

Research Article

Local Fractional Functional Method for Solving Diffusion Equations on Cantor Sets

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The analytical solutions for the diffusion equations on Cantor sets with the nondifferentiable terms are discussed by using the local fractional functional method, which is a coupling method for local fractional Fourier series and Laplace transform.

1. Introduction

The local fractional calculus [1, 2], as a new branch of fractional calculus, was successfully applied to describe the fractal problems from science and engineering. For example, the local fractional Fokker-Planck equation [3], the local fractional diffusion equations defined on Cantor sets [4, 5], the local fractional wave equation defined on Cantor sets [6, 7], the local fractional Korteweg-de Vries equation [8], the local fractional Schrödinger equation [9], local fractional Navier-Stokes equations on cantor sets [10], the local fractional Laplace equation [11], the local fractional heat-conduction equation [12–16], the local fractional differential equations arising in the fractal forest gap [17], and others [18–21] were discussed.

In this paper, we consider the local fractional diffusion equations defined on Cantor sets [5] given by

$$u_{xx}^{2\alpha} = \frac{1}{a^{2\alpha}} u_t^\alpha, \quad (1)$$

subject to the initial-boundary conditions

$$\begin{aligned} \frac{\partial^\alpha}{\partial x^\alpha} u(0, t) &= g(t), & u(0, t) &= f(t), \\ u(x, 0) &= u(x, l) = 0, \end{aligned} \quad (2)$$

where the local fractional partial derivatives denote

$$u_t^\alpha = \frac{\partial^\alpha u(x, t)}{\partial t^\alpha}, \quad u_{yx}^{2\alpha} = \frac{\partial^{2\alpha} u(x, t)}{\partial x^\alpha \partial y^\alpha}, \quad (3)$$

and $u(x, t)$, $g(t)$, and $f(t)$ are the local fractional continuous functions. In the high-speed railway healthy monitor system, the problems of diffusion equations with the nondifferentiable terms always exist in fault diagnosing of high-speed trains and their control systems, so we solve this by the local fractional diffusion equations defined on Cantor sets. The local fractional function decomposition method structured in [11, 22], which is a coupling method of the local fractional Fourier series [21, 22] and the Yang-Laplace transform [14, 16, 18, 22], was used to solve the inhomogeneous local fractional wave equations defined on Cantor sets. The main aim of this paper is to discuss the local fractional diffusion equations defined on Cantor sets by the local fractional functional method.

The paper is organized as follows. In Section 2 the basic theory of the local fractional calculus and the Yang-Laplace transform were given. In Section 3, the local fractional functional method is analyzed. Section 4 presents the applications for the local fractional diffusion equations defined on Cantor sets. Finally, the conclusions are given in Section 5.

2. Preliminaries

In this section, we present the basic theory of the local fractional calculus and the local fractional Laplace transform.

Definition 1 (see [1, 5–7]). The local fractional derivative of $f(x)$ at $x = x_0$ is given as follows:

$$\begin{aligned} D_x^\alpha f(x_0) &= \left. \frac{d^\alpha}{dx^\alpha} f(x) \right|_{x=x_0} = f^{(\alpha)}(x) \\ &= \lim_{x \rightarrow x_0} \frac{\Delta^\alpha (f(x) - f(x_0))}{(x - x_0)^\alpha}, \end{aligned} \tag{4}$$

where $\Delta^\alpha (f(x) - f(x_0)) \cong \Gamma(\alpha + 1)\Delta(f(x) - f(x_0))$.

The local fractional partial derivative of order α is defined as follows [1]:

$$\begin{aligned} \left. \frac{\partial^\alpha}{\partial x^\alpha} f(x, y) \right|_{x=x_0} &= f^{(\alpha)}(x, y) \\ &= \lim_{x \rightarrow x_0} \frac{\Delta^\alpha (f(x, y) - f(x_0, y))}{(x - x_0)^\alpha}, \end{aligned} \tag{5}$$

and the local fractional partial derivative of high order [1] is

$$\frac{\partial^{k\alpha} f(x, y)}{x^{k\alpha}} = \frac{\overset{k \text{ times}}{\partial^\alpha \partial x^\alpha \cdots \partial x^\alpha} f(x, y)}{\partial x^\alpha}, \tag{6}$$

where $\Delta^\alpha (f(x) - f(x_0)) \cong \Gamma(\alpha + 1)\Delta(f(x) - f(x_0))$.

Definition 2 (see [1, 8–12]). Let us consider a partition of the interval $[a, b]$, which is denoted as (t_j, t_{j+1}) , $j = 0, \dots, N - 1$, $t_0 = a$ and $t_N = b$ with $\Delta t_j = t_{j+1} - t_j$ and $\Delta t = \max\{\Delta t_0, \Delta t_1, \dots\}$. Local fractional integral of $f(x)$ in the interval $[a, b]$ is defined as follows:

$$\begin{aligned} {}_a I_b^{(\alpha)} f(x) &= \frac{1}{\Gamma(1 + \alpha)} \int_a^b f(t) (dt)^\alpha \\ &= \frac{1}{\Gamma(1 + \alpha)} \lim_{\Delta t \rightarrow 0} \sum_{j=0}^{N-1} f(t_j) (\Delta t_j)^\alpha. \end{aligned} \tag{7}$$

Definition 3 (see [1, 5, 11, 16, 21]). The Mittag Leffler, sine and cosine functions defined on Cantor sets are given as follows:

$$\begin{aligned} E_\alpha(x^\alpha) &= \sum_{k=0}^{\infty} \frac{x^{\alpha k}}{\Gamma(1 + k\alpha)}, \\ \sin_\alpha x^\alpha &= \sum_{k=0}^{\infty} (-1)^k \frac{x^{\alpha(2k+1)}}{\Gamma[1 + \alpha(2k + 1)]}, \\ \cos_\alpha x^\alpha &= \sum_{k=0}^{\infty} (-1)^k \frac{x^{2\alpha k}}{\Gamma(1 + 2\alpha k)}, \end{aligned} \tag{8}$$

for $x \in \mathbb{R}, 0 < \alpha < 1$.

Definition 4 (see [11, 20–22]). Let $f(x)$ be $2l$ -periodic. For $k \in \mathbb{Z}$, local fraction Fourier series of $f(x)$ is given as

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{\infty} \left(a_n \cos_\alpha \frac{\pi^\alpha (kx)^\alpha}{l^\alpha} + b_n \sin_\alpha \frac{\pi^\alpha (kx)^\alpha}{l^\alpha} \right), \tag{9}$$

where the local fraction Fourier coefficients are as follows:

$$\begin{aligned} a_n &= \frac{2}{l^\alpha} \int_0^l f(x) \cos_\alpha \frac{\pi^\alpha (kx)^\alpha}{l^\alpha} (dx)^\alpha, \\ b_n &= \frac{2}{l^\alpha} \int_0^l f(x) \sin_\alpha \frac{\pi^\alpha (kx)^\alpha}{l^\alpha} (dx)^\alpha. \end{aligned} \tag{10}$$

Definition 5 (see [14, 16, 18, 22]). Let $(1/\Gamma(1 + \alpha)) \int_0^\infty |f(x)|(dx)^\alpha < k < \infty$. The local fractional Laplace transform of $f(x)$ is given as

$$\begin{aligned} \tilde{L}_\alpha \{f(x)\} &= f_s^{\tilde{L}, \alpha}(s) = \frac{1}{\Gamma(1 + \alpha)} \int_0^\infty E_\alpha(-s^\alpha x^\alpha) f(x) (dx)^\alpha, \\ &0 < \alpha \leq 1. \end{aligned} \tag{11}$$

The inverse formula local fractional Laplace transform of $f(x)$ is given as [14, 16, 18, 22]

$$\begin{aligned} f(x) &= \tilde{L}_\alpha^{-1} \{f_s^{\tilde{L}, \alpha}(s)\} \\ &= \frac{1}{(2\pi)^\alpha} \int_{\beta - i\infty}^{\beta + i\infty} E_\alpha(s^\alpha x^\alpha) f_s^{\tilde{L}, \alpha}(s) (ds)^\alpha, \end{aligned} \tag{12}$$

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

There is the following formula [14, 16, 18, 22]:

$$\tilde{L}_\alpha \{y^{(2\alpha)}(x)\} = s^{2\alpha} \tilde{L}_\alpha \{y(x)\} - s^\alpha y(0) - f^{(\alpha)}(0). \tag{13}$$

The basic properties of the local fractional calculus and the local fractional Laplace transform were listed in [1, 14, 16, 18, 22].

3. Analysis of the Local Fractional Functional Method

In this section, we introduce the local fractional functional method for the local fractional diffusion equations defined on Cantor sets [11, 22].

Let us consider the nondifferentiable decomposition of the function with the nondifferentiable systems $\{\sin_\alpha n^\alpha (\pi t/l)^\alpha\}$. There are the following functional coefficients of (1) and (2), which are given as follows:

$$\begin{aligned} u(x, t) &= \sum_{n=1}^{\infty} A_n(x) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha, \\ g(t) &= \sum_{n=1}^{\infty} C_n \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha, \\ f(t) &= \sum_{n=1}^{\infty} D_n \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha, \end{aligned} \tag{14}$$

where

$$\begin{aligned} A_n(x) &= \frac{2}{l^\alpha} \int_0^1 u(x,t) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha (dt)^\alpha, \\ C_n &= \frac{2}{l^\alpha} \int_0^1 g(t) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha (dt)^\alpha, \\ D_n &= \frac{2}{l^\alpha} \int_0^1 f(t) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha (dt)^\alpha. \end{aligned} \tag{15}$$

If we submit (14) into (1) and (2), then we have

$$\begin{aligned} \frac{d^{2\alpha}}{dx^{2\alpha}} A_n(x) &= \frac{1}{a^{2\alpha}} A_n(x) \left(\frac{n\pi}{l}\right)^\alpha, \\ A_n^{(\alpha)}(0) &= C_n, \\ A_n(0) &= D_n. \end{aligned} \tag{16}$$

Taking the local fractional Laplace transform of (16) gives

$$\tilde{L}_\alpha \left\{ \frac{d^{2\alpha}}{dx^{2\alpha}} A_n(x) \right\} = s^{2\alpha} \tilde{L}_\alpha \{A_n(x)\} - s^\alpha A_n(0) - A_n^{(\alpha)}(0), \tag{17}$$

which leads to

$$s^{2\alpha} \tilde{L}_\alpha \{A_n(x)\} - s^\alpha D_n - C_n = \frac{1}{a^{2\alpha}} \left(\frac{n\pi}{l}\right)^\alpha \tilde{L}_\alpha \{A_n(x)\}. \tag{18}$$

We can rewrite (18) as

$$\begin{aligned} A_n(s) &= \tilde{L}_\alpha \{A_n(x)\} \\ &= \frac{s^\alpha D_n + C_n}{s^{2\alpha} - (1/a^{2\alpha})(n\pi/l)^\alpha} \\ &= \frac{D_n}{s^\alpha - (1/a^\alpha)(n\pi/l)^{\alpha/2}} + \frac{(C_n - (1/a^\alpha)(n\pi/l)^{\alpha/2} D_n)}{s^{2\alpha} - (1/a^{2\alpha})(n\pi/l)^\alpha} \\ &= \frac{D_n}{s^\alpha - (1/a^\alpha)(n\pi/l)^{\alpha/2}} \\ &+ P \left(\frac{1}{s^\alpha - (1/a^\alpha)(n\pi/l)^{\alpha/2}} - \frac{1}{s^\alpha + (1/a^\alpha)(n\pi/l)^{\alpha/2}} \right), \end{aligned} \tag{19}$$

where

$$P = \frac{C_n - (1/a^\alpha)(n\pi/l)^{\alpha/2} D_n}{(1/a^\alpha)(n\pi/l)^{\alpha/2}}. \tag{20}$$

The inverse formula local fractional Laplace transform of (19) gives

$$\begin{aligned} A_n(x) &= \tilde{L}_\alpha^{-1} \{A_n(s)\} \\ &= \frac{1}{(2\pi)^\alpha} \int_{\beta-i\infty}^{\beta+i\infty} E_\alpha(s^\alpha x^\alpha) A_n(s) (ds)^\alpha \\ &= \frac{1}{(2\pi)^\alpha} \\ &\times \int_{\beta-i\infty}^{\beta+i\infty} E_\alpha(s^\alpha x^\alpha) \left\{ \frac{D_n}{s^\alpha - (1/a^\alpha)(n\pi/l)^{\alpha/2}} \right. \\ &\quad \left. + P \left(\frac{1}{s^\alpha - (1/a^\alpha)(n\pi/l)^{\alpha/2}} - \frac{1}{s^\alpha + (1/a^\alpha)(n\pi/l)^{\alpha/2}} \right) \right\} (ds)^\alpha \\ &= D_n E_\alpha \left(\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right) + P E_\alpha \left(\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right) \\ &\quad - P E_\alpha \left(-\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right), \end{aligned} \tag{21}$$

where

$$P = \frac{C_n - (1/a^\alpha)(n\pi/l)^{\alpha/2} D_n}{(1/a^\alpha)(n\pi/l)^{\alpha/2}}. \tag{22}$$

Hence, the solution of (1) reads as follows:

$$\begin{aligned} u(x,t) &= \sum_{n=1}^\infty A_n(x) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha \\ &= \sum_{n=1}^\infty D_n E_\alpha \left(\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha \\ &\quad + \sum_{n=1}^\infty P E_\alpha \left(\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha \\ &\quad - \sum_{n=1}^\infty P E_\alpha \left(-\frac{1}{a^\alpha} \left(\frac{n\pi}{l}\right)^{\alpha/2} x^\alpha \right) \sin_\alpha n^\alpha \left(\frac{\pi t}{l}\right)^\alpha, \end{aligned} \tag{23}$$

where

$$P = \frac{C_n - (1/a^\alpha)(n\pi/l)^{\alpha/2} D_n}{(1/a^\alpha)(n\pi/l)^{\alpha/2}}. \tag{24}$$

4. The Exact Solutions for Local Fractional Diffusion Equations Defined on Cantor Sets

In this section we give two examples for initial boundary problems for local fractional diffusion equations defined on Cantor sets.

Example 6. The initial-boundary values of (1) read as follows:

$$\begin{aligned} \frac{\partial^\alpha}{\partial x^\alpha} u(0, t) &= \sin(t^\alpha), & u(0, t) &= 0, \\ u(x, 0) &= u(x, \pi) = 0. \end{aligned} \tag{25}$$

Making use of (14), we obtain the following formulas:

$$\begin{aligned} \sin(t^\alpha) &= \sum_{n=1}^{\infty} C_n \sin_\alpha n^\alpha t^\alpha, \\ 0 &= \sum_{n=1}^{\infty} D_n \sin_\alpha n^\alpha t^\alpha, \end{aligned} \tag{26}$$

which lead to the following parameters:

$$\begin{aligned} C_n &= 1, & n &= 1, \\ C_n &= 0, & n &> 1, \\ D_n &= 0, & n &\geq 1. \end{aligned} \tag{27}$$

Therefore, (23) gives the nondifferentiable solution of (1) with initial-boundary values (25)

$$\begin{aligned} u(x, t) &= \sum_{n=1}^{\infty} A_n(x) \sin_\alpha n^\alpha t^\alpha \\ &= \sum_{n=1}^{\infty} D_n E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha + \sum_{n=1}^{\infty} P E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha \\ &\quad - \sum_{n=1}^{\infty} P E_\alpha \left(-\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha \\ &= a^\alpha E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha t^\alpha - a^\alpha E_\alpha \left(-\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha t^\alpha. \end{aligned} \tag{28}$$

When $a = 1$, we get the nondifferentiable solution

$$u(x, t) = E_\alpha(x^\alpha) \sin_\alpha t^\alpha - E_\alpha(-x^\alpha) \sin_\alpha t^\alpha, \tag{29}$$

and its graph is shown in Figure 1.

Example 7. We present the initial-boundary values of (1) as

$$\begin{aligned} \frac{\partial^\alpha}{\partial x^\alpha} u(0, t) &= \sin(t^\alpha), & u(0, t) &= \sin(t^\alpha), \\ u(x, 0) &= u(x, \pi) = 0. \end{aligned} \tag{30}$$

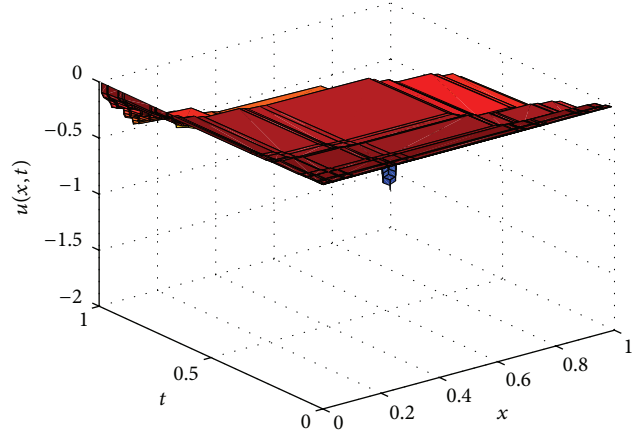


FIGURE 1: The solution of (1) with initial-boundary value (25) when $a = 1$ and $\alpha = \ln 2 / \ln 3$.

Using the relation (14), we get

$$0 = \sum_{n=1}^{\infty} C_n \sin_\alpha n^\alpha t^\alpha, \tag{31}$$

$$\sin(t^\alpha) = \sum_{n=1}^{\infty} D_n \sin_\alpha n^\alpha t^\alpha,$$

which reduce to

$$\begin{aligned} C_n &= 0, & n &\geq 1, \\ D_n &= 1, & n &= 1, \\ D_n &= 0, & n &> 1. \end{aligned} \tag{32}$$

Using (23), we hence have the nondifferentiable solution of (1) with initial-boundary values (30), which is given as

$$\begin{aligned} u(x, t) &= \sum_{n=1}^{\infty} A_n(x) \sin_\alpha n^\alpha t^\alpha \\ &= \sum_{n=1}^{\infty} D_n E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha + \sum_{n=1}^{\infty} P E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha \\ &\quad - \sum_{n=1}^{\infty} P E_\alpha \left(-\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha n^\alpha t^\alpha \\ &= E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha t^\alpha - a^\alpha E_\alpha \left(\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha t^\alpha \\ &\quad + a^\alpha E_\alpha \left(-\frac{1}{a^\alpha} x^\alpha \right) \sin_\alpha t^\alpha. \end{aligned} \tag{33}$$

For $a = 1$, the nondifferentiable solution rewrites as follows:

$$u(x, t) = E_\alpha(-x^\alpha) \sin_\alpha t^\alpha, \tag{34}$$

and its graph is illustrated in Figure 2.

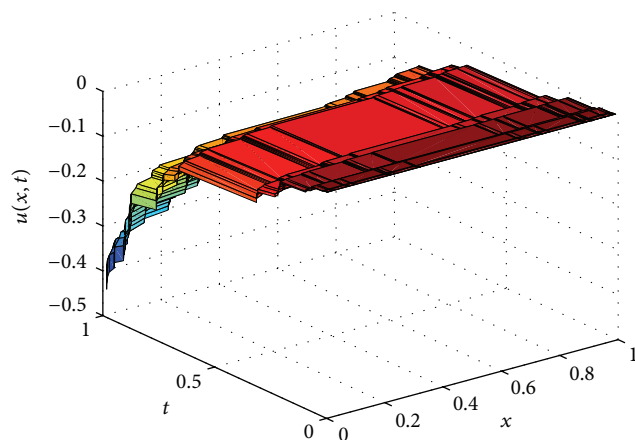


FIGURE 2: The solution of (1) with initial-boundary value (30) when $\alpha = 1$ and $\alpha = \ln 2 / \ln 3$.

5. Conclusions

Local fractional calculus was applied to describe the physical problems because of nondifferentiable characteristics. In this work, the initial-boundary value problems for the diffusion equation on Cantor sets within the local fractional derivatives were investigated by using the local fractional functional method, which is a coupling method for local fractional Fourier series and Laplace transform based upon the nondifferentiable decomposition of the function with the nondifferentiable systems. The two examples are given to express the efficiency of the presented method and their graphs are also obtained. The results of this paper could provide the theory support to the problems diffusion equations with the nondifferentiable terms in health monitor of high-speed trains and their control systems.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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