

The Solution of Caputo Fractional Partial Differential Equations By Sumudu Transform

Abstract

In this paper, we obtained an explicit solutions of the fractional diffusion-wave equations involving partial Caputo fractional derivative by using Sumudu transform. The solutions of the fractional diffusion-wave equations obtained in terms of Mittag-Leffler function and generalized Wright function. Some illustrative examples are also given.

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Keywords: Sumudu transform; Wright function; Mittag-Leffler function; Fractional derivatives; Fractional differential equations..

1 INTRODUCTION

In this paper, we apply the Sumudu transform to fractional integrals, derivatives, and use it to solve initial value fractional differential equations. In [[1],[2],[3],[4],[5],[6]], the authors studied many properties of the Sumudu transform in light of which they developed efficient and straightforward methodologies for treating ordinary [11] and partial differential equations . There is evident interest in further studying this transform, and applying it to various mathematical and physical sciences problems[13]. The Sumudu transform can be used to solve many types of difference and differential equations problems without resorting to a new frequency domain. The Sumudu transform was first defined by Watugala in 1993, which is used to solve engineering control problems [16], [17], [18]. The Weerakoon applied Sumudu transform to solve fractional differential equations [19],[20]. The fundamental properties of Sumudu transform are also used to solve the fractional differential equations {[8],[7]}. In this paper, we can find an explicit solution of the fractional diffusion-wave equations with Caputo fractional derivative by using the Sumudu transform method.

The fractional calculus is a generalization of differentiations and integrations to non-integers orders. There are many problems in physics and engineering formu-

lated in terms of fractional differential and integral equations, such as diffusion, signal processing, electrochemistry, viscosity etc. The exact and approximate solutions of fractional differential equations are investigated by many authors using different methods. The Sumudu transform method is applied to obtain the solution of ordinary differential equations [9]. The Sumudu transform was first defined by Watugala in 1993, which is used to solve engineering control problems[16]. The Weerakoon applied Sumudu transform to solve fractional differential equations [19]. The fundamental properties of Sumudu transform are also used to solve the fractional differential equations [1],[8],[7]. In this paper, we can find an explicit solution of the fractional diffusion-wave equations with Caputo fractional derivative by using the Sumudu transform method.

2 Preliminary Results, Notations and Terminology

In this section we give definitions and some basic results which are used in the paper.

Consider the general linear fractional partial differential equation

Definition 2.1

$$(D_{o+,t}^\alpha u)(x, t) = \sum_{j=1}^n a_j D_{x_j}^{\delta_j} u(x, t) + \sum_{j=1}^n b_j D_{x_j}^{\beta_j} u(x, t) + \sum_{j=1}^n c_j D_{x_j}^{\gamma_j} u(x, t) + du(x, t); \tag{2.1}$$

$$n - 1 < \alpha \leq n, 2 < \delta_j \leq 3, 1 < \beta_j \leq 2, 0 < \gamma_j \leq 1, n \in \mathbb{N}$$

where $x = (x_1, x_2, \dots, x_n) \in \mathbb{R}^n, a_j, b_j, c_j, d$ are non-negative real constants, $0 \leq t < T$

The fractional diffusion equation is

$$(D_{o+,t}^\alpha u)(x, t) = \sum_{j=1}^n b_j D_{x_j}^{\beta_j} u(x, t) \tag{2.2}$$

$$n - 1 < \alpha \leq n, 1 < \beta_j \leq 2, n \in \mathbb{N}$$

Definition 2.2 [12] *The Riemann-Liouville fractional integral of order $\alpha, \alpha > 0$ of a function $u(x, t)$ is denoted by $I_{0+,t}^\alpha u(x, t)$ and defined as*

$$I_{0+,t}^\alpha u(x, t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t - \tau)^{\alpha-1} u(x, \tau) d\tau, \quad t > 0, \alpha > 0 \tag{2.3}$$

Definition 2.3 [12] The Caputo fractional derivative of order $\alpha, \alpha > 0$ of a function $u(x, t)$ is denoted by ${}^c D_{0+,t}^\alpha u(x, t)$ and defined as

$${}^c D_{0+,t}^\alpha u(x, t) = \frac{1}{\Gamma(n - \alpha)} \int_0^t \frac{\partial^n u(x, \tau)}{(t - \tau)^{\alpha-n+1}} d\tau, \quad (x \in \mathbb{R}, t > 0, n-1 < \alpha < n, n \in \mathbb{N}) \quad (2.4)$$

2.1 Mittag-Leffler Function :

The Mittag-Leffler function was introduced by M. G. Mittag-Leffler and is denoted by $E_\alpha(z)$ [10]. It is one parameter generalization of exponential function and is defined as,

$$E_\alpha(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + 1)}, \quad \alpha \in \mathbb{C}, \operatorname{Re}(\alpha) > 0. \quad (2.5)$$

A two-parameter Mittag-Leffler function introduced by R. P. Agarwal [3], denoted by $E_{\alpha,\beta}(z)$, is defined as,

$$E_{\alpha,\beta}(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + \beta)}, \quad \alpha > 0, \beta > 0. \quad (2.6)$$

2.2 Wright Function :

The Wright function introduced by Wright, denoted by $\phi(\alpha, \beta; z)$ [12] is a generalization of Mittag-Leffler function and is defined as,

$$\phi(\alpha, \beta; z) = {}_0\Psi_1 \left[\begin{matrix} - & - & - & - & - \\ (\beta, \alpha) \end{matrix} \middle| z \right] = \sum_{k=0}^{\infty} \frac{1}{\Gamma(\alpha k + \beta)} \frac{z^k}{k!} \quad (2.7)$$

The more general Wright function ${}_p\Psi_q(z)$ $z, a_l, b_j \in \mathbb{C}$ and $\alpha_l, \beta_j \in \mathbb{R}$ ($l = 1, 2, \dots, p; j = 1, 2, \dots, q$) is defined by the series

$${}_p\Psi_q(z) = {}_1\Psi_1 \left[\begin{matrix} (a_l, \alpha_l)_{1,p} \\ (b_l, \beta_l)_{1,q} \end{matrix} \middle| z \right] = \sum_{k=0}^{\infty} \frac{\prod_{l=1}^p \Gamma(a_l + \alpha_l k)}{\prod_{j=1}^q \Gamma(b_j + \beta_j k)} \cdot \frac{z^k}{k!} \quad (2.8)$$

The Wright function with $p = q = 1$ of the form

$${}_1\Psi_1 \left[\begin{matrix} (n+1, n) \\ (\alpha n + \beta, \alpha) \end{matrix} \middle| z \right] = \sum_{j=0}^{\infty} \frac{\Gamma(n + j + 1)}{\Gamma(\alpha n + \beta + \alpha j)} \cdot \frac{z^j}{j!} = \left(\frac{\partial}{\partial z} \right)^n E_{\alpha,\beta}(z). \quad (2.9)$$

Consider a set A defined as [16]

$$A = \{f(t) | \exists M, \tau_1, \tau_2 > 0, |f(t)| \leq M e^{\frac{|t|}{\tau_j}} \text{ if } t \in (-1)^j \times [0, \infty)\}.$$

Definition 2.4 For all real $t \geq 0$, the Sumudu transform of a function $u \in A$, with respect to t denoted by $(S_t u)(x, p)$, is defined as

$$(S_t u)(x, p) = \int_0^\infty u(x, t) p e^{pt} dt, \quad u \in (-\tau_1, \tau_2), \quad \text{where} \left(p = -\frac{1}{u} \right) \quad (x \in \mathbb{R}; p > 0) \quad (2.10)$$

and the inverse Sumudu transform with respect to p is

$$(S_p^{-1} u)(x, p) = \frac{1}{2\pi} \int_{\gamma-i\infty}^{\gamma+i\infty} e^{pt} u(x, p) dp, \quad (x \in \mathbb{R}; \gamma = \Re(p) > \sigma u). \quad (2.11)$$

[13]The Sumudu transform of the Caputo fractional derivative of order $\alpha, \alpha > 0$ of a function $u(x, p)$ is denoted by $(S_t^c D_{0+,t}^\alpha u)(x, p)$ and defined as

$$(S_t^c D_{0+,t}^\alpha u)(x, p) = p^\alpha (S u)(x, p) - \sum_{k=0}^{l-1} p^{\alpha-j-1} \left(\frac{\partial^k u(x, 0)}{\partial t^k} \right) \quad (2.12)$$

with $x \in \mathbb{R}, l - 1 < \alpha \leq l$ and $n \in \mathbb{N}$.

Definition 2.5 [12]The Fourier transform with respect to $x \in \mathbb{R}$ denoted by $(F_x u)(\sigma, t)$ is defined as

$$(F_x u)(\sigma, t) = \int_{-\infty}^\infty u(x, t) e^{ix\sigma} dx, \quad (\sigma \in \mathbb{R}; t > 0) \quad (2.13)$$

and the inverse of the Fourier transform of $u(x, t)$ with respect to σ is

$$(F_\sigma^{-1} u)(x, t) = \frac{1}{2\pi} \int_{-\infty}^\infty u(\sigma, t) e^{-i\sigma x} d\sigma, \quad (\sigma \in \mathbb{R}; t > 0) \quad (2.14)$$

the relation with respect to $x \in \mathbb{R}$

$$F[D^k \phi(t)](x) = (-ix)^k (F\phi) \quad (k \in \mathbb{N}) \quad (2.15)$$

and the Fourier convolution operator of two functions f and g is defined by the integral

$$f * g = (f * g)(x) = \int_{-\infty}^\infty f(x - t)g(t)dt, \quad (x \in \mathbb{R}) \quad (2.16)$$

3 Solution of Cauchy Type Problems for Fractional Diffusion-Wave Equations With Caputo derivative :

In this section we apply the Sumudu transform method to the fractional diffusion-wave equations with Caputo fractional derivative. we can derive the explicit solution

to the fractional diffusion-wave equations of the form

In this section we consider a fractional differential equation of the form

$$({}^c D_{0+,t}^\alpha u)(x, t) = \lambda(\Delta_x u)(x, t) \quad (x \in \mathbb{R}; t > 0; 0 < \alpha < 2; \lambda > 0) \quad (3.1)$$

involving the partial Caputo fractional derivative $({}^c D_{0+,t}^\alpha u)(x, t)$ with respect to $t > 0$, and the Sumudu $(\Delta_x u)(x, t)$ with respect to $x \in \mathbb{R}^n$ given by

$$(\Delta_x u)(x, t) = \frac{\partial^2 u(x, t)}{\partial x_1^2} + \dots + \frac{\partial^2 u(x, t)}{\partial x_n^2} \quad (n \in \mathbb{N}) \quad (3.2)$$

In definition Caputo fractional derivative (2.4) of order $\alpha > 0$ and $l - 1 < \alpha \leq l (l \in \mathbb{N})$ is defined in terms of the Riemann-Liouville partial fractional derivative ${}^r D_{0+,t}^\alpha u$ by

$$({}^c D_{0+,t}^\alpha u)(x, t) = \left(D_{0+,t}^\alpha \left[u(x, \tau) - \sum_{k=0}^{l-1} \frac{\partial^k u(x, 0)}{\partial t^k} \frac{\tau^k}{k!} \right] \right)(x, t) \quad (3.3)$$

When, for any fixed $x \in \mathbb{R}$, $u(x, t) \in C^l(\mathbb{R}_+)$ as a function of $t > 0$, then $({}^c D_{0+,t}^\alpha u)(x, t)$ has the representation (2.4). In this section we apply the Fourier and Sumudu transform to obtain an explicit solution to the equation (3.1) with Cauchy initial conditions

$$\frac{\partial^k u(x, 0)}{\partial t^k} = f_k(x) \quad . \quad (x \in \mathbb{R}; k = 0 \quad \text{for } 0 < \alpha \leq 1; k = 1 \quad \text{for } 1 < \alpha < 2). \quad (3.4)$$

$$\frac{\partial^0 u(x, 0)}{\partial t^0} = u(x, 0) \quad (3.5)$$

Example 3.1 Solve the following partial differential equation of order $\alpha, 0 < \alpha < 2$

$$({}^c D_{0+,t}^\alpha u)(x, t) = \lambda^2 \frac{\partial^2 u(x, t)}{\partial x^2} \quad (x \in \mathbb{R}; t > 0; 0 < \alpha < 2; \lambda > 0). \quad (3.6)$$

$$\frac{\partial^k u(x, 0)}{\partial t^k} = f_k(x) \quad . \quad (x \in \mathbb{R}; k = 0 \quad \text{for } 0 < \alpha \leq 1; k = 1 \quad \text{for } 1 < \alpha < 2). \quad (3.7)$$

Applying the Sumudu transform (2.10) to equation (3.6) using the initial condition (3.7) with respect t

$$S[({}^c D_{0+,t}^\alpha u)(x, p)] = \lambda^2 \left(\frac{\partial^2}{\partial x^2} S_t u \right)(x, p) \quad (l = 1, 2) \quad (3.8)$$

Using (3.13) with $x \in \mathbb{R}, l - 1 < \alpha \leq l$ and $n \in \mathbb{N}$. If $l = 1$ and $l = 2$ in respective cases $0 < \alpha \leq 1$ and $1 < \alpha < 2$, and the initial conditions in (3.7), we have

$$p^\alpha (S_t u)(x, p) = \sum_{k=0}^{l-1} p^{\alpha-k-1} f_k(x) + \lambda^2 \left(\frac{\partial^k}{\partial x^k} \right) \quad (l = 1, 2) \quad (3.9)$$

Now, applying the Fourier transform (2.13) and using the formula (2.15) with $k = 2$, we have

$$\left(F_x \left[\frac{\partial^2 u(x, t)}{\partial x^2} \right] \right) (\sigma, t) = -|\sigma|^2 (F_x u)(\sigma, t), \quad (3.10)$$

By applying Fourier transform on equation (3.9) and using equation (3.10), we obtain

$$\begin{aligned} p^\alpha (F_x S_t u)(\sigma, p) &= \sum_{k=0}^{l-1} p^{\alpha-k-1} (F_x f_k)(\sigma) - \lambda^2 |\sigma|^2 (F_x S_t u)(\sigma, p) \\ (F_x S_t u)(\sigma, p) &= \sum_{k=0}^{l-1} \frac{p^{\alpha-k-1}}{p^\alpha + \lambda^2 |\sigma|^2} (F_x f_k)(\sigma), \quad (\sigma \in \mathbb{R}, t > 0, l = 1, 2). \end{aligned} \quad (3.11)$$

Now, we obtain the explicit solution $u(x, t)$ by using the inverse Fourier transform (2.14) with respect to σ and the inverse Sumudu transform (2.11) with respect to p .

$$(F_x e^{-c|x|})(\sigma) = \frac{2c}{c^2 + |\sigma|^2} \quad (\sigma \in \mathbb{R}; c > 0)$$

and

$$(F e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}}) = \frac{2\lambda p^{\frac{\alpha}{2}}}{p^\alpha + \lambda^2 |\sigma|^2}$$

From these equations, we have

$$\left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \right] \right) = \frac{p^{\alpha-k-1}}{p^\alpha + \lambda^2 |\sigma|^2} (\sigma) \quad (k = 0, 1)$$

Hence equation (3.11) becomes

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \right] \right) (\sigma) (F_x f_k)(\sigma) \quad (l = 1, 2).$$

By using the Fourier transform convolution property, we have

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} * x f_k \right] \right) (\sigma) \quad (l = 1, 2).$$

Now applying the inverse Fourier transform (2.14), we obtain

$$(S_t u)(x, p) = \frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} * x f_k \quad (l = 1, 2). \quad (3.12)$$

When $0 < \alpha < 2$, then the function $p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}}$ ($k = 0, 1$) are expressed through sumudu transform of the Wright function $\phi(-\frac{\alpha}{2}, b; z)$ as follows.

$$\left(S_t \left[t^{\frac{\alpha}{2}-k} \phi\left(-\frac{\alpha}{2}; k+1-\frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \right] \right) (p) = p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \quad \text{for } (k = 0, 1) \quad (3.13)$$

Applying the inverse Sumudu transform to (2.11) and using (3.13), we can obtain the solution.

$$u(x, t) = \frac{1}{2\lambda} t^{\frac{\alpha}{2}-k} \phi\left(-\frac{\alpha}{2}; k+1-\frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \quad \text{for } (k = 0, 1)$$

Theorem 3.1 *If $0 < \alpha < 2$ and $\lambda > 0$, then the Cauchy type problem (3.6) and (3.7) is solvable and its solution is given by*

$$u(x, t) = \sum_{k=1}^l \int_{-\infty}^{\infty} G_k^\alpha(x - \tau, t) f_k(\tau) d\tau \tag{3.14}$$

$$(l = 1 \quad \text{for } 0 < \alpha \leq 1; l = 2 \quad \text{for } 1 < \alpha < 2)$$

where

$$G_k^\alpha(x, t) = \frac{1}{2\lambda} t^{k-\frac{\alpha}{2}} \phi\left(-\frac{\alpha}{2}; k+1-\frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \quad \text{for } (k = 0, 1)$$

provided that integral in the right-hand side of (3.14) are convergent.

Proof: Applying the Sumudu transform (2.10) to equation (3.6) using the initial condition (3.7) with respect t

$$S[(^c D_{0+,t}^\alpha u)(x, p)] = \lambda^2 \left(\frac{\partial^2}{\partial x^2} S_t u \right)(x, p) \quad (l = 1, 2) \tag{3.15}$$

Using (3.13) with $x \in \mathbb{R}, l - 1 < \alpha \leq l$ and $n \in \mathbb{N}$. If $l = 1$ and $l = 2$ in respective cases $0 < \alpha \leq 1$ and $1 < \alpha < 2$, and the initial conditions in (3.7), we have

$$p^\alpha (S_t u)(x, p) = \sum_{k=0}^{l-1} p^{\alpha-k-1} f_k(x) + \lambda^2 \left(\frac{\partial^k}{\partial x^k} \right) \quad (l = 1, 2) \tag{3.16}$$

Now, applying the Fourier transform (2.13) and using the formula (2.15) with $k = 2$, we have

$$\left(F_x \left[\frac{\partial^2 u(x, t)}{\partial x^2} \right] \right)(\sigma, t) = -|\sigma|^2 (F_x u)(\sigma, t), \tag{3.17}$$

By applying Fourier transform on equation (2.13) and using equation (3.17), we obtain

$$\begin{aligned} p^\alpha (F_x S_t u)(\sigma, p) &= \sum_{k=0}^{l-1} p^{\alpha-k-1} (F_x f_k)(\sigma) - \lambda^2 |\sigma|^2 (F_x S_t u)(\sigma, p) \\ (F_x S_t u)(\sigma, p) &= \sum_{k=0}^{l-1} \frac{p^{\alpha-k-1}}{p^\alpha + \lambda^2 |\sigma|^2} (F_x f_k)(\sigma), \quad (\sigma \in \mathbb{R}, t > 0, l = 1, 2). \end{aligned} \tag{3.18}$$

Now, we obtain the explicit solution $u(x, t)$ by using the inverse Fourier transform (2.14) with respect to σ and the inverse Sumudu transform (2.11) with respect to p .

$$(F_x e^{-c|x|})(\sigma) = \frac{2c}{c^2 + |\sigma|^2} \quad (\sigma \in \mathbb{R}; c > 0)$$

and

$$(F e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}}) = \frac{2\lambda p^{\frac{\alpha}{2}}}{p^\alpha + \lambda^2 |\sigma|^2}$$

From these equations, we have

$$\left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \right] \right) = \frac{p^{\alpha-k-1}}{p^\alpha + \lambda^2 |\sigma|^2}(\sigma) \quad (k = 0, 1)$$

Hence, equation (3.18) becomes

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \right] \right)(\sigma) (F_x f_k)(\sigma) \quad (l = 1, 2).$$

By using the Fourier transform convolution property (2.16) we have

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} * x f_k \right] \right)(\sigma) \quad (l = 1, 2).$$

Now applying the inverse Fourier transform (2.14), we obtain

$$(S_t u)(x, p) = \frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} * x f_k \quad (l = 1, 2). \tag{3.19}$$

$$u(x, t) = \sum_{k=1}^l \int_{-\infty}^{\infty} G_k^\alpha(x - \tau, t) f_k(\tau) d\tau$$

$$(l = 1 \text{ for } 0 < \alpha \leq 1; l = 2 \text{ for } 1 < \alpha < 2)$$

where $G^\alpha(x, t)$ is the green function can be written as

$$G^\alpha(x, t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \sum_{k=0}^{l-1} \frac{1}{2\lambda} p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} x f_k(x) dp \quad (l = 1, 2). \tag{3.20}$$

When $0 < \alpha < 2$, then the function $p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}}$ ($k = 0, 1$) are expressed through sumudu transform of the Wright function $\phi(-\frac{\alpha}{2}, b; z)$ as follows.

$$\left(S_t \left[t^{\frac{\alpha}{2}-k} \phi\left(-\frac{\alpha}{2}; k+1-\frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \right] \right)(p) = p^{\frac{\alpha}{2}-k-1} e^{-\frac{|x|}{\lambda} p^{\frac{\alpha}{2}}} \quad \text{for } (k = 0, 1) \tag{3.21}$$

Applying the inverse Sumudu transform to (3.19) and using (3.21), we can obtain the solutin.

$$u(x, t) = \frac{1}{2\lambda} t^{\frac{\alpha}{2}-k} \phi\left(-\frac{\alpha}{2}; k+1-\frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \quad \text{for } (k = 0, 1)$$

Corollary 3.1 *If $0 < \alpha < 1$ and $\lambda > 0$, then the Cauchy problem*

$$\begin{aligned} ({}^c D_{0+,t}^\alpha u)(x,t) &= \lambda^2 \frac{\partial^2 u(x,t)}{\partial x^2} \quad (x \in \mathbb{R}; t > 0) \\ u(x,0) &= f(x) \end{aligned} \tag{3.22}$$

is solvable, and its solution has the form

$$u(x,t) = \int_{-\infty}^{\infty} G_1^\alpha(x-\tau,t) f_1(\tau) d\tau \tag{3.23}$$

where

$$G_1^\alpha(x,t) = \frac{1}{2\lambda} t^{-\frac{\alpha}{2}} \phi\left(-\frac{\alpha}{2}, 1 - \frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \tag{3.24}$$

provided that the integral in the right-hand side of (3.23) is convergent.

Corollary 3.2 *If $0 < \alpha < 2$ and $\lambda > 0$, then the Cauchy problem*

$$({}^c D_{0+,t}^\alpha u)(x,t) = \lambda^2 \frac{\partial^2 u(x,t)}{\partial x^2}, \quad (x \in \mathbb{R}; t > 0) \tag{3.25}$$

$$\begin{aligned} u(x,0) &= f_0(x) \\ \frac{\partial u(x,0)}{\partial t} &= f_1(x) \quad (x \in \mathbb{R}) \end{aligned} \tag{3.26}$$

is solvable, and its solution has the form

$$u(x,t) = \int_{-\infty}^{\infty} G_1^\alpha(x-\tau,t) f_0(\tau) d\tau + \int_{-\infty}^{\infty} G_2^\alpha(x-\tau,t) f_1(\tau) d\tau \tag{3.27}$$

where

$$G_1^\alpha(x,t) = \frac{1}{2\lambda} t^{-\frac{\alpha}{2}} \phi\left(-\frac{\alpha}{2}, 1 - \frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \tag{3.28}$$

and

$$G_2^\alpha(x,t) = \frac{1}{2\lambda} t^{1-\frac{\alpha}{2}} \phi\left(-\frac{\alpha}{2}, 2 - \frac{\alpha}{2}; -\frac{|x|}{\lambda} t^{-\frac{\alpha}{2}}\right) \tag{3.29}$$

provided that the integral in the right-hand side of (3.27) is convergent.

Example 3.2 *Solve the following Cauchy problem with $\alpha = \frac{1}{2}$*

$$\begin{aligned} ({}^c D_{0+,t}^{\frac{1}{2}} u)(x,t) &= \lambda^2 \frac{\partial^2 u(x,t)}{\partial x^2} \quad (x \in \mathbb{R}; t > 0) \\ u(x,0) &= f(x) \end{aligned} \tag{3.30}$$

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is solvable, and its solution has the form

$$u(x, t) = \int_{-\infty}^{\infty} G_1^{\frac{1}{2}}(x - \tau, t) f_1(\tau) d\tau \tag{3.31}$$

where

$$G_1^{\frac{1}{2}}(x, t) = \frac{1}{2\lambda} t^{-\frac{1}{4}} \phi\left(-\frac{1}{4}, \frac{3}{4}; -\frac{|x|}{\lambda} t^{-\frac{1}{4}}\right) \tag{3.32}$$

Applying the Sumudu transform (2.10) to equation (3.30) and using the initial condition with respect t

$$S[(^c D_{0+,t}^{\frac{1}{2}} u)(x, p)] = \lambda^2 \left(\frac{\partial^2}{\partial x^2} S_t u\right)(x, p) \quad (l = 1) \tag{3.33}$$

Using (2.12) with $x \in \mathbb{R}, l - 1 < \alpha \leq l$ and $n \in \mathbb{N}$. If $l = 1$ in respective cases $0 < \alpha \leq 1$ and the initial conditions in (3.30), we have

$$p^{\frac{1}{2}}(S_t u)(x, p) = p^{-\frac{1}{2}} f_0(x) + \lambda^2 \left(\frac{\partial^k}{\partial x^k}\right) \quad (l = 1) \tag{3.34}$$

Now, applying the Fourier transform (2.13) to equation (3.30) and using the formula (2.15) with $k = 2$, we have

$$\left(F_x \left[\frac{\partial^2 u(x, t)}{\partial x^2}\right]\right)(\sigma, t) = -|\sigma|^2 (F_x u)(\sigma, t) \tag{3.35}$$

By applying Fourier transform on equation(3.34) and using equation(3.35), we obtain

$$\begin{aligned} p^{\frac{1}{2}}(F_x S_t u)(\sigma, p) &= p^{-\frac{1}{2}} f_0(x)(\sigma) - \lambda^2 |\sigma|^2 (F_x S_t u)(\sigma, p), \quad (\sigma \in \mathbb{R}, t > 0, l = 1, 2) \\ (F_x S_t u)(\sigma, p) &= \frac{p^{-\frac{1}{2}} f_0(x)}{p^{\frac{1}{2}} + \lambda^2 |\sigma|^2} (F_x f_k)(\sigma), \quad (\sigma \in \mathbb{R}, t > 0, l = 1). \end{aligned} \tag{3.36}$$

The Fourier transform are

$$(F_x e^{-c|x|})(\sigma) = \frac{2c}{c^2 + |\sigma|^2} \quad (\sigma \in \mathbb{R}; c > 0)$$

and

$$(F_x e^{-\frac{|x|}{\lambda} p^{\frac{1}{4}}}) = \frac{2\lambda p^{\frac{1}{4}}}{p^{\frac{1}{2}} + \lambda^2 |\sigma|^2}$$

Hence equation (3.36) becomes

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{1}{4}}}\right]\right)(\sigma) (F_x f_0)(\sigma) \quad (l = 1)$$

By the convolution property of Fourier transform (2.16) we have

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}} x f_0 \right] \right) (\sigma) \quad (l = 1)$$

Now applying the inverse Fourier transform, we obtain

$$(S_t u)(\sigma, p) = \left(\left[\frac{1}{2\lambda} p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}} x f_0 \right] \right) (\sigma) \quad (l = 1) \quad (3.37)$$

Thus, we get

$$u(x, t) = \int_{-\infty}^{\infty} G_1^{\frac{1}{2}}(x - \tau, t) f_1(\tau) d\tau$$

where $G_1^{\frac{1}{2}}(x, t)$ is the Green function can be written as

$$G_1^{\frac{1}{2}}(x, t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{1}{2\lambda} p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}} * x f(x) dp \quad (3.38)$$

To obtain the solution of $G_1^{\frac{1}{2}}(x, t)$, when $0 < \alpha \leq 1$ then the function $p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}}$ can be expressed through Sumudu transform of the Wright function $\phi(-\frac{1}{4}, b; z)$ as follows

$$\left(S_t \left[t^{-\frac{1}{4}} \phi\left(-\frac{1}{4}, \frac{3}{4}; -\frac{|x|}{\lambda} p^{-\frac{1}{4}}\right) \right] \right) (p) = p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}} \quad (k = 0) \quad (3.39)$$

Applying the inverse Sumudu transform to (3.37) and using (3.38), we get where

$$G_1^{\frac{1}{2}}(x, t) = \frac{1}{2\lambda} t^{-\frac{1}{4}} \phi\left(-\frac{1}{4}; \frac{3}{4}; -\frac{|x|}{\lambda} t^{-\frac{1}{4}}\right) \quad \text{for } (k = 1)$$

Example 3.3 Solve the following Cauchy problem with $\alpha = \frac{3}{2}$

$$({}^c D_{0+,t}^{\frac{3}{2}} u)(x, t) = \lambda^2 \frac{\partial^2 u(x, t)}{\partial x^2} \quad (x \in \mathbb{R}; t > 0) \quad (3.40)$$

$$u(x, 0) = f_0(x) \quad . \quad (x \in \mathbb{R})$$

$$\frac{\partial u(x, 0)}{\partial t} = f_1(x) \quad . \quad (x \in \mathbb{R}). \quad (3.41)$$

has its solution is given by

$$u(x, t) = \int_{-\infty}^{\infty} G_1^{\frac{3}{2}}(x - \tau, t) f_0(\tau) d\tau + \int_{-\infty}^{\infty} G_2^{\frac{3}{2}}(x - \tau, t) f_1(\tau) d\tau \quad (3.42)$$

where

$$G_1^{\frac{3}{2}}(x, t) = \frac{1}{2\lambda} t^{-\frac{3}{4}} \phi\left(-\frac{3}{4}; \frac{1}{4}; -\frac{|x|}{\lambda} t^{-\frac{3}{4}}\right) \quad (3.43)$$

and

$$G_2^{\frac{3}{2}}(x, t) = \frac{1}{2\lambda} t^{\frac{1}{4}} \phi\left(-\frac{3}{4}; \frac{5}{4}; -\frac{|x|}{\lambda} t^{-\frac{3}{4}}\right) \quad (3.44)$$

Applying Sumudu transform (2.10) to (3.40) and using the initial condition (3.41), with respect to t , we obtain

$$S[(D_{0+,t}^\alpha u)(x, p)] = \lambda^2 \left(\frac{\partial^2}{\partial x^2} S_t u \right) (x, p) \quad (l = 1, 2) \quad (3.45)$$

Using (2.12) with $x \in \mathbb{R}, l - 1 < \alpha \leq l$ and $n \in \mathbb{N}$. If $l = 1, 2$ in respective cases $0 < \alpha \leq 1$ and $1 < \alpha < 2$ the initial conditions in (3.41), we have

$$p^{\frac{3}{2}}(S_t u)(x, p) = p^{\frac{1}{2}} f_0(x) - p^{-\frac{1}{2}} f_1(x) + \lambda^2 \left(\frac{\partial^2 u(x, 0)}{\partial x^2} \right) \quad (l = 1, 2) \quad (3.46)$$

Now, applying the Fourier transform (2.13) to equation (3.46) and using the formula (2.15) with $k = 2$, we have

$$\left(F_x \left[\frac{\partial^2 u(x, t)}{\partial x^2} \right] \right) (\sigma, t) = -|\sigma|^2 (F_x u)(\sigma, t), \quad (3.47)$$

By applying Fourier transform on equation (3.46) and using equation(3.47), we obtain

$$\begin{aligned} p^{\frac{3}{2}}(F_x S_t u)(\sigma, p) &= p^{\frac{1}{2}} F_x f_0(x)(\sigma) + p^{-\frac{1}{2}} F_x f_1(x)(\sigma) - \lambda^2 |\sigma|^2 (F_x S_t u)(\sigma, p) \\ (F_x S_t u)(\sigma, p) &= \frac{p^{\frac{1}{2}} f_0(x)}{p^{\frac{3}{2}} + \lambda^2 |\sigma|^2} + \frac{p^{-\frac{1}{2}} f_0(x)}{p^{\frac{3}{2}} + \lambda^2 |\sigma|^2} (F_x f_k)(\sigma), \quad (\sigma \in \mathbb{R}, t > 0, l = 1, 2). \end{aligned} \quad (3.48)$$

The Fourier transform are

$$(F_x e^{-c|x|})(\sigma) = \frac{2c}{c^2 + |\sigma|^2} \quad (\sigma \in \mathbb{R}; c > 0)$$

and

$$(F e^{-\frac{|x|}{\lambda}} p^{\frac{3}{4}}) = \frac{2\lambda p^{\frac{3}{4}}}{p^{\frac{3}{2}} + \lambda^2 |\sigma|^2}$$

Hence equation (3.48) becomes

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{-\frac{3}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{1}{4}} \right] \right) (\sigma) (F_x f_0)(\sigma) \quad (l = 1, 2)$$

By the convolution property of Fourier transform (2.16) we have

$$(F_x S_t u)(\sigma, p) = \left(F_x \left[\frac{1}{2\lambda} p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{3}{4}} x f_0 \right] \right) (\sigma) + \left(F_x \left[\frac{1}{2\lambda} p^{-\frac{5}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{3}{4}} x f_1 \right] \right) (\sigma) \quad (l = 1, 2).$$

Now applying the inverse Fourier transform,we obtain

$$(S_t u)(x, p) = \left(\left[\frac{1}{2\lambda} p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{3}{4}} x f_0(x) \right] \right) + \left(\left[\frac{1}{2\lambda} p^{-\frac{5}{4}} e^{-\frac{|x|}{\lambda}} p^{\frac{3}{4}} x f_1(x) \right] \right) \quad (l = 1, 2) \quad (3.49)$$

Thus we get

$$u(x, t) = \int_{-\infty}^{\infty} G_1^{\frac{3}{2}}(x - \tau, t) f_0(\tau) d\tau + \int_{-\infty}^{\infty} G_2^{\frac{3}{2}}(x - \tau, t) f_1(\tau) d\tau$$

Where $G_1^{\frac{3}{2}}(x, t)$ and $G_2^{\frac{3}{2}}(x, t)$ are the Green's functions can be written as

$$G_1^{\frac{3}{2}}(x, t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{1}{2\lambda} p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}} * x f(x) dp \tag{3.50}$$

and

$$G_2^{\frac{3}{2}}(x, t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{1}{2\lambda} p^{-\frac{5}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}} * x f(x) dp \tag{3.51}$$

To obtain the solution of $G_1^{\frac{3}{2}}(x, t)$ and $G_2^{\frac{3}{2}}(x, t)$ when $0 < \alpha \leq 1$ and $1 < \alpha < 2$ then the function $p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}}$ and $p^{-\frac{5}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}}$ can be expressed through Sumudu transform of the Wright function $\phi(-\frac{3}{4}, b; z)$ and $\phi(-\frac{5}{4}, b; z)$ as follows

$$\begin{aligned} & \left(S_t \left[t^{-\frac{3}{4}} \phi\left(-\frac{3}{4}, \frac{1}{4}; -\frac{|x|}{\lambda} p^{-\frac{3}{4}}\right) \right] \right) (p) + \left(S_t \left[t^{\frac{1}{4}} \phi\left(-\frac{3}{4}, \frac{5}{4}; -\frac{|x|}{\lambda} p^{-\frac{3}{4}}\right) \right] \right) (p) \\ & = p^{-\frac{1}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}} + p^{-\frac{5}{4}} e^{-\frac{|x|}{\lambda} p^{\frac{3}{4}}} \quad (k = 0, 1) \end{aligned} \tag{3.52}$$

Applying the inverse Sumudu transform to (3.49) and using (3.50) and (3.51), we get where

$$G_1^{\frac{3}{2}}(x, t) = \frac{1}{2\lambda} t^{-\frac{3}{4}} \phi\left(-\frac{3}{4}; \frac{1}{4}; -\frac{|x|}{\lambda} t^{-\frac{3}{4}}\right)$$

and

$$G_2^{\frac{3}{2}}(x, t) = \frac{1}{2\lambda} t^{\frac{1}{4}} \phi\left(-\frac{3}{4}; \frac{5}{4}; -\frac{|x|}{\lambda} t^{-\frac{3}{4}}\right)$$

Conclusion

In this paper, Sumudu transform of Caputo fractional derivatives have been used to solve fractional diffusion-wave equations. The solution of fractional diffusion-wave equations is obtained in terms of Mittag-Leffler function and generalized Wright function. The Sumudu transform and Fourier transform is an useful operational transform method which is an important in treating fractional diffusion-wave equations. The Sumudu transform and Fourier transform technique can be used to solve many types of initial value problems in applied and engineering fields.

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