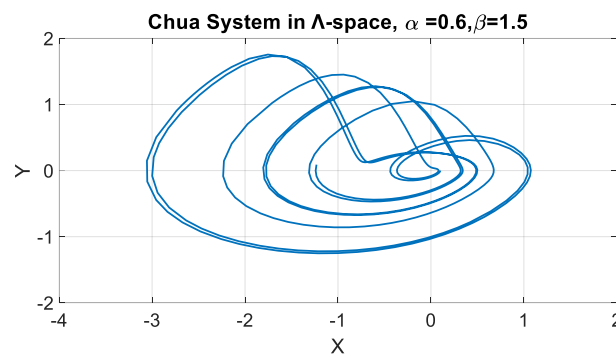


Figure 4. The x–y projection of the solution to the system in the Λ -fractional space for $\alpha = 0.6$ and $\beta = 1.5$.

Up to this point, the solution has followed conventional approaches. The results from the present Λ -space will be transferred into the real (initial) space, following the Λ -fractional analysis.

4. The Chaotic System in the Real Space

The differential equations describing the specific system in Λ -space have already been presented in Equations (17a–c). Those equations are transferred into the initial space according to the law,

$$w = {}^{RL}_0 D_t^{1-\gamma} (W(T(t))). \quad (19)$$

The system's real response is the one designed in real space. The responses in the Λ -space help determine the system's behavior in the real space. There are three dimensions, $\gamma = 0.9, 0.8, 0.5$, with $\gamma < 1$, discussed in the present paragraph.

4a. Transferring the solution to the real space from the Λ -fractional space with the fractional order $\gamma = 0.9$, Figures 5–7 exhibit the complete picture of the behavior of the system in the real space just for that fractional order.

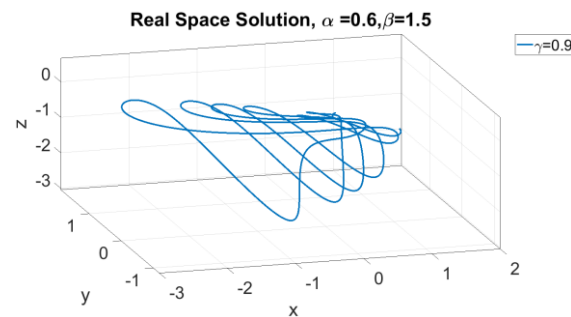


Figure 5. The real-space solution of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.9$.



Figure 6. The real-space solution (projection in the x-y plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.9$.

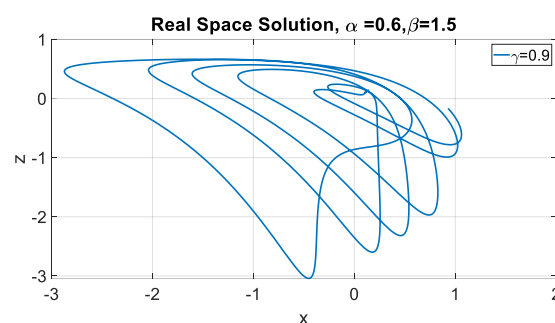


Figure 7. The real-space solution (projection in the x-z plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.9$.

4b. Transferring the solution to the real space from the Λ -fractional space with the fractional order $\gamma = 0.8$, Figures 8–10 exhibit the complete picture of the behavior of the system in the real space just for that fractional order.

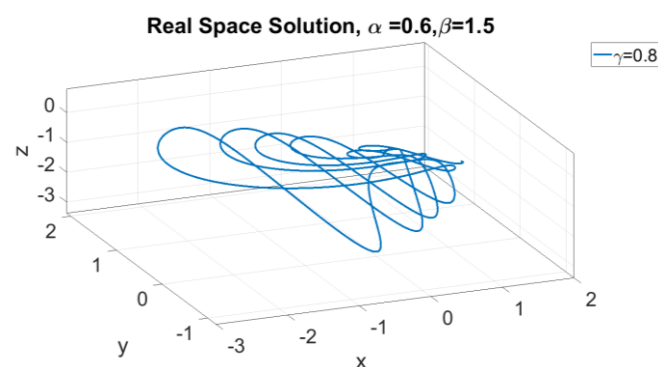


Figure 8. The real space solution of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.8$.

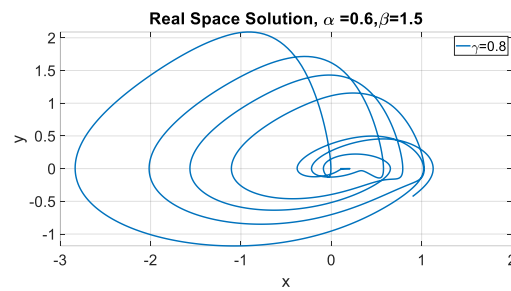


Figure 9. The real space solution (projection in the x–y plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.8$.

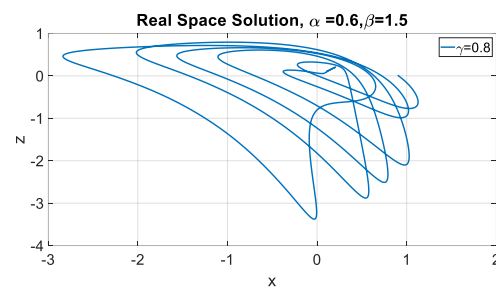


Figure 10. The real space solution (projection in the x–z plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.8$.

4c. Transferring the solution to the real space from the Λ -fractional space with the fractional order $\gamma = 0.5$, Figures 11–13 exhibit the complete picture of the behavior of the system in the real space just for that fractional order.

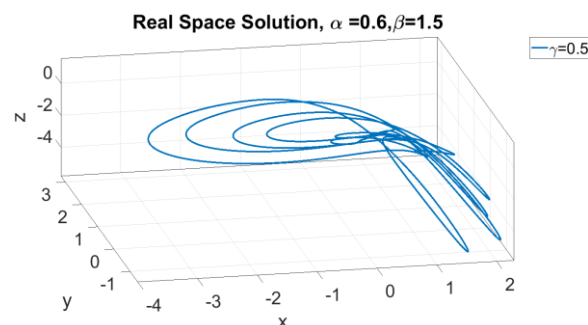


Figure 11. The real space solution of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.5$.

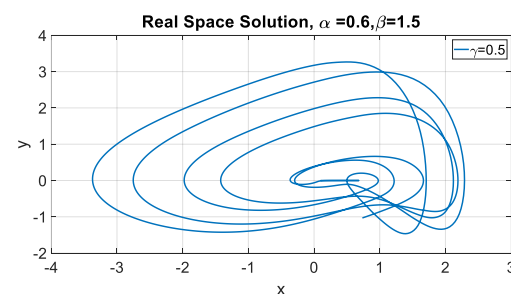


Figure 12. The real space solution (projection in the x–y plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.5$.

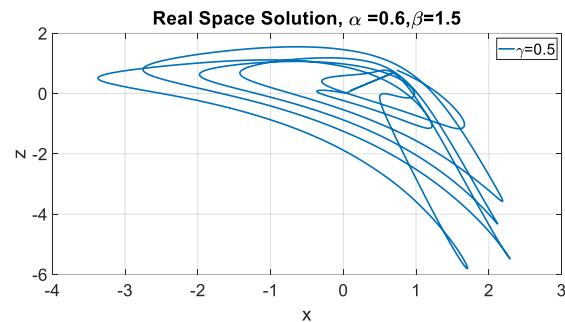


Figure 13. The real space solution (projection in the x - z plane) of the Λ -fractional Chua system with parameters $\alpha = 0.6$, $\beta = 1.5$, and fractional order $\gamma = 0.5$.

5. Comparison of the Chua Space Solutions Between the Λ -Fractional Analysis and Caputo Derivative Analysis

Just to compare the difference between the present analysis based upon the Λ -fractional analysis and the one presented by Sene [5], some solutions of the Chua problem are presented here with fractional orders presented in [5]. In fact, for $\gamma = 0.75$, the three-dimensional solution in the real space is presented in Figure 14.

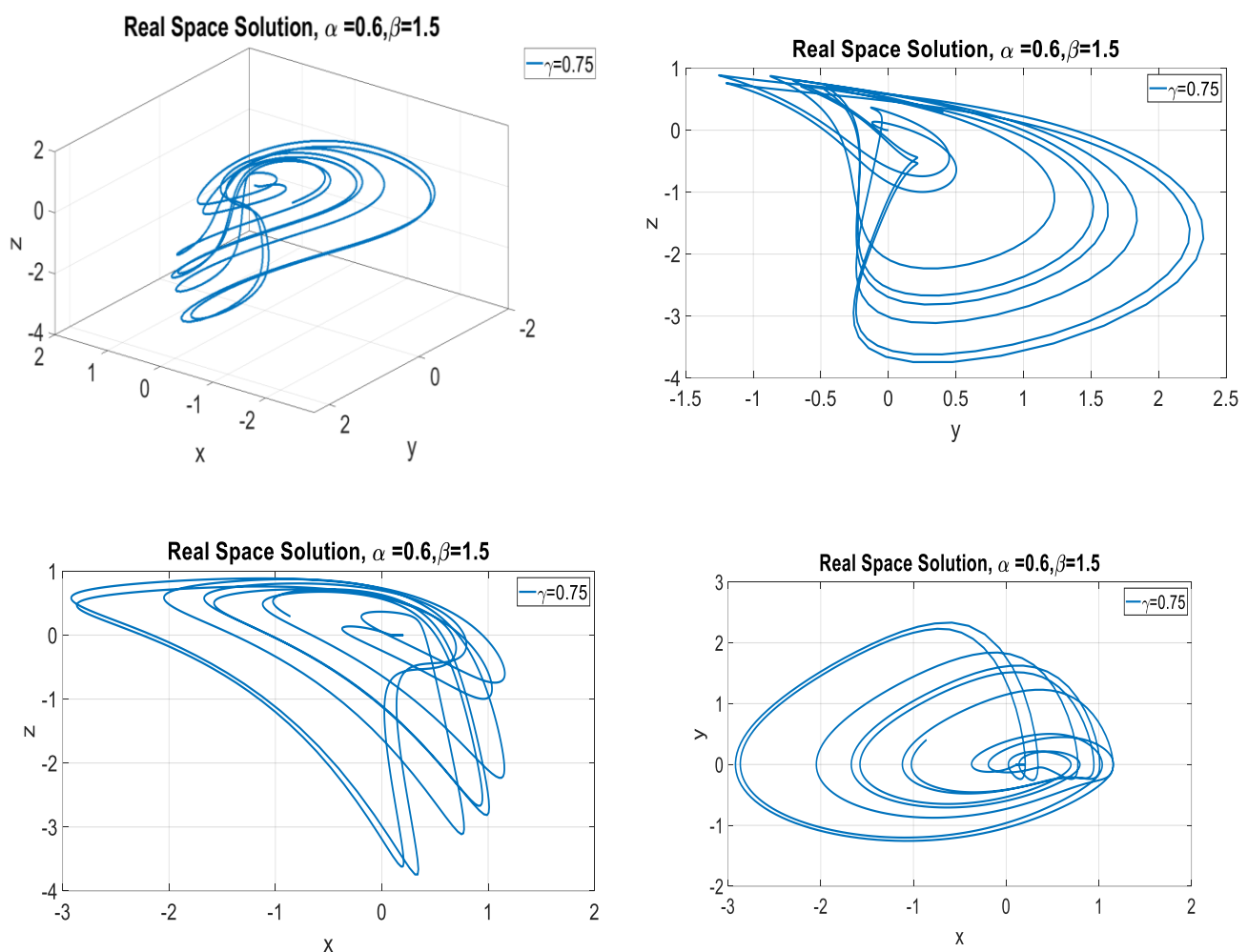


Figure 14. The solution in the real space for fractional order $\gamma = 0.75$.

The corresponding diagrams based upon Caputo's fractional derivative [5] are shown in Figure 15.

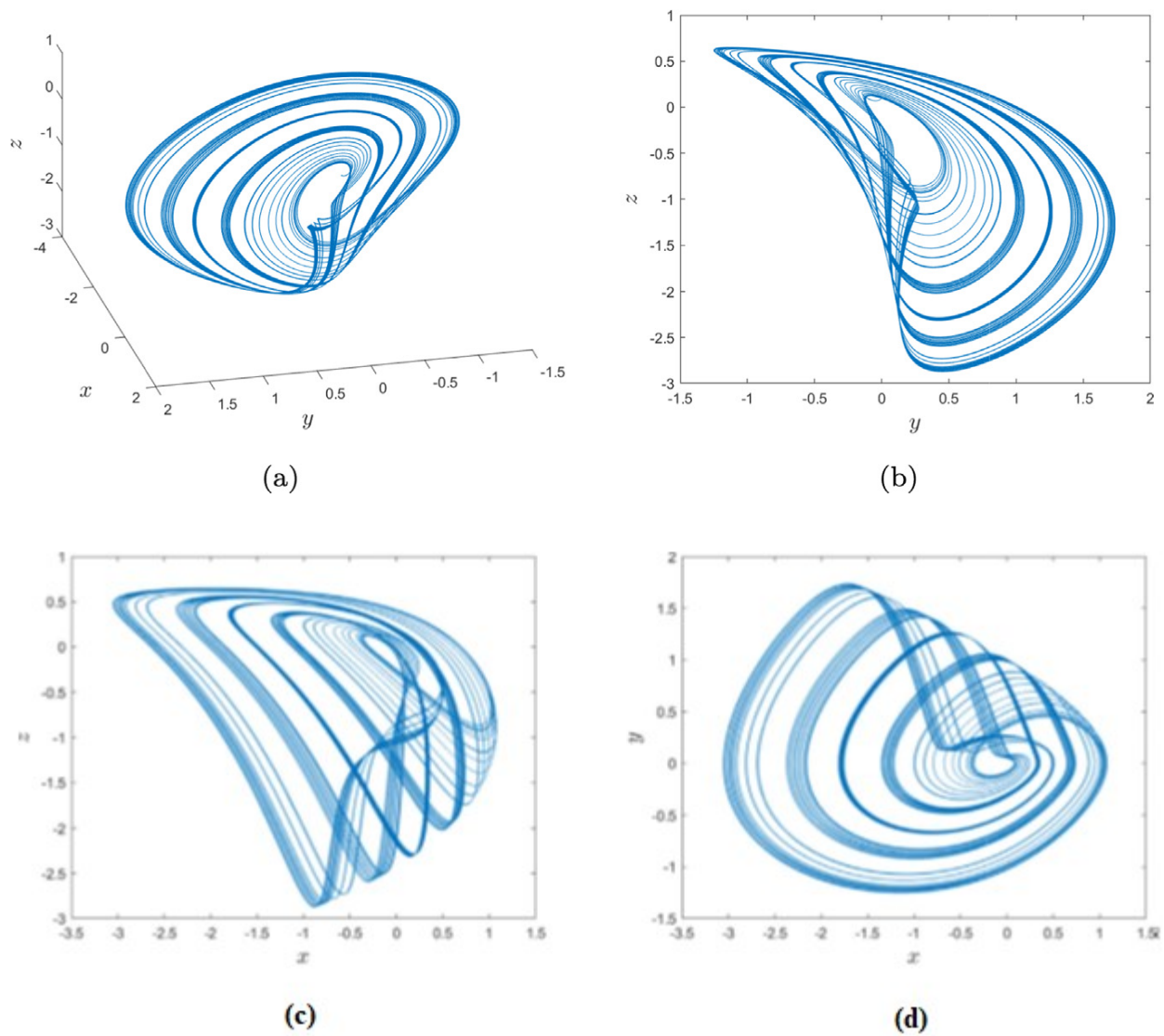
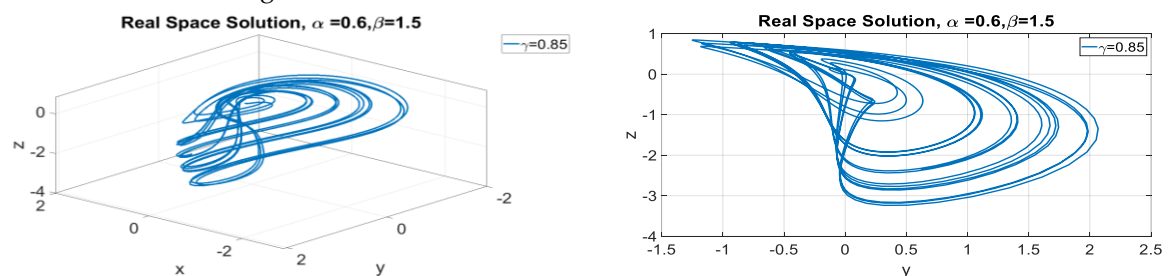


Figure 15. Results with Caputo derivative (order $\gamma = 0.75$) [5]. (a) xyz , (b) xyz , (c) xz , (d) xy .

Further results concerning Λ -fractional analysis with Λ -fractional order $\gamma=0.85$ are shown in Figure 16. The corresponding diagrams with Caputo derivative are shown in figure 17.



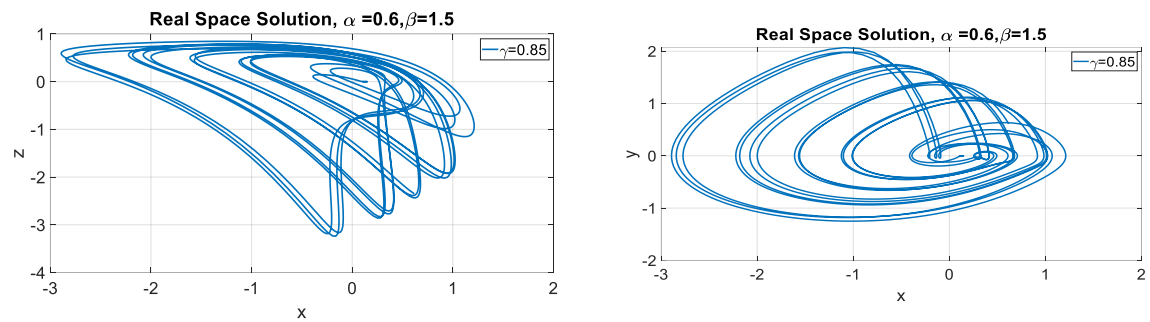


Figure 16. Results for Λ -fractional analysis and order $\gamma = 0.85$.

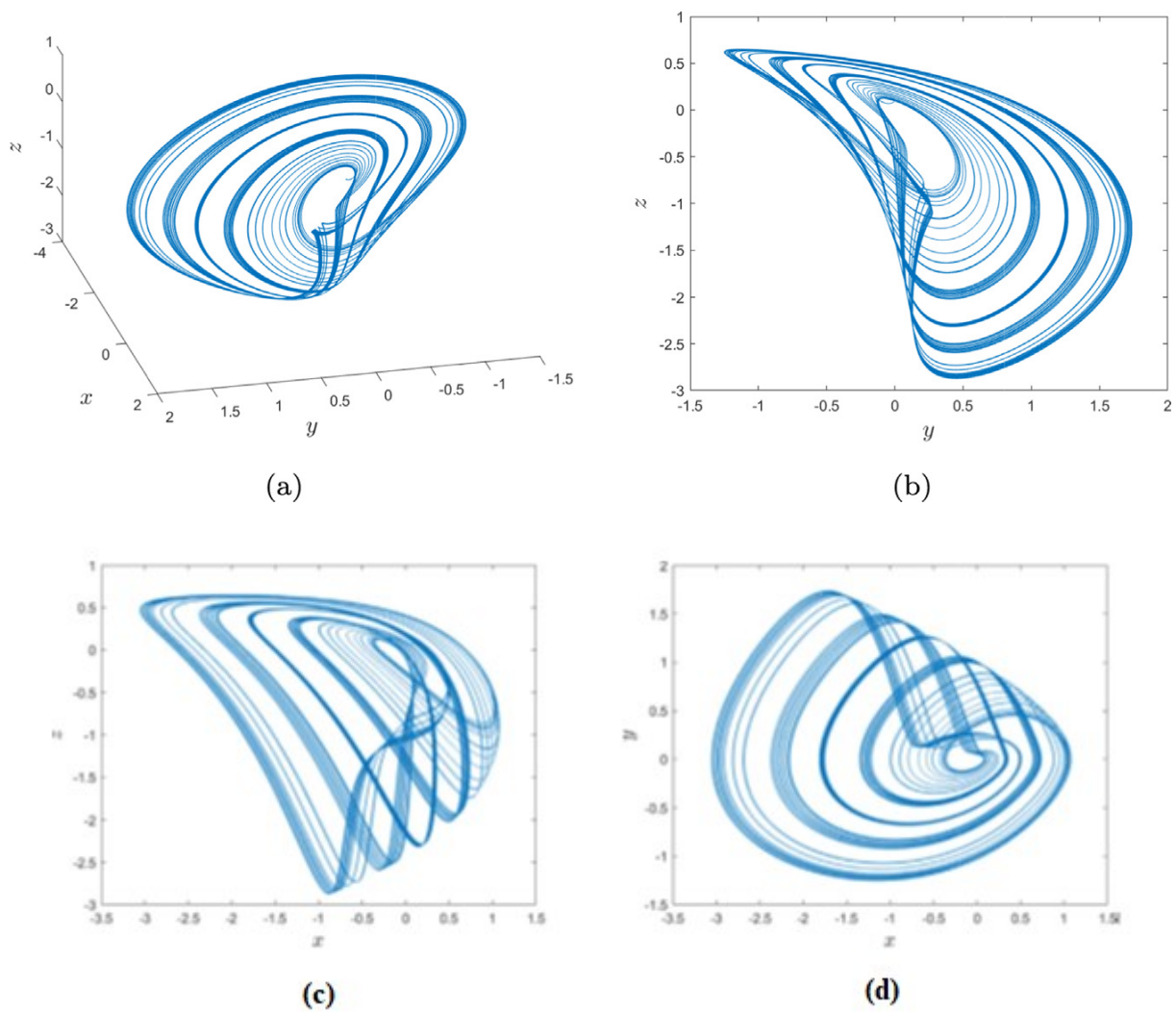


Figure 17. Results with Caputo derivative (order $\gamma = 0.85$) [5]. (a)xyz, (b)xyz, (c)xz, (d)xy.

Further results concerning Λ -fractional analysis with Λ -fractional order $\gamma=0.95$ are shown in Figure 18. The corresponding diagrams with Caputo derivative are shown in figure 19.

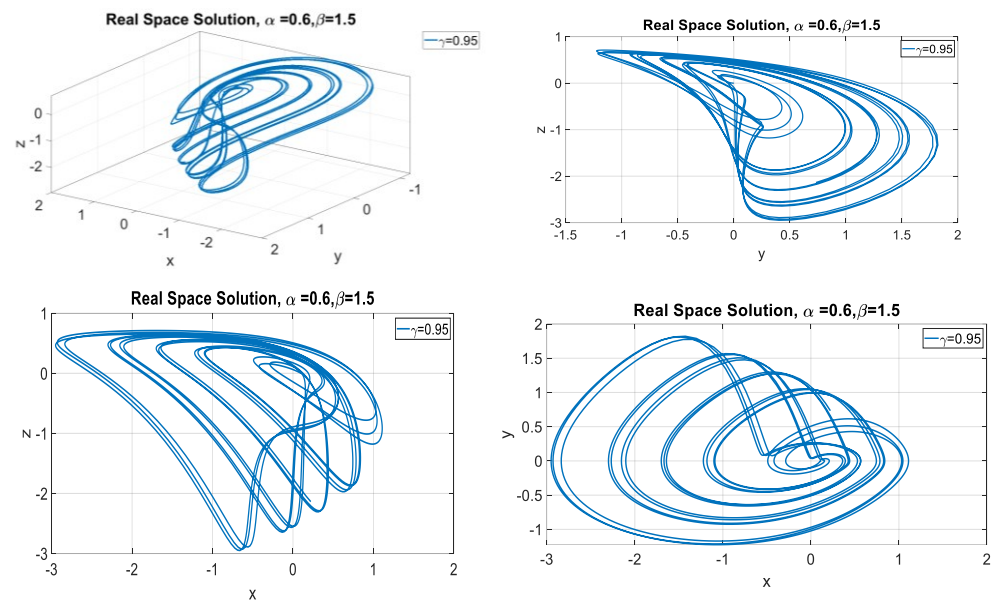


Figure 18. Results for Λ -fractional analysis and order $\gamma = 0.95$.

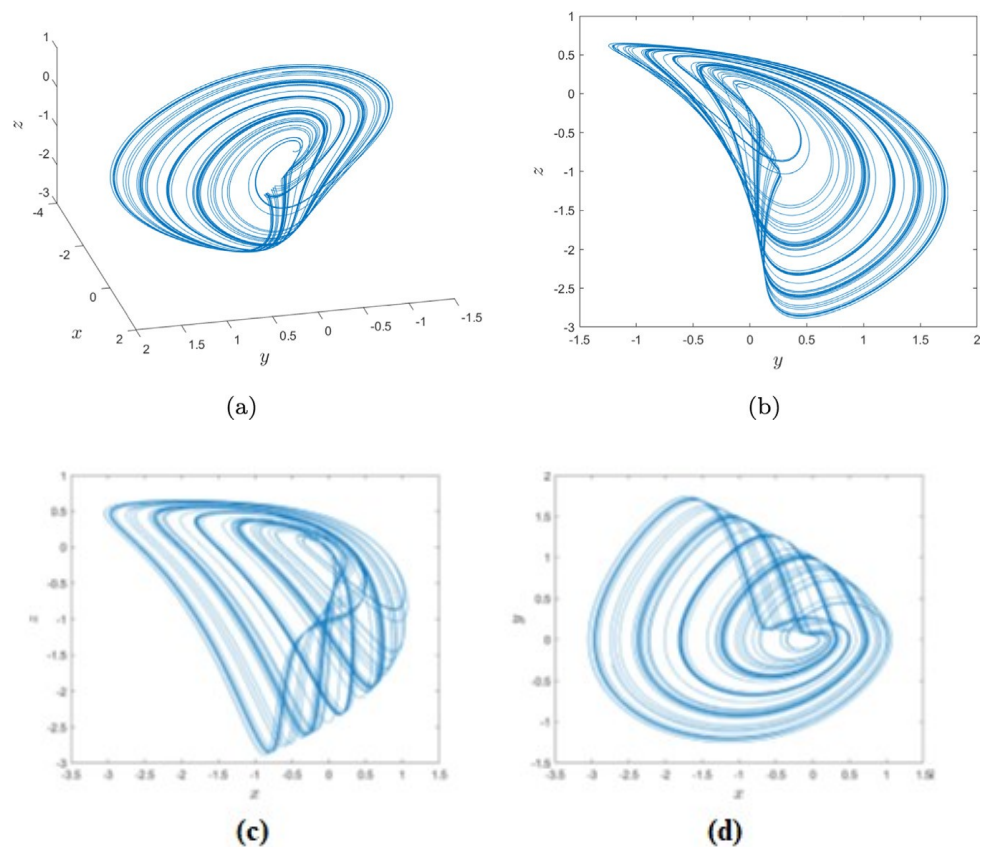


Figure 19. Results with Caputo derivative (order $\gamma = 0.95$) [5]. (a)xyz, (b)xyz, (c)xz, (d)xy.

The difference is quite evident. The results between the present Λ -fractional analysis and Caputo's fractional derivative are closer for high values of the fractional order (e.g., $\gamma = 0.95$).

6. The Solution of the Λ -Fractional Chua System for Fractional Order $1 < \gamma < 2$

Extension of the Λ -fractional analysis for $1 < \gamma$ has already been presented in Lazopoulos et al. [28], where the involvement of Dirac Delta Functions with the Λ -derivatives has been considered. For $1 < \gamma < 2$, the Λ -fractional derivative of order $\gamma_0 = \gamma/2$ will be considered. Indeed, $0 < \gamma_0 < 1$ and the Λ -fractional space $(X, F(X))$ is defined with

$$X = {}_a I_x^{1-\gamma_0} x \quad \text{and} \quad F(X) = {}_a I_x^{1-\gamma_0} f(x(X)) \quad (20)$$

Consequently, the Λ -fractional derivative in the Λ -fractional space is defined as the second-order derivative of the function $F(X)$ with respect to X . Indeed,

$${}^\Lambda D_x^\gamma f(x) = \frac{d^2 F(x(X))}{dX^2} = G(X) \quad (21)$$

Therefore, the function $G(X)$ in the Λ -fractional space is transferred to the initial space through

$$g(x) = {}^{RL}D_x^{1-\gamma_0} G(X(x)). \quad (22)$$

Hence, Chua's chaotic system at Λ -fractional space with $1 < \gamma < 2$ is defined by

$$\frac{d^2 X}{dT^2} = \frac{Y}{C'} \quad (23)$$

$$\frac{d^2 Y}{dT^2} = -\frac{1}{L} \cdot [X + \beta \cdot Y \cdot (Z^2 - 1)], \quad (24)$$

$$\frac{d^2 Z}{dT^2} = (Z - 1)Y - \alpha \cdot Z. \quad (25)$$

The fractional order γ corresponding to the Λ -fractional space is defined for $\gamma_0 = \gamma/2$ ($0.5 \leq \gamma_0 \leq 1$). To transfer the results from the Λ -space to the initial (real) one, Equation (22) is applied. The Chua system Equations (23–25) have been numerically solved for the constants $C = 1$, $L = 3$, $\beta = 1.5$, and $\alpha = 0.6$. Furthermore, the initial conditions are the following:

$$X(0) = 0.1, Y(0) = 0, Z(0) = 0.1, \quad (26a)$$

$$dX/dT(0) = 0, dY/dT(0) = 0, dZ/dT(0) = 0. \quad (26b)$$

The various solutions in the Λ -space have been obtained numerically, and they are presented in the diagrams of Figures 20 and 21.

Transferring the solution from the Λ -space to the initial one for various values of the fractional order γ , a quite different picture of the system is revealed. In fact, for $\gamma = 1$, the corresponding diagrams are shown in Figures 22 and 23.

Further, transferring the solution for fractional order $\gamma = 1.3$, the following solution appears in the initial space Figures 24 and 25:

Finally, for $\gamma = 1.6$ fractional order, the solution in the real space is presented in Figures 26 and 27.

Just comparing the diagrams for the fractional orders, $\gamma < 1$ and $\gamma > 1$, it is evident that the response of the Chua system is directly affected by the fractional order γ of the system.

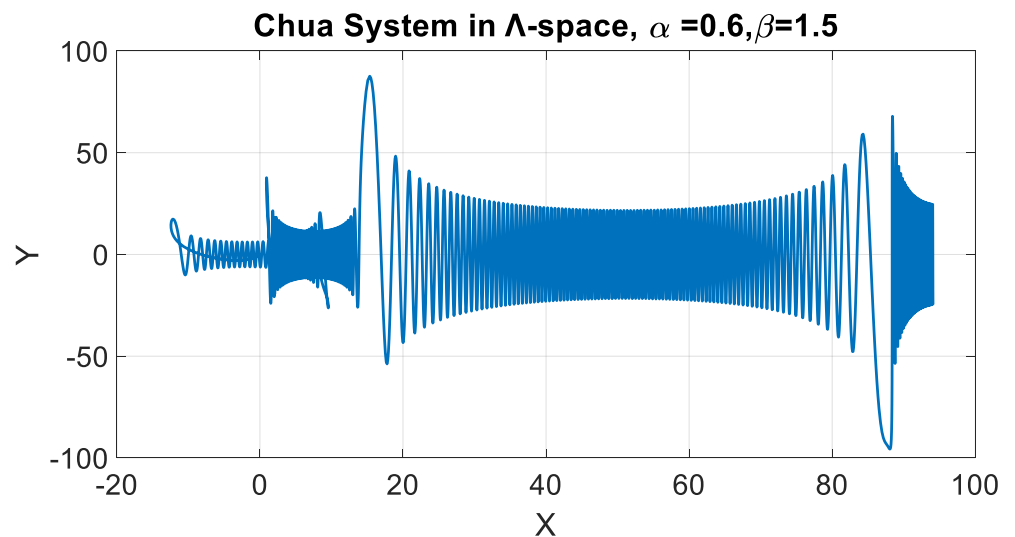


Figure 20. The (X,Y) plane response of the Chua system in the Λ -space.

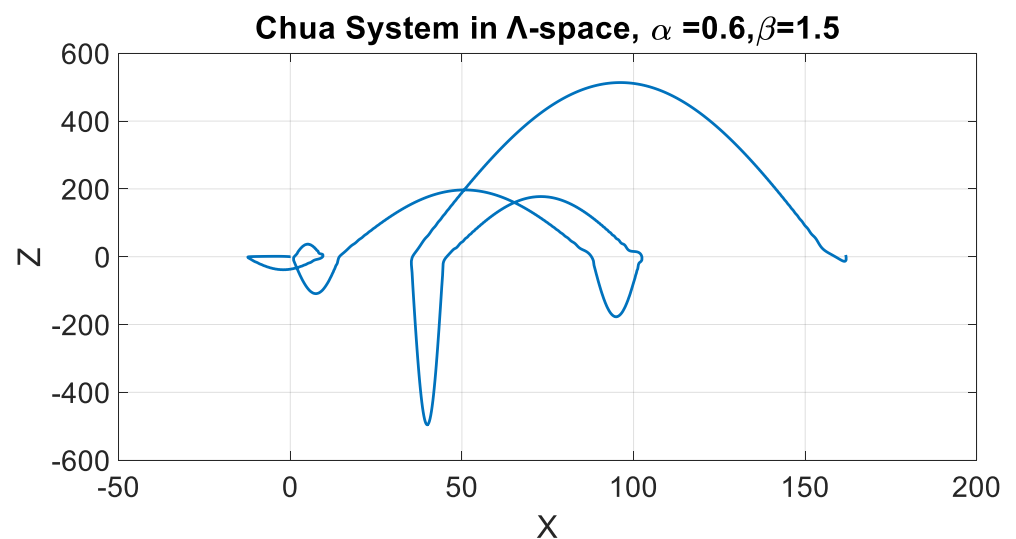


Figure 21. The (X,Z) plane response of the Chua system in the Λ -space.

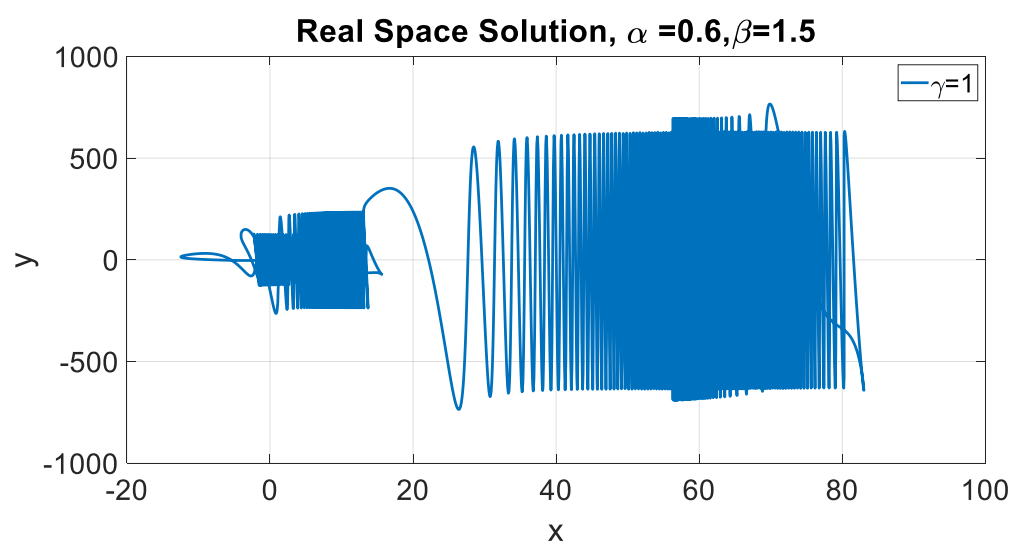


Figure 22. The real solution of the Chua system in the x - y plane for $\gamma = 1$.

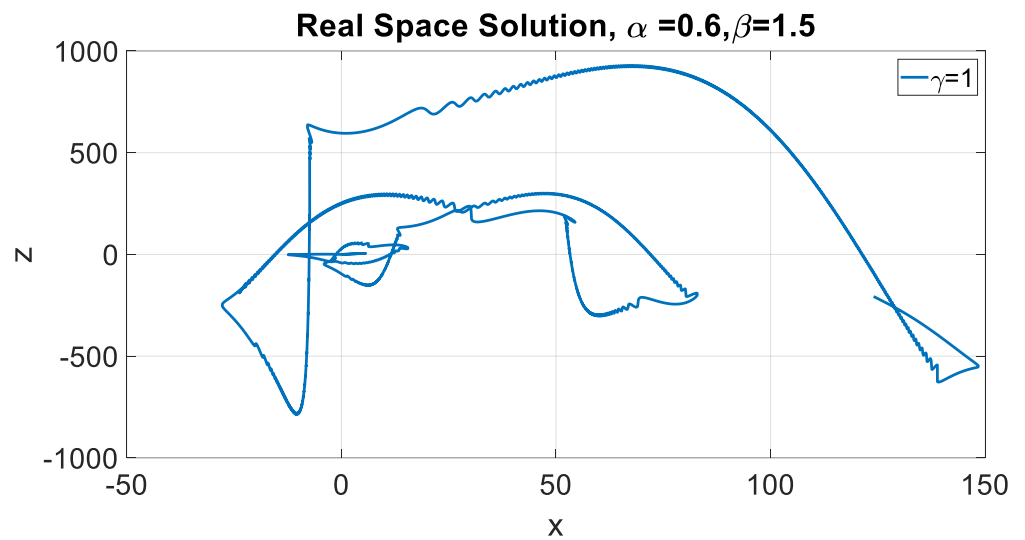


Figure 23. The real solution of the Chua system in the x - z plane for $\gamma = 1$.

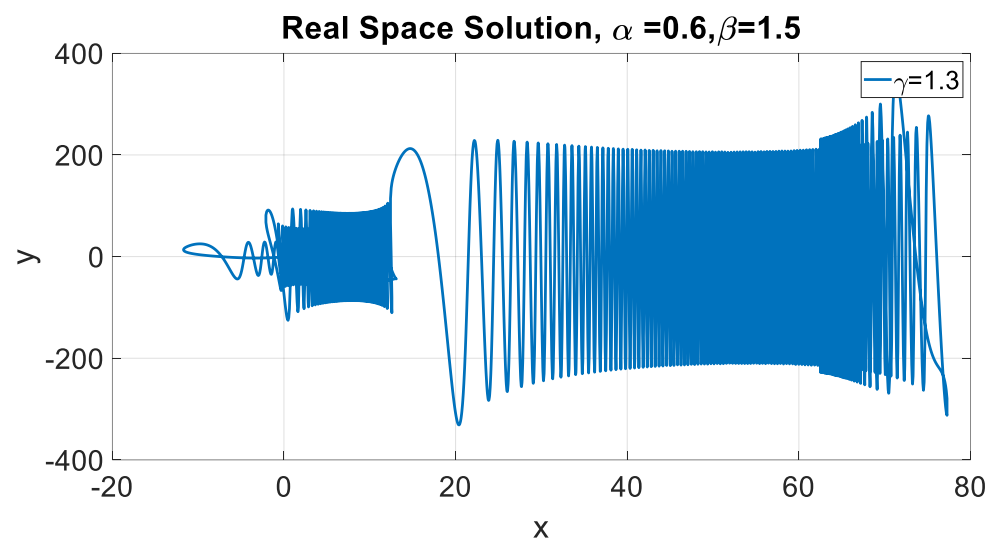


Figure 24. The real solution of the Chua system in the x - y plane for $\gamma = 1.3$.

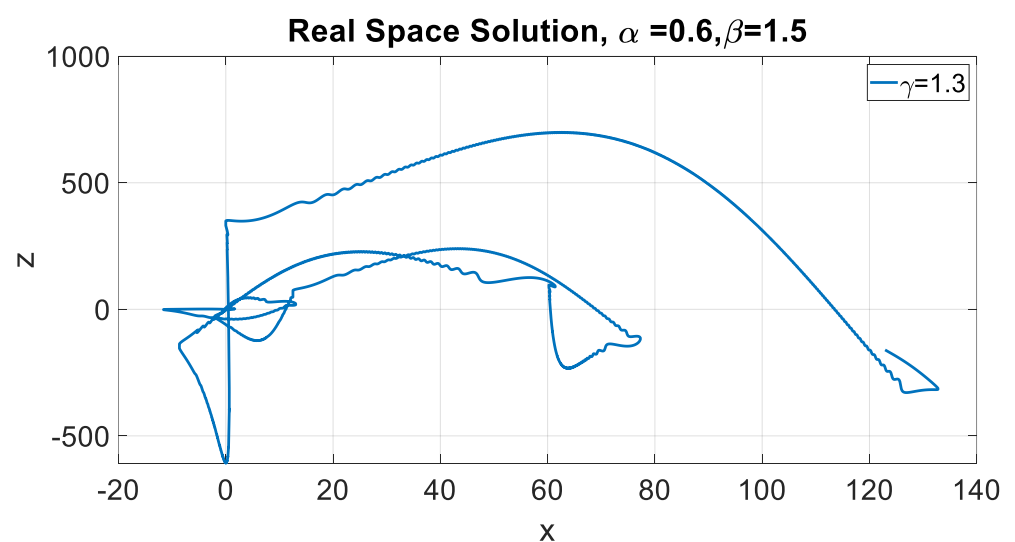


Figure 25. The real solution of the Chua system in the x - z plane for $\gamma = 1.3$.

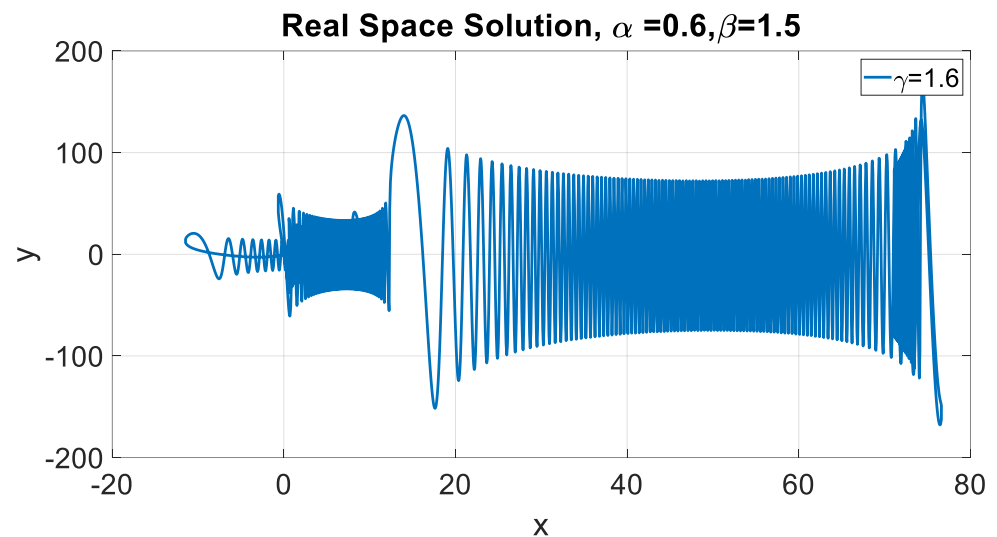


Figure 26. The real solution of the Chua system in the x–y plane for $\gamma = 1.6$.

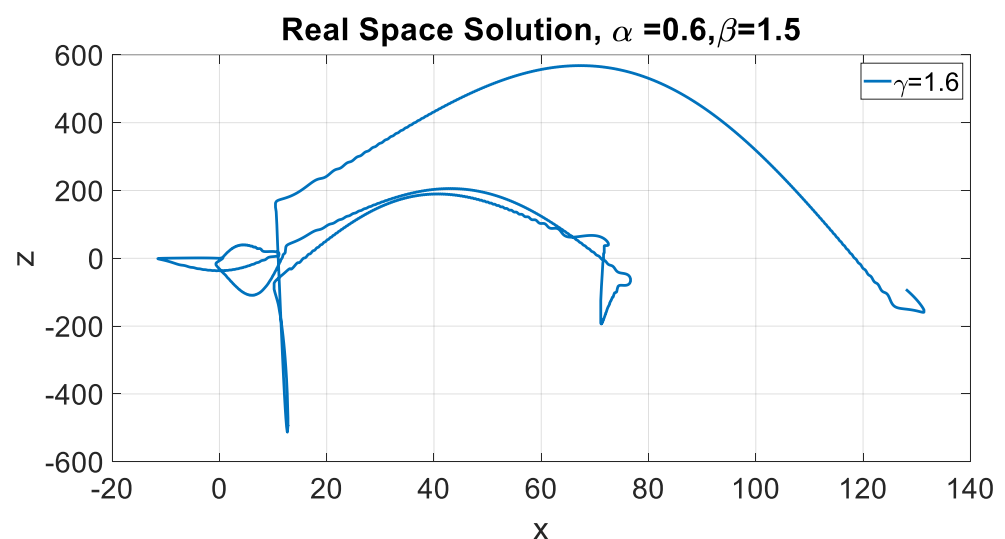


Figure 27. The real solution of the Chua system in the x–z plane for $\gamma = 1.6$.

7. Conclusions

The present work outlines the mathematical basis of the Λ -fractional analysis and addresses questions regarding the use of Caputo's fractional derivative in stability problems. Further, it presents problems with fractional derivatives of order higher than one.

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