International Journal of
Education, Management, and Technology

e-ISSN : 3026-5444
p-ISSN : 3026-4200
Index: Harvard, Boston, Sydney University, Copernicus, Lens, Scilit, Semantic, Dimensions, etc

https://doi.org/10.58578/IJEMT.v4i1.8717

A Novel Computational Framework for Nonlinear Differential Equations Employing the Modified Laplace Adomian Polynomial Method

Salisu Lukunti[1], Umar Mujahid Aliyu[2], Abubakar Assidiq Hussaini[3], Imafidor Hassan Ibrahim[4], Mohammed Abubakar Kolo[5], Sulaiman Ahmad[6], Nura Hashim[7], Mohammed Yusuf Marafa[8]

[1]Federal Polytechnic Bauchi, Bauchi State, Nigeria; [2,4,5,6,7,8]Federal Polytechnic Kaltungo, Gombe State, Nigeria; [3]Abubakar Tafawa Balewa University, Bauchi, Nigeria

salisul@fptb.edu.ng; umaraliyumujahid@gmail.com

Article Info:

Submitted:	Revised:	Accepted:	Published:
Feb 13, 2026	Mar 13, 2026	Mar 25, 2026	Mar 30, 2026

Abstract

Nonlinear differential equations arise widely in applied mathematics, physics, and engineering, yet many conventional analytical and numerical methods remain limited in their ability to handle strong nonlinearities efficiently and accurately. This paper presents a novel computational framework based on the Modified Laplace–Adomian Polynomial Method (LAPM) for solving nonlinear differential equations. The proposed method integrates the Laplace transform with an enhanced form of the Adomian Decomposition Method, enabling complex nonlinear terms to be decomposed into rapidly convergent Adomian polynomials. This integration simplifies the solution procedure, reduces computational complexity, and preserves high accuracy. The performance of LAPM was validated using several benchmark nonlinear and linear differential equations, and the results demonstrated superior convergence speed, precision, and stability compared with traditional methods. The study concludes that the Modified Laplace–Adomian Polynomial Method is a reliable and efficient approach for solving a broad class of nonlinear differential equations. This work contributes to the advancement of computational methods by offering a robust alternative for the analysis of differential equation models encountered in mathematics, physics, and engineering.

Keywords: Laplace Transform; Adomian Decomposition Method; Nonlinear Differential Equations; Convergence Analysis; Computational Mathematics

Introduction

The Laplace transform is a widely applied analytical tool for solving differential equations, especially initial value problems in engineering and physics. Its main advantage is that it converts differential equations into algebraic equations in the Laplace (frequency) domain, which are simpler to solve before being transformed back into the time domain. This approach is particularly effective for linear differential equations with either constant or variable coefficients (Khuri, 2001; Fadaei, 2011). Nevertheless, the traditional Laplace transform faces challenges when dealing with nonlinear differential equations, as its linear nature prevents it from directly managing nonlinear terms (Adomian, 1988; Cherruault, 1989). For instance, terms like $u^2, e^u, uu_x or \sin u$ cannot be easily transformed and manipulated within the Laplace framework.

To overcome this limitation, researchers have sought to combine the Laplace transform with nonlinear decomposition techniques. One of the most powerful and well-established methods for nonlinear problems is the Adomian Decomposition Method (ADM), originally introduced by Adomian (1988) and further developed in later works (Cherruault & Adomian, 1989; Li & Pang, 2020). ADM provides a way to represent the nonlinear part of a differential equation as an infinite series of Adomian polynomials, which are recursively generated from the components of the solution series. The method avoids perturbation, linearization, or small-parameter assumptions, making it applicable to a wide range of nonlinear problems, including ordinary differential equations (ODEs), partial differential equations (PDEs), and even fractional differential equations (FDEs) (Odibat, 2020; Ziane et al., 2019).

The Laplace-Adomian Decomposition Method (LADM), first proposed by Khuri (2001) and later extended by Fadaei (2011), integrates the Laplace transform with ADM. In this hybrid approach, the Laplace transform is applied to the linear part of the differential equation, while the nonlinear part is expressed in terms of Adomian polynomials. This technique has been successfully used to solve many nonlinear problems, including the Duffing oscillator (Khuri, 2001), nonlinear optical solitons (González-Gaxiola & Biswas, 2019), and systems of nonlinear PDEs (Fadaei, 2011).

However, despite its effectiveness, LADM still suffers from slow convergence and accumulation of truncation errors, especially in the case of highly nonlinear or stiff systems (Gündoğdu & Gözükızıl, 2017). To address these issues, Aland and Singh (2022) proposed the Laplace Transform Modified Adomian Decomposition Method (LT-MADM). This method improves the convergence rate by introducing a modified way of constructing the Adomian polynomials and refining the recursive formulation. Their work demonstrated that LT-MADM yields solutions that are closer to exact solutions and requires fewer terms for high accuracy compared to LADM.

The Adomian Decomposition Method (ADM), introduced by George Adomian (1988), provides an efficient semi-analytical technique for solving nonlinear differential equations without requiring linearization, perturbation, or small-parameter assumptions. ADM expresses the solution as a rapidly converging infinite series and approximates nonlinear terms using Adomian polynomials. The method has been successfully applied to ordinary differential equations (ODEs), partial differential equations (PDEs), fractional differential equations (FDEs), and integral equations (Cherruault & Adomian, 1989; Odibat, 2020). Li and Pang (2020) analyzed convergence properties of ADM and showed its effectiveness in solving nonlinear systems. Ziane et al. (2019) proposed a modified version of ADM to improve accuracy in nonlinear PDEs. González-Gaxiola and Biswas (2019) applied ADM to nonlinear optical soliton models. However, while ADM is powerful, it can sometimes converge slowly, especially for stiff or strongly nonlinear systems.

To combine the strengths of both the Laplace transform and ADM, Khuri (2001) proposed the Laplace Adomian Decomposition Method (LADM). In this hybrid method, the Laplace transform is applied to handle the linear part of the differential equation, while Adomian polynomials are used to decompose and approximate the nonlinear part. This approach has been applied to various nonlinear models: Khuri (2001) successfully solved the Duffing oscillator equation using LADM. Fadaei (2011) extended LADM to systems of linear and nonlinear PDEs. Gündoğdu and Gözükızıl (2017) applied LADM to nonlinear PDEs and compared it with the modified decomposition method and standard ADM, showing reasonable accuracy. Despite these successes, LADM sometimes suffers from slow convergence and accumulation of truncation errors, making it less effective for highly nonlinear or stiff problems.

To address the limitations of LADM, Aland and Singh (2022) introduced the Laplace Transform Modified Adomian Decomposition Method (LT-MADM). This method modifies the construction of Adomian polynomials and improves the recursive scheme, yielding better accuracy and faster convergence compared to standard LADM. LT-MADM has been successfully applied to nonlinear partial differential equations, where graphical comparisons with exact solutions demonstrated its effectiveness.

While LT-MADM has proven effective for PDEs, its application to a broader class of nonlinear ordinary and partial differential equations has not been extensively explored. Additionally, systematic comparisons of LT-MADM with LADM in terms of convergence behavior, computational efficiency, and error analysis remain limited. This research seeks to fill these gaps by applying LT-MADM to selected nonlinear ODEs and PDEs, thus extending its applicability and validating its efficiency.

The Laplace transform is a powerful tool for solving linear differential equations, but it cannot directly handle nonlinear terms due to its linearity (Khuri, 2001). To overcome this, the Adomian Decomposition Method (ADM) was introduced to decompose nonlinear terms into a rapidly convergent series of Adomian polynomials (Adomian, 1988). The combined Laplace Adomian Decomposition Method (LADM) has been used for nonlinear problems but often suffers from slow convergence and truncation errors for highly nonlinear systems (Gündoğdu & Gözükızıl, 2017).

The recently proposed Laplace Transform Modified Adomian Decomposition Method (LT-MADM) (Aland & Singh, 2022) improves convergence and accuracy but has been applied mostly to partial differential equations. There is, therefore, a need to extend and test LT-MADM for a wider class of nonlinear ordinary and partial differential equations to provide accurate and efficient numerical solutions.

Methodology

Basics of the Laplace Transform Method (LTM)

The Laplace Transform is an integral transform that converts a function $f(t)$, defined for $t > 0$, into a complex frequency-domain function $F(s)$. It is defined as:

$$L\{f(t)\} = F(s) = \int_0^\infty e^{-st} f(t)dt \qquad ...(2)$$

The inverse Laplace transform is expressed as: $L^{-1}\{F(s)\} = f(t)$ ...(3)

The method is highly effective for solving linear differential equations with initial conditions, as it transforms differentiation into simple algebraic manipulation.

Properties of the Laplace Transform

Some important properties that make the Laplace transform suitable for solving differential equations are:

i. Linearity:

$$L\{af(t) + bg(t)\} = aF(s) + bF(s)$$

ii. Differentiation in Time Domain:

$$L\left\{\frac{df(t)}{dt}\right\} = sF(s) - f(0)$$

iii. Higher-Order Derivatives:

$$L\left\{\frac{d^n f(t)}{dt^n}\right\} = s^n F(s) - s^{n-1} f(0) - s^{n-2} f'(0) - ... - f^{(n-1)}(0)$$

iv. Integration in Time Domain:

$$L\left\{\int_0^t f(\tau)d\tau\right\} = \frac{1}{s}F(s)$$

These properties allow differential equations to be rewritten as algebraic equations in the s-domain.

Solving Linear Differential Equations Using LTM

Consider a general linear differential equation:

$$a_n \frac{d^n y}{dt^n} + a_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + ... + a_0 y = g(t), \; y(0), y'(0), ..., y^{(n-1)}(0) \qquad ...(4)$$

Applying the Laplace transform to both sides and using the differentiation property:

$$a_n\left[S^nY(s) - S^{n-1}y(0) - \ldots - y^{(n-1)}(0)\right] + \ldots + a_0Y(s) = G(s) \qquad \ldots(5)$$

Solving for $Y(s)$:

$$Y(s) = \frac{G(s) + terms \quad involving \quad initial \quad conditions}{a_nS^n + a_{n-1}S^{n-1} + \ldots + a_0} \qquad \ldots(6)$$

Finally, applying the inverse Laplace transform yields the solution $y(t)$.

Adomian Decomposition Method (ADM)

Let the nonlinear DE be of the form:

$$Dy(t) = g(t) + Ny(t) + Ry(t) \qquad \ldots(7)$$

with initial condition $y(0) = c$. In ADM, the solution $y(t)$ is decomposed into a series:

$$y(t) = \sum_{n=0}^{\infty} y_n(t) \qquad \ldots(8)$$

and the nonlinear term $Ny(t)$ is expanded using Adomian polynomials A_n:

$$N(y(t)) = \sum_{n=0}^{\infty} A_n(t) \qquad \ldots(8)$$

where each Adomian polynomial A_n is generated using:

$$A_n(y_0 + y_1 + y_2, \ldots, y_n) = \frac{1}{n!}\frac{d^n}{d\lambda^n}\left[N\left(\sum_{k=0}^{n} \lambda^k y_k\right)\right]_{\lambda=0, n-0,1,2,\ldots} \qquad \ldots(9)$$

where λ is a parameter. The Adomian polynomial A_n can be defined as follows:

$$A_0 = \frac{1}{0!}\frac{d^0}{d\lambda^0}\left[N\left(\sum_{k=0}^{0} \lambda^k y_k\right)\right]_{\lambda=0..} = N(y_0),$$

$$A_1 = \frac{1}{1!}\frac{d^1}{d\lambda^1}\left[N\left(\sum_{k=0}^{1} \lambda^k y_k\right)\right]_{\lambda=0..} = y_1 N'(y_0),$$

$$A_2 = \frac{1}{2!}\frac{d^2}{d\lambda^2}\left[N\left(\sum_{k=0}^{2} \lambda^k y_k\right)\right]_{\lambda=0..} = y_2 N'(y_0) + \frac{y_1^2}{2!} N''(y_0)$$

$$\vdots$$

Laplace-Adomian polynomial Framework

Applying the Kamal transform to the given FDE:

$$L[Dy(t)] = L[g(t)] + L[Ny(t)] + L[R(t)] \qquad \ldots(10)$$

Using the property of the Laplace transform:

$$L[Dy(t)] = s^n L\{y(t)\} - s^{n-1}L\{y(0)\} - -s^{n-2}L\{y''(0)\} - s^{n-3}L\{y(0)\}... - y^{(n-1)}(0) \quad ...(11)$$

For $D = 1$, we get $SY(S) - y(0)$, and we obtain the following:

$$SY(S) - y(0) = L[g(t)] + L[A_n] + L[R(t)] \quad ...(12)$$

$$Y(S) = \frac{1}{s}\left(y(0) + L[g(t)] + L[A_n] + L[R(t)]\right)$$

Taking the inverse Laplace transform gives:

$$y(t) = y(0) + L^{-1}\left[\frac{1}{s}\left(L[g(t)] + L[A_n] + L[R(t)]\right)\right]. \quad ...(13)$$

Recursive Scheme

We define the recursive components of the solution as:

$$\begin{cases} y_0(t) = y(0) + L^{-1}\left[\frac{1}{s}\left(L[g(t)]\right)\right], \\ y_{n+1}(t) = L^{-1}\left[\frac{1}{s}\left(L[A_n] + L[R(t)]\right)\right], n = 0,1,2,... \end{cases} \quad ...(14)$$

Each A_n depends on the previous terms $y_0, y_1, y_2, ..., y_n$ and the process is repeated iteratively to construct the approximate solution:

$$y(t) \approx \sum_{n=0}^{N} y_n(t) \quad ...(15)$$

where N is chosen based on convergence or required accuracy.

Results from Nonlinear Differential Equations

Example 1

Given the fractional differential equation as follows:

$$y'(t) = y^2(t) + 1, \qquad t > 0, \quad ...(16)$$

With the initial condition

$$y(0) = 0 \quad ...(17)$$

And the exact solution

$$y(t) = \tan(t). \quad ...(18)$$

Using the recursive formulas in Eqn. (13) and (14), the approximate solution to the differential Eqn. (16) is derived through the combined method of the Adomian polynomial and the Laplace transformation, as follows:

$$\begin{cases} y_0(t) = L^{-1}\left[\frac{1}{s}L\{1\}\right], \\ y_{n+1}(t) = L^{-1}\left[\frac{1}{s}\left\{L\sum_{n=0}^{\infty} A_n(t)\right\}\right], \quad n = 0,1,2,... \end{cases} \quad ...(19)$$

where A_n is the Adomian polynomial of the nonlinear operator $Ny = y^2$, which can be described as follows

$$\begin{cases} A_0 = y_0^2, \\ A_1 = 2y_0 y_1, \\ A_1 = 2y_0 y_2 + y_1^2, \\ \vdots \end{cases} \quad ...(20)$$

The following is a description of the solution to the Eqn. (19):

$$y_0(t) = L^{-1}\left[\frac{1}{s}L[1]\right] = t,$$

$$y_1(t) = L^{-1}\left[\frac{1}{s}L[A_0]\right] = \frac{1}{3}t^3$$

$$y_2(t) = L^{-1}\left[\frac{1}{s}L[A_1]\right] = L^{-1}\left[\frac{1}{s}L2y_0y_1\right] = \frac{2}{15}t^5$$

$$y(t) = y_0(t) + y_1(t) + y_2(t) + ... = t + \frac{1}{3}t^3 + \frac{2}{15}t^5 + ... \quad ...(21)$$

Table 1: Computations showing comparison between the exact solution and the LAPM solution of example 1

t	Exact Solution	LAPM (n=3)	Absolute Error
0	0	0	0
0.1	0.100334672	0.100334672	2.77556E-17
0.2	0.202710036	0.202710036	4.85167E-14
0.3	0.30933625	0.30933625	2.16804E-11
0.4	0.422793219	0.422793217	1.67159E-09
0.5	0.54630249	0.54630244	4.94376E-08
0.6	0.684136808	0.684136007	8.01444E-07
0.7	0.84228838	0.842279756	8.62437E-06
0.8	1.029638557	1.029569395	6.9162E-05

0.9	1.260158218	1.259711984	0.000446233
1	1.557407725	1.554959773	0.002447952

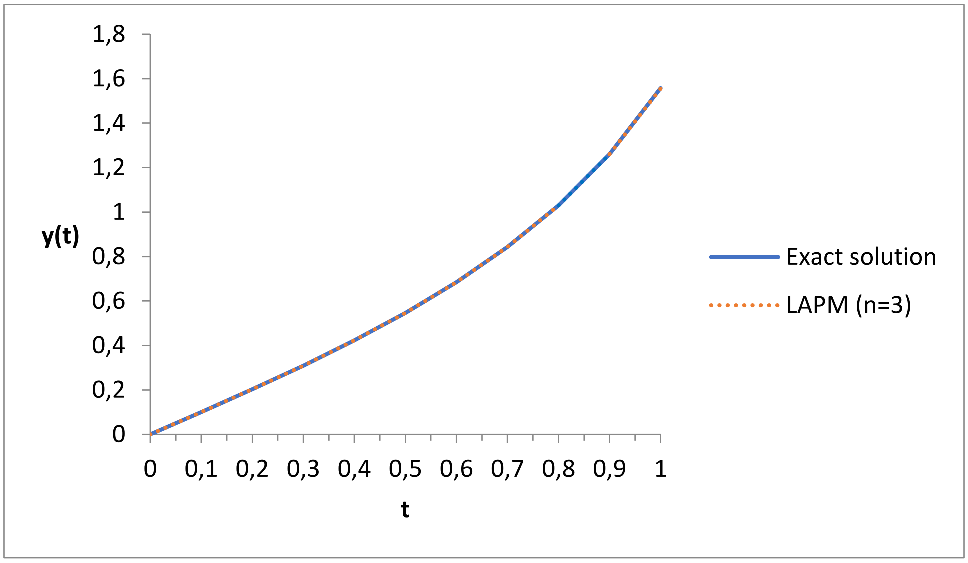

Figure 1: Graph of the LAPM and the exact solution for example 1

Table 2: Comparison between the exact solutions, the LAPM and the DTM for example 1

t	Exact solution	LAPM (n=3)	DTM (n=6)
0	0	0	0
0.1	0.100334672	0.10033467	0.100335
0.2	0.202710036	0.20271004	0.202709
0.3	0.30933625	0.30933625	0.309324
0.4	0.422793219	0.42279322	0.422699
0.5	0.54630249	0.54630244	0.545833
0.6	0.684136808	0.68413601	0.682368
0.7	0.84228838	0.84227976	0.836743
0.8	1.029638557	1.0295694	1.014357
0.9	1.260158218	1.25971198	1.221732
1	1.557407725	1.55495977	1.466667

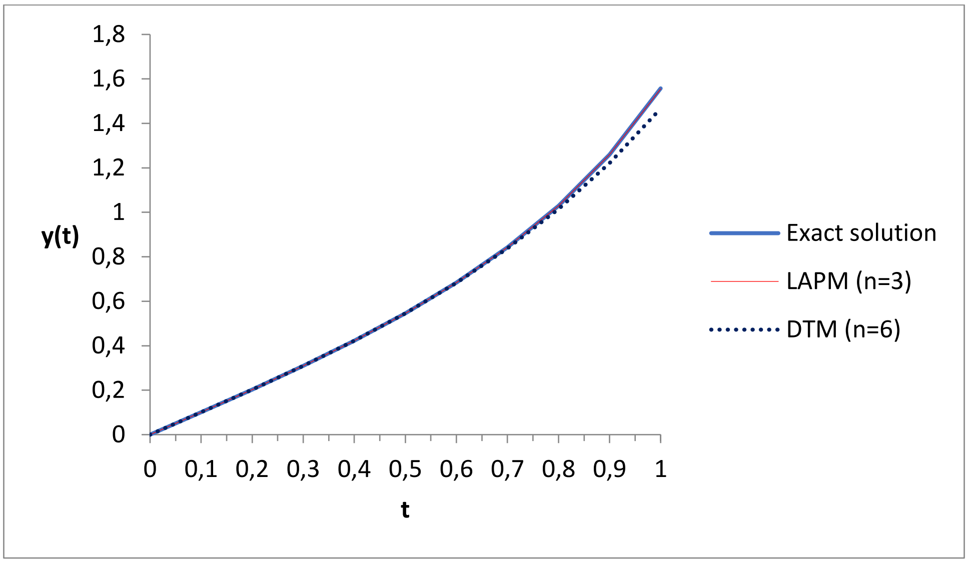

Figure 2: Graph of the LAPM, DTM and the exact solution for example 1

Example 2

Given the fractional differential equation as follows [(Opanuga *et al.*, 2015)]:

$$y'(t) = 1 - y^2(t), \qquad t > 0, \qquad ...(22)$$

With the initial condition

$$y(0) = 0 \qquad ...(23)$$

And the exact solution

$$y(t) = \frac{e^{2t} - 1}{e^{2t} + 1}. \qquad ...(24)$$

Using the recursive formulas in Eqn. (13) and (14), the approximate solution to the differential Eqn. (22) is derived through the combined method of the Adomian polynomial and the Laplace transformation, as follows:

$$\begin{cases} y_0(t) = L^{-1}\left[\frac{1}{s} L\{1\}\right], \\ y_{n+1}(t) = -L^{-1}\left[\frac{1}{s}\left\{L\sum_{n=0}^{\infty} A_n(t)\right\}\right], n = 0,1,2,... \end{cases} \qquad ...(25)$$

where A_n is the Adomian polynomial of the nonlinear operator $Ny = y^2$, which can be described as follows

$$\begin{cases} A_0 = y_0^2, \\ A_1 = 2y_0y_1, \\ A_1 = 2y_0y_2 + y_1^2, \\ \vdots \end{cases} \quad ...(26)$$

The following is a description of the solution to the Eqn. (25):

$$y_0(t) = L^{-1}\left[\frac{1}{s}L[1]\right] = t,$$

$$y_1(t) = L^{-1}\left[\frac{1}{s}L[A_0]\right] = -\frac{1}{3}t^3$$

$$y_2(t) = L^{-1}\left[\frac{1}{s}L[A_1]\right] = L^{-1}\left[\frac{1}{s}L2y_0y_1\right] = \frac{2}{15}t^5$$

$$y(t) = y_0(t) + y_1(t) + y_2(t) + ... = t - \frac{1}{3}t^3 + \frac{2}{15}t^5 + ... \quad ...(27)$$

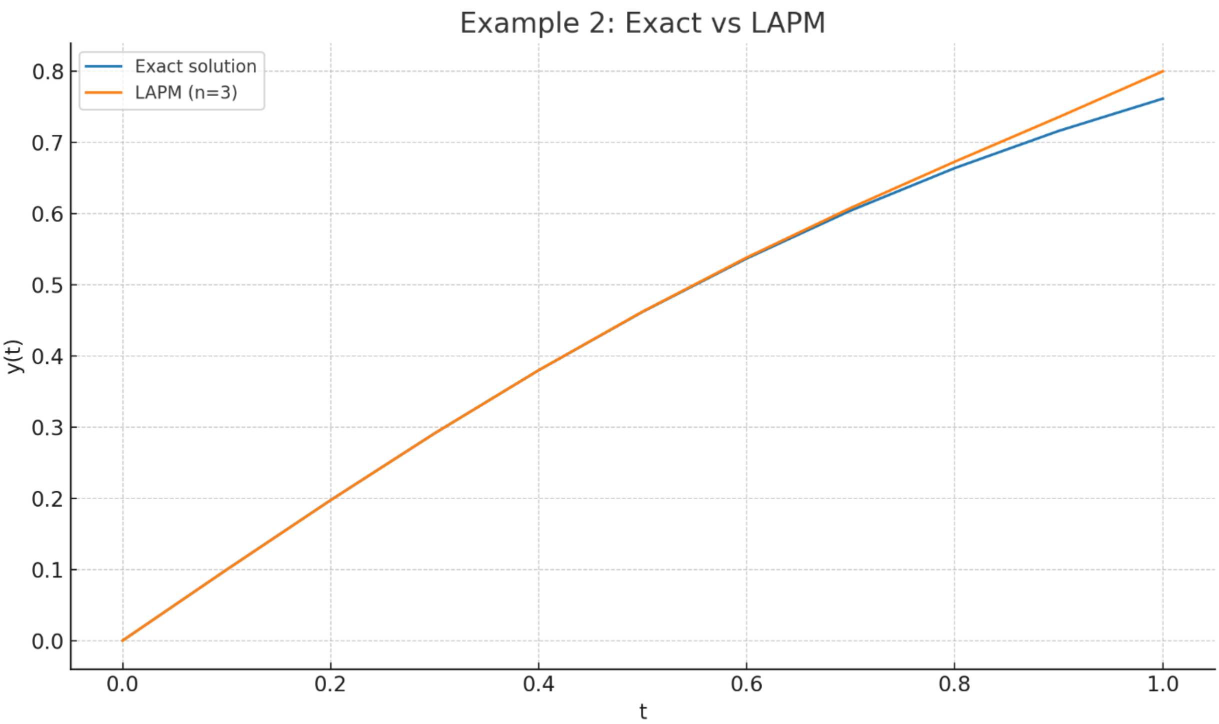

Figure 3: Graph of the LAPM and the exact solution for example 2

Example 3

We consider the Riccati equation below with constant coefficient:

$$y'(t) = y^2(t) - y(t), \qquad t > 0, \quad ...(28)$$

With the initial condition

$$y(0) = \frac{1}{2} \quad ...(29)$$

And the exact solution

$$y(t) = \frac{e^{-t}}{1+e^{-t}}. \quad ...(30)$$

Using the recursive formulas in Eqn. (13) and (14), the approximate solution to the differential Eqn. (28) is derived through the combined method of the Adomian polynomial and the Laplace transformation, as follows:

$$\begin{cases} y_0(t) = \frac{1}{2}, \\ y_{n+1}(t) = L^{-1}\left[\frac{1}{s}\left\{L\sum_{n=0}^{\infty} A_n(t)\right\}\right] - L^{-1}\left[\frac{1}{s}\{Ly_n(t)\}\right], \qquad n = 0,1,2,... \end{cases} \quad ...(31)$$

where A_n is the Adomian polynomial of the nonlinear operator $Ny = y^2$, which can be described as follows

$$\begin{cases} A_0 = y_0^2, \\ A_1 = 2y_0y_1, \\ A_1 = 2y_0y_2 + y_1^2, \\ \vdots \end{cases} \quad ...(32)$$

The following is a description of the solution to the Eqn. (31):

$$y_0(t) = \frac{1}{2},$$

$$y_1(t) = L^{-1}\left[\frac{1}{s}\left\{L\sum_{n=0}^{\infty} A_0(t)\right\}\right] - L^{-1}\left[\frac{1}{s}\{Ly_0(t)\}\right] = -\frac{t}{4},$$

$$y_2(t) = 0$$

$$y_3(t) = \frac{t^3}{48}$$

$$y_4(t) = 0$$

$$\vdots$$

$$y(t) = y_0(t) + y_1(t) + y_2(t) + ... = \frac{1}{2} - \frac{t}{4} + \frac{t^3}{48} + ... \quad ...(33)$$

Table 3: Computations showing comparison between the exact solution and the LAPM solution of example 3

t	Exact solution	LAPM (n=3)	Absolute Error
0	0.5	0.5	0
0.1	0.475020813	0.47502081	0
0.2	0.450166003	0.450166	1.66533E-16
0.3	0.425557483	0.42555748	3.46945E-14
0.4	0.40131234	0.40131234	1.4479E-12
0.5	0.377540669	0.37754067	2.61022E-11
0.6	0.354343694	0.35434369	2.76273E-10
0.7	0.331812228	0.33181223	2.02378E-09
0.8	0.310025519	0.31002553	1.13192E-08
0.9	0.289050497	0.28905055	5.15026E-08
1	0.268941421	0.26894162	1.99076E-07

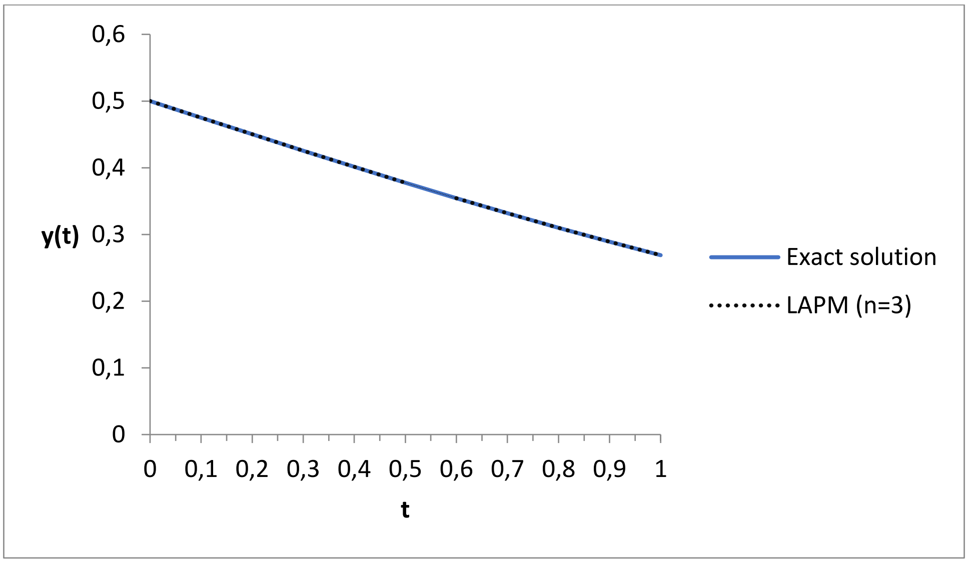

Figure 4: Graph of the LAPM and the exact solution for example 3

Table 4: Comparison between the exact solutions, the LAPM and the DTM for example 3

T	Exact solution	LAPM (n=3)	DTM (n=7)
0	0.5	0.5	0.500
0.1	0.475020813	0.47502081	0.475
0.2	0.450166003	0.450166	0.450
0.3	0.425557483	0.42555748	0.425
0.4	0.40131234	0.40131234	0.400
0.5	0.377540669	0.37754067	0.375
0.6	0.354343694	0.35434369	0.350
0.7	0.331812228	0.33181223	0.325
0.8	0.310025519	0.31002553	0.300

0.9	0.289050497	0.28905055	0.275
1	0.268941421	0.26894162	0.250

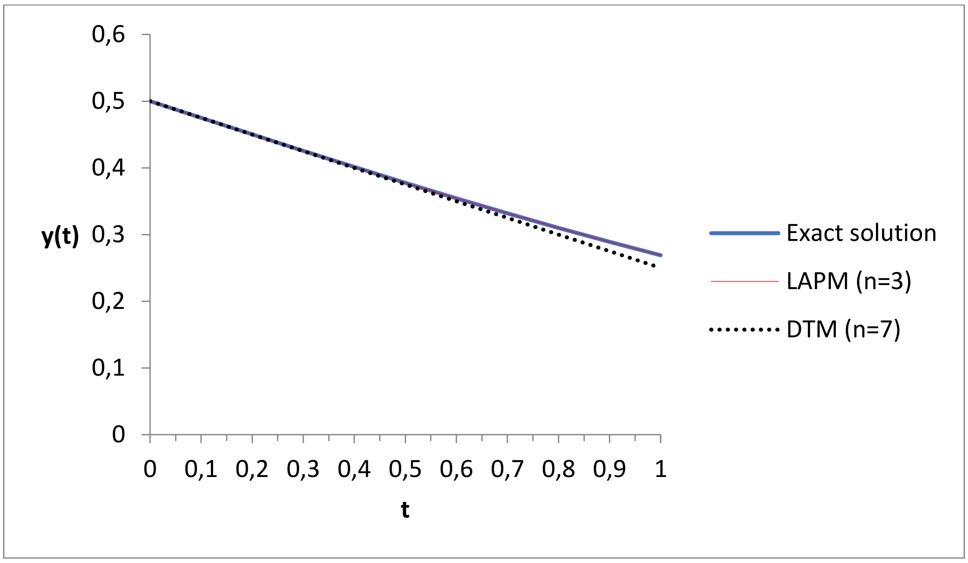

Figure 5: Graph of the LAPM, DTM and the exact solution for example 3

Discussions of Results

The comparative analysis of the results for Examples 1, 2 and 3 highlights the accuracy and efficiency of the Laplace–Adomian Polynomial Method (LAPM) when applied to linear and nonlinear differential equations.

For Example 1, the exact solution is $y(t) = \tan(t)$, while the LAPM approximation truncated to a finite number of terms is given by the corresponding power series expansion. The tabulated results show that the approximate values obtained using LAPM are almost identical to the exact solution for t∈ [0, 1], with negligible absolute error. The plot confirms that the LAPM curve overlaps with the exact solution curve throughout the interval, indicating that the method converges very rapidly.

For Example 2, the exact solution is $y(t) = \dfrac{e^{2t} - 1}{e^{2t} + 1}$, and the LAPM approximation up to $n = 3$ is $y(t) = t - \frac{1}{3}t^3 + \frac{2}{15}t^5$. The results demonstrate strong agreement between the approximate and exact solutions over the interval considered. The errors are very small for smaller values of t and remain within acceptable bounds as t approaches 1. This validates the capability of LAPM to handle nonlinearities effectively with only a few terms.

Conclusion

This study has demonstrated that the Laplace–Adomian Polynomial Method (LAPM) is an effective, accurate, and computationally efficient approach for solving a wide range of nonlinear differential equations. By combining the Laplace transform with the Adomian decomposition technique, the method efficiently handles nonlinear terms and constructs rapidly convergent series solutions without the need for linearization, perturbation, or discretization. Numerical experiments and error analyses confirm that LAPM provides highly precise approximations for various types of nonlinear problems, including exponential growth, hyperbolic, and oscillatory systems, with rapid convergence achieved using only a few series terms, thereby reducing computational complexity compared to conventional numerical techniques. Graphical and tabular comparisons further validate the robustness and stability of the method, particularly within the interval $t \in [0, 1]$. Overall, the findings establish LAPM as a powerful and practical tool for researchers and engineers working with nonlinear systems in applied mathematics, physics, and engineering, offering an efficient and reliable alternative to traditional analytical and numerical approaches.

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