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HIGHER ORDER CONFORMABLE FRACTIONAL SHEHU TRANSFORM, A GENERALIZED APPROACH AND ITS APPLICATION

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Abstract. In this study, we focus on extending the higher-order Shehu transform to the real of conformable fractional calculus. The proposed transform is rigorously established and then utilized to derive general analytical solutions for conformable fractional differential equations with variable coefficients, as well as for systems of non-homogeneous fractional differential equations. Several illustrative examples are provided to demonstrate the effectiveness and broad applicability of the proposed method in solving complex problems within this field.

1. Introduction

The exploration of fractional derivatives has a rich history dating back to the foundational principles of calculus. The inquiry into the meaning of $\frac{d^n f}{dx^n}$ when $n = \frac{1}{2}$, by L'Hospital in 1695, marked a pivotal moment, igniting a wave of research aimed at formalizing the concept of fractional derivatives. Over

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the years, several significant definitions have emerged, including the Riemann-Liouville fractional derivative, the Caputo fractional derivative, the Grünwald-Letnikov fractional derivative, the Atangana-Baleanu fractional definitions, the Hadamard fractional integral, the Caputo-Fabrizio fractional derivative, and the conformable fractional derivative. Among these, the conformable fractional derivative is particularly noteworthy for its intuitive nature, which allows for simpler and more accessible solutions to a variety of mathematical problems. This approach not only enhances the understanding of fractional calculus but also broadens its applicability across different fields. For those interested in further applications of the conformable fractional derivative, a wealth of resources is available in the literature, as referenced in [4, 5, 8, 10, 11].

In [8], the author introduced the conformable fractional Shehu transform, a powerful tool that simplifies the resolution of numerous fractional differential equations. To address more intricate challenges, such as non-homogeneous fractional differential equations with variable coefficients of higher order, we propose an extension of the conformable fractional Shehu transform to accommodate these complexities. This generalization not only enhances the versatility of the transform but also enables the effective solution of a broader class of fractional differential equations and systems. For additional insights into the conformable fractional Shehu transform and its applications, we encourage readers to consult references [1, 6, 12].

This work is divided into the following sections: In Section 2, we present the basic preleminarises that will be used in third section. In section 3, we define the generalisation of higher-order of fractional conformable Shehu transform and prove the transformation and then use it to derive general analytical solutions for appropriate fractional differential equations with variable coefficients. Finally, we provide several illustrative examples to demonstrate the effectiveness of applying the proposed method. Finally, in the last section, we provide a summary of the work presented here.

Definition 1.1. ([2]) (The conformable fractional derivative) Let $f : [0, \infty) \to \mathbb{R}$ be a function. The conformable derivative of the function f with order σ is defined by

$$T_\sigma(f)(t) = \lim_{\varepsilon \to 0} \frac{f(t + \varepsilon t^{1-\sigma}) - f(t)}{\varepsilon} \tag{1.1}$$

for all $t > 0$, $\sigma \in (0, 1]$.

Definition 1.2. (The conformable fractional integral) Let $0 < \sigma \leq 1$ and $f : (0, \infty) \to \mathbb{R}$. The conformable fractional integral of f of order σ from 0 to x is defined as:

$$I^\sigma f(x) = \int_0^x f(t)\, d_\sigma t = \int_0^x f(t)\, t^{\sigma-1}\, dt, \tag{1.2}$$

where the above integral is the usual improper Riemann integral.

Furthermore, if $f(x)$ is an σ-differentiable function in some $(0,\infty)$ and $0<\sigma\leq 1$, then

$$D^{\sigma}f(x)=x^{1-\sigma}\frac{df(x)}{dx}$$

and

$$D^{\sigma}I^{\sigma}f(x)=f(x).$$

Definition 1.3. (The conformable fractional Shehu transform (CFSHT)) Let $0<\sigma\leq 1$ and $\zeta:\ \big[0,\infty\big)\to\mathbb{R}$ be a real value function. Then, the conformable fractional Shehu of order σ is defined by

$$Sh_{\sigma}\left[\zeta(z)\right]=V_{\sigma}(s;\ u)=\int_{0}^{\infty}\exp\left(\tfrac{-s}{u}\tfrac{z^{\sigma}}{\sigma}\right)\zeta(z)\,z^{\sigma-1}dz, \tag{1.3}$$

provided the integral exists.

Theorem 1.4. ([8]) *Let* $\zeta:\ \big[0,\infty\big)\to\mathbb{R}$ *be a real value function and* $0<\sigma\leq 1$. *Then*

$$V_{\sigma}\left[D^{\sigma}\zeta(z)\right]=\frac{s}{u}V_{\sigma}(s;\ u)-\zeta(0). \tag{1.4}$$

Theorem 1.5. ([8]) *Let* $\zeta:\ \big[0,\infty\big)\to\mathbb{R}$ *be a real value function and* $0<\sigma\leq 1$. *Then*

$$V_{\sigma}(s;\ u)=V\big\{\zeta(\sigma z)\big\}\left(s,\ u\right). \tag{1.5}$$

Theorem 1.6. ([8]) *Let* a, c *and* $p\in\mathbb{R}$ *and* $0<\sigma\leq 1$. *Then*

(1) $V_{\sigma}\left\{c\right\}(s;\ u)=c\dfrac{u}{s}$.

(2) $V_{\sigma}\left\{z^{p}\right\}(s;\ u)=\sigma^{\frac{p}{\sigma}}\left(\dfrac{u}{s}\right)^{\frac{p}{\sigma}+1}\Gamma(1+\dfrac{p}{\sigma})$.

(3) $V_{\sigma}\left\{\exp(a\dfrac{z^{\sigma}}{\sigma})\right\}(s;\ u)=\dfrac{u}{s-au},\ \dfrac{s}{u}>0$.

(4) $V_{\sigma}\left\{\sin(a\dfrac{z^{\sigma}}{\sigma})\right\}(s;\ u)=\dfrac{au^{2}}{s^{2}+a^{2}u^{2}},\ \dfrac{s}{u}>0$.

(5) $V_{\sigma}\left\{\cos(a\dfrac{z^{\sigma}}{\sigma})\right\}(s;\ u)=\dfrac{su}{s^{2}+a^{2}u^{2}},\ \dfrac{s}{u}>0$.

(6) $V_{\sigma}\left\{\sinh(a\dfrac{z^{\sigma}}{\sigma})\right\}(s;\ u)=\dfrac{au^{2}}{s^{2}-a^{2}u^{2}},\ \dfrac{s}{u}>\left|a\right|$.

(7) $V_{\sigma}\left\{\cosh(a\dfrac{z^{\sigma}}{\sigma})\right\}(s;\ u)=\dfrac{su}{s^{2}-a^{2}u^{2}},\ \dfrac{s}{u}>\left|a\right|$.

Theorem 1.7. ([8]) (Some Properties of the Conformable Fractional Shehu Transform)

(1) *The conformable fractional Shehu transform is linear operator:*

$$V_\sigma\big[\mu\zeta(z) \pm \lambda\varphi(z)\big] = \mu V_\sigma\big[\zeta(z)\big] \pm \lambda V_\sigma\big[\varphi(z)\big],$$

where μ and λ are constants.

(2) *Shifting property:*

$$V_\sigma\left\{\exp(a\frac{z^\sigma}{\sigma})\zeta(z)\right\}(s;\, u) = V\left(\zeta(\sigma z)\right)\big|_{s=s+au} = V_\sigma(s+au;\, u).$$

(3) *The conformable fractional Shehu transform of the conformable fractional integral:*

$$Sh_\sigma\left[I^\sigma\zeta(z)\right] = \frac{u}{s}V_\sigma(s;\, u).$$

(4) *Convolution property:*

$$Sh_\sigma\left\{(\zeta\star\phi)(t)\right\}(s;\, u) = V_\sigma\left\{\zeta(z)\right\}(s;\, u).V_\sigma\left\{\phi(z)\right\}(s;\, u).$$

2. Generalization of higher order of fractional conformable Shehu transform

Theorem 2.1. *Let $\zeta:\ \big[0,\infty\big)\to\mathbb{R}$ be a continuous real value function and $0<\sigma\le 1$. Then*

$$Sh_\sigma\left[D^{2\sigma}\zeta(z)\right] = \left(\frac{s}{u}\right)^2 V_\sigma(s;\, u) - \frac{s}{u}\zeta(0) - \zeta^\sigma(0). \tag{2.1}$$

Proof. By using the Definition 1.3 and integration by parts, we obtain

$$\begin{aligned}
Sh_\sigma\left[D^{2\sigma}\zeta(z)\right] &= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) D^{2\sigma}\zeta(z)\, z^{\sigma-1}dz \\
&= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) D^{\sigma}D^{\sigma}\zeta(z)\, z^{\sigma-1}dz \\
&= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) z^{1-\sigma}\frac{d}{dz}D^{\sigma}\zeta(z)\, z^{\sigma-1}dz \\
&= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) \frac{d}{dz}D^{\sigma}\zeta(z)\, dz
\end{aligned}$$

$$= \lim_{y\to\infty} \left[\exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) D^\sigma\zeta(z)\right]_0^y + \frac{s}{u}\int_0^\infty \exp\left(\tfrac{-s}{u}z^\sigma\right) z^{\sigma-1}D^\sigma\zeta(z)\,dz$$
$$= \frac{s}{u}Sh_\sigma\left[D^\sigma\zeta(z)\right] - \zeta^\sigma(0)$$
$$= \left(\frac{s}{u}\right)^2 V_\sigma(s;\ u) - \frac{s}{u}\zeta(0) - \zeta^\sigma(0).$$

This completes the proof. □

Theorem 2.2. *Let* $\zeta :\ \big[0,\infty\big) \to \mathbb{R}$ *be a continuous real value function and* $0 < \sigma \le 1$*, then for any integer number* $n \ge 1$*, we have*

$$Sh_\sigma\left[D^{n\sigma}\zeta(z)\right] = \left(\frac{s}{u}\right)^n V_\sigma(s;\ u) - \sum_{i=0}^{n-1}\left(\frac{s}{u}\right)^i \zeta^{(n-i-1)\sigma}(0), \quad \frac{s}{u} > 0. \tag{2.2}$$

Proof. We prove this theorem by induction on n. For $n = 1$, the propriety is true. We suppose that the propriety is true for n and prove it for $(n+1)$, that's to say,

$$Sh_\sigma\left[D^{n\sigma}\zeta(z)\right] = \left(\frac{s}{u}\right)^n V_\sigma(s;\ u) - \sum_{i=0}^{n-1}\left(\frac{s}{u}\right)^i \zeta^{(n-i-1)\sigma}(0)$$

is true. Using integration by parts and Definition 1.3, we get

$$Sh_\sigma\left[D^{(n+1)\sigma}\zeta(z)\right] = \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) D^{(n+1)\sigma}\zeta(z)\, z^{\sigma-1}dt$$
$$= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) D^\sigma D^{n\sigma}\zeta(z)\, z^{\sigma-1}dz$$
$$= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) z^{1-\sigma}\frac{d}{dz}D^{n\sigma}\zeta(z)\, z^{\sigma-1}dz$$
$$= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) z^{1-\sigma}\frac{d}{dz}D^{n\sigma}\zeta(z)\, z^{\sigma-1}dz$$
$$= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) z^{1-\sigma}\frac{d}{dz}D^{n\sigma}\zeta(z)\, z^{\sigma-1}dz$$

$$= \lim_{y\to\infty} \left[\exp\left(\tfrac{-s}{u}\tfrac{z^{\sigma}}{\sigma}\right) D^{n\sigma}\zeta(z)\right]_0^y + \frac{s}{u}\int_0^{\infty} \exp\left(\tfrac{-s}{u}z^{\sigma}\right) z^{\sigma-1} D^{n\sigma}\zeta(z)\,dz$$

$$= -\zeta^{n\sigma}(0) + \frac{s}{u}\int_0^{\infty} \exp\left(\tfrac{-s}{u}z^{\sigma}\right) z^{\sigma-1} D^{n\sigma}\zeta(z)\,dz$$

$$= -\zeta^{n\sigma}(0) + \frac{s}{u} Sh_{\sigma}\left[D^{(n)\sigma}\zeta(z)\right]$$

$$= -\zeta^{n\sigma}(0) + \frac{s}{u}\left[\left(\frac{s}{u}\right)^n V_{\sigma}(s;\ u) - \sum_{i=0}^{n-1}\left(\frac{s}{u}\right)^i \zeta^{(n-i-1)\sigma}(0)\right]$$

$$= \left(\frac{s}{u}\right)^{n+1} V_{\sigma}(s;\ u) - \zeta^{n\sigma}(0) - \sum_{i=0}^{n-1}\left(\frac{s}{u}\right)^{i+1} \zeta^{(n-i-1)\sigma}(0)$$

$$= \left(\frac{s}{u}\right)^{n+1} V_{\sigma}(s;\ u) - \zeta^{n\sigma}(0) - \sum_{i=1}^{n}\left(\frac{s}{u}\right)^{i} \zeta^{(n-i)\sigma}(0)$$

$$= \left(\frac{s}{u}\right)^{n+1} V_{\sigma}(s;\ u) - \sum_{i=0}^{n}\left(\frac{s}{u}\right)^{i} \zeta^{(n-i)\sigma}(0).$$

Hence, it is true for every n. □

3. Applications

Applications In this section, we study two examples using the conformable fractional Shehu transform to solve linear and nonhomogeneous conformable fractional differential equations.

Example 3.1. Consider the following system of equations:

$$\begin{cases} D_z^{\sigma}X(z) = \lambda X(z), \\ D_z^{\sigma}Y(z) = X(z) + \lambda Y(z), 0 < \sigma < 1, \\ D_z^{\sigma}K(z) = Y(z) + \lambda K(z), \end{cases} \tag{3.1}$$

with initial conditions

$$X(0) = c_1,\ Y(0) = c_2,\ K(0) = c_3. \tag{3.2}$$

Let $Sh_{\sigma}(X(z)) = V_{\sigma}$, $Sh_{\sigma}(Y(z)) = W_{\sigma}$, $Sh_{\sigma}(K(z)) = R_{\sigma}$. We applying the conformable fractional Shehu transform of system (3.1), and with the Theorem 1.4, we obtain

$$\begin{cases} V_{\sigma}\left[D_z^{\sigma}X(z)\right] = \lambda V_{\sigma}\left[X(z)\right], \\ W_{\sigma}\left[D_z^{\sigma}Y(z)\right] = V_{\sigma}\left[X(z)\right] + \lambda W_{\sigma}\left[Y(z)\right], \\ R_{\sigma}\left[D_z^{\sigma}K(z)\right] = W_{\sigma}\left[Y(z)\right] + \lambda R_{\sigma}\left[K(z)\right]. \end{cases}$$

It implies

$$\begin{cases} V_\sigma\left[X(z)\right] = \dfrac{c_1 u}{s-\lambda u}, \\ W_\sigma\left[Y(z)\right] = \dfrac{c_2 u}{s-\lambda u} + \dfrac{u}{s-\lambda u} V_\sigma\left[X(z)\right], \\ R_\sigma\left[K(z)\right] = \dfrac{c_3 u}{s-\lambda u} + \dfrac{u}{s-\lambda u} W_\sigma\left[Y(z)\right]. \end{cases}$$

So, we have

$$\begin{cases} X(z) = V_\sigma^{-1}\left[\dfrac{c_1 u}{s-\lambda u}\right] = c_1 \exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right), \\ Y(z) = W_\sigma^{-1}\left[\dfrac{c_2 u}{s-\lambda u}\right] + Sh_\sigma\left[\exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right)\right] V_\sigma\left[X(z)\right], \\ K(z) = R_\sigma^{-1}\left[\dfrac{c_3 u}{s-\lambda u}\right] + Sh_\sigma\left[\exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right)\right] W_\sigma\left[Y(z)\right]. \end{cases}$$

Hence, we have

$$\begin{cases} X(z) = c_1 \exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right), \\ Y(z) = c_2 \exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right) + \int\limits_0^z X\left(z-v\right) \exp\left(\lambda \dfrac{v^\sigma}{\sigma}\right) dv, \\ K(z) = c_3 \exp\left(\lambda \dfrac{z^\sigma}{\sigma}\right) + \int\limits_0^z Y\left(z-v\right) \exp\left(\lambda \dfrac{v^\sigma}{\sigma}\right) dv. \end{cases}$$

Example 3.2. Consider the following linear initial value problem

$$Y^{(4\sigma)}\left(z\right) = \frac{q\left(z\right)}{EI} \quad . \tag{3.3}$$

Where E and I are respectively the Young's modulus of the beam material and the section moment of inertia of the beam with

$$q\left(z\right) = \begin{cases} q_0 \quad if \quad 0 \leq z \leq \dfrac{L}{2}, \\ 0, \quad if \quad \dfrac{L}{2} \leq z \leq L. \end{cases} \tag{3.4}$$

with initial conditions

$$Y^{(4\sigma)}\left(L\right) = Y^{(3\sigma)}\left(L\right) = 0, \qquad Y^{(\sigma)}\left(0\right) = Y\left(0\right) = 0. \tag{3.5}$$

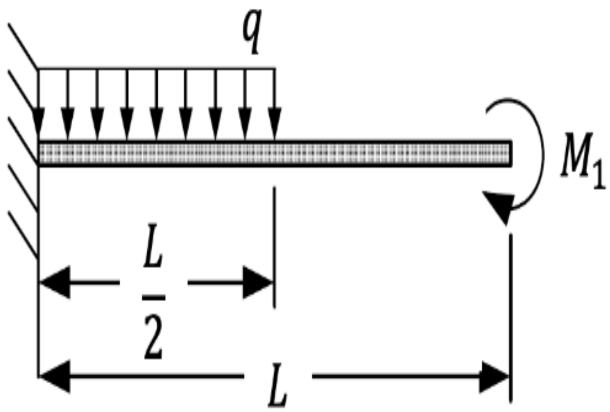

Figure 1: The cantilever beam is subjected to uniform distributed load (q) and a concentrated a moment (M_1).

First, we find the conformable Shehu transform of $q(z)$, so

$$\begin{aligned} Sh_\sigma\left[q(z)\right] &= \int_0^\infty \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right) q(z)\, z^{\sigma-1} dz \\ &= q_0 \int_0^{\frac{L}{2}} \exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right)\, z^{\sigma-1} dz \\ &= -q_0\left(\frac{u}{s}\right)\left[\exp\left(\tfrac{-s}{u}\tfrac{z^\sigma}{\sigma}\right)\right]_0^{\frac{L}{2}} \\ &= q_0\left(\frac{u}{s}\right)\left[1-\exp\left(\tfrac{-s}{u}\tfrac{L^\sigma}{\sigma 2^\sigma}\right)\right]. \end{aligned}$$

If we choose $\eta = \dfrac{L^\sigma}{\sigma 2^\sigma}$, then we have

$$Sh_\sigma\left[q(z)\right] = q_0\left(\frac{u}{s}\right)\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right].$$

We taking the conformable fractional Shehu transform of system (3.3), and with the Theorem 1.4, and using the conditions (3.5), we get

$$\left(\frac{s}{u}\right)^4 V_\sigma(s;\, u) - Y^{3\sigma}(0) - \frac{s}{u}Y^{2\sigma}(0) = \frac{q_0}{EI}\left(\frac{u}{s}\right)\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right].$$

Hence,

$$V_\sigma(s;\, u) = \left(\frac{u}{s}\right)^4 Y^{3\sigma}(0) + \left(\frac{u}{s}\right)^3 Y^{2\sigma}(0) + \left(\frac{u}{s}\right)^5 \frac{q_0}{EI}\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right]. \quad (3.6)$$

We applying the conformable fractional Shehu transform of equation (3.6), to find the solution

$$Y(z) = V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^4 Y^{3\sigma}(0)\right] + V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^3 Y^{2\sigma}(0)\right] + V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^5 \frac{q_0}{EI}\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right]\right].$$

Therefore, the approximate solution of Eq (3.3) is given as:

$$Y(z) = \frac{Y^{3\sigma}(0)}{24\sigma^3}z^{3\sigma} + \frac{Y^{2\sigma}(0)}{6\sigma^2}z^{2\sigma} + V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^5 \frac{q_0}{EI}\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right]\right].$$

So, we know that the equivalent in neighborhood of $1-\exp\left(\frac{-s}{u}\eta\right) \simeq \dfrac{s}{u}\eta$, then

$$V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^5 \frac{q_0}{EI}\left[1-\exp\left(\tfrac{-s}{u}\eta\right)\right]\right] \simeq \frac{q_0}{EI}V_\sigma^{-1}\left[\left(\frac{u}{s}\right)^4 \eta\right] = \frac{q_0}{EI}\frac{\eta}{24\sigma^3}z^{3\sigma}.$$

Finally, the solution of Eq (3.3) is given as

$$Y(z) \simeq \begin{cases} \dfrac{1}{24\sigma^3}\left(Y^{3\sigma}(0) + \dfrac{\eta q_0}{EI}\right)z^{3\sigma} + \dfrac{Y^{2\sigma}(0)}{6\sigma^2}z^{2\sigma}, & 0 \le z \le \dfrac{L}{2}, \\ 0, \quad \dfrac{L}{2} \le z \le L. \end{cases} \tag{3.7}$$

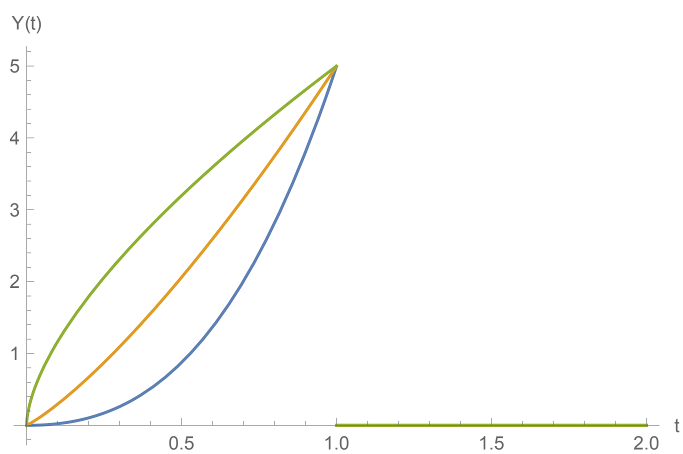

Figure 2: 2-D figure of $Y(z)$ given by (3.7) for $L = 2$ and ($\sigma = 1; 0.5; 0.25$) respectively, from bottom to top.

4. Conclusion

We conclude that the conformable fractional Shehu transform is highly effective in solving complex fractional differential equations and systems, as demonstrated in the solution of Problem 3.1. Furthermore, this fractional transform exhibits significant potential for applications in physics and engineering, as illustrated in Problem 3.2.

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