Stability Analysis of Additive Runge-Kutta Methods for Delay-Integro-Differential Equations

Hongyu Qin,1 Zhiyong Wang,2 Fumin Zhu,3 and Jinming Wen

1Wenhua College, Wuhan 430074, China
2School of Mathematical Sciences, University of Electronic Science and Technology of China, Sichuan 611731, China
3College of Economics, Shenzhen University, Shenzhen 518060, China
4Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada M5S3G4

Correspondence should be addressed to Fumin Zhu; zhufumin@szu.edu.cn

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1. Introduction

Spatial discretization of many nonlinear parabolic problems usually gives a class of ordinary differential equations, which have the stiff part and the nonstiff part; see, e.g., [1–5]. In such cases, the most widely used time-discretizations are the special organized numerical methods, such as the implicit-explicit numerical methods [6, 7], the additive Runge-Kutta methods [8–12], and the linearized methods [13, 14]. When applying the split numerical methods to numerically solve the equations, it is important to investigate the stability of the numerical methods.

In this paper, it is assumed that the spatial discretization of time-dependent partial differential equations yields the following nonlinear delay-integro-differential equations:

\[
y'(t) = f^{[1]}(t, y(t)) + f^{[2]}(t, y(t), y(t - \tau), \int_{t-\tau}^{t} g(t, s, y(s)) ds), \quad \tau > 0,
\]

\[
y(t) = \psi(t), \quad -\tau \leq t \leq 0.
\]

Here \( \tau \) is a positive delay term, \( \psi(t) \) is continuous, \( f^{[1]}: [t_0, +\infty) \times X \to X \), and \( f^{[2]}: [t_0, +\infty) \times X \times X \to X \), such that problem (1) owns a unique solution, where \( X \) is a real or complex Hilbert space. Particularly, when \( g \equiv 0 \), problem (1) is reduced to the nonlinear delay differential equations. When the delay term \( \tau = 0 \), problem (1) is reduced to the ordinary differential equations.


In the present work, we present the additive Runge-Kutta methods with some appropriate quadrature rules
to numerically solve the nonlinear delay-integrodifferential equations (1). It is shown that if the additive Runge-Kutta methods are algebraically stable, the obtained numerical solutions are globally and asymptotically stable under the given assumptions, respectively. The rest of the paper is organized as follows. In Section 2, we present the numerical methods for problems (1). In Section 3, we consider stability analysis of the numerical schemes. Finally, we present some extensions in Section 4.

2. The Numerical Methods

In this section, we present the additive Runge-Kutta methods with the appropriate quadrature rules to numerically solve problem (1).

The coefficients of the additive Runge-Kutta methods can be organized in Butcher tableau as follows (cf. [31]):

\[
\begin{array}{c|cc}
  & A^1 & A^2 \\
  c & (b^1)^T & (b^2)^T \\
\end{array}
\]  

where \( c = [c_1, \cdots, c_s]^T \), \( b^1 = [b_1^1, \cdots, b_s^1]^T \), and \( A^2 = (a_{ij}^2)_{i,j=1}^s \) for \( k = 1, 2 \).

Then, the presented ARKMs for problem (1) can be written by

\[
y_{n+1} = y_n + h \sum_{j=1}^s b_j^1 f^{[1]}(t_n + c_j h, y_j^{(n)}) + h \sum_{j=1}^s b_j^2 f^{[2]}(t_n + c_j h, y_j^{(n)}, y_j^{(n)}) \\
y_j^{(n)} = y_n + h \sum_{j=1}^s a_{ij}^1 f^{[1]}(t_n + c_j h, y_j^{(n)}) + h \sum_{j=1}^s a_{ij}^2 f^{[2]}(t_n + c_j h, y_j^{(n)}, y_j^{(n)}, y_j^{(n)}) \\
\]

where \( y_n \) and \( y_j^{(n)} \) are approximations to the analytic solution \( y(t_n) \) and \( y(t_n + c_j h) \), respectively, \( y_n = \psi(t_n) \) for \( n \leq 0 \), \( y_j^{(n)} = \varphi(t_n + c_j h) \) for \( t_n + c_j h \leq 0 \), and \( y_j^{(n)} \) denotes the approximation to \( \int_{t_n + c_j h - \tau}^{t_n + c_j h} g(t_n + c_j h, \xi, y(\xi))d\xi \), which can be computed by some appropriate quadrature rules

\[
y_j^{(n)} = h \sum_{k=0}^m p_k g(t_n + c_j h, t_{n-k} + c_j h, y_j^{(n-k)}) \\
\]

For example, we usually adopt the repeated Simpson’s rule or Newton-Cotes rule, etc., according to the requirement of the convergence of the method (cf. [18]).

3. Stability Analysis

In this section, we consider the numerical stability of the proposed methods. First, we introduce a perturbed problem, whose solution satisfies

\[
y' = f(t, z(t)) + f^{[2]}(t, z(t), z(t - \tau), \int_{t-\tau}^{t} g(t, s, z(s)) ds), \quad t > 0,
\]

\[
y(t) = \phi(t), \quad -\tau \leq t \leq 0.
\]

It is assumed that there exist some inner product < , > and the induced norm \( \| \cdot \| \) such that

\[
\begin{align*}
&\text{Re}\left< y - z, f^{[1]}(t, y) - f^{[1]}(t, z) \right> \leq \alpha \| y - z \|^2, \\
&\text{Re}\left< y - z, f^{[2]}(t, y, u_1, v_1) - f^{[2]}(t, z, u_2, v_2) \right> \\
&\hspace{1cm} \leq \beta_1 \| y - z \|^2 + \beta_2 \| u_1 - u_2 \|^2 + \gamma \| v_1 - v_2 \|^2, \\
&\| g(t, v, s_1) - g(t, v, s_2) \| \leq \theta \| s_1 - s_2 \|,
\end{align*}
\]

where \( \alpha < 0, \beta_1 < 0, \beta_2 > 0, \gamma > 0, \) and \( \theta > 0 \) are constants. It is remarkable that the conditions can be equivalent to the assumptions in [32, 33] (see [34] Remark 2.1).

Definition 1 (cf. [9]). An additive Runge-Kutta method is called algebraically stable if the matrices

\[
\begin{align*}
&\mathbf{B}_v := \text{diag}(b_1^v, \cdots, b_s^v), \quad v = 1, 2, \\
&M_{\eta} := \mathbf{B}_v A^{[\eta]} + A^{[\eta]T} \mathbf{B}_u - b^v [b^v]^T
\end{align*}
\]

are nonnegative.

Theorem 2. Assume an additive Runge-Kutta method is algebraically stable and \( \beta_1 + \beta_2 + 4 \gamma r^2 \eta^2 \Theta^2 < 0 \), where \( \eta = \max \{p_1, p_2, \cdots, p_s\} \). Then, it holds that

\[
\| y_n - z_n \| \leq \left( 1 + 2 \sum_{i=1}^s \tau b_i^2 \beta_2 + 4 \gamma r^2 \eta^2 \Theta^2 \right) \max_{-\tau \leq s \leq 0} \| y(s) - \phi(s) \|,
\]

where \( y_n \) and \( z_n \) are numerical approximations to problems (1) and (5), respectively.
Proof. Let \( \{ y_{n,1}^{(0)}, y_{n}^{(n)} \} \) and \( \{ z_{n,1}^{(0)}, z_{n}^{(n)} \} \) be two sequences of approximations to problems (1) and (5), respectively, by ARKM with the same stepsize \( h \) and write

\[
U_{i}^{(n)} = y_{i}^{(n)} - z_{i}^{(n)},
\]

\[
\tilde{U}_{i}^{(n)} = \tilde{y}_{i}^{(n)} - \tilde{z}_{i}^{(n)},
\]

\[
U_{0}^{(n)} = y_{n} - z_{n},
\]

\[
W_{i}^{[1]} = h \left[ f^{[1]} \left( t_{n} + c_{i}^{[1]} h, y_{i}^{(n)} \right) - f^{[1]} \left( t_{n} + c_{i}^{[1]} h, z_{i}^{(n)} \right) \right],
\]

\[
W_{i}^{[2]} = h \left[ f^{[2]} \left( t_{n} + c_{i}^{[2]} h, y_{i}^{(n)}, y_{i}^{(n-m)}, \tilde{y}_{i}^{(n)} \right) - f^{[2]} \left( t_{n} + c_{i}^{[2]} h, z_{i}^{(n)}, z_{i}^{(n-m)}, \tilde{z}_{i}^{(n)} \right) \right].
\]

With the notation, the ARKMs for (1) and (5) yield

\[
U_{0}^{(n+1)} = U_{0}^{(n)} + \sum_{\mu=1}^{s} \sum_{j=1}^{s} b_{\mu}^{[\mu]} W_{j}^{[\mu]},
\]

\[
U_{i}^{(n)} = U_{0}^{(n)} + \sum_{\mu=1}^{s} \sum_{j=1}^{s} d_{ij}^{[\mu]} W_{j}^{[\mu]}, \quad i = 1, 2, \ldots, s.
\]

Thus, we have

\[
\begin{array}{l}
\| U_{0}^{(n+1)} \|^2 = \left\langle U_{0}^{(n)} + \sum_{\mu=1}^{s} \sum_{j=1}^{s} b_{\mu}^{[\mu]} W_{j}^{[\mu]}, U_{0}^{(n)} \right\rangle \\
+ \sum_{j=1}^{s} \sum_{\mu=1}^{s} b_{\mu}^{[\mu]} b_{j}^{[\mu]} \left\langle W_{j}^{[\mu]}, [W_{j}^{[\mu]}] \right\rangle,
\end{array}
\]

\[
= \| U_{0}^{(n)} \|^2 + 2 \sum_{\mu=1}^{s} b_{\mu}^{[\mu]} \left\langle U_{0}^{(n)}, W_{j}^{[\mu]} \right\rangle
\]

\[
+ \sum_{j=1}^{s} \sum_{\mu=1}^{s} b_{\mu}^{[\mu]} b_{j}^{[\mu]} \left\langle W_{j}^{[\mu]}, [W_{j}^{[\mu]}] \right\rangle.
\]

Since that the matrix \( \mathcal{M} \) is a nonnegative matrix, we obtain

\[
- \sum_{\mu=1}^{s} \sum_{j=1}^{s} \left( b_{\mu}^{[\mu]} d_{ij}^{[\mu]} + a_{ij}^{[\mu]} b_{j}^{[\mu]} - b_{i}^{[\mu]} b_{j}^{[\mu]} \right) \left\langle W_{i}^{[\mu]}, W_{j}^{[\mu]} \right\rangle \leq 0.
\]

Furthermore, by conditions (6), we find

\[
\text{Re} \left\langle U_{i}^{(n)}, W_{i}^{[1]} \right\rangle \leq \alpha h \| U_{i}^{(n)} \|^2,
\]

and

\[
\text{Re} \left\langle U_{i}^{(n)}, W_{i}^{[2]} \right\rangle \leq \beta_{1} h \| U_{i}^{(n)} \|^2 + \beta_{2} h \| U_{i}^{(n-m)} \|^2 + \gamma h \| U_{i}^{(n)} \|^2.
\]

Together with (11), (12), (13), and (14), we get

\[
\| t_{j}^{(n+1)} \|^2 \leq \| U_{0}^{(n)} \|^2 + 2 \sum_{\mu=1}^{s} h b_{\mu}^{[\mu]} \| U_{i}^{(n)} \|^2
\]

\[
+ 2 \sum_{i=1}^{s} h b_{i}^{[\mu]} \left( \beta_{1} h \| U_{i}^{(n)} \|^2 + \beta_{2} h \| U_{i}^{(n-m)} \|^2 + \gamma h \| U_{i}^{(n)} \|^2 \right).
\]

Note that

\[
\| U_{i}^{(n)} \|^2 = \| h \sum_{k=0}^{m} g \left( t_{n} + c_{i} h, t_{n-k} + c_{i} h, y_{i}^{(n-k)} \right) - g \left( t_{n} + c_{i} h, t_{n-k} + c_{i} h, z_{i}^{(n-k)} \right) \|^{2} \leq (m + 1)
\]

\[
\cdot \eta^{2} \theta^{2} h^{2} \sum_{k=0}^{m} \| U_{i}^{(n-k)} \|^2.
\]

Then, we obtain

\[
\| t_{j}^{(n+1)} \|^2 \leq \| U_{0}^{(n)} \|^2 + 2 \sum_{\mu=1}^{s} h b_{\mu}^{[\mu]} \left( \beta_{1} \| U_{i}^{(n)} \|^2 + \beta_{2} \| U_{i}^{(n-m)} \|^2 + \gamma \| U_{i}^{(n)} \|^2 \right)
\]

\[
+ \beta_{2} \| U_{i}^{(n-m)} \|^2 + \gamma (m + 1) \eta^{2} \theta^{2} h^{2} \sum_{k=0}^{m} \| U_{i}^{(n-k)} \|^2.
\]
Assume an additive Runge-Kutta method is algebraically stable, the obtained numerical solutions are independent of the time. Besides, the asymptotical stability of the methods is also discussed in the present paper.

4. Conclusion

The additive Runge-Kutta methods with some appropriate quadrature rules are applied to solve the delay-integro-differential equations. It is shown that if the additive Runge-Kutta methods are algebraically stable, the obtained numerical solutions can be globally and asymptotically stable, respectively. In the future works, we will apply the methods to solve more real-world problems.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References


