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Analysis Of Solving Ordinary Differential Equations With A Comparison of Adam-Bashforth Moulton and Milne-Simpson Methods

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Abstract
Ordinary Differential Equations (ODEs) are mathematical models widely used in various fields of science and engineering to represent dynamic phenomena. This study aims to compare the performance of two multi-step numerical methods, namely the Adams-Bashforth-Moulton (ABM) method and the Milne-Simpson (MS) method in terms of accuracy, numerical stability, and computational efficiency. The analysis was carried out by implementing both methods using the Python programming language and comparing their numerical results to the exact solution. Based on the simulation graphs, both methods produced results that closely matched the exact solution, with nearly overlapping curves throughout the time interval from zero to two. However, the absolute error analysis showed that the MS method generated smaller errors and a more stable error growth compared to the ABM method, especially at longer time steps. This indicates that although both methods are accurate, the Milne-Simpson method tends to be more stable over time. This study provides a comprehensive overview of the strengths of each method and can serve as a reference in selecting efficient and accurate numerical methods for solving ordinary differential equations.

Keywords: Ordinary Differential Equation; Numerical Method; Adams–Bashforth–Moulton; Milne–Simpson; Stability Analysis

Abstrak
Persamaan Diferensial Biasa (Ordinary Differential Equations / ODE) merupakan model matematika yang banyak digunakan dalam berbagai bidang ilmu pengetahuan dan teknik untuk merepresentasikan fenomena dinamis. Penelitian ini bertujuan untuk membandingkan kinerja dua metode numerik multilangkah, yaitu Metode Adams-Bashforth-Moulton (ABM) dan Metode Milne-Simpson (MS) dalam hal akurasi, kestabilan numerik, dan efisiensi komputasi. Analisis dilakukan dengan mengimplementasikan kedua metode menggunakan bahasa pemrograman Python dan membandingkan hasil numeriknya dengan solusi eksak. Berdasarkan grafik simulasi, kedua metode menghasilkan hasil yang sangat mendekati solusi eksak, dengan kurva yang hampir berimpit sepanjang interval waktu dari nol hingga dua. Namun, analisis galat absolut menunjukkan bahwa metode MS menghasilkan galat yang lebih kecil serta pertumbuhan galat yang lebih stabil dibandingkan dengan metode ABM, terutama pada langkah waktu yang lebih panjang. Hal ini mengindikasikan bahwa meskipun keduanya akurat, metode Milne–Simpson cenderung lebih stabil seiring berjalannya waktu. Penelitian ini memberikan gambaran komprehensif mengenai keunggulan masing-masing metode dan dapat menjadi acuan dalam pemilihan metode numerik yang efisien dan akurat untuk menyelesaikan persamaan diferensial biasa.

Kata Kunci: Persamaan Diferensial Biasa; Metode Numerik; Adams–Bashforth–Moulton; Milne–Simpson; Analisis Kestabilan

1. INTRODUCTION

Ordinary differential equations (ODEs) are mathematical models widely employed across various disciplines, including engineering, medicine, economics, and mathematics, to represent dynamic phenomena. An ODE consists of derivatives of one or more unknown functions. These equations are typically classified into linear and nonlinear types. A system composed of multiple differential equations is referred to as a system of differential equations (Djojodihardjo, 2000). Nonlinear ODEs are characterized by dependent variables and their derivatives raised to powers greater than one, products involving these variables and their derivatives, or functions such as sine or exponential that can be expanded into Taylor series.

ODEs can be solved analytically or numerically. However, most nonlinear ODEs are analytically intractable, necessitating the use of numerical methods to obtain approximate solutions. These approximations inherently contain errors relative to the exact solutions.

Numerical methods are techniques that reformulate mathematical problems into forms solvable through basic arithmetic operations (Finizio & Ladas, 1988). In solving ODEs, numerical approaches are generally categorized into one-step and multi-step methods. One-step methods, such as the Runge-Kutta methods, require only an initial value to compute the next solution point. In contrast, multi-step methods use several previously computed solution values, which are often generated by a one-step method.

Multi-step methods are also known as predictor-corrector methods, comprising a predictor equation followed by a corrector equation. The Adams-Bashforth-Moulton (ABM) method is a notable example of a multi-step predictor-corrector scheme that does not require explicit evaluation of function derivatives (Henrici, 1966). The fourth-order Runge-Kutta method (RK4) is frequently employed to provide the initial values required by the fourth-order ABM method (Munif, 1995). The Milne-Simpson (MS) method, another multi-step approach, is distinct in being the only linear two-step method that achieves optimal order, albeit with limitations in absolute stability (Munir, 2022).

In addressing initial value problems that are analytically unsolvable, methods like ABM and MS are preferred in numerical computation. The ABM method combines explicit and implicit components to achieve high accuracy with efficient function evaluations. Studies, such as by Adekoya and Ogunwobi (Adekoya & Ogunwobi, 2021), have demonstrated that ABM can outperform MS in solving second-order ODEs, yielding lower errors when compared to exact solutions. Although MS has stability limitations, it has been improved through techniques such as filtered MS, which extends its stability region without compromising convergence order (Aluthge & Sarra, 2023), (Milne & Reynolds, 1959).

Alorgbey, et al. theoretically confirmed the zero-stability and convergence properties of the filtered MS method (Alorgbey et al., 2025). Application-wise, ABM has been successfully implemented in population modeling, with minimal deviation from empirical data (Nwaigwe & Atangana, 2025). Computational tools such as NodePy facilitate the implementation of ABM and MS methods in Python, enabling streamlined numerical experimentation and result visualization (Ketcheson et al., 2020).

Fractional variants of ABM have also been proposed to handle long-memory effects in complex systems (Zhang et al., 2023), (Zayernouri & Matzavinos, 2016). Conformable fractional ABM adaptations are emerging to address contemporary modeling needs (Elpianora et al., 2024). Meanwhile, MS has also been integrated into the method-of-lines approach for solving partial differential equations (PDEs), demonstrating robust stability in multidimensional contexts (Olaoluwa Omole et al., 2024).

Both ABM and MS have been applied in diverse nonlinear scenarios, including predator-prey dynamics, robotic systems, and mechanical stability analyses (Samperisam et al., 2024). Comparative studies have shown their varying strengths, with MS often offering better long-term stability and ABM delivering faster convergence under specific conditions. Although ABM and MS are widely used predictor-corrector methods for solving ordinary differential equations, most previous studies focus only on theory or on specific applied models. The novelty of this research is the comprehensive comparison of ABM and MS under identical conditions using exact-solution benchmarking, absolute-error analysis, and stability evaluation. This provides clearer insights into the strengths and weaknesses of each method for solving first-order ODEs.

Given these developments, this study conducts a comparative analysis of the ABM and filtered MS methods in terms of accuracy, numerical stability, and computational efficiency. All simulations and evaluations are performed using Python to ensure transparency, reproducibility, and practical relevance.

2. METHODS

This research process begins with the identification of problems. Once the problems are identified, the next stage is data collection, in which relevant information and supporting data are gathered to ensure the accuracy and validity of the study. Following this, the model formulation stage is conducted to construct an appropriate mathematical or conceptual model that represents the problem under investigation. The next is program implementation, where the model is translated into a computational form, often using a suitable programming language. Afterward, the simulation and validation are performed to evaluate its performance and comparing the results with either exact solutions. Once it is evaluated, the study moves to the analysis of results. Final step is the conclusion.

3. RESULT AND DISCUSSION

In line with the aim of this study, the comparison between the ABM and MS methods is based on three aspects that is accuracy, numerical stability, and computational efficiency. Accuracy is assessed by comparing the numerical solutions with the exact solution and observing how closely the curves match. Numerical stability is evaluated from the absolute error at each time step and how the error grows over the simulation interval. Computational efficiency is examined through the Python implementation, including the computation steps required and the consistency of the results produced. These three aspects provide a clear basis for comparing the performance of the two methods.

For solving Ordinary Differential Equations using the Adam-Bashforth-Moulton method and the Milne-Simpson method, the implementation is done directly in Python. The exact solution is determined, and initialization is performed using the 4th Order Runge-Kutta method for the subsequent calculations using the ABM and MS methods. The equation is

$$\frac{dy}{dt} = y - t^2 + 1, \qquad y(0) = 0.5. \tag{1}$$

This matches the standard linear form

$$\frac{dy}{dt} + P(t)y = Q(t). \tag{2}$$

In this case, $P(t) = -1$ and $Q(t) = -t^2 + 1$. Compute the integrating factor $\mu(t)$ and we get

$$\mu(t) = e^{\int P(t)dt} = e^{\int -1dt} = e^{-t}. \tag{3}$$

Multiply the equation by integrating the factor

$$\begin{aligned} e^{-t}\left(\frac{dy}{dt} - y\right) &= e^{-t}(-t^2 + 1) \\ \frac{d}{dt}(y \cdot e^{-t}) &= (-t^2 + 1)e^{-t}. \end{aligned} \tag{4}$$

Integrate both sides and we obtain

$$\begin{aligned} \int \frac{d}{dt}(ye^{-t})dt &= \int (-t^2 + 1)e^{-t}dt \\ ye^{-t} &= \int (-t^2 + 1)e^{-t}dt + C. \end{aligned} \tag{5}$$

By solving the integral, we get

$$\int(-t^2+1)e^{-t}dt = -\int t^2e^{-t}dt + \int e^{-t}dt$$
$$\int(-t^2+1)e^{-t}dt = e^{-t}(t^2-2t+1). \quad (6)$$

Here, we obtain the general solution that is

$$ye^{-t} = e^{-t}(t^2-2t+1)+C$$
$$y(t) = (t+1)^2 + Ce^0. \quad (7)$$

For $y(0) = 0.5$, the value of $C = -0.5$ is obtained and the exact solution equation becomes

$$y(t) = (t+1)^2 - 0.5e^t. \quad (8)$$

Next, the initialization is performed using the 4th Order Runge-Kutta Method. The initial condition is

$$y(t) = y_0. \quad (9)$$

The Runge-Kutta 4th order method updates the solution using the following formulas.

$$k_1 = h \times f(t_n, y_n),$$
$$k_2 = h \times f\left(t_n + \frac{h}{2}, y_n + \frac{k_1}{2}\right),$$
$$k_3 = h \times f\left(t_n + \frac{h}{2}, y_n + \frac{k_2}{2}\right), \quad (10)$$
$$k_4 = h \times f\left(t_n + \frac{h}{2}, y_n + \frac{k_3}{2}\right).$$

Then, the next value of y is computed as

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (11)$$

and the value of t is

$$t_{n+1} = t_n + h \quad (12)$$

where $h = 0.2$ is the step size, t_n is the current value of the independent variabel, y_n is the current approximation of the dependent variabel, and k_1, k_2, k_3, and k_4 are intermediate slopes (slope in the beginning interval is k_1, in the midpoint are k_2 and k_3, and k_4 is in the end of interval).

Here we calculate the Runge-Kutta 4th order. For $t = 0$ until $t = 0.2$, we get

$$
\begin{aligned}
k_1 &= 0.2 \times (0.5 - 0^2 + 1) = 0.3,\\
k_2 &= 0.2 \cdot \left(0.5 + \frac{0.3}{2} - (0.1)^2 + 1\right) = 0.328,\\
k_3 &= 0.2 \cdot \left(0.5 + \frac{0.328}{2} - (0.1)^2 + 1\right) = 0.3308,\\
k_4 &= 0.2 \cdot (0.5 + 0.3308 - (0.2)^2 + 1) = 0.35816,\\
y_1 &= 0.5 + \frac{1}{6}(0.3 + 2(0.328) + 2(0.3308) + 0.35816) = 0.82929.
\end{aligned}
\tag{13}
$$

Now, for $t = 0.2$ until $t = 0.4$, we obtain

$$
\begin{aligned}
k_1 &= 0.2\,(0.82929 - (0.2)^2 + 1) = 0.35786,\\
k_2 &= 0.2 \cdot \left(0.82929 + \frac{0.35786}{2} - (0.3)^2 + 1\right) = 0.38364,\\
k_3 &= 0.2 \cdot \left(0.82929 + \frac{0.38364}{2} - (0.3)^2 + 1\right) = 0.38502,\\
k_4 &= 0.2 \cdot (0.82929 + 0.38502 - (0.4)^2 + 1) = 0.41086,\\
y_2 &= 0.82929 + \frac{1}{6}(0.35786 + 2(0.38364) + 2(0.38502) + 0.41086)\\
&= 1.21346.
\end{aligned}
\tag{14}
$$

Lastly, for $t = 0.4$ to $t = 0.6$, we provide

$$
\begin{aligned}
k_1 &= 0.2\,(1.21346 - (0.4)^2 + 1) = 0.41069,\\
k_2 &= 0.2 \cdot \left(1.21346 + \frac{0.41069}{2} - (0.5)^2 + 1\right) = 0.43376,\\
k_3 &= 0.2 \cdot \left(1.21346 + \frac{0.43376}{2} - (0.5)^2 + 1\right) = 0.43527,\\
k_4 &= 0.2 \cdot (1.21346 + 0.43527 - (0.6)^2 + 1) = 0.45775,
\end{aligned}
\tag{15}
$$

$$y_3 = 1.21346 + \frac{1}{6}(0.41069 + 2(0.43376) + 2(0.43527) + 0.45775)$$
$$= 1.64954.$$

Proceed by implementing the initialized values in Python with the following

$$f_n = y_n - {t_n}^2 + 1. \tag{16}$$

As a result, the following values were obtained.

$$\begin{aligned} f_0 = y_0 - {t_0}^2 + 1 = 0.5 - (0.0)^2 + 1 = 1.5, \\ f_1 = y_1 - {t_1}^2 + 1 = 0.82929 - (0.2)^2 + 1 = 1.78929, \\ f_2 = y_2 - {t_2}^2 + 1 = 1.21346 - (0.4)^2 + 1 = 2.05346, \\ f_3 = y_3 - {t_3}^2 + 1 = 1.64954 - (0.6)^2 + 1 = 2.28954. \end{aligned} \tag{17}$$

3.1 Adams-Bashforth-Moulton (ABM) Method

a. Predictor – Adams-Bashforth 4-step :

$$y_{n+1}^{pred} = y_n + \frac{h}{24}(55f_n - 59f_{n-1} + 37f_{n-2} - 9f_{n-3}). \tag{18}$$

For $t = 0.8$, $n + 1 = 4$.

$$\begin{aligned} y_4^{pred} &= 1.64954 + \frac{0.2}{24}\big(55(2.28954) - 59(2.05346) + 37(1.78929) - 9(1.5)\big) \\ y_4^{pred} &= 2.13014. \end{aligned} \tag{19}$$

b. Corrector – Adams-Bashforth 4-step :

$$y_{n+1} = y_n + \frac{h}{24}\big(9f_{n+1}^{pred} + 19f_n - 5f_{n-1} + f_{n-2}\big). \tag{20}$$

For $t = 0.8$, $n + 1 = 4$.

$$\begin{aligned} f_4^{pred} &= y_4^{pred} - {t_4}^2 + 1 = 2.13014 - (0.8)^2 + 1 = 2.49014 \\ y_4 &= 1.64954 + \frac{0.2}{24}\big(9(2.49014) + 19(2.28954) - 5(2.05346) \\ &\quad + (1.78929)\big) \\ y_4 &= 2.12814. \end{aligned} \tag{21}$$

3.2 Milne-Simpson (MS) Method

a. Predictor – Milne's Method.

$$y_{n+1}^{pred} = y_{n-3} + \frac{4h}{3}(2f_n - f_{n-1} + 2f_{n-2}). \tag{22}$$

For $t = 0.8$, $n + 1 = 4$.

$$y_4^{pred} = 0.5 + \frac{4(0.2)}{3}\big(2(2.28954) - 2.05346 + 2(1.78929)\big)$$
$$y_4^{pred} = 2.12775. \tag{23}$$

b. Corrector – Simpson's Method.

$$y_{n+1} = y_{n-1} + \tfrac{h}{3}\big(f_{n-1} + 4f_n + f_{n+1}^{pred}\big). \tag{24}$$

For $t = 0.8$, $n + 1 = 4$.

$$f_4^{pred} = y_4^{pred} - {t_4}^2 + 1 = 2.12775 - (0.8)^2 + 1 = 2.48775$$

$$y_4 = 1.21346 + \frac{0.2}{3}(2.05346 + 4(2.28954) + 2.48775) \tag{25}$$
$$y_4 = 2.12673.$$

Here we show the comparison result of Adam-Bashforth-Moulton method (ABM), Milne-Simpson method (MS), and exact solution in Table 1.

Tabel 1. Comparison result of ABM, MS, and exact solution.

Time (t)	Solution		
	ABM	MS	Exact
0.0	0.50000	0.50000	0.50000
0.2	0.82929	0.82929	0.82930
0.4	1.21346	1.21346	1.21409
0.6	1.64954	1.64954	1.64894
0.8	2.12814	2.12673	2.12723
1.0	2.64083	2.64086	2.64086
1.2	3.17990	3.17992	3.17994
1.4	3.73235	3.73238	3.73240
1.6	4.28342	4.28345	4.28348
1.8	4.81510	4.81514	4.81518
2.0	5.30537	5.30543	5.30547

In Figure 1, we plot the data from Table 1. As it shown in Figure 1, we compare between the exact solution and the numerical solution obtained by the Adams–Bashforth–Moulton (ABM) and Milne–Simpson (MS) methods over the time interval t=0 to t=2. The three diferent lines (orange for the exact solution, red dots for ABM, and red squares for MS) appear to overlap strongly. It is indicating that both numerical methods produce solutions that are very close to the exact solution.

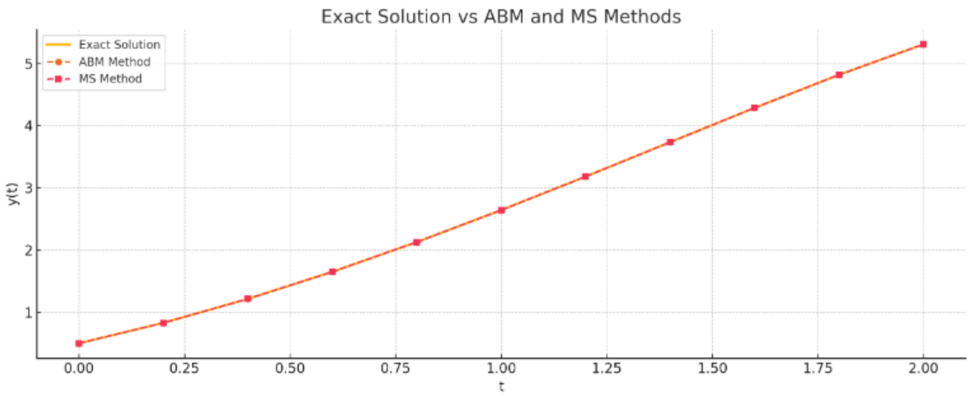

Figure 1. Plotting of comparison result of ABM, MS, and exact solution.

The closeness of the curve positions indicates that both ABM and MS are able to reconstruct the behavior of the function very well over the tested interval. Thus, it can be concluded that both methods are quite reliable in solving ODEs with high accuracy although the previous analysis of absolute errors suggests that MS is slightly more stable in the long run. The galat absolute pointwase is

$$\boldsymbol{Error_n} = \left|y_n^{numerik} - y_n^{eksak}\right|. \tag{26}$$

In Table 2, we compare the absolute error of ABM with MS.

Tabel 2. Result of Error.

Time (t)	Absolute Error	
	ABM	MS
0.0	0.00000	0.00000
0.2	0.00001	0.00001
0.4	0.00063	0.00063
0.6	0.00060	0.00060
0.8	0.00091	0.00050
1.0	0.00003	0.00000
1.2	0.00004	0.00002

1.4	0.00005	0.00002
1.6	0.00006	0.00003
1.8	0.00008	0.00004
2.0	0.00010	0.00004

Figure 2 shows the absolute error of ABM and MS comparison in solving differential equations over a finite time range . It can be seen that the red curve (ABM) experiences a sharper increase in error than the green curve (MS), especially after indicating that the error accumulation in the ABM method is more significant. In contrast, the MS curve shows a more stable and lower error growth. This indicating that MS method is more consistent in maintaining accuracy throughout the time interval. Therefore, in terms of numerical stability and long-term accuracy, the MS (Milne–Simpson) method is proven to be superior than the ABM (Adam-Bashforth-Moulton) method.

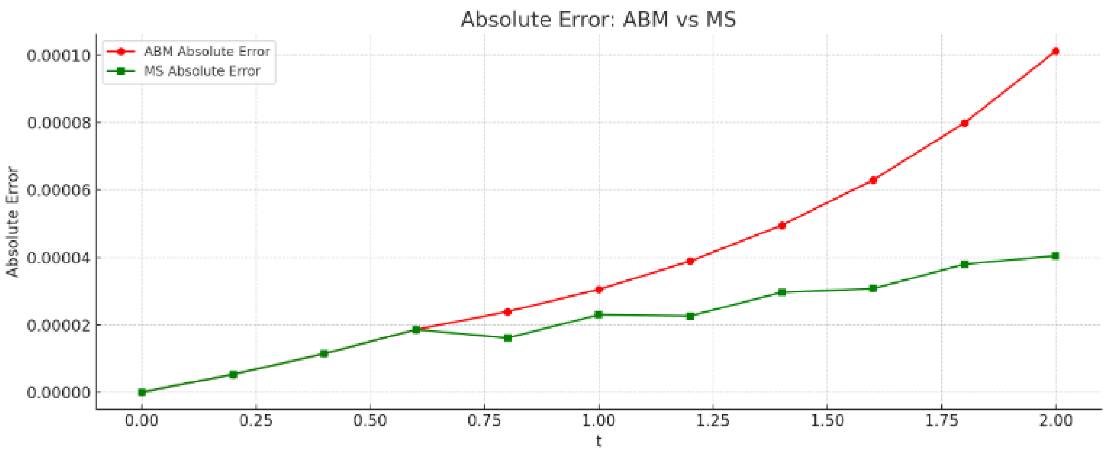

Figure 2. Comparison result of ABM and MS absolute error.

Table 3 presents the comparison analysis of Adams-Bashforth-Moulton (ABM) method and Milne-Simpson (MS) method based on the accuracy test results and implementation in Python.

Tabel 3. Comparative study of ABM and MS in solving ODEs.

Aspect	ABM	MS
Method Type	Predictor-Corrector, 4th order	Predictor-Corrector, 4th order
Initialization Requirement	Requires 3 initial values from RK4 method	Requires 3 initial values from RK4 method
Predictor Formula	Adams-Bashforth 4-step	Milne's Method
Corrector Formula	Adams-Moulton 4-step	Simpson's Method
Step Size Used	0.2	0.2

Stability	Stable, but slightly more sensitive to initial error	More stable and consistent
Absolute Error Accuracy	Slightly higher error compared to MS	Lower and more consistent error
Global Maximum Error	Around 0.0001	Around 0.00004
Fit to Exact Solution	Close to exact but small deviations near the end	Almost perfectly matches exact solution throughout
Advantages	Good for quick estimation and efficient implementation	More accurate and consistent across all steps
Disadvantages	Slightly higher error toward the final time steps	Requires careful computation in correction steps

4. CONCLUSION

Both the Adams-Bashforth-Moulton (ABM) and Milne-Simpson (MS) methods effectively solved the given initial value problem with high numerical accuracy. However, the MS method consistently produced slightly lower absolute errors and demonstrated more stable error growth, indicating superior numerical stability compared to the ABM method. In terms of computational stability, both methods performed effectively, especially when initialized using the fourth-order Runge-Kutta method, although the MS method showed slightly more consistent performance across all steps. This makes MS marginally superior in performance for this problem. Overall, both methods performed well, especially when initialized using the fourth-order Runge-Kutta method, highlighting the reliability and effectiveness of predictor-corrector techniques for solving ordinary differential equations.

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6. RECOMENDATION

We recommend comparing other methods like Taylor Series Method.

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