

Differential Equations Solved Using New Numerical Techniques

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Abstract

In this article, we describe brand-new numerical strategies for dealing with both linear and nonlinear ordinary differential equations. To create a new family of numerical methods, we use the Daftardar-Gejji methodology on the theta-method. It is demonstrated that the formulation of the approach is equivalent to that of a Runge-Kutta method. Analyses are done on the approaches' stability.

Indexing terms/Keywords : Iterative Method, Ordinary Differential Equations, and Numerical Method

Introduction

Numerical methods are one of the main techniques used for solving differential equations. For many years, the construction of accurate and stable numerical methods for the solutions of ordinary differential equations (ODEs) with initial value problems has been considered widely and with great new contributions. Recently, the method proposed by Daftardar-Gejji and Jafari (DJM) [1] is powerful technique for solving a widerange of nonlinear equations, see [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. In this paper, we employ the (DJM) to construct a new family of numerical scheme for solving ordinary differential equations and discuss error, stability and convergence of the proposed methods.

1 Daftardar-Gejji and Jafari Method

To illustrate the basic concept of the new iterative method, we consider the following general nonlinear system

$$u = f + L(u) + N(u), \quad (1)$$

where f is a given function, L and N are linear and nonlinear operators respectively. It is assumed that the [DJM] solution for the Eq. (1) has the form:

$$u = \sum_{i=0}^{\infty} u_i. \quad (2)$$

Since L is linear

$$L\left(\sum_{i=0}^{\infty} u_i\right) = \sum_{i=0}^{\infty} L(u_i). \quad (3)$$



The nonlinear operator N in Eq. (1) is decomposed by [DJM] as bellow:

$$N \left(\sum_{i=0}^{\infty} u_i \right) = N(u_0) + \sum_{i=1}^{\infty} \left\{ N \left(\sum_{j=0}^{\infty} u_j \right) - N \left(\sum_{j=0}^{i-1} u_j \right) \right\}. \quad (4)$$

Using Eqs. (2), (3) and (4) in Eq. (1), we get

$$\sum_{i=0}^{\infty} u_i = f + \sum_{i=0}^{\infty} L(u_i) + \sum_{i=0}^{\infty} G_i \quad (5)$$

The DJM series terms are generated as bellow:

$$u_0 = f, u_{m+1} = L(u_m) + G_m, m = 0, 1, 2, \dots \quad (6)$$

The k-term approximate solution is given by

$$u = \sum_{i=0}^{k-1} u_i \quad (7)$$

for suitable integer k.

3. New Family of Numerical Methods

Consider the initial value problem

$$\frac{dy}{dx} = f(x, y), y'(x_0) = \eta, i = 1, 2, \dots, n, \quad (8)$$

Where $y : [a, b] \rightarrow R^n, \eta \in R^n, f : [a, b] \times R^n \rightarrow R^n$.

Recently, J. Patade et al [15] proposed new method by applying [DJM] on the implicit trapezium method to get a new second order formula and denoted by [NNM]. Now, let us consider the famous family of methods, called by θ -methods which has the following formula

$$y_{j+1} = y_j + h [\theta f(x_j, y_j) + (1 - \theta) f(x_{j+1}, y_{j+1})], \theta \in [0, 1] \quad (9)$$

where $h = x_j - x_{j-1}$ and $x_j = x_0 + jh, j = 1, 2, \dots, n$.

We can take different value of θ in formula (10) to generate many of methods, for example:

$$\begin{cases} \theta = 1, & \text{Explicit Euler method;} \\ \theta = 1/2, & \text{Implicit Trapezoidal rule;} \\ \theta = 0, & \text{Implicit Euler method.} \end{cases}$$

We can rewrite formula(10) as the form of(1) by consider

$$\begin{aligned}u &= y_{j+1}, \\f &= y_j + h\theta f(x_j, y_j), \\N(u) &= h(1 - \theta)f(x_{j+1}, y_{j+1})\end{aligned}$$

Now, let us apply [DJM] on (10) to get 3-term solution as

$$\begin{aligned}u &= u_0 + u_1 + u_2, \\&= u_0 + N(u_0) + N(u_0 + u_1) - N(u_0), \\&= u_0 + N(u_0 + u_1), \\&= u_0 + N(u_0 + N(u_0)).\end{aligned}$$

which is

$$y_{j+1} = y_j + h\theta f(x_j, y_j) + N(y_j + h\theta f(x_j, y_j) + N(y_j + h\theta f(x_j, y_j))) .j = 0, 1, \dots \quad (10)$$

Or

$$y_{j+1} = y_j + h\theta f(x_j, y_j) + h(1 - \theta)f(x_{j+1}, y_j + h\theta f(x_j, y_j) + h(1 - \theta)f(x_{j+1}, y_j + h\theta f(x_j, y_j))) .(11)$$

Therefore, we obtain a new family of θ method. However, the new family can be formulated in an equivalent way as a RungeKutta method as follow

$$\begin{aligned}k_1 &= f(x_j, y_j), \\k_2 &= f(x_{j+1}, y_j + h\theta k_1), \\k_3 &= f(x_{j+1}, y_j + h\theta k_1 + h(1 - \theta)k_2),\end{aligned} \quad (12)$$

where

$$y_{j+1} = y_j + h\theta k_1 + h(1 - \theta)k_3. \quad (13)$$

Now, to obtain some examples for the new family we choose some different values of θ in (12) as follow:

for $\theta = 0$, we get

$$\begin{aligned}k_1 &= f(x_j, y_j), \\k_2 &= f(x_{j+1}, y_j), \\k_3 &= f(x_{j+1}, y_j + hk_2),\end{aligned} \quad (14)$$

Where

$$y_{j+1} = y_j + hk_3.$$

for $\theta = 1/2$, we get

$$\begin{aligned}k_1 &= f(x_j, y_j), \\k_2 &= f(x_{j+1}, y_j + \frac{h}{2}k_1), \\k_3 &= f(x_{j+1}, y_j + \frac{h}{2}k_1 + \frac{h}{2}k_2),\end{aligned} \quad (15)$$

where

which is the method proposed in [15]. for $\theta = 3/4$, we get

$$\begin{aligned} k_1 &= f(x_j, y_j), \\ k_2 &= f(x_{j+1}, y_j + \frac{3h}{4}k_1), \\ k_3 &= f(x_{j+1}, y_j + \frac{3h}{4}k_1 + \frac{h}{4}k_2), \end{aligned} \quad (16)$$

where

$$y_{j+1} = y_j + \frac{3h}{4}k_1 + \frac{h}{4}k_3.$$

for $\theta = 1$, we get

$$\begin{aligned} k_1 &= f(x_j, y_j), \\ k_2 &= f(x_{j+1}, y_j + hk_1), \\ k_3 &= f(x_{j+1}, y_j + hk_1), \end{aligned} \quad (17)$$

Where

$$y_{j+1} = y_j + h\theta k_1.$$

Theorem. The new family defined by (12) and (14) are of Second order if $\theta = 1/2$, and first order for any another choice of θ .

Proof: The Taylor series expansion of y_{j+1} may be written as

$$y(x_{j+1}) = y_j + hf + \frac{1}{2}h^2 ff_y + \frac{1}{6}h^3 (ff_y^2 + f^2 f_{yy}) + O(h^4). \quad (18)$$

Notice that for simplicity of the algebra f have been considered as a function of y only, without loss of generality. This will considerably reduce the Taylor series expansions of k_i , $i = 1, 2, 3$, in (12) to the following

$$k_1 = f, \quad (19)$$

$$k_2 = f + f\theta h f_y + \frac{1}{2}\theta^2 f^2 h^2 f_{yy} + \frac{1}{6}\theta^3 f^3 h^3 f_{yyy} + \dots, \quad (20)$$

$$k_3 = f + f_y \left(\theta fh + (1 - \theta)h \left(f + \theta fh f_y + \frac{1}{2}\theta^2 f^2 h^2 f_{yy} + \frac{1}{6}\theta^3 f^3 h^3 f_{yyy} \right) \right)^2 + \dots \quad (21)$$

Traditionally, the equation (19), (20) and (21) would be substituted in (14) to obtain an expression of y_{j+1} .

Since the error of the method can be measured using the expression

$$T_{j+1} = y(x_{j+1}) - y_{j+1},$$

therefore,

$$T_{j+1} = \left(\theta - \frac{1}{2}\right) fh^2 f_y + \left(\frac{1}{6} - \theta + 2\theta^2 - \theta^3\right) fh^3 f_y^2 + \left(\frac{\theta}{2} - \frac{1}{3}\right) f^2 h^3 f_{yy} + \dots \quad (22)$$

Clearly, by choosing $\theta = 1/2$ we get

$$T_{j+1} = \frac{1}{24} fh^3 f_y^2 - \frac{1}{12} f^2 h^3 f_{yy} + O(h^4), \quad (23)$$

which is mean the method is second order, otherwise its first order.

Definition. [16] A scheme is said to be consistent if the difference of the computation formula exactly approximates the differential equation it tends to solve.

Theorem. The new family of modified θ method is consistent.

Proof: Subtract y_j on both sides of (14), and we have:

$$y_{j+1} - y_j = h(\theta k_1 + (1 - \theta)k_3). \quad (24)$$

Dividing all through by h and taking limit as h tend to zero on both sides, we have

$$\lim_{h \rightarrow 0} \frac{y_{j+1} - y_j}{h} = \lim_{h \rightarrow 0} (\theta k_1 + (1 - \theta)k_3) = f(x_j, y_j). \quad (25)$$

Hence, the method is consistent.

4. The Stability Function for The New Modification Methods

In order to validate the stability of the method, the equation (12) and (14) are substituted in the simple test equation

$$y' = \lambda y, \lambda \in C, \text{Re}(\lambda) < 0, \quad (26)$$

we get

$$\begin{aligned} k_1 &= \lambda y_j, \\ k_2 &= \lambda y_j(1 + \theta \lambda h), \\ k_3 &= \lambda y_j(1 + \theta \lambda h + \lambda h(1 - \theta)(1 + \theta \lambda h)). \end{aligned} \quad (27)$$

Substituting (27) in (14) and letting $z = h\lambda$, the simplified equation is obtained as follows:

$$y_{j+1} = y_j(1 + z + z^2 - \theta z^2 - \theta z^3 + 2\theta^2 z^3 - \theta^3 z^3) \quad (28)$$

or in more simplified form

$$y_{j+1} = y_j R(z)$$

$$R(z) = (1 + z + z^2 - \theta z^2 - \theta z^3 + 2\theta^2 z^3 - \theta^3 z^3)$$

Conclusion

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