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Solving Fractional Black-Scholes Eruopean Option Pricing Equations by Aboodh Transform Decomposition Method

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Abstract

In this paper we apply the Aboodh transform decomposition method to solve fractional Black-Scholes equation. This method is a mixture between Aboodh transform and Adomian decomposition method, we use this method to solve Black -Scholes equation with constant and non constant coefficients. This method is highly recommended for solving linear and nonlinear fractional differential equations.

Keywords

Fractional differential equation, Aboodh transform, Adomian decomposition method, Black-scholes equation.

1 Introduction

Nowadays, several real world scientific and engineering phenomena cannot be handled by the usual integer order integrals and derivatives and can be handled by fractional order integrals and derivatives. There are a lot of different methods for solving fractional differential equations such as Adomin decomposition method (ADM)[1, 2], Homotopy perturbation method (HPM)[19, 20], the finite difference method[21], the variational iteration method(VIM)[3, 4, 5]. Nonlinear partial differential equations can't be solved by integral transformations such as Laplace, sumudu , Elzaki and Aboodh , so researchers are working in the mixture of these methods with other methods. One of these combinations , Adomian decomposition method and Aboodh transform method, which is studied in this article. In 2013, khalid Aboodh , has introduced a new integral transform derived from the classical fourier integral named the Aboodh transform this transform and some of its fndamental properites are used to solve fractonal differential equations, see[7, 8, 9, 10, 11, 1, 13]. In the present paper the Aboodh transform decomposition method is applied to solve the following fractional Black-Scholes equation of the form:

$$D_t^{\alpha} u = \frac{1}{2}\sigma^2 \frac{\partial^2 u}{\partial x^2} + \left(r - \frac{1}{2}\sigma^2\right)\frac{du}{dx} - ru(x,t), \quad -\infty < x < \infty, \quad 0 < t < T, \tag{1.1}$$

subject to the initial condition:

$$u\left(x, 0\right) = max\left\{e^x - 1, 0\right\},$$

Where $D_t^{\alpha} u$ is the Caputo fractional derivative with $0 < \alpha \leq 1$, $u(x,t)$ is the price of the option, r is the risk fee interested rate, σ is the volatility of the stock, and T is the expire date.

A lot of researchers used different method to derive the analytical solution of equation (1.1) See[14, 15, 16].

The outline of this article is as follows. In section 2 we present some basic definitions and properties of fractional calculus. In section 3 we give a brief introduction to Aboodh transform and some of its properties. In section 4 we give a basic idea of adomian decomposition method coupled with Aboodh transform. In section 5 the Aboodh decomposition method is applied to solve some examples of the Black-scholes equation. This paper ends in section 6 with conclusion.

2 Preliminaries

In this section we introduce definitions and present some known results of the fractional calculus.

Definition 2.1 The Riemann-Liouville fractional integral of order α for a continuous function $\varphi : [a,\infty] \to \mathbb{R}$ is defined by

$$\left({}_{RL}I_{0^+}^{q}\varphi\right)(t) = \frac{1}{\Gamma(\alpha)}\int_0^t (t-s)^{\alpha-1}\varphi(s)\,ds,$$

where

$$\Gamma(\alpha) = \int_0^\infty e^{-t}t^{\alpha-1}dt, \forall\alpha > 0,$$

is the Euler Gamma function.

Definition 2.2 The Caputo derivative of order α for a function $\varphi : [0,+\infty] \to R$ is defined as:

$$\left({}_{C}D_{0^+}^{\alpha}\varphi\right)(t) = \begin{cases} \int_0^t \frac{(t-s)^{n-\alpha-1}\varphi^{(n)}(s)}{\Gamma(n-\alpha)}ds, n-1<\alpha<n, \\ \varphi^{(n)}(t), \alpha \in N. \end{cases}$$

depends on the previous definition the following properties are holds:

$$D_t^\alpha I_t^\alpha \varphi(t) = \varphi(t), \ \ \alpha > 0,$$

$$I_t^\alpha D_t^\alpha \varphi(t) = \varphi(t) - \sum_{k=0}^{n-1}\varphi^k(0)\frac{t^k}{k!}, \ \ \alpha > 0, \ \ t > 0, \ \ n-1<\alpha<n, \ \ n \in \mathrm{N},$$

$$I_t^\alpha (t)^{\beta-1} = \frac{\Gamma(\beta)}{\Gamma(\beta+\alpha)}(t)^{\beta+\alpha-1}, \ \ \alpha > 0, \ \ \beta > 0 \ \ , t > 0,$$

$$D_t^\alpha (t)^{\beta-1} = \frac{\Gamma(\beta)}{\Gamma(\beta-\alpha)}(t)^{\beta-\alpha-1}, \ \ \alpha > 0, \ \ \beta > 0, \ \ t > 0.$$

3 Aboodh transform

Aboodh transform is derived from the classical Fourier integral. This transform defined for function of exponential order.

We consider functions in the set B defined by:

$$B = \left\{f(t) : \exists M, k_1, k_2 > 0, |f(t)| < Me^{-Vt}\right\},$$

the constant M must be finite number,k_1, k_2 my be finite or infinite. the Aboodh transform denoted by the operator $A(.)$ defined by integral equation in the form:

$$A\left[f\left(t\right)\right]=\frac{1}{v}\int_{0}^{\infty}f\left(t\right)e^{-vt}dt,t\geq 0,k_1\leq v\leq k_2, \tag{3.1}$$

from the definition of Aboodh transform and by simple calculation, we can obtain the following results:

$$A\left[1\right]=\tfrac{1}{v^2},$$

$$A\left[t^{\mu}\right]=\tfrac{\Gamma(\mu+1)}{v^{\mu+2}},\;\; 0\leq\mu,$$

$$A\left[e^{-at}\right]=\tfrac{1}{v^2+av},$$

$$A\left[\sin(at)\right]=\tfrac{a}{v(v^2+a^2)},$$

$$A\left[t^{\mu}\right]=\tfrac{\Gamma(\mu+1)}{v^{\mu+2}},\;\; 0\leq\mu,$$

$$A\left[u'\left(t\right)\right]=vA\left(u(t)\right)-\tfrac{u(0)}{v},$$

$$A\left[u''\left(t\right)\right]=v^2A\left(u(t)\right)-\tfrac{u^{'}(0)}{v}-u(0),$$

$$A\left[u^{(n)}\left(t\right)\right]=v^n\left[A\left(u(t)\right)-\sum_{k=0}^{n-1}\tfrac{u^{(k)}(0)}{v^{2+k}}\right].$$

for more about Aboodh transform see [22, 24, 25, 26].

4 The method of solution

To explain how the Aboodh decomposition method works, we consider the following non linear fractional differential equation:

$$D_t^{\alpha}u\left(x,t\right)=L\left(u\left(x,t\right)\right)+N\left(u\left(x,t\right)\right)+f\left(x,t\right) \tag{4.1}$$

with initial conditions

$D_0^k u\left(x,0\right)=f_k, k=0,\ldots .n-1.$
where $D_t^{\alpha}u\left(x,t\right)$ is the Caputo fractional operator, f is known function, L represents the linear differential operator and N is the nonlinear differential operator.
Taking the Aboodh transform for both side of equation (4.1), we get:

$$A[D_t^{\alpha}u\left(x,t\right)]=A[L(u(x,t))]+A[N(u(x,t))]+A[f(x,t)], \tag{4.2}$$

by using the properties of Aboodh transform and the initial conditions, we get:

$$v^{\alpha}\left[A\left[u\left(x,t\right)\right]-\sum_{k=0}^{m-1}v^{-k-2}u^{(k)}\left(x,0\right)\right]=A\left[L\left(u\left(x,t\right)\right)\right]+A\left[N\left(u\left(x,t\right)\right)\right]+A\left(f(x,t)\right). \tag{4.3}$$

Equation (4.3) can be written as:

$$A\left[u\left(x,t\right)\right]=v^{-\alpha}A\left[L\left(u\left(x,t\right)\right)\right]+v^{-\alpha}A\left[N\left(u\left(x,t\right)\right)\right]+v^{-\alpha}A\left(f(x,t)\right)+\sum_{k=0}^{m-1}v^{-k-2}u^{(k)}\left(x,0\right)$$

now,by taking the Aboodh inverse on both side of the previous equation , we have:

$$u(x,t) = F(x,t) + A^{-1}\left[v^{-\alpha}A\left[L\left(u\left(x,t\right)\right)\right] + v^{-\alpha}A\left[N\left(u\left(x,t\right)\right)\right]\right], \tag{4.4}$$

where $F(x,t)$ represent Aboodh inverse of $v^{-\alpha}A\left(f(x,t)\right) + \sum\limits_{k=0}^{m-1} v^{-k-2}u^{(k)}(x,0)$.
Now, assume that the solution of (4.1) can be expressed by the following infinite series:

$$u(x,t) = \sum_{n=0}^{\infty} u_n(x,t), \tag{4.5}$$

and the nonlinear term $Nu(x,t)$ is replaced by the series of the Adomian polynomials[1, 2] given by:

$$Nu(x,t) = \sum_{n=0}^{\infty} A_m(u_0, u_1, u_2, ...), \tag{4.6}$$

where,

$$A_m = \frac{1}{m!}\frac{d^m}{d\lambda^m}\left[N\left(\sum_{n=0}^{\infty}\lambda^n u_n(x,t)\right)\right]_{\lambda=0}, m = 0, 1, 2, ...,$$

substituting equations (4.5),(4.6) we get:

$$\sum_{n=0}^{\infty} u_n(x,t) = F(x,t) + A^{-1}\left[v^{-\alpha}A\left[L\left(\sum_{n=0}^{\infty} u_n(x,t)\right)\right] + v^{-\alpha}A\left[\sum_{n=0}^{\infty} A_m(u_0, u_1, u_2, ...)\right]\right], \tag{4.7}$$

equation (4.7) is the coupling of Aboodh transform and Adomian transform method.
comparing both side of equation 6 we obtain the general recursive relation:

$$u_0 = F(x,t),$$

$$u_1 = A^{-1}\left[v^{-\alpha}A\left[L\left(u_0(x,t)\right)\right] + v^{-\alpha}A\left[A_0\right]\right],$$

$$u_2 = A^{-1}\left[v^{-\alpha}A\left[L\left(u_1(x,t)\right)\right] + v^{-\alpha}A\left[A_1\right]\right],$$

$$u_{n+1} = A^{-1}\left[v^{-\alpha}A\left[L\left(u_n(x,t)\right)\right] + v^{-\alpha}A\left[A_m\right]\right], n \geq 0.$$

5 Applications

In this section we present some numerical results of solving the fractional black-scholes option pricing equation.

Example 1 consider the following Black-Scholes fractional differential equation[17]:

$$D_t^{\alpha}u(x,t) = D_x^2 u(x,t) + (k-1)D_x u(x,t) - ku(x,t), \tag{5.1}$$

subject to:

$$u\,(x,0) = max\,\{e^{x} - 1,\, 0\}\ .$$

Applying the Aboodh transform for both side of equation (5.1) we get:

$$A(D_t^{\alpha} u) = A(D_x^2 u + (k-1)\, D_x u - ku),$$

by using the property of Aboodh transform we get:

$$\begin{aligned} v^{\alpha}\left[A\left[u\ (x,t\ )\right] - \frac{1}{v^2}u(x,0)\right] &= A(D_x^2 u + (k-1)\, D_x u - ku), \\ A\left[u\ (x,t\ )\right] &= \frac{1}{v^2}u\,(x,0) + v^{-\alpha} A\left[D_x^2 u + (k-1)\, D_x u - k\ u\right], \end{aligned}$$

by applying the Aboodh inverse transform we get:

$$u\,(x,t) = max\,\{e^{x} - 1,\, 0\}\, + A^{-1}(v^{-\alpha} A\left[D_x^2 u + (k-1)\, D_x u - k\ u\right])\ , \tag{5.2}$$

we represent the approximated solution as:

$$u\,(x,t) = \sum_{n=0}^{\infty} u_n(x,t),$$

$$\sum_{n=0}^{\infty} u_n(x,t) = max\,\{e^{x} - 1,\, 0\}\, + A^{-1}(V^{-\alpha} A\left[D_x^2 \sum_{n=0}^{\infty} u_n + (k-1)\, D_x \sum_{n=0}^{\infty} u_n - k \sum_{n=0}^{\infty} u_n\right])\ ,$$

we get the following recursive relation:

$$\begin{cases} u_0 = max\,\{e^{x} - 1,\, 0\} \\ u_{n+1}(x,t) = A^{-1}\left[V^{-\alpha}\ (AD_x^2 u_n + (k-1)\, D_x u_n - ku_n\ )\right], \end{cases} \tag{5.3}$$

Now we obtain some few term from (5.3) as follows:

$$u_1(x,t) = A^{-1}\left[v^{-\alpha}\ A(D_x^2 u_0 + (k-1)\,D_x u_0 - k u_0\ )\right]$$

$$= A^{-1}\left[v^{-\alpha}\ A(D_x^2 max\,\{e^x - 1, 0\} + (k-1)\,D_x max\,\{e^x - 1, 0\} - k max\,\{e^x - 1, 0\}\ )\right]$$

$$= A^{-1}\left[v^{-\alpha}\ (\frac{1}{v^2} max\,\{e^x, 0\} + \frac{1}{v^2}\,(k-1)\,max\,\{e^x, 0\} - \frac{1}{v^2} k\,(max\,\{e^x - 1, 0\})\ )\right]$$

$$= A^{-1}\left[\frac{k}{v^{2+\alpha}} max\,\{e^x, 0\} - \frac{k}{v^{2+\alpha}}\,(max\,\{e^x - 1, 0\})\right]$$

$$= max\,\{e^x, 0\}\ \frac{kt^\alpha}{\Gamma(\alpha+1)} - max\,\{e^x - 1, 0\}\ \frac{kt^\alpha}{\Gamma(\alpha+1)}$$

$$= \frac{kt^\alpha}{\Gamma(\alpha+1)}\left[max\,\{e^x, 0\} - max\,\{e^x - 1, 0\}\right],$$

and

$$u_2(x,t) = A^{-1}\left[v^{-\alpha}\ A(D_x^2 u_1 + (k-1)\,D_x u_1 - k u_1\ )\right]$$

$$= -A^{-1}\left[v^{-\alpha}\ (\frac{k^2}{v^2} max\,\{e^x, 0\} - \frac{k^2}{v^2}\,(max\,\{e^x - 1, 0\})\ )\right]$$

$$= -A^{-1}\left[\frac{k^2}{v^{2+2\alpha}} max\,\{e^x, 0\} - \frac{k^2}{v^{2+2\alpha}}\,(max\,\{e^x - 1, 0\})\right]$$

$$= -max\,\{e^x, 0\}\ \frac{k^2 t^{2\alpha}}{\Gamma(2\alpha+1)} + max\,\{e^x - 1, 0\}\ \frac{k^2 t^{2\alpha}}{\Gamma(2\alpha+1)}$$

$$= \frac{-k^2 t^{2\alpha}}{\Gamma(\alpha+1)}\left[max\,\{e^x, 0\} - max\,\{e^x - 1, 0\}\right],$$

in the same manor we have:

$$u_n = \frac{(-1)^{n+1} k^n t^{n\alpha}}{\Gamma(n\alpha+1)}\ max\,\{e^x, 0\} - max\,\{e^x - 1, 0\}, \tag{5.4}$$

Hence our solution will be:

$$u(x,t) = \sum_{n=0}^{\infty} u_n(x,t)$$

$$= max\,\{e^x - 1, 0\} + \sum_{n=1}^{\infty} \frac{(-1)^{n+1} k^n t^{n\alpha}}{\Gamma(n\alpha+1)}\left[max\,\{e^x, 0\} - max\,\{e^x - 1, 0\}\right].$$

Figures 1 and 2 show the solution of problem (5.1) in Example 1 and the behaviour of $u(x,t)$with respect to x and t when $\alpha = 1$ and for fixed k

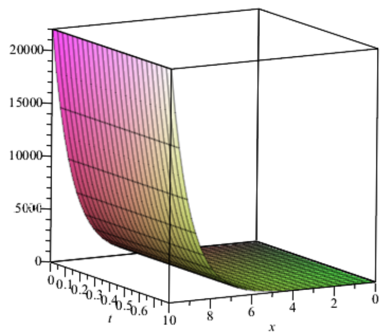

Figure 1: The surface shows the $u(x,t)$ for equation(5.1) at $k = 3$ and $\alpha = 1$

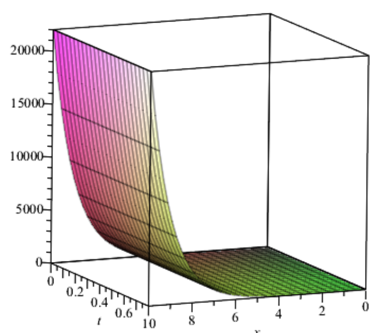

Figure 2: The approximate solution of $u(x,t)$ at $k = 3$ and $\alpha = 1$ when $n = 70$

Example 2 consider the Black-Scholes equation[18]:

$$D_t^\alpha u\,(x,t) + 0.08(2+\sin(x))^2 x^2 D_x^2 u\,(x,t) + 0.06 x D_x u\,(x,t) - 0.06u(x,t) = 0 \tag{5.5}$$

subject to the initial condition:

$$u(x,0) = \max\{x - 25e^{-0.06}, 0\}$$

applying the same procedure before , we get the following recursive relation:

$$\begin{cases} u_0 = \max\left\{x - 25e^{-0.06}, 0\right\} \\ u_{n+1}(x,t) = -A^{-1}\left[v^{-\alpha}\; A(0.08(2+\sin(x))^2 x^2 D_x^2 u_n + 0.06 D_x u_n - 0.06 u_n\;)\right] \end{cases}$$

from the previous relation we get:

$$u_1 = -\frac{0.06t^{\alpha}}{\Gamma(2\alpha+1)}\left[x - max\left\{x - 25e^{-0.06}, 0\right\}\right],$$

$$u_2 = -\frac{(0.06)^2 t^{2\alpha}}{\Gamma(2\alpha+1)}\left[x - max\left\{x - 25e^{-0.06}, 0\right\}\right],$$

$$u_n = -\frac{(0.06)^n t^{n\alpha}}{\Gamma(n\alpha+1)}\left[x - max\left\{x - 25e^{-0.06}, 0\right\}\right],$$

hence,the solution of equation (5.5)will be:

$$\begin{aligned} u\left(x,t\right) &= \sum_{n=0}^{\infty} u_n(x,t) \\ &= max\left\{x - 25e^{-0.06}, 0\right\} - \sum_{n=1}^{\infty} \frac{(0.06t)^{n\alpha}}{\Gamma(n\alpha+1)}\left[x - max\left\{x - 25e^{-0.06}, 0\right\}\right]. \end{aligned}$$

Figures 3 and 4 show the solution of problem (5.5) in Example 2 and the behaviour of $u(x,t)$ with respect to x and t when $\alpha = 1$ and for fixed k

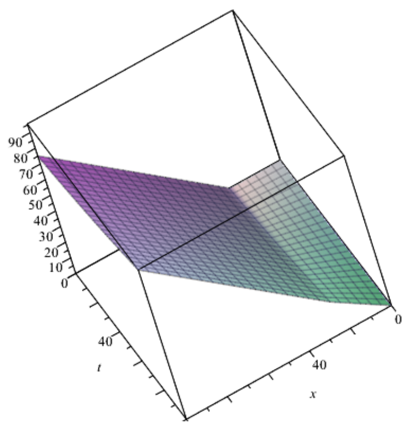

Figure 3: The surface shows the $u(x,t)$ for equation(5.5) at $k = 3$ and $\alpha = 1$

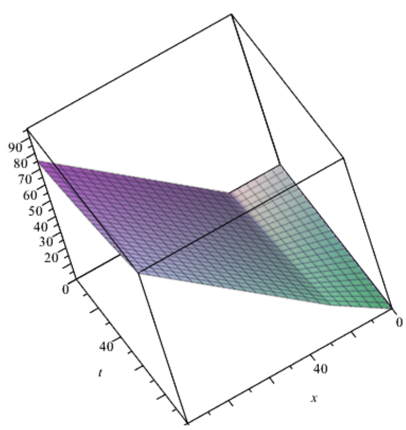

Figure 4: The approximate solution of $u(x,t)$ at $k = 3$ and $\alpha = 1$ when $n = 70$

6 Conclusions

In this paper the Aboodh Decomposition method is successfully applied to solve the Black-Scholes fractional differential equation with constant and non constant coefficients. Aboodh transform has deeper connection with the Laplace and Sumudu Transforms these three methods are powerful and efficient. Aboodh transform is a convenient tool for solving differential equations in the time domain without the need for performing an inverse Aboodh transform. In this study we present two examples from the literature. The results of the illustrated examples are in agreement with the results of the methods presented in [17, 18, 20]. We use the Maple program version 18 to plot the exact and approximate solutions of our problems (5.1) ,(5.5) depends on these 3D surface plots we make a comparison between our obtained results with their associated exact forms. This method can be used easily to solve higher order linear and nonlinear fractional differential equations,so this method is strongly recommended for solving fractional differential equations.

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