An eighth order Backward Differentiation Formula with Continuous Coefficients for Stiff Ordinary Differential Equations

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Abstract—A block backward differentiation formula of uniform order eight is proposed for solving first order stiff initial value problems (IVPs). The conventional 8-step Backward Differentiation Formula (BDF) and additional methods are obtained from the same continuous scheme and assembled into a block matrix equation which is applied to provide the solutions of IVPs on non-overlapping intervals. The stability analysis of the method indicates that the method is $L_0$-stable. Numerical results obtained using the proposed new block form show that it is attractive for solutions of stiff problems and compares favourably with existing ones.

Keywords—Stiff IVPs, System of ODEs, Backward differentiation formulas, Block methods, Stability.

I. INTRODUCTION

NUMERICAL solutions for ordinary differential equations (ODEs) are very important in scientific computation, as they are widely used to model real world problems. Stiff systems are considered difficult because explicit numerical methods designed for non-stiff problems are used with very small step sizes. In the quest for better methods for solving these systems, Curtiss and Hirschfelder [1] discovered the backward differentiation formulae (BDF).

Since then, a great effort has been made in order to obtain new numerical integration methods with strong stability properties desirable for solving stiff systems. For a survey on methods for stiff systems, see [2]. Since we are concerned with the 8-step BDF which is an example of a linear multistep method, we review briefly the basic idea behind the algorithm and obtain a continuous representation of the form

$$y' = f(t,y), \quad y(t_0) = y_0, \quad x \in [t_0,T_n]$$

where $f$ satisfies the Lipschitz condition as given in Henrici [3]. The $k$-step LMM is conventionally written as

$$\sum_{j=0}^{k} \alpha_j y_{n+j} = h \sum_{j=0}^{k} \beta_j f_{n+j}$$

which has $2k+1$ unknown $\alpha_j$s and $\beta_j$s and therefore can be of order $2k$, where $k$ is the step number, however, according to Dahlquist [4], the order of (2) cannot exceed $k + 1$ ($k$ is odd) or $k + 2$ ($k$ is even) for the method to be stable. Several authors such as Lambert [5], Gear [6], Gragg and Stetter [7], Butcher [8], Akinfenwa et al. [9] proposed modified forms of (2) known as hybrid methods which were shown to overcome the Dahlquist barrier theorem. Several other methods have been proposed for efficiently solving (1) (see Keiper and Gear [10], Enright [11, 12], Hairer and Wanner [2], Cash [13] and Brugnano and Trigiante [14]).

In this paper, the conventional 8-step BDF and additional methods are obtained from the same continuous scheme and assembled into a block matrix equation which is applied to provide the solutions for (1). We note that block methods were first introduced by Milne [15] for use only as a means of obtaining starting values for predictor-corrector algorithms and has since then been developed by several researchers (see [16], [17], [18]), for general use. The advantage of a block method is that in each application, the solution is approximated at more than one point. The number of points depends on the structure of the block method. Therefore, applying these methods can give faster solutions to the problem which can be managed to produce a desired accuracy.

The paper is presented as follows: In section 2, we discuss the basic idea behind the algorithm and obtain a continuous representation $Y(t)$ for the exact solution $y(t)$ which is used to generate members of the block method for solving (1). In section 3, we present the stability analysis of our block implicit algorithm. In section 4, we briefly discuss the implementation of the method. In section 5, we show the accuracy of our method. Finally, in section 6 we present some concluding remarks.

II. DERIVATION OF THE METHOD

We proceed by assuming that the exact solution $y(t)$ is locally represented in the range $[t_0, t_0 + 8h]$ by the continuous solution $Y(t)$ of the form

$$Y(t) = \sum_{j=0}^{8} b_j \phi_j(t)$$

where $b_j$ are unknown coefficients to be determined and $\phi_j(t)$ are polynomial basis function of degree 8. We thus construct the 8-point BDF method with $\phi_j(t) = t^j, j = 0, \ldots, 8$ by imposing the following conditions.
\[ Y(t_{n+1}) = y_{n+j}, \quad j = 0, \ldots, 7 \quad Y'(t_{n+8}) = f_{n+8}, \quad (4) \]

where \( y_{n+j} \) is the approximation for the exact solution \( y(t_{n+j}), f_{n+8} = f(t_{n+8}, y_{n+8}) \) and \( n \) is the grid index.

It should be noted that equation (4) leads to a system of equations which must be solved to obtain the coefficients \( b_j, j = 0, \ldots, 8 \) which are substituted into (3) and after some algebraic computation, our continuous representation yields the form

\[ Y(t) = -\sum_{j=0}^{7} \alpha_j(t)y_{n+j} + h\beta_8(t)f_{n+8} \quad (5) \]

where \( \alpha_j(t) \) and \( \beta_8(t) \) are continuous coefficients. The method (5) is then used to generate the \( 8 \)-step standard BDF (6) at point \( t = t_{n+8} \).

The additional methods are obtained by evaluating the first derivative of (5) given by (7) at the points \( t = t_{n+j}, j = 1, \ldots, 7 \). Thus we have the additional methods as (8).

The integrators (8) together with (6) are combined as a one block 8 point block BDF methods of order \( (8, 8, 8, 8, 8) \) with error constants:

\[ c_0 = \left( \frac{1}{6088}, -\frac{2431}{159810}, \frac{1204}{6849}, \frac{159810}{347}, -\frac{2563}{18264}, \frac{159810}{191772}, \frac{351}{159810}, \frac{139}{6849}, \frac{1}{3} \right)^T \]

### III. STABILITY ANALYSIS

In what follows, (6) and (8) can be rearranged and rewritten as a matrix finite difference equation of the form

\[ A^{(1)} Y_{n+1} = A^{(0)} Y_n + hB^{(1)} F_\omega \quad (9) \]

where

\[ Y_{n+1} = \begin{pmatrix} y_{n+1} + y_{n+2} - y_{n-5} - y_{n-6} + y_{n-7} - y_{n-8} \\ y_{n+2} + y_{n+3} - y_{n-4} - y_{n-5} + y_{n-6} - y_{n-7} + y_{n-8} \\ \vdots \end{pmatrix} \]
\[ Y_n = \begin{pmatrix} y_{n-1} + y_{n-2} - y_{n-3} - y_{n-4} + y_{n-5} - y_{n-6} + y_{n-7} - y_{n-8} \\ \vdots \end{pmatrix} \]
\[ F_\omega = \begin{pmatrix} f_{n+1} + f_{n+2} - f_{n-4} - f_{n-5} - f_{n-6} + f_{n-7} + f_{n-8} \\ \vdots \end{pmatrix} \]

for \( \omega = 0, \ldots \) and \( n = 0, 8, \ldots, N - 8 \), and the matrices \( A^{(1)}, A^{(0)} \), \( B^{(1)} \) are 8 by 8 matrices whose entries are given by the coefficients of (6) and (8). In particular, the matrices are defined as equation (10).

#### A. Zero-stability

It is worth noting that zero-stability is concerned with the stability of the difference system in the limit as \( h \to 0 \). Thus, as \( h \to 0 \), the method (9) tends to the difference system

\[ A^{(1)} Y_{n+1} - A^{(0)} Y_n = 0 \]

whose first characteristic polynomial \( \rho(R) \) is given by

\[ \rho(R) = \det(RA^{(1)} + A^{(0)}) = \frac{2890}{761} R^7 (1 - R) \quad (11) \]

Following Fatunla[19], the block method (9) is zero-stable, since from (11), \( \rho(R) = 0 \) satisfies \( |R_j| \leq 1, j = 1, \ldots, 8 \), and for those roots with \( |R_j| = 1 \), the multiplicity does not exceed 1.

1) Consistency: The block method (9) is consistent as it has order \( p > 1 \). According to Henrici[3], convergent, since convergence = zerostability + consistency.

#### B. Linear stability

The linear stability properties of the eight point block BDF methods are determined by expressing them in the form (9) and applying them to the test equation

\[ y' = \lambda y, \quad \lambda < 0 \]

which is applied to (9) to yield

\[ Y_{n+1} = D(z)Y_n, \quad z = \lambda h, \quad (12) \]

where the matrix \( D(z) \) is given by

\[ D(z) = -(A^{(1)} - zB^{(1)})^{-1} A^{(0)} \]

From (12) we obtain the stability function \( R(z) : C \to C \) which is a rational function with real coefficients given by (13).

The stability domain of the method (region of absolute stability), \( S \), is defined as

\[ S = \{ z \in C : R(z) \leq 1 \} \quad (14) \]

Specifically, when the left-half complex plane is contained in \( S \), the method is said to be A-stable. Below in Fig. 1, we show the plot with rectangle representing the zeros and plus sign representing the poles of (13). The plot in white represents the stability region which corresponds to the stability function (13). Clearly, from the figure, it is obvious that our method is not A-stable since according to Hairer and Wanner [2] it has at least a pole of the stability function (13) in the left half complex plane.

However, the method is \( L_0 \)-stable as in Cash [13] since it satisfies the requirement that:

\[ \max_{z \leq 0} |R(z)| \leq 1, \quad z \text{ real and } \lim_{z \to -\infty} R(z) = 0 \]
\[ y_{n+8} = \frac{280h}{701} f_{n+8} - \frac{35}{701} y_n + \frac{320}{701} y_{n+1} - \frac{3920}{2283} y_{n+2} + \frac{3136}{701} y_{n+3} - \frac{4900}{701} y_{n+4} + \frac{15680}{2283} y_{n+5} - \frac{3920}{701} y_{n+6} + \frac{3920}{701} y_{n+7} \quad (6) \]

\[ Y'(t) = \frac{1}{R} \sum_{i=0}^{7} \alpha'_i(t) y_{n+j} + h \beta'_i(t) f_{n+8} = f(t_{n+j}, y_{n+j}) \quad (7) \]

\[ h f_{n+1} - \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 383 \ 15841 \ 3920 \ 3136 \ 4900 \ 15680 \ 3920 \ \frac{4242}{701} \ y_n + \frac{5215}{9132} y_{n+1} + \frac{25585}{9132} y_{n+2} + \frac{14861}{9132} y_{n+3} + \frac{4627}{9132} y_{n+4} + \frac{521}{9132} y_{n+5} - \frac{521}{9132} y_{n+7} \end{pmatrix} \]

\[ h f_{n+2} + \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 1159 \ 128731 \ 391 \ \frac{4242}{701} \ y_n + \frac{11157}{9132} y_{n+1} + \frac{2311}{9132} y_{n+2} - \frac{1385}{9132} y_{n+3} + \frac{3725}{9132} y_{n+4} - \frac{2172}{9132} y_{n+5} + \frac{677}{9132} y_{n+6} - \frac{517}{9132} y_{n+7} \end{pmatrix} \]

\[ h f_{n+3} - \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 190 \ 2423 \ 2353 \ - \frac{620}{9132} y_{n+1} + \frac{35}{1222} y_{n+2} + \frac{8852}{9132} y_{n+3} - \frac{891}{9132} y_{n+4} + \frac{2204}{9132} y_{n+5} - \frac{1723}{9132} y_{n+7} \end{pmatrix} \]

\[ h f_{n+4} + \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 1229 \ 136980 \ 136980 \ \frac{4242}{701} \ y_n + \frac{5349}{9132} y_{n+1} + \frac{2423}{9132} y_{n+2} + \frac{2305}{9132} y_{n+3} - \frac{1765}{9132} y_{n+4} + \frac{67241}{136980} y_{n+5} + \frac{21441}{136980} y_{n+6} - \frac{1723}{9132} y_{n+7} \end{pmatrix} \]

\[ h f_{n+5} - \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 933 \ 2283 \ \frac{4242}{701} \ y_n + \frac{905}{9132} y_{n+1} + \frac{246}{9132} y_{n+2} + \frac{2563}{9132} y_{n+3} - \frac{1690}{9132} y_{n+4} + \frac{4155}{9132} y_{n+5} - \frac{4846}{9132} y_{n+6} + \frac{15850}{9132} y_{n+7} + \frac{2242}{9132} y_{n+8} \end{pmatrix} \]

\[ h f_{n+6} + \frac{5h}{2283} f_{n+8} = \begin{pmatrix} 563 \ 106540 \ \frac{4242}{701} \ y_n + \frac{1001}{9132} y_{n+1} + \frac{2084}{9132} y_{n+2} + \frac{6095}{9132} y_{n+3} - \frac{33687}{9132} y_{n+4} + \frac{19901}{9132} y_{n+5} + \frac{6307}{9132} y_{n+6} + \frac{208903}{9132} y_{n+7} \end{pmatrix} \]


\[ A^{(0)} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]

\[ B^{(1)} = \begin{pmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]

\[ R(z) = \frac{3(1680 + 5880z + 9600z^2 + 9800z^3 + 6709z^4 + 3283z^5 + 1089z^6 + 210z^7)}{5040 - 22680z + 49140z^2 - 68040z^3 + 67347z^4 - 50463z^5 + 29531z^6 - 13698z^7 + 5040z^8} \quad (13) \]

**IV. Implementation**

The implementation of the above block method is summarized as follows:

**A. Summary**

On the partition \( I_N : \{ a = t_0 < t_1 < \ldots < t_{N-1} < t_N = b, n = 0, 1, 2, \ldots, N - 1 \} \).

Step 1. Choose \( N = 8, h = \frac{b-a}{N} \) the number of blocks \( \pi \stackrel{N}{=} \frac{N}{N} \) using (9) \( n = 0, \omega = 0 \) the values \( (y_1, y_2, \ldots, y_N)^T \) are generated simultaneously over the subinterval \([t_0, t_8]\) as \( y_0 \) are known from the IVP (1).

Step 2. for \( n = 8, \omega = 1 \), \((y_9, y_{10}, \ldots, y_{16})^T \) are obtained over the subinterval \([t_8, t_{16}]\) since \( y_8 \) is known from the first block.

Step 3. The process is continued for \( n = 2k, \ldots, N-k \) and \( \omega = 2, \ldots, \pi \) to obtain approximate solutions to (1) on sub-
Thus the Newton iteration of the 8 point block BDF method for (15) takes the form:

\[ y_{n+1}^{(j+1)} = y_{n+1}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

where

\[ F(n_{j+1}) = f(n_{j+1}, y_{n+1}^{(j)}) \]

Thus the Newton iteration of the 8 point block BDF method for (15) takes the form:

\[ y_{n+1}^{(j+1)} = y_{n+1}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

Where

\[ D_1, D_2, \ldots, D_8 \]

are known from the initial value of the problem. Thus we obtain the approximated values of

\[ y_{n+1}, y_{n+2}, \ldots, y_{n+8} \]

as

\[ y_{n+1}^{(j+1)} = y_{n+1}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+2}^{(j+1)} = y_{n+2}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+3}^{(j+1)} = y_{n+3}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+4}^{(j+1)} = y_{n+4}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+5}^{(j+1)} = y_{n+5}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+6}^{(j+1)} = y_{n+6}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+7}^{(j+1)} = y_{n+7}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

\[ y_{n+8}^{(j+1)} = y_{n+8}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

V. NUMERICAL EXAMPLES

A. Example 1

Example 1: Our first example is the problem whose Jacobian matrix J has purely imaginary eigenvalues on the range 0 ≤ t ≤ T

\[ y'_1 = -\alpha y_2 + (1 + \eta)\cos(t), \quad y_1(0) = 0 \]

\[ y'_2 = \alpha y_2 - (1 + \eta)\sin(t), \quad y_2(0) = 1 \]

With exact solution of the system given by

\[ y_1 = \sin(t), \quad y_2 = \cos(t) \]

For any value of the parameter \( \eta \). Thus, the jacobian J has the following expression

\[ J = \begin{pmatrix}
-\alpha & \eta \\
\eta & -\alpha
\end{pmatrix} \]

We explain briefly the implementation of the block methods. For linear problem we use the Gaussian elimination to solve the resulting k x k matrix in each block with our written Matlab code. While for non-linear problem the code uses the Newton iteration. The following notation is used to specify the iteration \( y_{n+1}^{(j+1)} \) denotes the \( (j+1)\)th iterative value of \( y_{n+1} \) and \( y_{n+1}^{(j)} = y_{n+1}^{(j)} \) for \( i = 1, 2, \ldots, k \) and \( i = 1, 2, \ldots, \).

Thus the Newton iteration of the 8 point block BDF method for (15) takes the form:

\[ y_{n+1}^{(j+1)} = y_{n+1}^{(j)} + \frac{F(n_{j+1})}{f'(n_{j+1})} F(n_{j+1}) \]

The stiffness ratio is 1:100. In Table II, we present result for that BGH stiff solver in Hall and Watt [24] and the version of the Gear method in Stubrowski [22], along with that of V.SCRK_8 in Vigo-Aguiar and Ramos [23]. For our method we use the step h = 0.1. The parameters considered are the number of function evaluations, feval, and the total number of integration steps, nstep. The exact solution, our numerical solution and the absolute error at the end of the last 10 time step (0.1, 10) are presented in Table III.

Remark: Although the V.SCRK_8 has fewer functions evaluations the method was evaluated with an initial step \( h = 10^{-4} \) but our method uses relatively large step size at \( h = 10^{-4} \) which shows its' efficiency and good accuracy.

<table>
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<th>h</th>
<th>M(s, r^2)</th>
<th>Our BDF</th>
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<td>0.1</td>
<td>3.45</td>
<td>3.39</td>
</tr>
<tr>
<td>0.25</td>
<td>6.67</td>
<td>6.38</td>
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<td>0.5</td>
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<td>12.45</td>
</tr>
<tr>
<td>1/40</td>
<td>12.57</td>
<td>14.23</td>
</tr>
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</table>
C. Example 3

Example 3: Consider the Stiffly nonlinear problem which was proposed by Kaps [25] in the range

\[ y'_1 = (e^{-1} + 2)y_1 + e^{-1}y_2, \quad y_1(0) = 1 \]

\[ y'_2 = y_1 - y_2 - y_2^3, \quad y_2(0) = 1 \]

The smaller \( \epsilon \) is, the more serious the stiffness of the system. Its exact solution is given by

\[ y_1 = y_2^2, \quad y_2 = e^{-t} \]

We compare our method with that of Wu and Xia [26], PRM of Li rong and and de-gui liu [27] and \( M(8, r8) \) in Chartier [20] taking values \( e^{-3}, e^{-6} \) and \( e^{-8} \) respectively.

The table below shows the result of our method compared with that of [27]. Lastly, for this example the result of our method compared with that of [20]. It can be seen that for this example our method show superiority over the all the three methods for the different values of \( \epsilon \) compared especially when the step size \( h \) is relatively high.

For our last example we present without comparison the result for different choices of the constant stepsize \( h \), the absolute error for \( h \) at the end of the interval \( T = 10 \).

D. Example 4

Example 4: Consider the weakly damped oscillatory problem in the range \( 0 \leq t \leq 10 \)
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