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A COLLOCATION TECHNIQUE BASED ON AN ORTHOGONAL POLYNOMIAL FOR SOLVING MULTI-FRACTIONAL ORDER INTEGRO DIFFERENTIAL EQUATIONS

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ABSTRACT

This paper deals with the construction of orthogonal polynomial functions and the application of same to solve multi-order fractional integro- differential equations. The method used in the work is referred to as the standard collocation method. The method assumes an approximate solution in which the constructed orthogonal polynomials are used as basis functions. The assumed solution is substituted into the general class of multi-order fractional integro-differential equations and the resulting equation is then collocated at equally spaced interior points, thus resulting in algebraic linear system of equations which are to be solved by Gaussian elimination method in order to obtain the unknown constants in the assumed solution. Some numerical examples are presented to illustrate the validity and applicability of the method. The results obtained using the method is shown on tables of result.

Keywords: Orthogonal functions, Weight functions and Multi-fractional order integro-differential equations.

1. INTRODUCTION

Orthogonal polynomial systems are very useful in many problems of approximation theory, mathematical and Numerical analysis and their applications. Orthogonal polynomials are special functions of mathematical physics. Fractional Calculus is a generalization of ordinary differentiation and integration to an arbitrary order. This class of calculus has been gaining some considerable attention in the recent years as researchers utilize it in solving problems in the field of Physics, Chemistry Engineering and Technology. It is worth noting that most problems of fractional integro differential equations cannot be solved analytically. Hence, good approximate solutions using numerical methods are usually employed to solve such problems. To this end, many numerical techniques have been developed and these include Homotopy Analysis Method (HAM), Adomian Decomposition Method (ADM), Variational Iteration Method (VIM) etc. Omar (2014) considered fractional integro differential equations as a very important class of integro differential equations where the differentiation and the integration appears in the equation of non integer order. He solved some multi fractional order integro differential equations using Variational Iterative Method (VIM).

Taiwo et al (2013) used iterative decomposition method to solve multi- term fractional differential equation. Ibtisam (2011) solved some multi fractional order integro differential equations using Homotopy Analysis Method. In this work an orthogonal system was developed and applied to solve multi fractional order integro differential equations.

1.1 Basic Definitions

Definition 1: Orthogonal Polynomial: A system S of elements of an inner product space is called orthogonal if $\langle y_n, y_m \rangle = 0$ for every $n \neq m$, ($y_n, y_m \in S$). If $\langle y_n, y_m \rangle \neq 0$ for each $n = m$, then the system is called orthonormal.

For orthogonality:

$$\langle y_n, y_m \rangle_w = \int_a^b w(x) y_n(x) y_m(x) dx = 0, \quad n \neq m, \quad (1)$$

The orthogonal polynomial of $y_n(x), y_m(x)$ on interval (a, b) with respect to the inner product of the form:

$$\langle y_n, y_m \rangle_w = \int_a^b w(x) y_n(x) y_m(x) dx, \quad (2)$$

are called the Classical orthogonal polynomials if their weight functions $w(x)$ satisfy the differential equation:

$$\text{where} \quad \frac{d}{dx}(A(x)w(x)) = B(x)w(x)$$

$$A(x) = \begin{cases} 1-x^2 & \text{if } (a, b) = (-1, 1) \\ x & \text{if } (a, b) = (0, +\infty) \\ 1 & \text{if } (a, b) = (-\infty, \infty) \end{cases} \quad (3)$$

and $B(x)$ is a polynomial of the first degree.

Definition 2: Multi-fractional order Integro-differential Equation- The general form of multi-fractional order integro-differential equation is given as:

$$D_t^\alpha y(x) = f(x) + J^{s_1} y(x) + J^{s_2} y(x) + J^{s_3} y(x) + \dots + J^{s_N} y(x) \quad (4)$$

where D_t^α and J^β are in the Caputo sense of the differential integral functions respectively, and α and β are parameters denoting the fractional order derivative and integral of the function respectively.

Some important properties of $D_t^\alpha f(t)$ and $J^\beta f(t)$ are:

$$D_t^\alpha t^n = \frac{\Gamma(n+1)}{\Gamma(n-\alpha+1)} t^{n-\alpha}$$

and

$$J^{-\alpha} t^n = \frac{\Gamma(n+1)}{\Gamma(n+\beta+1)} t^{n+\beta+1}$$

(5)

1.2 Construction of Orthogonal Polynomials

Here, we constructed orthogonal polynomials using a basic quadratic weighted functions $w(t) = t^2 - t + 1$.

The first few numbers of the orthogonal polynomials then constructed using the weight function $w(t) = t^2 - t + 1$, $0 \leq t \leq 1$, are

$$P_0(t) = 1$$

$$P_1(t) = (2t - 1)$$

$$P_2(t) = \frac{1}{4}(25t^2 - 25t + 4)$$

$$P_3(t) = \frac{1}{2}(-42t^3 - 63t^2 + 25t - 2)$$

$$P_4(t) = \frac{1}{29}(2142t^4 - 4284t^3 + 2744t^2 - 602t + 29)$$

$$P_5(t) = \frac{1}{49}(13068t^5 - 32670t^4 + 28980t^3 - 10800t^2 + 1520t - 49)$$

(6)

1.3 Bernstein Polynomials

2. METHODOLOGY

Here, we consider multi-fractional order integro-differential equation of the form (4).

We assumed an approximate solution of the form:

$$y_N(t) = \sum_{i=0}^N c_i P_i(t)$$

(7)

where $c_i, i = 0(1)N$ are unknown constants to be determined and $P_i(t)$ are the orthogonal polynomials constructed using the three different weight functions, $w(t)$, earlier mentioned. Substituting (7) into (4), we have

$$c_i D_t^\alpha \sum_{i=0}^N P_i(t) = f(x) + k(x, t) c_i J^{\beta_1} \sum_{i=0}^N P_i(t) + k(x, t) c_i J^{\beta_2} \sum_{i=0}^N P_i(t) + k(x, t) c_i J^{\beta_3} \sum_{i=0}^N P_i(t) + \dots + k(x, t) c_i J^{\beta_N} \sum_{i=0}^N P_i(t) \quad (8)$$

Thus, (8) simplifies further to:

$$c_0 D_t^\alpha (P_0(t)) + c_1 D_t^\alpha (P_1(t)) + c_2 D_t^\alpha (P_2(t)) + \dots + c_N D_t^\alpha (P_N(t)) = f(x) + c_0 J^{\beta_1} (P_0(t)) + c_1 J^{\beta_1} (P_1(t)) + c_2 J^{\beta_1} (P_2(t)) + \dots + c_N J^{\beta_1} (P_N(t)) + c_0 J^{\beta_2} (P_0(t)) + c_1 J^{\beta_2} (P_1(t)) + c_2 J^{\beta_2} (P_2(t)) + \dots + c_N J^{\beta_2} (P_N(t)) + \dots \quad (9)$$

Applying the fractional differential operator, D_t^α , and the integral operator, J^β , to

equation (9) leads to:

$$c_0 \frac{\Gamma(n-1)}{\Gamma(n-\alpha-1)} t^{n-\alpha-1} + c_1 \frac{\Gamma(n-1)}{\Gamma(n-\alpha-1)} t^{n-\alpha-1} + c_2 \frac{\Gamma(n-1)}{\Gamma(n-\alpha-1)} t^{n-\alpha-1} + \dots + c_N \frac{\Gamma(n-1)}{\Gamma(n-\alpha-1)} t^{n-\alpha-1} = f(x) + c_0 \frac{\Gamma(n+1)}{\Gamma(n+\beta_1+1)} t^{n+\beta_1} + c_1 \frac{\Gamma(n+1)}{\Gamma(n+\beta_1+1)} t^{n+\beta_1} + c_2 \frac{\Gamma(n+1)}{\Gamma(n+\beta_1+1)} t^{n+\beta_1} + \dots + c_N \frac{\Gamma(n+1)}{\Gamma(n+\beta_1+1)} t^{n+\beta_1} + c_0 \frac{\Gamma(n+1)}{\Gamma(n+\beta_2+1)} t^{n+\beta_2} + c_1 \frac{\Gamma(n+1)}{\Gamma(n+\beta_2+1)} t^{n+\beta_2} + c_2 \frac{\Gamma(n+1)}{\Gamma(n+\beta_2+1)} t^{n+\beta_2} + \dots + c_N \frac{\Gamma(n+1)}{\Gamma(n+\beta_2+1)} t^{n+\beta_2} + \dots \quad (10)$$

where, from equation (5), n indicates the power of t in the individual terms of the orthogonal polynomials. Equation (10) is collocated at equally spaced interior points; $t_i = (b-a)/N$, ($i = 0(1)N$), to give $(N+1)$ linear equations in $(N+1)$ unknown constants which are put in the forms:

$$\begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1m} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & A_{m3} & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \\ \vdots \\ c_{m-1} \end{pmatrix} = \begin{pmatrix} B_{11} \\ B_{22} \\ \vdots \\ B_{mm-1} \end{pmatrix} \quad (11)$$

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where A_{is} are the coefficients of C_{is} and B_{is} are the values $f(t_i)$.

These $(N+1)$ linear equations are then solved using the Gaussian elimination method

to obtain the unknown constants $c_i, (i = 0(1)N)$, and which are then substituted back into the approximate solution to give the required approximate solution.

3. NUMERICAL EXAMPLES

-We present some examples to illustrate the method.

Example 1

Consider the initial value problem that consists of the multi-fractional order nonlinear integro differential equation:

$$D^{0.75}y(t) = \frac{1}{\Gamma(1.25)}t^{0.25} - \frac{2}{\Gamma(3.75)}t^{2.75} + J^{0.75}y^2(t) \quad t \in [0, 1] \quad (12)$$

together with the initial condition; $y(t) = 0$ The exact solution is $y(t) = t$. We use orthogonal polynomial basis function with weight function $w(t) = t^2 - t + 1$ to solve this IVP of multi fractional order differential problem for $N = 2$ by assuming an approximate solution of the form (7). We apply $D^{0.75}$ and $J^{0.75}$ to (12), to have

$$\begin{aligned} c_0 \frac{\Gamma 1}{\Gamma \frac{1}{4}} t^{-\frac{3}{4}} + c_1 \left(2 \frac{\Gamma 2}{\Gamma \frac{5}{4}} t^{\frac{1}{4}} - \frac{\Gamma 1}{\Gamma \frac{1}{4}} t^{-\frac{3}{4}} \right) + \frac{c_2}{4} \left(25 \frac{\Gamma 3}{\Gamma \frac{9}{4}} t^{\frac{5}{4}} - 25 \frac{\Gamma 2}{\Gamma \frac{5}{4}} t^{\frac{1}{4}} + \right. \\ \left. 4 \frac{\Gamma 1}{\Gamma \frac{1}{4}} t^{-\frac{3}{4}} \right) = \frac{1}{\Gamma(\frac{5}{4})} t^{\frac{1}{4}} - \frac{2}{\Gamma(\frac{15}{4})} t^{\frac{11}{4}} + (c_0^2 - 2c_0c_1 + c_1^2 - 2c_1c_2 + c_2^2) \frac{\Gamma 1}{\Gamma \frac{1}{4}} t^{\frac{3}{4}} \\ + (-4c_1^2 - \frac{25}{2}c_0c_2 + 4c_0c_1 + \frac{33}{2}c_1c_2 - \frac{25}{2}c_2^2) \frac{\Gamma 2}{\Gamma \frac{5}{4}} t^{\frac{5}{4}} + (4c_1^2 + \frac{25}{2}c_0c_2 - \frac{55}{2}c_1c_2 + \frac{25}{16}c_2^2) \frac{\Gamma 3}{\Gamma \frac{9}{4}} t^{\frac{9}{4}} \\ + (25c_1c_2 - \frac{625}{8}c_2^2) \frac{\Gamma 4}{\Gamma \frac{13}{4}} t^{\frac{13}{4}} + \frac{625}{2}c_2^2 \frac{\Gamma 5}{\Gamma \frac{17}{4}} t^{\frac{17}{4}} \quad (13) \end{aligned}$$

Equation (13) is collocated at equally spaced points of $[0,1]$, to obtain:

$$c_0 = 0.499999979, c_1 = 0.5000000000, c_2 = -4.6319682218e^{-10}$$

Substituting these values into assumed solution, we have the approximate solution,

$$y_2(t) = -2563196822e^{-9} + 1.0000000003t - 2.894980135e^{-9}t^2$$

Table 1: Numerical Results for Example 1.

x	Exact	Approximate	Error
0.0	0.0000000000	-0.0000000026	2.5632e-09
0.1	0.1000000000	0.0999999977	2.2921e-09
0.2	0.2000000000	0.1999999979	2.0790e-09
0.3	0.3000000000	0.2999999980	1.9237e-09
0.4	0.4000000000	0.3999999981	1.8264e-09
0.5	0.5000000000	0.4999999982	1.7869e-09
0.6	0.6000000000	0.5999999982	1.8054e-09
0.7	0.7000000000	0.6999999981	1.8817e-09
0.8	0.8000000000	0.7999999979	2.0160e-09
0.9	0.9000000000	0.8999999978	2.2081e-09
1.0	1.0000000000	0.9999999971	2.4582e-09

Example 2: Consider the initial value problem that consists of the multi-fractional order integro differential equation

$$D^{\alpha} y(t) = \frac{6}{\Gamma(3.5)} t^{2.5} - \frac{\Gamma(4)}{\Gamma(5.5)} t^{4.5} + J^{1.5} y(t) - t^2 \quad (11)$$

tion is $y(t) = t^3$. We use orthogonal polynomial

n $w(t) = t^2 - t + 1$ to solve this IVP of multi-fractional

4 by assuming an approximate solution of the form(7).

nd then follow the same procedure, to obtain:

$$y(t) = 2.36 - 7t^2 + 0.9999999153t^3 + 7.601117908e - 29t^4$$

Table 2: Numerical Results for Example 2.

x	Exact	Approximate	Error
0.0	0.0000000000	0.0000000016	1.5629e-09
0.1	0.0010000000	0.0010000009	9.3897e-10
0.2	0.0080000000	0.0080000005	4.5717e-10
0.3	0.0270000000	0.0269999998	1.8242e-10
0.4	0.0640000000	0.0639999987	1.2633e-09
0.5	0.1250000000	0.1249999970	3.0495e-09
0.6	0.2160000000	0.2159999942	5.7872e-09
0.7	0.3430000000	0.3429999902	9.7042e-09
0.8	0.5120000000	0.5119999850	1.5010e-08
0.9	0.7290000000	0.7289999781	2.1896e-08
1.0	1.0000000000	0.9999999695	3.0536e-08

Example 3: Consider the initial value problem that consists of the multi-fractional order integro-differential equation:

$$D^{\frac{1}{2}} y(t) = \frac{6}{\Gamma(\frac{7}{2})} t^{\frac{5}{2}} - \frac{6}{\Gamma(\frac{9}{2})} t^{\frac{7}{2}} - \frac{6}{\Gamma(\frac{11}{2})} t^{\frac{9}{2}} + J^{\frac{1}{2}} y(t) + J^{\frac{3}{2}} y(t), \quad t \in [0, 1] \quad (15)$$

together with the initial condition; $y(0) = 0$.

Exact solution is $y(t) = t^3$.

We use orthogonal polynomial basis function with weight function $w(t) = t^2 - t + 1$ to solve this IVP of multi-fractional order differential problem for $N = 4$ by assuming an approximate solution of the form (7)

The same procedure was followed for $N = 4$ and we obtained:

$$y_4(t) = 3.042988983e^{-9} - 1.3e^{-8}t + 4.6e^{-7}t^2 + .9999999487t^3 + 2.161077249e^{-7}t^4$$

Table 3: Numerical Results for Example 3.

x	Exact	Approximate	Error
0.0	0.0000000000	0.0000000030	3.0430e-09
0.1	0.0010000000	0.0010000022	2.1539e-09
0.2	0.0080000000	0.0080000019	1.9072e-09
0.3	0.0270000000	0.0270000021	2.0732e-09
0.4	0.0640000000	0.0640000025	2.4738e-09
0.5	0.1250000000	0.1250000030	2.9830e-09
0.6	0.2160000000	0.2160000035	3.5268e-09
0.7	0.3430000000	0.3430000011	4.0830e-09
0.8	0.5120000000	0.5120000017	4.6814e-09
0.9	0.7290000000	0.7290000054	5.4038e-09
1.0	1.0000000000	1.0000000060	6.3838e-09

4. CONCLUSION

We applied specially constructed orthogonal polynomials to solve multi fractional order integro differential equations. The method was used to solve both linear and nonlinear form of integro differential equations and from the results obtained using the constructed orthogonal polynomial, we can conclude that these solutions agreed closely with the exact solution.

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