

Some results of KKAT transform in fractional calculus

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ABSTRACT

This paper advances the study of the Karry-Kalim-Adnan Transform (KKAT) within fractional calculus by extending its use to fractional derivatives and integrals and examining its fundamental properties. The framework for fractional orders is clarified, and the main structural properties of KKAT, including linearity, stability under order variation, and compatibility with standard fractional operators, are established under conditions that ensure a well-defined transform. Building on this foundation, a modified solution procedure based on KKAT is formulated for solving fractional integro-differential equations. The proposed workflow is designed for straightforward implementation using common symbolic or numerical routines, with emphasis on transparency in the intermediate steps. The performance of the method is assessed using several benchmark problems with known or high-accuracy reference solutions, documenting convergence behavior and computational effort. The results indicate that the KKAT-based method can streamline the solution process and improve interpretability compared with direct time-domain techniques. It may also reduce computational steps compared with other integral-transform approaches for solving linear and nonlinear fractional integro-differential equations. Future directions include parameter identification in data-driven models and applications in viscoelasticity, anomalous diffusion, and control systems, where fractional dynamics naturally arise. Further work may also explore modified transforms derived from existing integral transforms, such as the Aboodh, Elzaki, Mohand, Al-Zughair, Mahgoub, and SEE transforms. These transforms are generally related to the Laplace transform through suitable modifications adapted to specific mathematical problems and physical phenomena.

Keywords: *Convolution theorem, Fractional derivative and integral, KKAT transform*

1 INTRODUCTION

Nowadays, fractional calculus has a wide range of real-life applications that cannot be adequately described using ordinary differential equations alone. For this reason, many methods have been proposed for finding exact, approximate, or numerical solutions to fractional problems [1].

Fractional derivatives and fractional integrals are useful for modeling memory effects and hereditary properties in different materials and systems. In recent decades, fractional calculus has emerged as an important mathematical tool with applications in several branches of science, including physics, chemistry, biology, engineering, and

related fields [2].

One of the most important and efficient methods for finding exact solutions to these problems is the use of integral transforms. Since Laplace introduced the well-known transform that bears his name, many other integral transforms have been derived from or related to the Laplace transform. It is worth noting that the classical Laplace transform depends on one transform parameter. Recently, however, several transforms involving more than one parameter have been introduced because some mathematical models and physical phenomena require more than one parameter for their description. Among these cases are fractional equations used to describe

dynamical systems with multiparameter behavior. The Karry-Kalim-Adnan Transform (KKAT) is one of these transforms; it is related to the Laplace transform and depends on two parameters [1, 2].

Studying KKAT in the field of fractional calculus is important from two perspectives. First, fractional calculus has broad applications in many real-life problems. Second, two-parameter integral transforms may provide efficient tools for solving integral and differential equations [1].

In this paper, we focus on fractional calculus in view of the widespread use of integral and differential equations of arbitrary order [1, 2]. Some properties of KKAT are obtained and proved. These properties are then used to solve fractional integro-differential equations effectively. The proposed procedure involves applying KKAT to the given equation, isolating the transformed unknown function, and then applying the inverse transform to obtain the exact solution. Several examples are also presented to illustrate the applicability of the obtained results [3, 4].

Based on the known family of Laplace-related transforms, selecting a suitable transform is important for determining analytic solutions to specific problems. Different transforms may vary in their ability to simplify the solution process and in the number of mathematical operations required to obtain the desired solution [4]. In this work, we assume that the solutions of the considered problems exist under the stated conditions.

As an operator, KKAT is linear. This property is stated and used to simplify fractional integro-differential equations of arbitrary order. The proof of this property is straightforward and is included in this article.

Useful properties of KKAT and its applications to several important functions were presented in [1, 2]. In addition, applications to convolution-type linear Volterra operator equations were discussed in [1]. Further applications of KKAT to mechanics, electrical circuits, and growth-and-decay problems were discussed in [2, 5, 6], respectively.

Many authors have studied fractional differential and integral equations to solve different real-life problems. Patil and Khakale [7] used the SEE transform and the convolution theorem to solve linear homogeneous and nonhomogeneous fractional differential equations with constant coefficients. Radhwan et al. [8, 9] obtained several results in fractional calculus using the Sadik transform. Luchko and Kiryakova [10] presented selected applications of the Mellin integral transform in fractional calculus, particularly as convolution-type integral trans-

forms. Fanoga [11] reviewed several real-life applications of fractional calculus in different scientific fields, including fluid flow, rheology, diffusive transport, electrical networks, electromagnetic theory, and probability. That review also discussed several valuable contributions by other authors.

As mentioned in [1], there is no absolute comparison between any two integral transforms. Instead, the nature of the problem and the mathematical model determine which transform is more suitable in terms of time, simplicity, and the number of mathematical operations required [12].

The next section presents the basic definitions, related lemmas, and a summary of KKAT applied to some elementary functions. Section 3 includes the main results and proved theorems. Section 4 presents examples involving fractional integro-differential equations in which the fractional derivative appears more than once, illustrating the proposed procedure for solving fractional integro-differential equations. Finally, Section 5 presents the conclusion and future work. Developing useful new transforms for emerging classes of problems may open new directions in integral-transform methods by expanding the range of solvable problems and reducing the calculations required to obtain accurate solutions.

2 PRELIMINARIES

Here we present basic definitions with needed lemmas.

Definition 2.1 (Karry-Kalim Adnan Transformation KKAT) [2]

Let $S = \{h(x) : \exists p, \alpha_1, \alpha_2 > 0, |h(x)| < p e^{\frac{|x|}{\alpha_i}}, x \in [0, \infty), i = 1, 2\}$ where p is finite constant, α_1, α_2 be finite or infinite constant.

KKAT is defined as an operator $k(\cdot)$ for function $h(x) \in S$ as following:

$$k(h(x)) = \frac{1}{s} \int_0^\infty h(vx) e^{-sx} dx, x \geq 0, s, v \in [\alpha_1, \alpha_2] \quad (1)$$

Where s and v are parameters and $s, v \neq 0$

Rewrite (1), to get $k(h(x))$ as :

$$k(h(x)) = \frac{1}{sv} \int_0^\infty h(x) e^{-\frac{s}{v}x} dx = F\left(\frac{s}{v}\right) \quad (2)$$

Using transform usually needs for using the inverse function of the transform itself, for the case of KKAT the inverse function is given by:

$$h(x) = k^{-1} \left(F \left(\frac{s}{v} \right) \right) = \frac{1}{2\pi j} \int_{\epsilon-j\infty}^{\epsilon+j\infty} s v F \left(\frac{s}{v} \right) e^{-\frac{s}{v}x} ds \quad (3)$$

$j \in C$, where C is the set of complex numbers.

In following table (1), KKAT for some important functions are listed, for more familiar functions see [1,3]:

Table 1 KKAT integral transform for some important basic functions

$h(x)$	$F(s/v)$
1	$\frac{1}{v^2}$
$x^n, n > -1$	$\Gamma(n+1) \frac{v^n}{s^{n+2}}$
$x^n e^{\lambda x}, n > -1$	$\Gamma(n+1) \frac{v^n}{s(s-\lambda v)^{n+1}}$
$e^{\lambda x}$	$\frac{1}{s(s-\lambda v)}$
$\sin \lambda x$	$\frac{\lambda v}{s(s^2 + \lambda^2 v^2)}$
$\cos \lambda x$	$\frac{1}{s^2 + \lambda^2 v^2}$
$\sinh x$	$\frac{v}{s(s^2 - v^2)}$
$\cosh x$	$\frac{1}{s^2 - \lambda^2 v^2}$
$h(x)$	$\left(\frac{s}{v} \right) k\{h(x)\} - \frac{h(0)}{vs}$
$h''(x)$	$\left(\frac{s^2}{v^2} \right) k\{h(x)\} - \frac{h'(0)}{vs} - \frac{h(0)}{v^2}$

Where $\Gamma(\cdot)$ is the well-known Gamma function, which reads:

$$\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} dt, z \in C \quad (4)$$

Special cases for some formulae above written as following:

1 - If $h(x) = x^n, n \in N$ we get:

$$F \left(\frac{s}{v} \right) = \frac{n! v^n}{s^{n+2}}$$

2 - If $h(x) = x^n e^{\lambda x}, n \in N$ we get:

$$F \left(\frac{s}{v} \right) = \frac{n! v^n}{s(s-\lambda v)^{n+1}}$$

Consequently, the property of linearity for KKAT holds, i.e.,

If $F_1 \left(\frac{s}{v} \right)$ and $F_2 \left(\frac{s}{v} \right)$ are KKAT of $h_1(x), h_2(x) \in S$ respectively, then KKAT of $ah_1(x) + bh_2(x)$ is:

$$aF_1 \left(\frac{s}{v} \right) + bF_2 \left(\frac{s}{v} \right) \text{ where } a, b \in R.$$

$$k(ah_1(x) + bh_2(x)) = aF_1 \left(\frac{s}{v} \right) + bF_2 \left(\frac{s}{v} \right) \quad (5)$$

Also, KKAT is very close to the father of transforms - Laplace - where KKAT may be considered as a generalization of the well-known Laplace transform if we set $v = 1$ in KKAT transform to be:

$$k(h(x)) = \frac{1}{s} \int_0^\infty h(x) e^{-sx} dx = F \left(\frac{s}{1} \right) = \frac{1}{s} L(h(x)) \quad (6)$$

Definition 2.2 [13]

Let f be an integrable function on $(a, \infty), q > 0$. Then the left sided Riemann-Liouville integral of order q of the function f is defined as following:

$$I_{\alpha^+}^q f(t) = \frac{1}{\Gamma(q)} \int_a^t (t-\tau)^{q-1} f(\tau) d\tau \quad (7)$$

Where $\Gamma(\cdot)$ is defined in (4)

Definition 2.3 [13]

Let $f \in C[a, b](a, \infty), n-1 < q < n, n \in N$. Then the left sided Riemann-Liouville fractional derivative of order q of the function f is defined as following:

$$D_{\alpha^+}^q f(t) = \left(\frac{d}{dt} \right)^n I_{\alpha^+}^{n-q} f(t)$$

$$= \left(\frac{d}{dt} \right)^n \frac{1}{\Gamma(q)} \int_a^t (t-\tau)^{q-1} f(\tau) d\tau \quad (8)$$

Where $n = [q] + 1$ and $[q]$ is the integer part of real q .

Lemma 2.1

The n^{th} derivative of the left side Riemann Liouville integral of order $q \in R$ is given by:

$$\frac{d^n}{dt^n} (I_{\alpha^+}^q f(t)) = \frac{\Gamma(n-q)}{\Gamma(1-q)} \int_a^t (t-\tau)^{-q} f(\tau) d\tau \quad (9)$$

Proof

By Leibniz integral rule ,

$$\frac{d}{dt} (I_{\alpha^+}^q f(t)) = \int_a^t (n-q-1)(t-\tau)^{n-q-2} f(\tau) d\tau \quad (10)$$

By repeating process for n times we get:

$$\frac{d^n}{dt^n} (I_{\alpha^+}^q + f(t)) = (n-q-1)(n-q-2) \dots (1-q) \int_a^t (t-\tau)^{-q} f(\tau) d\tau \quad (11)$$

Therefore

$$\frac{d^n}{dt^n} (I_{\alpha^+}^q f(t)) = \frac{\Gamma(n-q)}{\Gamma(1-q)} \int_a^t (t-\tau)^{-q} f(\tau) d\tau \quad (12)$$

Lemma 2.2 (Linearity of KKAT) [2]

If $F_1\left(\frac{s}{v}\right)$ and $F_2\left(\frac{s}{v}\right)$ are two KKAT of $f_1(t)$ and $f_2(t)$ respectively, where $f_1(t), f_2(t) \in S$, then KKAT of the combination $\alpha f_1(t) + \beta f_2(t)$ is given by $\alpha F_1\left(\frac{s}{v}\right) + \beta F_2\left(\frac{s}{v}\right)$

3 MAIN RESULTS

Theorem 3.1

Let $q > 0, f \in C[a, b]$. Then applying KKAT transform to definition of Riemann-Liouville integral of function f is given by:

$$k\left(I_{\alpha^+}^q(f(t))\right) = \left(\frac{s}{v}\right)^{-q-1} F\left(\frac{s}{v}\right), \quad \text{where } F\left(\frac{s}{v}\right) = k(f(t)) \quad (13)$$

Proof By definition of Riemann-Liouville integral with convolution theorem [1] we get:

$$I_{\alpha^+}^q f(t) = \frac{1}{\Gamma(q)} \int_a^t (t-\tau)^{q-1} f(\tau) d\tau \quad (14)$$

$$I_{\alpha^+}^q f(t) = \frac{t^{q-1}}{\Gamma(q)} \cdot f(t)$$

By applying definition of KKAT (2) for both sides of above equation (14) we get:

$$k\left(I_{\alpha^+}^q + f(t)\right) = k\left(\frac{t^{q-1}}{\Gamma(q)} \cdot f(t)\right) = \frac{1}{\Gamma(q)} s v k\left(t^{q-1}\right) \cdot F\left(\frac{s}{v}\right)$$

From table(1) we conclude that:

$$= \frac{1}{\Gamma(q)} \frac{\Gamma(q)}{\left(\frac{s}{v}\right)^{q+1}} \cdot F\left(\frac{s}{v}\right) = \left(\frac{s}{v}\right)^{-q-1} \cdot F\left(\frac{s}{v}\right)$$

Theorem 3.2

Let $q > 0, f \in C[a, b]$. The KKAT transform for definition of q -order Riemann-Liouville derivative of the function f is given by:

$$k\left(D_{\alpha^+}^q f(t)\right) = \frac{\Gamma(1+q)}{\Gamma(1-q)} \left(\frac{v}{s}\right)^{q+1} F\left(\frac{s}{v}\right) \quad (15)$$

where $F\left(\frac{s}{v}\right) = k(f(x))$

Proof

Take KKAT for (8) we get:

$$k\left(D_{\alpha^+}^q f(t)\right) = k\left(\frac{d^n}{dx^n} I_{\alpha^+}^{n-q} f(t)\right) = k\left(\frac{d^n}{dx^n} \frac{1}{\Gamma(n-q)} \int_a^t (t-\tau)^{n-q-1} f(\tau) d\tau\right) \quad (16)$$

By Lemma (2.1)

$$k\left(D_{\alpha^+}^q f(t)\right) = k\left(\frac{1}{\Gamma(1-q)} \int_0^t (t-\tau)^{-q} f(\tau) d\tau\right) \quad (17)$$

$$= \frac{1}{\Gamma(1-q)} k\left(\int_0^t (t-\tau)^{-q} f(\tau) d\tau\right) \quad (18)$$

Again by convolution theorem:

$$k\left(D_{\alpha^+}^q f(t)\right) = \frac{\Gamma(q+1)}{\Gamma(1-q)} \left(\frac{v}{s}\right)^{q+1} F\left(\frac{s}{v}\right) \quad (19)$$

4 EXAMPLES

In this section, some examples will be considered to illustrate our results.

Example 4.1 Consider the following fractional differential equation:

$$D_{\alpha^+}^q f(t) + f(t) = \frac{2t^{2-q}}{\Gamma(3-q)} - \frac{t^{1-q}}{\Gamma(2-q)} + t^2 - t \quad (20)$$

Subject to the initial condition:

$$f(0) = 0, \quad q \in (0, 1] \quad (21)$$

Solution By taking KKAT for both sides (20) above using the property of linearity of KKAT (5) we get:

$$\begin{aligned} k(D_{\alpha^+}^q f(t)) + k(f(t)) &= k\left(\frac{2t^{2-q}}{\Gamma(3-q)}\right) \\ &\quad - k\left(\frac{t^{1-q}}{\Gamma(2-q)}\right) + k(t^2) - k(t) \\ &\quad \frac{\Gamma(1+q)}{\Gamma(1-q)} \left(\frac{v}{s}\right)^{q+1} F\left(\frac{s}{v}\right) + F\left(\frac{s}{v}\right) \\ &= \frac{2\Gamma(3-q)}{\Gamma(3-q)} \frac{v^{2-q}}{s^{4-q}} - \frac{\Gamma(2-q)}{\Gamma(2-q)} \frac{v^{1-q}}{s^{3-q}} + \frac{2v^2}{s^4} - \frac{v}{s^3} \end{aligned} \quad (22)$$

where $F\left(\frac{s}{v}\right) = k(f(x))$

$$\frac{\Gamma(1+q)}{\Gamma(1-q)} \left(\frac{v}{s}\right)^{q+1} F\left(\frac{s}{v}\right) + F\left(\frac{s}{v}\right) = 2 \frac{v^{2-q}}{s^{4-q}} - \frac{v^{1-q}}{s^{3-q}} + \frac{2v^2}{s^4} - \frac{v}{s^3}$$

After some simple computations we get:

$$F\left(\frac{s}{v}\right) = \Gamma(3) \frac{v^2}{s^4} - \Gamma(2) \frac{v}{s^3} \quad (23)$$

Taking inverse of KKAT for above equation (23) to get:

$$\begin{aligned} k^{-1}\left(F\left(\frac{s}{v}\right)\right) &= k^{-1}\left(\Gamma(3) \frac{v^2}{s^4} - \Gamma(2) \frac{v}{s^3}\right) \\ k^{-1}\left(F\left(\frac{s}{v}\right)\right) &= k^{-1}\left(\Gamma(3) \frac{v^2}{s^4}\right) - k^{-1}\left(\Gamma(2) \frac{v}{s^3}\right) \end{aligned}$$

Then the exact solution of (20) is:

$$f(t) = t^2 - t$$

Example 4.2 In this example consider the following fractional Differential equation of Bagley-Torvik which reads:

$$D^2 f(t) + D_{\alpha^+}^{\frac{3}{2}} f(t) + f(t) = 1 + t \quad (24)$$

Subject to the initial conditions:

$$f(0) = f'(0) = 1 \quad (25)$$

Solution Take KKAT for (24) to get

$$\begin{aligned} k(f''(t)) + k\left(D_{\alpha^+}^{\frac{3}{2}} f(t)\right) + k(f(t)) &= k(1) + k(t) \\ \left(\frac{s^2}{v^2}\right) k\{f(t)\} - \frac{f'(0)}{vs} - \frac{f(0)}{v^2} + \frac{\Gamma\left(1 + \frac{3}{2}\right)}{\Gamma\left(1 - \frac{3}{2}\right)} \left(\frac{v}{s}\right)^{\frac{3}{2}+1} \\ &\quad k(f(t)) + k(f(t)) = \frac{1}{s^2} + \frac{v}{s^3} \\ \left(\frac{s^2}{v^2}\right) F\left(\frac{s}{v}\right) - \frac{1}{vs} - \frac{1}{v^2} + \frac{-3}{8} \left(\frac{v}{s}\right)^{\frac{5}{2}} F\left(\frac{s}{v}\right) \\ &\quad + F\left(\frac{s}{v}\right) = \frac{1}{s^2} + \frac{v}{s^3} \end{aligned} \quad (26)$$

After some computations we get:

$$F\left(\frac{s}{v}\right) = \frac{1}{v^2} + \Gamma(2) \frac{v}{s^3} \quad (27)$$

Again, by taking inverse KKAT for (27) we conclude that:

$$\begin{aligned} k^{-1}\left(F\left(\frac{s}{v}\right)\right) &= k^{-1}\left(\frac{1}{v^2} + \Gamma(2) \frac{v}{s^3}\right) \\ k^{-1}\left(F\left(\frac{s}{v}\right)\right) &= k^{-1}\left(\frac{1}{v^2}\right) + k^{-1}\left(\Gamma(2) \frac{v}{s^3}\right) \end{aligned}$$

From table 2.1 we conclude that:

$$f(t) = 1 + t$$

5 CONCLUSION

In this research paper, the KKAT transform was studied, and several results were proved for fractional derivatives and fractional integrals. The transform was also applied to solve fractional integro-differential equations effectively, yielding exact solutions through simple computational steps, as illustrated by the presented examples. These findings indicate that the KKAT transform can be considered a useful tool for solving fractional integro-differential equations.

For future work, researchers may apply the proposed scheme to obtain exact solutions for broader classes of fractional integro-differential equations of arbitrary order using different definitions of fractional derivatives and fractional integrals. Moreover, comparative studies between different integral transforms may help identify or develop improved transforms for solving various linear, nonlinear, and delay systems.

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