

## Research Article

# Mappings for Special Functions on Cantor Sets and Special Integral Transforms via Local Fractional Operators

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The mappings for some special functions on Cantor sets are investigated. Meanwhile, we apply the local fractional Fourier series, Fourier transforms, and Laplace transforms to solve three local fractional differential equations, and the corresponding nondifferentiable solutions were presented.

## 1. Introduction

Special functions [1] play an important role in mathematical analysis, function analysis physics, and so on. We recall here some very well examples, the Gamma function [2], hypergeometric function [3], Bessel functions [4], Whittaker function [5], G-function [6], q-special functions [7], Fox's H-functions [8], Mittag-Leffler function [9], and Wright's function [10].

The Mittag-Leffler function had successfully been applied to solve the practical problems [11–15]. For example, the Mittag-Leffler-type functions in fractional evolution processes were suggested [15]. Solutions for fractional reaction-diffusion equations via Mittag-Leffler-type functions were discussed [16]. The Mittag-Leffler stability of fractional order nonlinear dynamic systems was presented [17]. Models based on Mittag-Leffler functions for anomalous relaxation in dielectrics were proposed [18]. In [19], the anomalous relaxation via the Mittag-Leffler functions was reported.

The continuous-time finance based on the Mittag-Leffler function was given [20]. In [21], the fractional radial diffusion in a cylinder based on the Mittag-Leffler function was investigated. In [22], the Mittag-Leffler stability theorem for fractional nonlinear systems with delay was considered. The stochastic linear Volterra equations of convolution type based on the Mittag-Leffler function were suggested in [23].

Recently, based on the Mittag-Leffler functions on Cantor sets via the fractal measure, the special integral transforms based on the local fractional calculus theory were suggested in [24]. In this work, some applications for the local fractional calculus theory are studied in [24–36]. The main aim of this paper is to investigate the mappings for special functions on Cantor sets and some applications of special integral transforms to nondifferentiable problems.

The paper is organized as follows. In Section 2, the mappings for special functions on Cantor sets are investigated. In Section 3, the special integral transforms within local fractional calculus and some applications to nondifferentiable

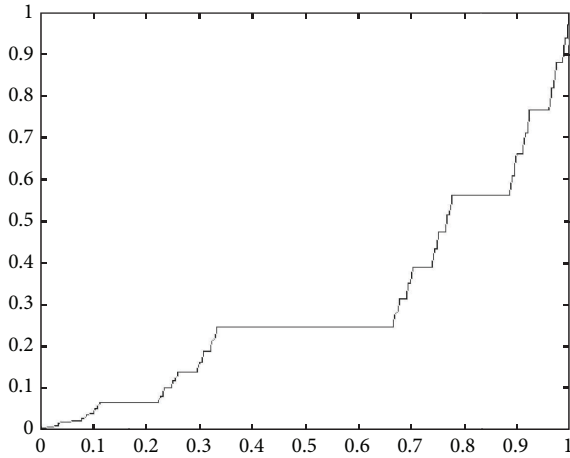


FIGURE 1: Graph of  $x^{2\alpha}$  for  $\alpha = \ln 2 / \ln 3$ .

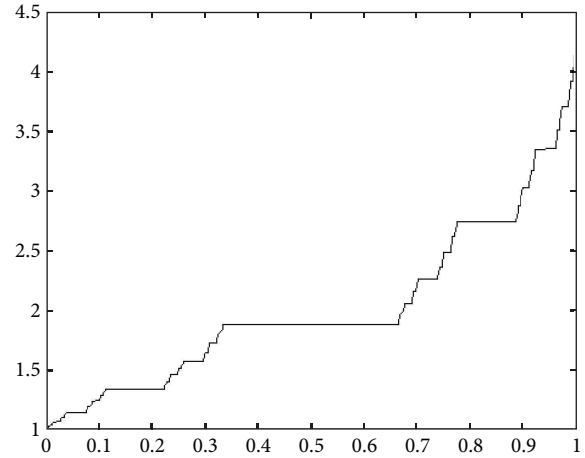


FIGURE 2: Graph of  $E_\alpha(x^\alpha)$  for  $\alpha = \ln 2 / \ln 3$ .

problems are presented. Finally, in Section 4, the conclusions are presented.

## 2. Mappings for Special Functions on Cantor Sets

In order to give the mappings for special functions on Cantor sets, we first recall some basic definitions about the fractal measure theory [25].

Let Lebesgue-Cantor staircase function be defined as [25]

$$H_\alpha(F \cap (0, x)) = \Gamma(1 + \alpha) {}_0I_x^{(\alpha)} 1, \quad (1)$$

where  $F$  is a cantor set,  $H_\alpha(\cdot)$  is the  $\alpha$ -dimensional Hausdorff measure,  ${}_0I_x^{(\alpha)}(\cdot)$  is local fractional integral operator [24–31], and  $\Gamma(\cdot)$  is a Gamma function.

Following (1), we obtain

$$H_\alpha(F \cap (0, x)) = x^\alpha, \quad (2)$$

which is a Lebesgue-Cantor staircase function. For its graph, please see [28].

In this way, we define some real-valued functions on Cantor sets as follows [24–26].

The Cantor staircase function is defined as [25]

$$f(x) = x^{2\alpha}, \quad (3)$$

and its graph is shown in Figure 1.

The Mittag-Leffler functions on Cantor sets are given by [24, 25]

$$E_\alpha(x^\alpha) = \sum_{k=0}^{\infty} \frac{x^{\alpha k}}{\Gamma(1 + k\alpha)}, \quad (4)$$

and we draw the corresponding graph in Figure 2.

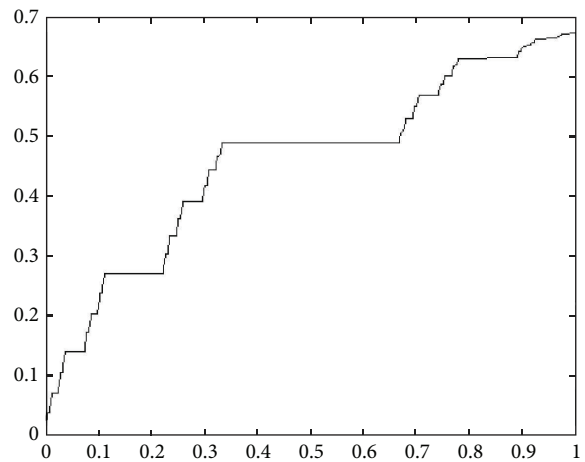


FIGURE 3: Graph of  $\sin_\alpha x^\alpha$  for  $\alpha = \ln 2 / \ln 3$ .

The sine on Cantor sets is defined by [24, 25]

$$\sin_\alpha x^\alpha = \sum_{k=0}^{\infty} (-1)^k \frac{x^{\alpha(2k+1)}}{\Gamma[1 + \alpha(2k+1)]}, \quad (5)$$

and its corresponding graph is depicted in Figure 3.

The cosine on Cantor sets is [24, 25]

$$\cos_\alpha x^\alpha = \sum_{k=0}^{\infty} (-1)^k \frac{x^{2\alpha k}}{\Gamma(1 + 2\alpha k)}, \quad (6)$$

with graph in Figure 4.

Hyperbolic sine on Cantor sets is defined by [24, 25]

$$\sinh_\alpha x^\alpha = \sum_{k=0}^{\infty} \frac{x^{\alpha(2k+1)}}{\Gamma[1 + \alpha(2k+1)]}, \quad (7)$$

and we draw its graphs as shown in Figure 5.

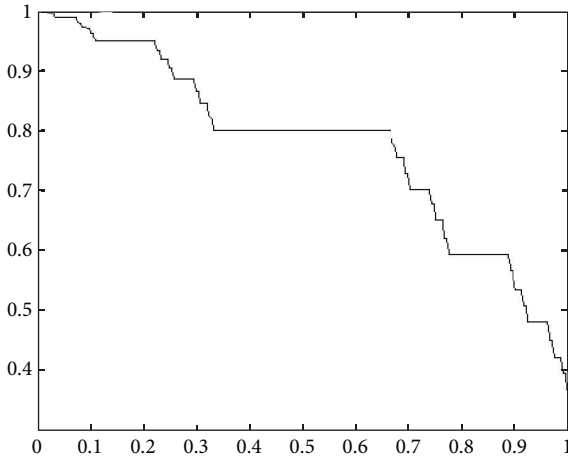


FIGURE 4: Graph of  $\cos_\alpha x^\alpha$  for  $\alpha = \ln 2 / \ln 3$ .

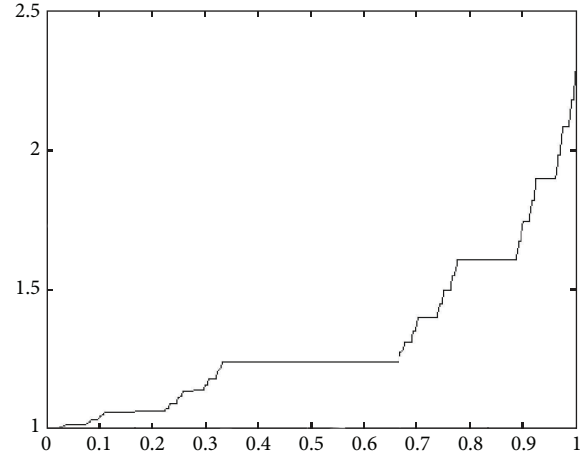


FIGURE 6: Graph of  $\cosh_\alpha x^\alpha$  for  $\alpha = \ln 2 / \ln 3$ .

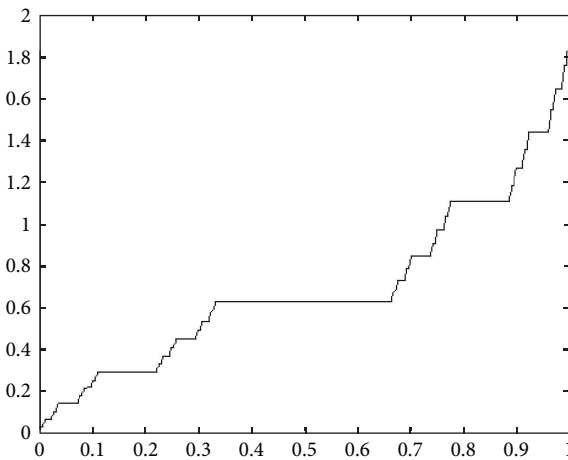


FIGURE 5: Graph of  $\sinh_\alpha x^\alpha$  for  $\alpha = \ln 2 / \ln 3$ .

Hyperbolic cosine on Cantor sets is defined as [24, 25]

$$\cosh_\alpha x^\alpha = \sum_{k=0}^{\infty} \frac{x^{2\alpha k}}{\Gamma(1 + 2\alpha k)}, \quad (8)$$

and its graph is shown in Figure 6.

Following (4)–(8), we have

$$E_\alpha(i^\alpha x^\alpha) = \cos_\alpha x^\alpha + i^\alpha \sin_\alpha x^\alpha, \quad (9)$$

where  $i^\alpha$  is a fractal unit of an imaginary number [24, 26–32].

If for  $\varepsilon, \delta > 0$  and  $\varepsilon, \delta \in R$ ,  $f(x)$  satisfies the condition [24–26]

$$|f(x) - f(x_0)| < \varepsilon^\alpha; \quad (10)$$

for  $x \in [a, b]$  we write it as follows:

$$f(x) \in C_\alpha(a, b). \quad (11)$$

### 3. Special Integral Transforms within Local Fractional Calculus

In this section, we introduce the conceptions of special integral transforms within the local fractional calculus concluding the local fractional Fourier series and Fourier and Laplace transforms. After that, we present three illustrative examples.

*3.1. Definitions of Special Integral Transforms within Local Fractional Calculus.* We here present briefly some results used in the rest of the paper.

Let  $f(x) \in C_\alpha(-\infty, \infty)$ . Local fractional trigonometric Fourier series of  $f(x)$  is given by [24, 26–28]

$$f(x) = a_0 + \sum_{i=1}^{\infty} a_k \sin_\alpha(k^\alpha \omega_0^\alpha x^\alpha) + \sum_{i=1}^{\infty} b_k \cos_\alpha(k^\alpha \omega_0^\alpha x^\alpha). \quad (12)$$

The local fractional Fourier coefficients read as

$$a_0 = \frac{1}{T^\alpha} \int_0^T f(x) (dx)^\alpha, \\ a_k = \left(\frac{2}{T}\right)^\alpha \int_0^T f(x) \sin_\alpha(k^\alpha \omega_0^\alpha x^\alpha) (dx)^\alpha, \quad (13) \\ b_k = \left(\frac{2}{T}\right)^\alpha \int_0^T f(x) \cos_\alpha(k^\alpha \omega_0^\alpha x^\alpha) (dx)^\alpha.$$

We notice that the above results are obtained from Pythagorean theorem in the generalized Hilbert space [24, 26–28].

Let  $f(x) \in C_\alpha(-\infty, \infty)$ . The local fractional Fourier transform of  $f(x)$  is suggested by [24, 29–32]

$$F_\alpha\{f(x)\} = f_\omega^{F_\alpha}(\omega) = \frac{1}{\Gamma(1 + \alpha)} \int_{-\infty}^{\infty} E_\alpha(-i^\alpha \omega^\alpha x^\alpha) f(x) (dx)^\alpha. \quad (14)$$

The inverse formula is expressed as follows [24, 29–32]:

$$\begin{aligned}
 f(x) &= F_\alpha^{-1} \left( f_\omega^{F,\alpha}(\omega) \right) \\
 &= \frac{1}{(2\pi)^\alpha} \int_{-\infty}^{\infty} E_\alpha(i^\alpha \omega^\alpha x^\alpha) f_\omega^{F,\alpha}(\omega) (d\omega)^\alpha.
 \end{aligned}
 \tag{15}$$

Let  $f(x) \in C_\alpha(-\infty, \infty)$ . The local fractional Laplace transform of  $f(x)$  is defined as [24, 32, 33]

$$\begin{aligned}
 L_\alpha \{f(x)\} &= f_s^{L,\alpha}(s) \\
 &= \frac{1}{\Gamma(1+\alpha)} \int_0^\infty E_\alpha(-s^\alpha x^\alpha) f(x) (dx)^\alpha.
 \end{aligned}
 \tag{16}$$

The inverse formula local fractional Laplace transform of  $f(x)$  is derived as [24, 32, 33]

$$\begin{aligned}
 f(x) &= L_\alpha^{-1} \{f_s^{L,\alpha}(s)\} \\
 &= \frac{1}{(2\pi)^\alpha} \int_{\beta-i\infty}^{\beta+i\infty} E_\alpha(s^\alpha x^\alpha) f_s^{L,\alpha}(s) (ds)^\alpha,
 \end{aligned}
 \tag{17}$$

where  $f(x)$  is local fractional continuous,  $s^\alpha = \beta^\alpha + i^\alpha \infty^\alpha$ , and  $\text{Re}(s) = \beta > 0$ .

For more details of special integral transforms via local fractional calculus, see [24, 32, 33] and the references therein.

**3.2. Applications of Local Fractional Fourier Series and Fourier and Laplace Transforms to the Differential Equation on Cantor Sets.** We now present the powerful tool of the methods presented above in three illustrative examples.

*Example 1.* Let us begin with the local fractional differential equation on Cantor set in the following form:

$$a \frac{d^\alpha y}{d^\alpha x} + by(x) = f(x), \quad x \in (-\infty, +\infty), \tag{18}$$

where  $a$  and  $b$  are constants and the nondifferentiable function  $f(x)$  is periodic of period  $2\pi$  so that it can be expanded in a local fractional Fourier series as follows:

$$f(x) = \sum_{n=1}^{\infty} \sin_\alpha(n^\alpha x^\alpha). \tag{19}$$

Here, we give a particular solution in the following form:

$$\begin{aligned}
 y_p(x) &= a_0 + \sum_{n=1}^{\infty} A_n \sin_\alpha(n^\alpha x^\alpha) \\
 &\quad + \sum_{n=1}^{\infty} B_n \cos_\alpha(n^\alpha x^\alpha).
 \end{aligned}
 \tag{20}$$

Following (20), we have

$$\begin{aligned}
 y_p^{(\alpha)}(x) &= \sum_{n=1}^{\infty} A_n n^\alpha \cos_\alpha(n^\alpha x^\alpha) \\
 &\quad + \sum_{n=1}^{\infty} B_n n^\alpha \sin_\alpha(n^\alpha x^\alpha).
 \end{aligned}
 \tag{21}$$

Submitting (20)-(21) into (18), we obtain

$$\begin{aligned}
 a \left( \sum_{n=1}^{\infty} A_n n^\alpha \cos_\alpha(n^\alpha x^\alpha) \right. \\
 \left. + \sum_{k=1}^{\infty} B_k n^\alpha \sin_\alpha(n^\alpha x^\alpha) \right) \\
 + b \left( a_0 + \sum_{n=1}^{\infty} A_n \sin_\alpha(n^\alpha x^\alpha) \right. \\
 \left. + \sum_{n=1}^{\infty} B_n \cos_\alpha(n^\alpha x^\alpha) \right) \\
 = \sum_{n=1}^{\infty} \sin_\alpha(n^\alpha x^\alpha).
 \end{aligned}
 \tag{22}$$

Hence, we get

$$\begin{aligned}
 a_0 b &= 0, \\
 a A_n n^\alpha + b B_n &= 0, \\
 a B_n n^\alpha + b A_n &= 1.
 \end{aligned}
 \tag{23}$$

Therefore, we can calculate

$$\begin{aligned}
 a_0 &= 0, \\
 A_n &= -\frac{b}{a^2 n^{2\alpha} - b^2}, \\
 B_n &= \frac{a n^\alpha}{a^2 n^{2\alpha} - b^2}.
 \end{aligned}
 \tag{24}$$

In view of (24), we give the solution of (18) as follows:

$$\begin{aligned}
 y_p(x) &= -\sum_{n=1}^{\infty} \frac{b}{a^2 n^{2\alpha} - b^2} \sin_\alpha(n^\alpha x^\alpha) \\
 &\quad + \sum_{n=1}^{\infty} \frac{a n^\alpha}{a^2 n^{2\alpha} - b^2} \cos_\alpha(n^\alpha x^\alpha).
 \end{aligned}
 \tag{25}$$

*Example 2.* We now consider the following differential equation on Cantor sets:

$$\frac{d^{2\alpha} x}{d^{2\alpha} t} + px = f(t), \quad +\infty > t > -\infty, \tag{26}$$

subject to the initial value condition

$$\left. \frac{d^\alpha x}{d^\alpha t} \right|_{t=0} = 0, \quad x(0) = 0, \tag{27}$$

where  $p$  is constant and  $f(t)$  is the local fractional continuous function so that its local fractional Fourier transform exists.

Application of local fractional Fourier transform gives

$$-\omega^{2\alpha} x_\omega^{F,\alpha}(\omega) + p x_\omega^{F,\alpha}(\omega) = f_\omega^{F,\alpha}(\omega), \tag{28}$$

so that

$$(-\omega^{2\alpha} + p)x_\omega^{F,\alpha}(\omega) = f_\omega^{F,\alpha}(\omega). \tag{29}$$

From (29), we have

$$x_\omega^{F,\alpha}(\omega) = \frac{f_\omega^{F,\alpha}(\omega)}{(-\omega^{2\alpha} + p)}. \tag{30}$$

Therefore, taking the inverse formula of local fractional Fourier transform, we have

$$x(t) = -\frac{p^{-(1/2)}}{\Gamma(1+\alpha)} \int_{-\infty}^t f(t-\tau) \sin_\alpha(p^{1/2}\tau^\alpha) (d\tau)^\alpha. \tag{31}$$

*Example 3.* Let us find the solution to the differential equation on Cantor sets

$$\frac{d^{2\alpha}x}{d^{2\alpha}t} + \frac{d^\alpha x}{d^\alpha t} - 2x = f(t), \quad t > 0, \tag{32}$$

subject to the initial value condition

$$\left. \frac{d^\alpha x}{d^\alpha t} \right|_{t=0} = 0, \quad x(0) = 0, \tag{33}$$

where  $f(t)$  is the local fractional continuous function so that its local fractional Laplace transform exists.

Taking the local fractional Laplace transform, from (32), we have

$$\begin{aligned} & (s^{2\alpha}x_s^{L,\alpha}(s) - s^\alpha x(0) - x^{(\alpha)}(0)) + (s^\alpha x_s^{L,\alpha}(s) - x(0)) \\ & + 2x_s^{L,\alpha}(s) = f_s^{L,\alpha}(s), \end{aligned} \tag{34}$$

so that

$$x_s^{L,\alpha}(s) = \frac{f_s^{L,\alpha}(s)}{s^{2\alpha} + s^\alpha - 2}. \tag{35}$$

When the local fractional convolution of two functions is given by [24]

$$f_1(t) * f_2(t) = \frac{1}{\Gamma(1+\alpha)} \int_0^t f_1(t-\tau) f_2(\tau) (d\tau)^\alpha \tag{36}$$

and the local fractional Laplace transform of  $f_1(t) * f_2(t)$  is [24]

$$L_\alpha\{f_1(t) * f_2(t)\} = f_{s,1}^{L,\alpha}(s) f_{s,2}^{L,\alpha}(s), \tag{37}$$

the inverse formula of the local fractional Laplace transform together with the local fractional convolution theorem gives the solution

$$x(t) = \frac{1}{\Gamma(1+\alpha)} \int_0^t f(t-\tau) (E_\alpha(-2\tau^\alpha) + E_\alpha(\tau^\alpha)) (d\tau)^\alpha. \tag{38}$$

### 4. Conclusions

In this work, we investigated the mappings for special functions on Cantor sets and special integral transforms via local fractional calculus, namely, the local fractional Fourier series, Fourier transforms, and Laplace transforms, respectively. These transformations were applied successfully to solve three local fractional differential equations, and the nondifferentiable solutions were reported.

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