Stability properties of differential-algebraic equations and spin-stabilized discretizations *

Peter Kunkel † Volker Mehrmann ‡

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Abstract

Classical stability properties of solutions that are well-known for ordinary differential equations (ODEs) are generalized to differential-algebraic equations (DAEs). A new test equation is derived for the analysis of numerical methods applied to DAEs with respect to the stability of the numerical approximations. Morevover, a stabilization technique is developed to improve the stability of classical DAE integration methods. The stability regions for these stabilized discretization methods are determined and it is shown that they much better reproduce the stability properties known for the ODE case than in the unstabilized form. Movies that depict the stability regions for several methods are included for interactive use.

Keywords: nonlinear differential-algebraic equations, stability, asymptotic stability, Lyapunov stability, spin-stabilized discretization, test equation, strangeness index

AMS(MOS) subject classification: 65L80, 65L20, 34D20, 34D23

1 Introduction and survey of previous results

In this paper we study different stability concepts for differential-algebraic equations (DAEs) as well as stabilization techniques for numerical methods. In particular, we consider initial value problems for general implicit systems of DAEs

$$F(t, x, \dot{x}) = 0, \tag{1}$$

with an initial condition

$$x(t_0) = x_0 \tag{2}$$

on the unbounded interval $\mathbb{I} = [t_0, \infty)$, with $F \in C^0(\mathbb{I} \times \mathbb{D}_x \times \mathbb{D}_{\dot{x}}, \mathbb{R}^n)$ sufficiently smooth and $\mathbb{D}_x, \mathbb{D}_{\dot{x}} \subseteq \mathbb{R}^n$ open sets.

DAEs like (1) arise in constrained multibody dynamics [9], electrical circuit simulation [11, 12], chemical engineering [7, 8] and many other applications, in particular when the dynamics of a system is constrained to a manifold or when different physical models are coupled together [28].

While DAEs provide a very convenient modeling concept, many numerical difficulties arise due to the fact that the dynamics is constrained to a manifold, which often is only given implicitly, see [31] or the recent textbook [21]. These difficulties are typically characterized by one of many index concepts that exist for DAEs, see [2, 10, 13, 21]. The fact that the dynamics of DAEs is constrained also requires a modification of the classical stability concepts that were developed for ODEs.

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†Mathematisches Institut, Universität Leipzig, Augustusplatz 10–11, D-04109 Leipzig, Fed. Rep. Germany.

‡Institut für Mathematik, MA 4-5, Technische Universität Berlin, D-10623 Berlin, Fed. Rep. Germany. Supported by *Deutsche Forschungsgemeinschaft*, through MATHEON, the DFG Research Center "Mathematics for Key Technologies" in Berlin.

Appropriate stability concepts for DAEs have been discussed already in several publications. The extension of the classical Lyapunov stability theory for linear DAEs with constant coefficients has been studied in [36, 37, 38]. For particular classes of DAEs, the classical stability concepts known for ODEs and for the corresponding integration methods have been analyzed in [1, 15, 16, 25, 27, 33, 34, 39]. Often this leads to modifications of the DAEs to avoid instabilities in the numerical methods.

All these papers deal with special classes or special formulations of DAEs and usually some restrictions on the size of the index of the DAE. In this paper we extend the classical stability concepts for ordinary differential equations to general DAEs of the form (1) and we analyze instabilities that may arise. We will discuss these concepts in Section 3.

The second topic of this paper is the development of stable integration methods for DAEs, where stability problems arise that cannot be observed for ODEs, as e.g. the following example taken from [27] demonstrates.

Example 1 Consider the linear DAE

$$\begin{bmatrix} \delta-1 & \delta t \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\eta(\delta-1) & -\eta\delta t \\ \delta-1 & \delta t-1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix},$$

with real parameters η and $\delta \neq 1$. This system has the solution

$$x_1(t) = (\delta-1)^{-1}(1-\delta t)x_2(t), \quad x_2(t) = e^{(\delta-\eta)t}x_2(0).$$

Obviously, $x(t) \to 0$ as $t \to \infty$ independently of $x_2(0)$ for $\delta < \eta$. On the other hand, using a constant stepsize h, the implicit Euler method yields numerical approximations

$$x_{i,1} = (\delta-1)^{-1}(1-\delta t_i)x_{i,2}, \quad x_{i,2} = \frac{1+h\delta}{1+h\eta}x_{i-1,2},$$

which satisfy $x_i \to 0$ as $i \to \infty$ independently of $x_{0,2}$ if and only if $|1+h\delta| < |1+h\eta|$. Hence, there exist parameter values (δ, η) for which the exact solution asymptotically goes to zero while the numerical solution grows unboundedly.

Example 1 demonstrates that for DAEs instabilities may arise that cannot be observed for ODEs and thus the classical test equation

$$\dot{x} = \lambda x, \quad \lambda \in \mathbb{C}, \tag{3}$$

is not sufficient to analyze this instability.

For this reason and in order to allow a better comparison of different integration methods for DAEs, in Section 4 we will take up on Example 1 and suggest a new linear test equation for DAEs which generalizes (3). This new test equation is

$$\begin{bmatrix} 1 & -\omega t \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \lambda & \omega(1-\lambda t) \\ -1 & 1+\omega t \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

and combines the classical test equation with an algebraic equation in such a way that the kernel of the corresponding matrix function E spins and ω is a measure for the size of the time derivative of a kernel function.

We will show that with the variation of these two parameters many stability properties of classical DAE integration methods can be tested and compared. A comparison of well-known DAE integration methods for this test equation is presented in Section 5, where also DAE stability functions for these methods are derived.

Finally, in Section 6 we derive a new stabilization technique for general DAE integration methods (which we call *spin-stabilization*). We analyze the stability behavior of several classical DAE integrators and show that with this technique more appropriate stability regions can be achieved.

2 Preliminaries, Notation, and Definitions

2.1 Notation

For x_0 in some vector space $\mathbb{X}$ and $\varrho > 0$, we denote the open ball with radius ϱ around x_0 in $\mathbb{X}$ by $\mathcal{B}(x_0, \varrho)$, i.e.

$$\mathcal{B}(x_0, \varrho) = \{x \in \mathbb{X} \mid \|x - x_0\| < \varrho\},$$

and the corresponding closed ball by $\overline{\mathcal{B}}(x_0, \varrho)$, i.e.

$$\overline{\mathcal{B}}(x_0, \varrho) = \overline{\mathcal{B}(x_0, \varrho)} = \{x \in \mathbb{X} \mid \|x - x_0\| \leq \varrho\}.$$

By $\langle \cdot, \cdot \rangle$, we denote the *Euclidian scalar product* and by $\|x\|_2$ the associated *Euclidian norm* in $\mathbb{R}^n$ as well as the associated *spectral norm* for matrices in $\mathbb{R}^{n,n}$.

We use the relation $X \geq Y$ for symmetric (Hermitian) matrices X, Y to denote that $X - Y$ is positive semidefinite.

If (1) together with (2) possesses a unique solution on $\mathbb{I}$, then we denote it by $x(t; t_0, x_0)$ when we want to stress its dependence on the initial condition.

2.2 DAE theory

In this section we briefly recall some concepts from the theory of differential-algebraic equations, see [2, 10, 21, 30]. We follow [21] in notation and style of presentation.

Definition 1 *Consider system (1) with sufficiently smooth F. A function $x : \mathbb{I} \to \mathbb{R}^n$ is called a* solution *of (1) if $x \in C^1(\mathbb{I}, \mathbb{R}^n)$ and x satisfies (1) pointwise. It is called a* solution of the initial value problem *(1)–(2) if x is a solution of (1) and satisfies (2). An initial condition (2) is called* consistent *if the corresponding initial value problem has at least one solution.*

It is possible to weaken this solution concept [22, 26, 29], but we will not consider such weaker solution concepts in this paper.

For the DAE system (1), as in [4, 5, 19], we introduce a nonlinear derivative array of the form

$$F_\ell(t, x, \dot{x}, \ldots, x^{(\ell+1)}) = 0,$$

which stacks the original equation and all its derivatives up to level ℓ in one large system, i. e.,

$$F_\ell(t, x, \dot{x}, \ldots, x^{(\ell+1)}) = \begin{bmatrix} F(t, x, \dot{x}) \\ \frac{d}{dt} F(t, x, \dot{x}) \\ \vdots \\ \frac{d^\ell}{dt^\ell} F(t, x, \dot{x}) \end{bmatrix}.$$

Partial derivatives of F_ℓ with respect to selected variables p from $z_\ell = (t, x, \dot{x}, \ldots, x^{(\ell+1)})$ are denoted by $F_{\ell;p}$, e. g.,

$$F_{\ell;x} = \frac{\partial}{\partial x} F_\ell, \quad F_{\ell;\dot{x},\ldots,x^{(k+1)}} = [\, \frac{\partial}{\partial \dot{x}} F_\ell \;\; \cdots \;\; \frac{\partial}{\partial x^{(\ell+1)}} F_\ell \,].$$

A corresponding notation is also used for partial derivatives of other functions.

In order to analyze existence and uniqueness of solutions, we introduce the *solution set* of the nonlinear algebraic equation associated with the derivative array F_μ for some integer μ, given by

$$\mathbb{L}_\mu = \{z_\mu \in \mathbb{I} \times \mathbb{R}^n \times \mathbb{R}^n \times \ldots \times \mathbb{R}^n \mid F_\mu(z_\mu) = 0\}.$$

We make the following hypothesis, see [21].

Hypothesis 1 *Consider the general system of nonlinear differential-algebraic equations (1). There exist integers μ, r, a, d, and v such that $\mathbb{L}_\mu$ is not empty and for every point $(t_0, x_0, \dot{x}_0, \ldots, x_0^{(\mu+1)}) \in \mathbb{L}_\mu$ there exists a (sufficiently small) neighborhood in which the following properties hold:*

1. *We have* $\operatorname{rank} F_{\mu;\dot{x},\ldots,x^{(\mu+1)}} = (\mu+1)n - a$ *on* $\mathbb{L}_\mu$ *such that there exists a smooth full rank matrix function* Z_2 *of size* $(\mu+1)m \times a$ *satisfying*

$$Z_2^T F_{\mu;\dot{x},\ldots,x^{(\mu+1)}} = 0$$

on $\mathbb{L}_\mu$.

2. *We have* $\operatorname{rank} Z_2^T F_{\mu;x} = a$ *on* $\mathbb{L}_\mu$ *such that there exists a smooth full rank matrix function* T_2 *of size* $n \times (n-a)$ *satisfying*

$$Z_2^T F_{\mu;x} T_2 = 0.$$

3. *We have* $\operatorname{rank} F_{\dot{x}} T_2 = d = n - a$ *such that there exists a smooth full rank matrix function* Z_1 *of size* $n \times d$ *satisfying*

$$\operatorname{rank} Z_1^T F_{\dot{x}} T_2 = d.$$

As in [19, 21], we call the smallest possible μ for which Hypothesis 1 is valid the *strangeness index* of (1). Systems with vanishing strangeness index are called *strangeness-free*.

It has been shown in [20] that Hypothesis 1 implies locally (via the implicit function theorem) the existence of a *reduced system* such that the solutions are in one-to-one correspondence and the differential and algebraic part contained in the given DAE are separated. This result can be globalized when we start with a solution x in the sense that we have path

$$(t, x(t), \mathcal{P}(t)) \in \mathbb{L}_{\mu+1} \text{ for all } t \in \mathbb{I}.$$

In the present context, where stability questions are concerned, we must take care that the involved transformations do not alter the behavior of the solution as $t \to \infty$. We therefore sketch the construction of the reduced system along the lines of [21] and pay special attention to the conservation of the stability properties of the given DAE.

Due to Hypothesis 1 there exist

$$Z_2 \in C^0(\mathbb{I}, \mathbb{R}^{(\mu+1)n,a}), \quad T_2 \in C^0(\mathbb{I}, \mathbb{R}^{n,n-a}), \quad Z_1 \in C^0(\mathbb{I}, \mathbb{R}^{n,d}),$$

with the described properties. Since Gram-Schmidt orthonormalization is a smooth process, we may assume without loss of generality that the columns of these matrix functions are pointwise orthonormalized. Let then

$$Z_2' \in C^0(\mathbb{I}, \mathbb{R}^{(\mu+1)n,(\mu+1)n-a}), \quad T_2' \in C^0(\mathbb{I}, \mathbb{R}^{n,a}), \quad Z_1' \in C^0(\mathbb{I}, \mathbb{R}^{n,n-d}),$$

be such that

$$[\, Z_2' \;\; Z_2 \,], \quad [\, T_2' \;\; T_2 \,], \quad [\, Z_1' \;\; Z_1 \,]$$

are pointwise orthogonal. Furthermore, there exist

$$T_1 \in C^0(\mathbb{I}, \mathbb{R}^{(\mu+1)n,a}), \quad T_1' \in C^0(\mathbb{I}, \mathbb{R}^{(\mu+1)n,(\mu+1)n-a})$$

such that

$$[\, T_1' \;\; T_1 \,]$$

is pointwise orthogonal and

$$Z_2'(t)^T F_{\mu;\dot{x},\ldots,x^{(\mu+1)}}(t, x(t), \mathcal{P}(t)) T_1(t) = 0 \text{ for all } t \in \mathbb{I}.$$

If we define a function $\mathcal{H}$ via

$$\mathcal{H}(t, x, p, \phi) = \begin{bmatrix} F_\mu(t, x, p) + Z_2(t)\phi \\ T_1(t)^T (p - \mathcal{P}(t)) \end{bmatrix},$$

then

(a) $\mathcal{H}(t, x(t), \mathcal{P}(t), 0) = 0,$

(b) $\mathcal{H}_{p,\phi}(t, x(t), \mathcal{P}(t), 0) = \begin{bmatrix} F_{\mu;\dot{x},\ldots,x^{(\mu+1)}}(t, x(t), \mathcal{P}(t)) & Z_2(t) \\ T_1(t)^T & 0 \end{bmatrix}.$

By construction $\mathcal{H}_{p,\phi}(t, z(t), \mathcal{P}(t), 0)$ is nonsingular for all $t \in \mathbb{I}$. Thus we can locally solve for p and ϕ as

$$\phi = \hat{F}_2(t, x), \quad p = \hat{\mathcal{P}}(t, x).$$

It can then be shown that the equation

$$\hat{F}_2(t, x) = 0 \tag{4}$$

is just the requirement that x satisfies all constraints that are contained in (1) for time t.

With the change of variables

$$x = T_2 x_1 + T_2' x_2, \quad x_1 = T_2^T x, \quad x_2 = {T_2'}^T x$$

the equation (4) turns into

$$\hat{F}_2(t, T_2(t)x_1 + T_2'(t)x_2) = 0. \tag{5}$$

Note that this transformation and the corresponding back-transformation preserve the Euclidian norm of the unknown functions at every point $t \in \mathbb{I}$. If we set $x_1(t) = T_2^T(t)x(t)$, $x_2(t) = T_2'(t)^T x(t)$ then it follows that for all $t \in \mathbb{I}$

(a) $\hat{F}_2(t, T_2(t)x_1(t) + T_2'(t)x_2(t)) = 0,$
(b) $\hat{F}_{2;x}(t, x(t))T_2'(t)$ is nonsingular.

Thus, we can solve (5) for x_2 as $x_2 = \mathcal{R}(t, x_1)$ and we have

$$x_2(t) = \mathcal{R}(t, x_1(t)) \text{ for all } t \in \mathbb{I}. \tag{6}$$

Besides (6) we have

$$p_2(t) = \mathcal{R}_t(t, x_1(t)) + \mathcal{R}_{x_1}(t, x_1(t))p_1(t), \tag{7}$$

where we use the partition

$$[\, I_n \;\; 0 \;\; \cdots \;\; 0 \,]\tilde{\mathcal{P}} = \begin{bmatrix} p_1(t) \\ p_2(t) \end{bmatrix},$$

compare the proof of Theorem 4.13 in [21]. We then obtain

$$Z_1(t)^T F(t, T_2(t)x_1(t) + T_2'(t)\dot{x}_2(t), \dot{T}_2(t)x_1(t) + T_2(t)p_1(t) + \dot{T}_2'(t)x_2(t) + T_2'(t)x_2(t)) = 0 \quad \text{for all } t \in \mathbb{I}, \tag{8}$$

in which we can eliminate x_2, p_2 via (6) and (7), respectively. If we define

$$\begin{aligned}\hat{F}_1(t, x_1, p_1) = Z_1(t)^T F(t, T_2(t)x_1 + T_2'(t)\mathcal{R}(t, x_1),\\ \dot{T}_2(t)x_1 + T_2(t)p_1(t) + \dot{T}_2'(t)\mathcal{R}(t, x_1) + T_2'(t)(\mathcal{R}_t(t, x_1) + \mathcal{R}_{x_1}(t, x_1)p_1)),\end{aligned}$$

then $(t, x_1(t), x_1(t))$ solves $\hat{F}_1(t, z_1, p_1) = 0$. Furthermore,

$$\hat{F}_{1;p_1}(t, x_1(t), p_1(t)) = Z_1(t)^T F_{\dot{x}}(t, x(t), p(t))(T_2(t) + T_2'(t)\mathcal{R}_{x_1}(t, x_1(t))),$$

where $[\, I_n \;\; 0 \;\; \cdots \;\; 0 \,]\mathcal{P} = p$. To determine $\mathcal{R}_{x_1}(t, x_1(t))$ one observes that from

$$\hat{F}_2(t, T_2(t)x_1(t) + T_2'(t)\mathcal{R}_{x_1}(t, x_1(t))) = 0 \text{ for all } t \in \mathbb{I},$$

it follows that

$$\hat{F}_{2;x}(t, x(t))(T_2(t) + T_2'(t)\mathcal{R}_{x_1}(t, x_1(t))) = 0 \text{ for all } t \in \mathbb{I}$$

and hence, using (4) we obtain

$$Z_2(t)^T F_{\mu;x}(t, x(t), \mathcal{P}(t))(T_2(t) + T_2'(t)\mathcal{R}_{x_1}(t, x_1(t))) = 0 \text{ for all } t \in \mathbb{I}.$$

By the construction of Z_2, T_2, and T_2', we immediately obtain that

$$\mathcal{R}_{x_1}(t, x_1(t)) = 0 \text{ for all } t \in \mathbb{I}$$

and that $\hat{F}_{1;p_1}(t, x_1(t), p_1(t))$ is nonsingular for all $t \in \mathbb{I}$. Thus, we can solve $\hat{F}_1(t, x_1, p_1)$ for p_1 according to

$$p_1 = \mathcal{L}(t, x_1).$$

If we require that x_1 is continuously differentiable and that that the part p_1 of $\mathcal{P}$ satisfies $p_1(t) = \dot{x}_1(t)$ for all $t \in \mathbb{I}$, then we see that the given x solves the DAE

$$\begin{array}{ll} \text{(a)} & \dot{x}_1 = \mathcal{L}(t, x_1), \\ \text{(b)} & x_2 = \mathcal{R}(t, x_1). \end{array} \tag{9}$$

Summarizing the above construction, we observe that we only have applied one transformation of the variable x. This transformation together with its inverse are pointwise orthogonal such that it preserves the behavior of the solution as $t \to \infty$. For the applications of the implicit function theorem, however, we must require that the corresponding neighborhoods do not shrink to a point as $t \to \infty$. Sufficient for this is the additional assumption that there exists a set $\mathbb{V} \subseteq \mathbb{I} \times \mathbb{R}^n \times \cdots \times \mathbb{R}^n$ such that $(t, x(t), \mathcal{P}(t)) \in \mathbb{V}$ for sufficiently large t and that the implicit function theorem can always applied in the whole set $\mathbb{V}$. Note that this condition is trivially satisfied when we study an equilibrium solution x of (1) given by the property that $x(t) = x^* \in \mathbb{R}^n$ and $(t, x^*, 0) \in \mathbb{L}_{\mu+1}$ for all $t \in \mathbb{I}$. Instead of (1) we can then concentrate on the investigation of (9) due to the fact that under mild assumptions the solutions of (1) and (9) are locally in one-to-one correspondence, see [21].

In the special case of a linear DAE

$$E(t)\dot{x} = A(t)x + f(t), \tag{10}$$

where $E, A \in C^0(\mathbb{I}, \mathbb{R}^{n,n})$ and $f \in C^0(\mathbb{I}, \mathbb{R}^n)$ are sufficiently smooth, the corresponding reduced DAE (9) is linear as well and of the form

$$\begin{array}{ll} \text{(a)} & \dot{x}_1 = A_{11}(t)x_1 + f_1(t), \\ \text{(b)} & x_2 = A_{21}(t)x_1 + f_2(t). \end{array} \tag{11}$$

This also shows that if the DAE belonging to a pair $(\hat{E}, \hat{A})$ of matrix functions is strangeness-free then there is a pointwise nonsingular matrix function $P \in C^0(\mathbb{I}, \mathbb{R}^{n,n})$ and a pointwise orthogonal matrix function $Q \in C^1(\mathbb{I}, \mathbb{R}^{n,n})$ such that

$$P\hat{E}Q = \begin{bmatrix} I_d & 0 \\ 0 & 0 \end{bmatrix}, \quad P\hat{A}Q - P\hat{E}\dot{Q} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & -I_a \end{bmatrix}. \tag{12}$$

2.3 Stability concepts for ODEs

In this section, we briefly recall classical stability concepts for ordinary differential equations

$$\dot{x} = f(t, x), \quad t \in \mathbb{I}. \tag{13}$$

See e.g. [17, 35] for more details on this topic. We include proofs when we need the notation and parts of them when we discuss similar results for DAEs.

Definition 2 *A solution $x : t \mapsto x(t; t_0, x_0)$ of (13) is called*

1. stable *if for every $\varepsilon > 0$ there exists $\delta > 0$ such that*
   (a) *the initial value problem (13) with initial condition $x(t_0) = \hat{x}_0$ is solvable on $\mathbb{I}$ for all $\hat{x}_0 \in \mathbb{R}^n$ with $\|\hat{x}_0 - x_0\| < \delta$;*
   (b) *the solution $x(t; t_0, \hat{x}_0)$ satisfies $\|x(t; t_0, \hat{x}_0) - x(t; t_0, x_0)\| < \varepsilon$ on $\mathbb{I}$.*

2. asymptotically stable *if it is stable and there exists* $\varrho > 0$ *such that*

   (a) *the initial value problem (13) with initial condition* $x(t_0) = \hat{x}_0$ *is solvable on* $\mathbb{I}$ *for all* $\hat{x}_0 \in \mathbb{R}^n$ *with* $\|\hat{x}_0 - x_0\| < \varrho$*;*

   (b) *the solution* $x(t; t_0, \hat{x}_0)$ *satisfies* $\lim_{t\to\infty} \|x(t; t_0, \hat{x}_0) - x(t; t_0, x_0)\| = 0$*.*

3. exponentially stable *if it is stable and* exponentially attractive*, i.e. if there exist* $\delta > 0$*,* $L > 0$*, and* $\gamma > 0$ *such that*

   (a) *the initial value problem (13) with initial condition* $x(t_0) = \hat{x}_0$ *is solvable on* $\mathbb{I}$ *for all* $\hat{x}_0 \in \mathbb{R}^n$ *with* $\|\hat{x}_0 - x_0\| < \delta$*;*

   (b) *the solution satisfies the estimate* $\|x(t; t_0, \hat{x}_0) - x(t; t_0, x_0)\| < Le^{-\gamma(t-t_0)}$ *on* $\mathbb{I}$*.*

Note that we can transform the ODE (13) in such a way that a given solution $x(t; t_0, x_0)$ is mapped to the trivial solution by simply shifting the arguments according to

$$\dot{\tilde{x}} = \tilde{f}(t, \tilde{x}) = f(t, \tilde{x} + x(t; t_0, x_0)) - \tfrac{\partial}{\partial t} x(t; t_0, x_0). \tag{14}$$

When studying the stability of a selected solution, we may therefore assume without loss of generality that the selected solution is the trivial solution. This also applies to DAEs. In the following, we will concentrate on *equilibrium solutions* x^*, i.e. solutions with $x(t; t_0, x_0) = x^*$ independent of t, although we may simply set $x^* = 0$.

We will also study further concepts which are not related to a selected solution such as contractivity and dissipativity.

Definition 3 *The ODE (13) is called* contractive *if for any two solutions* x, y *the scalar function* $d : \mathbb{I} \to \mathbb{R}_0^+$ *defined by* $d(t) = \|x(t) - y(t)\|_2^2$ *is monotonically non-increasing. It is called* exponentially contractive *if* d *decays exponentially.*

Definition 4 *The ODE (13) is called* dissipative *if there exists a bounded set* $\mathbb{B} \subseteq \mathbb{R}^n$ *with the property that for any bounded set* $\mathbb{E} \subseteq \mathbb{R}^n$ *there exists* $\hat{t} \geq t_0$ *with* $x(t; t_0, \hat{x}_0) \in \mathbb{B}$ *for all* $\hat{x}_0 \in \mathbb{E}$ *and* $t > \hat{t}$*. In this case the set* $\mathbb{B}$ *is called* absorbing*.*

We start our survey of stability results with the special case of linear ODEs. In view of (14) it is sufficient to study homogeneous equations

$$\dot{x} = A(t)x. \tag{15}$$

Since we obtain (15) no matter which solution we want to look at, the stability properties of Definition 2 are merely properties of the given linear ODE. In particular, the initial value problem

$$\tfrac{\partial}{\partial t}\Phi(t, t_0) = A(t)\Phi(t, t_0), \quad \Phi(t_0, t_0) = I_n.$$

possesses a solution $t \mapsto \Phi(t, t_0)$ on $\mathbb{I}$, so-called *fundamental solution*, and the solution x of (15) with $x(t_0) = x_0$ can be written as $x(t) = \Phi(t, t_0)x_0$. The following characterizations are then straightforward.

Theorem 5 *The trivial solution of the linear homogeneous ODE (15)*

1. *is stable if and only if there exists a constant* $L > 0$ *with* $\|\Phi(t, t_0)\| \leq L$ *on* $\mathbb{I}$*;*
2. *is asymptotically stable if and only if* $\|\Phi(t, t_0)\| \to 0$ *for* $t \to \infty$*;*
3. *is exponentially stable if exists* $L > 0$ *and* $\gamma > 0$ *such that* $\|\Phi(t, t_0)\| \leq Le^{-\gamma(t-t_0)}$ *on* $\mathbb{I}$*.*

In the general nonlinear case, we can only expect sufficient conditions that guarantee the specific stability properties. The classical result is given in the so-called Lyapunov stability theorems, see e.g. [17].

Definition 6 *Let $\mathbb{U}$ be an (open) neighborhood of an equilibrium solution x^* of the ODE (13). A function $V \in C^1(\mathbb{I} \times \mathbb{U}, \mathbb{R}_0^+)$ is called* Lyapunov function *associated with x^* if*

1. *$V(t, x^*) = 0$ for all $t \in \mathbb{I}$,*
2. *$\dot{V}(t, x) \leq 0$ for all $(t, x) \in \mathbb{I} \times \mathbb{U}$, where $\dot{V}(t, x) = V_x(t, x)f(t, x) + V_t(t, x)$,*
3. *there exists a continuous function $W : \mathbb{U} \to \mathbb{R}_0^+$ with $W(x) > 0$ for all $x \in \mathbb{U} \setminus \{x^*\}$ and $V(t, x) \geq W(x)$ for all $(t, x) \in \mathbb{I} \times \mathbb{D}$.*

Theorem 7 *Let V be a Lyapunov function associated with an equilibrium solution x^* of (13). Then x^* is stable.*

Theorem 8 *Let V be a Lyapunov function associated with an equilibrium solution x^* of (13) satisfying*

1. *for all $\varepsilon < 0$ there exists $\delta > 0$ such that $V(t, x) < \varepsilon$ for all $t \in \mathbb{I}$ and all $x \in \mathbb{U}$ with $\|x - x^*\| < \delta$;*
2. *there exists a continuous function $\tilde{W} : \mathbb{U} \to \mathbb{R}_0^+$ with $\tilde{W}(x) > 0$ for all $x \in \mathbb{U} \setminus \{x^*\}$, $\tilde{W}(x^*) = 0$, and $\dot{V}(t, x) \geq -\tilde{W}(x)$ for all $(t, x) \in [t_0, \infty) \times \mathbb{D}$.*

Then x^* is asymptotically stable.

In the linear case (15), one looks for Lyapunov functions of the form

$$V(t, x) = x^T X(t) x$$

with pointwise symmetric $X \in C^1(\mathbb{I}, \mathbb{R}^{n,n})$. By definition, we then have

$$\begin{aligned} \dot{V}(t, x) &= V_x(t, x)f(t, x) + V_t(t, x) \\ &= x^T A(t)^T X(t) x + x^T X(t) A(t) x + x^T \dot{X}(t) x \\ &= x^T (\dot{X}(t) + A(t)^T X(t) + X(t) A(t)) x. \end{aligned}$$

such that $\dot{V}(t, x) = -x(t)^T Y(t) x(t)$ with the so-called *Lyapunov differential equation*

$$\dot{X}(t) + A(t)^T X(t) + X(t) A(t) + Y(t) = 0 \tag{16}$$

Hence, a Lyapunov function can be constructed if one can find appropriate X and Y solving (16). In particular, we have the following result.

Corollary 9 *Let $X \in C^1(\mathbb{I}, \mathbb{R}^{n,n})$ and $Y \in C^0(\mathbb{I}, \mathbb{R}^{n,n})$ solve the Lyapunov differential equation (16). The trivial solution of the linear homogeneous ODE (15)*

1. *is stable if there is $w > 0$ such that $X(t) \geq w I_n$ and $Y(t) \geq 0$ on $\mathbb{I}$.*
2. *is asymptotically stable if there are $w, \hat{w}, \tilde{w} > 0$ such that $\hat{w} I_n \geq X(t) \geq w I_n$ and $Y(t) \geq \tilde{w} I_n$ on $\mathbb{I}$.*

We turn now to stability properties which are not associated with a particular solution. All proofs are based on the following auxiliary result known as Gronwall's lemma.

Lemma 10 *Let $z \in C^1(\mathbb{I}, \mathbb{R})$ satisfy*

$$\dot{z}(t) \leq a z(t) + b \text{ for all } t \in \mathbb{I},$$

with constants $a, b \in \mathbb{R}$. Then on $\mathbb{I}$ we have that

$$z(t) \leq \begin{cases} e^{a(t-t_0)} z(t_0) + \frac{b}{a}(e^{a(t-t_0)} - 1) & \text{for } a \neq 0, \\ z(t_0) + b(t - t_0) & \text{for } a = 0. \end{cases}$$

Recall for the following that we assume that $f \in C^0(\mathbb{I}\times\mathbb{U},\mathbb{R}^n)$ is sufficiently smooth. Moreover, we suppose that the interesting domain $\mathbb{U}$ is sufficiently large.

Theorem 11 *Let $f \in C^0(\mathbb{I}\times\mathbb{U},\mathbb{R}^n)$ satisfy a one-sided Lipschitz condition with constant $c \in \mathbb{R}$, i.e. let*

$$\langle f(t,x)-f(t,y),x-y\rangle \le c\|x-y\|_2^2 \text{ for all } t\in\mathbb{I} \text{ and } x,y\in\mathbb{U}.$$

If $c=0$, then (13) is contractive. If $c<0$, then (13) is exponentially contractive.

Proof. For two solutions x, y of (13), we have

$$\begin{aligned}\tfrac{1}{2}\tfrac{d}{dt}\|x(t)-y(t)\|_2^2 &= \langle \dot{x}(t)-\dot{y}(t),x(t)-y(t)\rangle\\ &= \langle f(t,x(t))-f(t,y(t)),x(t)-y(t)\rangle \le c\|x(t)-y(t)\|_2^2.\end{aligned}$$

Setting $d(t)=\|x(t)-y(t)\|_2^2$, this relation reads $\dot{d}(t)\le 2cd(t)$ and Lemma 10 yields

$$d(t)\le e^{2c(t-t_0)}d(t_0)$$

in both cases. □

Theorem 12 *Let $f \in C^0(\mathbb{I}\times\mathbb{U},\mathbb{R}^n)$ satisfy*

$$\langle f(t,x),x\rangle \le \alpha-\beta\|x\|_2^2 \text{ for all } t\in\mathbb{I} \text{ and } x\in\mathbb{U},$$

with constants $\alpha\ge 0$ and $\beta>0$. Then the ODE (13) is dissipative with absorbing set $\mathbb{B}=\mathcal{B}(0,\sqrt{\alpha/\beta+\varepsilon})$ for arbitrary $\varepsilon>0$.

Proof. Let x be a solution of (13). Since

$$\tfrac{1}{2}\tfrac{d}{dt}\|x(t)\|_2^2 = \langle f(t,x(x)),x(t)\rangle \le \alpha-\beta\|x(t)\|_2^2,$$

Lemma 10 yields

$$\|x(t)\|_2^2 \le \alpha/\beta + e^{-2\beta t}(\|x(t_0)\|_2^2-\alpha/\beta) \le \max\{\|x(t_0)\|_2^2,\alpha/\beta\}$$

such that

$$\|x(t)\|_2 \le \max\{\|x(t_0)\|_2,\sqrt{\alpha/\beta}\}.$$

Hence, $\mathbb{B}$ is positive invariant, i.e.

$$x(t;t_0,\hat{x}_0)\in\mathbb{B} \text{ for all } t\ge t_0,\ \hat{x}_0\in\mathbb{B}.$$

Let

$$R=\sup_{\hat{x}_0\in\mathbb{E}}\|\hat{x}_0\|_2.$$

The estimate

$$\|x(t)\|_2 \le \alpha/\beta + e^{-2\beta t}(R^2-\alpha/\beta) \le \alpha/\beta+\varepsilon$$

finally gives

$$e^{-2\beta\hat{t}}(R^2-\alpha/\beta)\le\varepsilon$$

as condition on $\hat{t}$ in Definition 4. □

Theorem 13 *Let $f \in C^0(\mathbb{I}\times\mathbb{U},\mathbb{R}^n)$ satisfy*

$$\langle f(t,x),x\rangle < 0 \text{ for all } t\in\mathbb{I} \text{ and } x\in\mathbb{U} \text{ with } \|x\|_2>R.$$

Then the ODE (13) is dissipative with absorbing set $\mathbb{B}=\mathcal{B}(0,R+\varepsilon)$ for arbitrary $\varepsilon>0$.

Proof. A solution x of (13) satisfies

$$\tfrac{1}{2}\tfrac{d}{dt}\|x(t)\|_2^2 = \langle f(t,x(x)), x(t)\rangle.$$

If $x(t) \in \mathbb{R}^n \setminus \mathbb{B}$, then $\frac{d}{dt}\|x(t)\|_2 < 0$ and therefore

$$\|x(t)\|_2 < \max\{\|x(t_0)\|_2, R+\varepsilon\} \text{ for all } t > t_0.$$

Hence, $\mathbb{B}$ is positive invariant. Let

$$r > \max\{\sup_{\hat{x}_0 \in \mathbb{E}} \|\hat{x}_0\|_2, R+\varepsilon\}$$

and let $\hat{\mathbb{B}} = \overline{\mathcal{B}}(0,r)$. Because of $\hat{\mathbb{B}} \supseteq \mathbb{B}$ we have $\mathbb{R}^n \setminus \hat{\mathbb{B}} \subseteq \mathbb{R}^n \setminus \mathbb{B}$ and therefore $\frac{d}{dt}\|x(t)\|_2^2 < 0$ as long as $x(t) \in \hat{\mathbb{B}} \setminus \mathbb{B}$. Hence, $\hat{\mathbb{B}}$ is positive invariant as well. Moreover, $\hat{\mathbb{B}} \setminus \mathbb{B}$ in compact and $\langle f(t,x(x)), x(t)\rangle < 0$ on $\hat{\mathbb{B}} \setminus \mathbb{B}$. Due to the continuity of f there exists $\delta > 0$ with

$$\tfrac{d}{dt}\|x(t)\|_2^2 < -\delta \text{ on } \hat{\mathbb{B}} \setminus \mathbb{B}$$

as long as $x(t) \in \hat{\mathbb{B}} \setminus \mathbb{B}$. For $\hat{x}_0 \in \mathbb{E}$ it then follows that

$$x(t; t_0, \hat{x}_0) \in \mathbb{B} \text{ for all } t > \hat{t} = (r^2 - (R+\varepsilon)^2)/\delta,$$

with $\hat{t}$ as required in Definition 4. □

3 Stability results for DAEs

In this section we generalize the classical ODE stability results that we have reviewed in Section 2.3 to DAEs.

The key idea to obtain these analytical results is to consider first the transformation to the reduced system (9) which has the same solution set and consider the stability results in this framework. After this has been done we then transform back to the original system.

3.1 Linear DAEs

We begin our analysis with linear DAEs (10) with variable coefficients. The stability analysis for such equations has been studied for systems of tractability index up to 2 in [14, 15, 16, 27, 39], we study here the general case.

In the case of linear DAEs, the reduced system has the form (11) with

$$x = Q \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad Q = [\, T_2' \;\; T_2 \,] \tag{17}$$

according to the notation of Section 2.2. For the homogeneous system

$$E(t)\dot{x} = A(t)x, \quad x(t_0) = x_0 \tag{18}$$

with consistent x_0 we then have an explicit representation of the solution x as

$$x(t) = Q(t) \begin{bmatrix} I_d \\ A_{2,1}(t) \end{bmatrix} \hat{\Phi}(t,t_0) \begin{bmatrix} I_d & 0 \end{bmatrix} Q(t_0)^T x_0,$$

where $\hat{\Phi}(t,t_0)$ is a fundamental solution of the so-called *inherent ODE* associated with (10) given by

$$\dot{x}_1 = A_{1,1}(t)x_1(t). \tag{19}$$

In particular, $\hat{\Phi}(t,t_0)$ solves the linear matrix differential equation

$$\tfrac{\partial}{\partial t}\hat{\Phi}(t,t_0) = A_{1,1}(t)\hat{\Phi}(t,t_0), \quad \hat{\Phi}(t_0,t_0) = I_d.$$

It follows that the fundamental solution $\Phi(t,t_0)$ of the homogeneous case (18) in the sense that the solution x can be written as $x(t) = \Phi(t,t_0)x_0$ is given by

$$\Phi(t,t_0) = Q(t)\begin{bmatrix} I_d \\ A_{2,1}(t) \end{bmatrix}\hat{\Phi}(t,t_0)\begin{bmatrix} I_d & 0 \end{bmatrix}Q(t_0)^T,$$

with

$$\|\Phi(t,t_0)\|_2 = \left\|\begin{bmatrix} I_d \\ A_{2,1}(t) \end{bmatrix}\hat{\Phi}(t,t_0)\begin{bmatrix} I_d & 0 \end{bmatrix}\right\|_2,$$

since Q is pointwise orthogonal. Thus, we have

$$\|\Phi(t,t_0)\|_2 \geq \|\hat{\Phi}(t,t_0)\|_2,$$

and the implications

$$\begin{aligned} \|\Phi(t,t_0)\|_2 \leq L &\implies \|\hat{\Phi}(t,t_0)\|_2 \leq L, \\ \|\Phi(t,t_0)\|_2 \to 0 &\implies \|\hat{\Phi}(t,t_0)\|_2 \to 0, \\ \|\Phi(t,t_0)\|_2 \leq Le^{-\gamma(t-t_0)} &\implies \|\hat{\Phi}(t,t_0)\|_2 \leq Le^{-\gamma(t-t_0)} \end{aligned}$$

hold. From this, it is clear that for the different stability concepts to extend to DAEs it is necessary that the inherent ODE (19) satisfies the corresponding stability concepts in the classical sense.

On the other hand, since

$$\|\Phi(t,t_0)\|_2^2 \leq \left\|\begin{bmatrix} I_d \\ A_{2,1}(t) \end{bmatrix}\right\|_2^2 \|\hat{\Phi}(t,t_0)\|_2^2 \leq (1+\|A_{2,1}(t)\|_2^2)\,\|\hat{\Phi}(t,t_0)\|_2^2,$$

we have the implications

$$\begin{aligned} \|\hat{\Phi}(t,t_0)\|_2 \leq L,\ \|A_{2,1}(t)\|_2 \leq c &\implies \|\Phi(t,t_0)\|_2 \leq \sqrt{1+c^2}L, \\ \|\hat{\Phi}(t,t_0)\|_2 \to 0,\ \|A_{2,1}(t)\|_2 \leq c &\implies \|\Phi(t,t_0)\|_2 \to 0, \\ \|\hat{\Phi}(t,t_0)\|_2 \leq Le^{-\gamma(t-t_0)},\ \|A_{2,1}(t)\|_2^2 \leq c(t-t_0)^k &\implies \|\Phi(t,t_0)\|_2 \leq \tilde{L}e^{-\tilde{\gamma}(t-t_0)}, \end{aligned}$$

where $k \geq 0$ is an arbitrary integer and $\tilde{L}, \tilde{\gamma} > 0$ are appropriate constants. We thus have obtained the following sufficient conditions.

Theorem 14 *Consider system (10) and its reduced form (11) with inherent ODE (19).*

1. *If the inherent ODE is stable and $\|A_{2,1}(t)\|_2 \leq c$ holds with some constant $c > 0$ for all $t \in \mathbb{I}$, then (10) is stable in the sense that $\|\Phi(t,t_0)\| < \tilde{L}$ on $\mathbb{I}$ for some positive constant $\tilde{L}$.*

2. *If the inherent ODE is asymptotically stable and $\|A_{2,1}(t)\|_2 \leq c$ holds for some constant $c > 0$ for all $t \in \mathbb{I}$, then (10) is asymptotically stable in the sense that $\Phi(t,t_0) \to 0$ as $t \to \infty$.*

3. *If the inherent ODE is exponentially stable and $\|A_{2,1}(t)\|_2 \leq c(t-t_0)^k$ holds for some constant $c > 0$ and integer $k \geq 0$ for all $t \in \mathbb{I}$, then (10) is exponentially stable in the sense that $\|\Phi(t,t_0)\| < \tilde{L}e^{-\tilde{\gamma}(t-t_0)}$ on $\mathbb{I}$ for some constants $\tilde{L}, \tilde{\gamma} > 0$.*

3.2 Nonlinear DAEs

We turn now to the general case of a nonlinear DAE (1) with corresponding reduced problem (9). As in the linear case, the unknowns are connected by the transformation (17) such that it is again sufficient to study the reduced problem. Corresponding to the condition $\|A_{21}(t)\|_2 \leq c$ for all $t \in \mathbb{I}$ we require here that the function $\mathcal{R}$ is globally Lipschitz continuous on a sufficiently large domain $\mathbb{U}$ for x_1, i.e.,

$$\|\mathcal{R}(t, x_1) - \mathcal{R}(t, y_1)\|_2 \leq L\|x_1 - y_1\|_2 \text{ for all } t \in \mathbb{I} \text{ and all } x_1, y_1 \in \mathbb{U}, \tag{20}$$

with some constant $L > 0$. It is then clear that stability and asymptotic stability of the inherent ODE $\dot{x}_1 = \mathcal{L}(t, x_1)$ carry over to the whole reduced DAE (9). In particular, we have the following result for an equilibrium solution (x_1^*, x_2^*) of (9).

Corollary 15 *Consider the nonlinear DAE (1) and its associated reduced system (9) and assume that (20) holds.*

1. *If V satisfies the assumptions of Theorem 7 for the inherent ODE $\dot{x}_1 = \mathcal{L}(t, x_1)$, then (x_1^*, x_2^*) is stable in the sense of Definition 2 with $\hat{x}_0$ restricted to be consistent.*
2. *If V satisfy the assumptions of Theorem 8 for the inherent ODE $\dot{x}_1 = \mathcal{L}(t, x_1)$, then (x_1^*, x_2^*) is asymptotically stable in the sense of Definition 2 with $\hat{x}_0$ restricted to be consistent.*

Contractivity and dissipativity for nonlinear DAEs have been studied for special cases in [15, 16]. In more generality, we obtain the following results.

In view of Theorem 11 we first require that $\mathcal{L}$ of the inherent ODE satisfies a one-sided Lipschitz condition, i.e.

$$\langle \mathcal{L}(t, x_1) - \mathcal{L}(t, y_1), x_1 - y_1 \rangle_2 \leq c\|x_1 - y_1\|_2^2 \text{ for all } t \in \mathbb{I} \text{ and } x_1, y_1 \in \mathbb{U}. \tag{21}$$

Then for two solutions x_1, y_1 of (19) and their squared difference $d_1(t) = \|x_1(t) - y_1(t)\|_2^2$ we obtain

$$\begin{aligned} \tfrac{1}{2}\tfrac{d}{dt} d_1(t) &= \tfrac{1}{2}\tfrac{d}{dt}\|x_1(t) - y_1(t)\|_2^2 = \langle \dot{x}_1(t) - \dot{y}_1(t), x_1(t) - y_1(t) \rangle_2 \\ &= \langle \mathcal{L}(t, x_1(t)) - \mathcal{L}(t, y_1(t)), x_1(t) - y_1(t) \rangle_2 \leq c\|x_1(t) - y_1(t)\|_2^2. \end{aligned}$$

As in Section 2.3, the relation

$$\dot{d}_1(t) \leq 2c d_1(t)$$

yields

$$\dot{d}_1(t) \leq e^{2c(t-t_0)} d_1(t_0)$$

by Lemma 10. Introducing $d(t) = \|x(t) - y(t)\|_2^2 = \|x_1(t) - y_1(t)\|_2^2 + \|x_2(t) - y_2(t)\|_2^2$ and using (20), we obtain

$$\begin{aligned} d(t) &\leq \|x_1(t) - y_1(t)\|_2^2 + \|\mathcal{R}(t, x_1(t)) - \mathcal{R}(t, y_1(t)))\|_2^2 \\ &\leq \|x_1(t) - y_1(t)\|_2^2 + L^2\|x_1(t) - y_1(t)\|_2^2 \\ &\leq (1 + L^2) e^{2c(t-t_0)} d_1(t_0). \end{aligned}$$

Corollary 16 *Consider the nonlinear DAE (1) and its associated reduced system (9). Let $\mathcal{L} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^d)$ satisfy a one-sided Lipschitz condition with constant $c \in \mathbb{R}$ according to (21) and let $\mathcal{R} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^a)$ be Lipschitz continuous according to (20). If $c = 0$, then (9) is contractive in the sense that $\|x(t) - y(t)\|_2$ is monotonically non-increasing for two solutions x, y of (9). If $c < 0$, then (9) is exponentially contractive in the sense that $\|x(t) - y(t)\|_2$ decays exponentially for two solutions x, y of (9).*

To study dissipativity, we first require that

$$\langle \mathcal{L}(t, x_1), x_1 \rangle \leq \alpha - \beta\|x_1\|_2^2 \text{ for all } t \in \mathbb{I} \text{ and } x \in \mathbb{U}, \tag{22}$$

with $\alpha \geq 0$ and $\beta > 0$. Then

$$\tfrac{1}{2}\tfrac{d}{dt}\|x_1(t)\|_2^2 = \langle \dot{x}_1(t), x_1(t)\rangle = \langle \mathcal{L}(t, x_1), x_1\rangle \leq \alpha - \beta\|x_1\|_2^2,$$

and as in Theorem 12 we obtain

$$x_1(t) \in \mathcal{B}(0, \sqrt{\alpha/\beta + \varepsilon}) \text{ for } t > \hat{t}.$$

With the natural requirement that $\mathcal{R}$ is bounded according to

$$\|x_1\|_2 < \alpha/\beta + \varepsilon \quad \Longrightarrow \quad \|x_2\|_2 < M \text{ for } t > \hat{t}, \tag{23}$$

where $M > 0$ is a suitable constant depending on ε, we obtain

$$\|x(t)\|_2^2 = \|x_1(t)\|_2^2 + \|x_2(t)\|_2^2 < \alpha/\beta + \varepsilon + M^2$$

and thus

$$\|x(t)\|_2 \in \mathcal{B}(0, \sqrt{\alpha/\beta + \varepsilon + M^2}) \text{ for } t > \hat{t}.$$

Corollary 17 *Consider the nonlinear DAE (1) and its associated reduced system (9). Let $\mathcal{L} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^d)$ satisfy (22) and let $\mathcal{R} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^a)$ satisfy (20) and (23). Then the DAE (9) is dissipative in the sense of Definition 4 with $\hat{x}_0$ restricted to be consistent. An absorbing set is given by $\mathbb{B} = \mathcal{B}(0, \sqrt{\alpha/\beta + \varepsilon + M^2})$ for arbitrary $\varepsilon > 0$.*

Finally, we assume that

$$\langle \mathcal{L}(t, x_1), x_1\rangle < 0 \text{ for all } t \in \mathbb{I} \text{ and } x_1 \in \mathbb{U} \text{ with } \|x_1\|_2 > R. \tag{24}$$

As in Theorem 13 we obtain that

$$x_1(t) \in \mathcal{B}(0, R + \epsilon) \text{ for } t > \hat{t},$$

and we can proceed as for (22).

Corollary 18 *Consider the nonlinear DAE (1) and its associated reduced system (9). Let $\mathcal{L} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^d)$ satisfy (24) and let $\mathcal{R} \in C^0(\mathbb{I} \times \mathbb{U}, \mathbb{R}^a)$ satisfy (20) and (23). Then the DAE (9) is dissipative in the sense of Definition 4 with $\hat{x}_0$ restricted to be consistent. An absorbing set is given by $\mathbb{B} = \mathcal{B}(0, \sqrt{(R + \varepsilon)^2 + M^2})$ for arbitrary $\varepsilon > 0$.*

Recall that the domain $\mathbb{U}$ must be sufficiently large to ensure that $x(t)$ does not leave the domain of definition in finite time, i.e. one has to assume that the solution exists at least until $\hat{t}$ and that the desired absorbing set is contained in $\mathbb{U}$. Besides these technical assumptions we can observe that also in the nonlinear case the various stability concepts for DAEs require the corresponding properties to hold for the inherent ODE and sufficient conditions are obtained under natural assumptions on the algebraic constraints.

4 A test equation for DAEs

In this section we propose and investigate a new test equation for differential-algebraic equations. To get an idea how a suitable test equation should look like, we must understand the reasons for the instabilities in Example 1.

Suppose that we discretize the linear homogeneous problem (18) with the implicit Euler method, i.e.,

$$(E_i - hA_i)x_i = E_i x_{i-1},$$

where $E_i = E(t_i)$, $A_i = A(t_i)$, and x_i is an approximation to $x(t_i)$. If we scale the equation by a pointwise nonsingular matrix function $P \in C^0(\mathbb{I}, \mathbb{R}^{n,n})$ and the solution by a pointwise nonsingular matrix function $Q \in C^1(\mathbb{I}, \mathbb{R}^{n,n})$, then the transformed equation reads

$$\tilde{E}(t)\dot{\tilde{x}} = \tilde{A}(t)\tilde{x}, \tag{25}$$

where

$$\tilde{E} = PEQ, \quad \tilde{A} = PAQ - PE\dot{Q}, \quad x = Q\tilde{x}.$$

Setting $P_i = P(t_i)$, $Q_i = Q(t_i)$, $\dot{Q}_i = \dot{Q}(t_i)$, and defining $\tilde{x}_i$ by $x_i = Q_i\tilde{x}_i$, we obtain the following sequence of equivalent formulations

$$\begin{aligned}
P_i(E_iQ_i - hA_iQ_i)\tilde{x}_i &= P_iE_iQ_{i-1}\tilde{x}_{i-1},\\
(\tilde{E}_i - h\tilde{A}_i - hE_i\dot{Q}_i)\tilde{x}_i &= \tilde{E}_iQ_i^{-1}Q_{i-1}\tilde{x}_{i-1},\\
(\tilde{E}_i - h\tilde{A}_i - h\tilde{E}_iQ_i^{-1}\dot{Q}_i)\tilde{x}_i &= \tilde{E}_iQ_i^{-1}Q_{i-1}\tilde{x}_{i-1}.
\end{aligned}$$

Since $Q_{i-1} = Q_i - h\dot{Q}_i + \mathcal{O}(h^2)$, we can rewrite this as

$$\begin{aligned}
(\tilde{E}_i - h\tilde{A}_i - h\tilde{E}_iQ_i^{-1}\dot{Q}_i)\tilde{x}_i &= \tilde{E}_iQ_i^{-1}(Q_i - h\dot{Q}_i + \mathcal{O}(h^2))\tilde{x}_{i-1},\\
(\tilde{E}_i(I - hQ_i^{-1}\dot{Q}_i) - h\tilde{A}_i)\tilde{x}_i &= \tilde{E}_i(I - hQ_i^{-1}\dot{Q}_i + \mathcal{O}(h^2))\tilde{x}_{i-1}
\end{aligned}$$

If we would directly discretize the equation (25), then we would instead obtain

$$(\tilde{E}_i - h\tilde{A}_i)\tilde{x}_i = \tilde{E}_i\tilde{x}_{i-1}.$$

Example 1 shows that these perturbations to $\tilde{E}_i$ may have the effect that the numerical method is unstable even though the DAE itself is asymptotically stable. Obviously, to have an effect on the solution behavior, the perturbation $h\tilde{E}_iQ_i^{-1}\dot{Q}_i$ must be reasonably large. In order to simulate this behavior in a test equation, we consider for x_1 the classical test equation (3), which is (allowing here as usual for complex solutions) asymptotically stable if $Re(\lambda) < 0$.

As we have seen in Section 3, we still obtain asymptotic stability if in (9) the entry $A_{2,1}$ is bounded. In the simplest case we can choose $A_{2,1}(t) = 1$. In order to simulate the effect that the kernel of $E(t)$ is changing and, therefore, to have a nontrivial transformation with a derivative that depends on a parameter that can be used to control the rate of change, we will choose

$$R(t) = \begin{bmatrix} 1 & \omega t \\ 0 & 1 \end{bmatrix}, \tag{26}$$

with a real parameter ω.

Remark 1 It should be noted that $Q(t)$ in (26) is not pointwise orthogonal. An orthogonal variation of this transformation would be to choose

$$R(t) = \frac{1}{\sqrt{1+\omega^2t^2}} \begin{bmatrix} 1 & \omega t \\ -\omega t & 1 \end{bmatrix}$$

or the case of a rotation with frequency ω

$$R(t) = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix}.$$

The problem with these two orthogonal transformations is that the analysis of the stability regions of different numerical methods becomes very technical analytically. Numerical tests, however, show that there is no essential difference in the corresponding stability regions.

In the following we, therefore, consider the test equation

$$\begin{bmatrix} 1 & -\omega t \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \lambda & \omega(1-\lambda t) \\ -1 & 1+\omega t \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \tag{27}$$

with coefficients

$$\begin{aligned}
E(t) &= \tilde{E}(t)R(t)^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & -\omega t \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -\omega t \\ 0 & 0 \end{bmatrix},\\
A(t) &= \tilde{A}(t)R(t)^{-1} - \tilde{E}(t)\tfrac{d}{dt}(R(t)^{-1})\\
&= \begin{bmatrix} \lambda & 0 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} 1 & -\omega t \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & -\omega \\ 0 & 0 \end{bmatrix}\\
&= \begin{bmatrix} \lambda & \omega(1-\lambda t) \\ -1 & 1+\omega t \end{bmatrix}.
\end{aligned}$$

With initial data $x_1(0) = 1$, $x_2(0) = 1$, equation (27) has the solution

$$x(t) = \begin{bmatrix} 1 & \omega t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} e^{\lambda t} \\ e^{\lambda t} \end{bmatrix} = \begin{bmatrix} (1+\omega t)e^{\lambda t} \\ e^{\lambda t} \end{bmatrix}.$$

Since we will need it later in the course of this paper, we describe the transformation of (27) to the reduced form corresponding to (11). With

$$Q(t) = \frac{1}{\sqrt{1+\omega^2 t^2}} \begin{bmatrix} 1 & \omega t \\ -\omega t & 1 \end{bmatrix}, \quad \dot{Q}(t) = \frac{\omega}{(1+\omega^2 t^2)^{3/2}} \begin{bmatrix} -\omega t & 1 \\ -1 & -\omega t \end{bmatrix}, \tag{28}$$

according to (17) we obtain that

$$\begin{aligned} EQ &= \frac{1}{\sqrt{1+\omega^2 t^2}} \begin{bmatrix} 1+\omega^2 t^2 & 0 \\ 0 & 0 \end{bmatrix}, \\ AQ - E\dot{Q} &= \frac{1}{\sqrt{1+\omega^2 t^2}} \begin{bmatrix} \lambda - \omega^2 t(1-\lambda t) & \lambda\omega t + \omega(1-\lambda t) \\ -1 - \omega t(1+\omega t) & -\omega t + (1+\omega t) \end{bmatrix} \\ &\quad - \frac{\omega}{(1+\omega^2 t^2)^{3/2}} \begin{bmatrix} 0 & 1+\omega^2 t^2 \\ 0 & 0 \end{bmatrix} \\ &= \frac{1}{\sqrt{1+\omega^2 t^2}} \begin{bmatrix} \lambda - \omega^2 t + \lambda\omega^2 t^2 & 0 \\ -1 - \omega t - \omega^2 t^2 & 1 \end{bmatrix}, \end{aligned}$$

and thus, by scaling with a diagonal matrix from the left, the pair (E, A) is equivalent to the pair

$$(\tilde{E}, \tilde{A}) = \left(\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} \lambda - \frac{\omega^2 t}{1+\omega^2 t^2} & 0 \\ 1 + \omega t + \omega^2 t^2 & -1 \end{bmatrix} \right), \tag{29}$$

which is the required reduced form (11) of the test equation (27).

Note that there is an important difference between this new test equation and the standard test equation (3) for ODEs. Due to the requirement that the new test equation must involve a changing kernel of E, it cannot be autonomous. As a consequence, the difference equation for the numerical solution which is typically obtained by discretization will explicitely include time positions.

5 DAE integration methods and DAE stability functions

To demonstrate the properties of the test equation (27) let us apply some of the well-known DAE integration methods to this equation. In analogy to the classical stability functions $R(h\lambda) = R(z)$ for ODEs, see [13], we will introduce *DAE stability functions* of the form $R(h\lambda, h\omega) = R(z, w)$, using the abbreviations $z = h\lambda$, $w = h\omega$. We will present several plots of stability functions. In all cases the plots depict the region given by $(z, w) \in [-9, 9]^2$. The color coding is chosen so that the dark regions are those with $|R(z, w)| \leq 1$ and the shading is according to the modulus of $R(z, w)$.

5.1 Implicit Euler method

Applying the implicit Euler method to the test equation (27), we obtain the following iteration and equivalent formulations.

$$\begin{aligned} &\left(\begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} - h \begin{bmatrix} \lambda & \omega(1-\lambda t_i) \\ -1 & 1+\omega t_i \end{bmatrix} \right) \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} = \begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix}, \\ &\begin{bmatrix} 1-h\lambda & -\omega t_i - \omega h(1-\lambda t_i) \\ h & -h(1+\omega t_i) \end{bmatrix} \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} = \begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix}, \\ &\begin{bmatrix} 1-h\lambda & -\omega t_i - \omega h + \omega h\lambda t_i) \\ -1 & 1+\omega t_i \end{bmatrix} \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} = \begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix}. \end{aligned}$$

The coefficient matrix on the left side has determinant

$$D = 1 - h(\lambda + \omega)$$

and, thus, for $D \neq 0$ the linear system has a unique solution given by

$$\begin{aligned}\begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} &= \frac{1}{D} \begin{bmatrix} 1+\omega t_i & \omega t_i + \omega h - \omega h \lambda t_i \\ 1 & 1 - h\lambda \end{bmatrix} \begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix} \\ &= \frac{1}{D} \begin{bmatrix} 1+\omega t_i & -\omega t_i(1+\omega t_i) \\ 1 & -\omega t_i \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix}.\end{aligned}$$

Since $x_{1,i-1} = (1+\omega t_{i-1}) x_{2,i-1}$, we obtain

$$\begin{aligned}\begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} &= \frac{1}{D} \begin{bmatrix} 1+\omega t_i & -\omega t_i(1+\omega t_i) \\ 1 & -\omega t_i \end{bmatrix} \begin{bmatrix} (1+\omega t_{i-1}) x_{2,i-1} \\ x_{2,i-1} \end{bmatrix} \\ &= \frac{1}{D} \begin{bmatrix} (1+\omega t_i)(1+\omega t_{i-1}) - \omega t_i(1+\omega t_i) \\ 1 + \omega t_{i-1} - \omega t_i \end{bmatrix} x_{2,i-1} \\ &= \frac{1}{D} \begin{bmatrix} 1 - \omega h + \omega t_i(1 + \omega t_{i-1} - \omega t_i) \\ 1 - \omega h \end{bmatrix} x_{2,i-1} \\ &= \frac{1}{D} \begin{bmatrix} (1-\omega h)(1+\omega t_i) \\ 1 - \omega h \end{bmatrix} x_{2,i-1} \\ &= \frac{1-\omega h}{1-(\lambda+\omega)h} \begin{bmatrix} 0 & 1+\omega t_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{1,i-1} \\ x_{2,i-1} \end{bmatrix} \\ &= \left(\frac{1-\omega h}{1-(\lambda+\omega)h} \right)^i \begin{bmatrix} 0 & 1+\omega t_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{1,0} \\ x_{2,0} \end{bmatrix}.\end{aligned}$$

We see that the stability behavior of the equation depends on the *DAE stability function*

$$R(z,w) = \frac{1-w}{1-z-w}.$$

Note that for $w = 0$ the DAE stability function $R(z,w)$ reduces to the stability function $R(z) = (1-z)^{-1}$ of the ODE case. A plot of this function is given in Figure 1.

5.2 Radau IIa method with two stages

Applying the 2-stage Radau IIa method (see e.g. [13]) given by the Butcher tableau

$$\begin{array}{c|cc} \frac{1}{3} & \frac{5}{12} & -\frac{1}{12} \\ 1 & \frac{3}{4} & \frac{1}{4} \\ \hline & \frac{3}{4} & \frac{1}{4} \end{array}$$

to (27), we obtain the iteration

$$\begin{aligned} x_{1,i} &= x_{1,i-1} + \tfrac{3}{4} h \dot{X}_{1,1} + \tfrac{1}{4} h \dot{X}_{2,1}, \\ x_{2,i} &= x_{2,i-1} + \tfrac{3}{4} h \dot{X}_{1,2} + \tfrac{1}{4} h \dot{X}_{2,2}, \end{aligned}$$

where the stage values and derivatives satisfy

$$\begin{aligned} \dot{X}_{1,1} - \omega(t_{i-1} + \tfrac{h}{3}) \dot{X}_{1,2} &= \lambda X_{1,1} + \omega(1 - \lambda(t_{i-1} + \tfrac{h}{3})) X_{1,2}, \\ 0 &= -X_{1,1} + (1 + \omega(t_{i-1} + \tfrac{h}{3})) X_{1,2}, \\ \dot{X}_{2,1} - \omega t_i \dot{X}_{2,2} &= \lambda X_{2,1} + \omega(1 - \lambda t_i) X_{2,2}, \\ 0 &= -X_{2,1} + (1 + \omega t_i) X_{2,2}, \\ X_{1,1} &= x_{1,i-1} + \tfrac{5}{12} h \dot{X}_{1,1} - \tfrac{1}{12} h \dot{X}_{2,1}, \\ X_{1,2} &= x_{2,i-1} + \tfrac{5}{12} h \dot{X}_{1,2} - \tfrac{1}{12} h \dot{X}_{2,2}, \\ X_{2,1} &= x_{1,i-1} + \tfrac{3}{4} h \dot{X}_{1,1} + \tfrac{1}{4} h \dot{X}_{2,1}, \\ X_{2,2} &= x_{2,i-1} + \tfrac{3}{4} h \dot{X}_{1,2} + \tfrac{1}{4} h \dot{X}_{2,2}. \end{aligned}$$

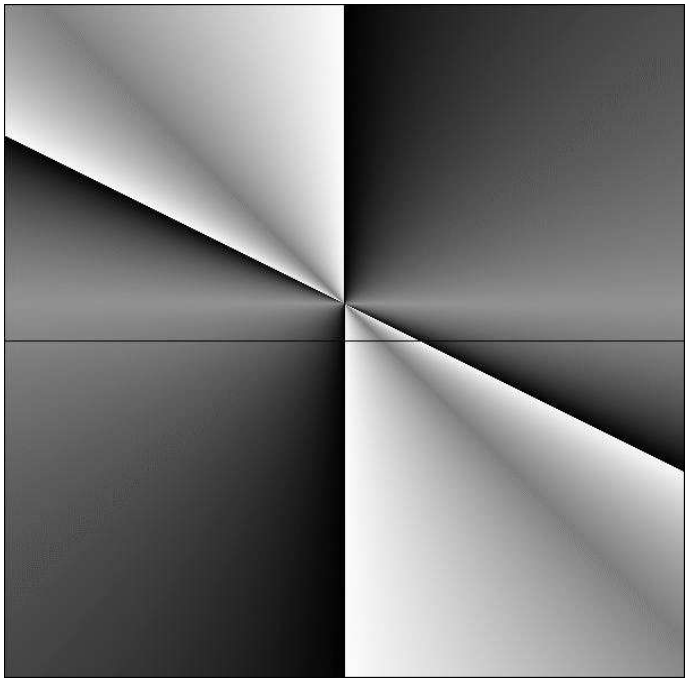

Figure 1: DAE stability function for the implicit Euler method

The linear system that we obtain for the vector of stage derivatives is then given by

$$\begin{bmatrix} 1-\frac{5}{12}h\lambda & -\omega(t_{i-1}+\frac{h}{3})-\frac{5}{12}\omega h(1-\lambda(t_{i-1}+\frac{h}{3})) & \frac{1}{12}h\lambda & \frac{1}{12}\omega h(1-\lambda(t_{i-1}+\frac{h}{3})) \\ \frac{5}{12}h & -\frac{5}{12}\omega h(1+\omega(t_{i-1}+\frac{h}{3})) & -\frac{1}{12}h\lambda & \frac{1}{12}h(1+\omega(t_{i-1}+\frac{h}{3})) \\ -\frac{3}{4}h\lambda & -\frac{3}{4}h\omega(1-\lambda t_i) & 1-\frac{1}{4}h\lambda & -\omega t_i-\frac{1}{4}h\omega(1-\lambda t_i) \\ \frac{3}{4}h\lambda & -\frac{3}{4}h(1+\omega t_i) & \frac{1}{4}h & -\frac{1}{4}h(1+\omega t_i) \end{bmatrix} \cdot \begin{bmatrix} \dot{X}_{1,1} \\ \dot{X}_{1,2} \\ \dot{X}_{2,1} \\ \dot{X}_{2,2} \end{bmatrix} = \begin{bmatrix} \lambda x_{1,i-1}+\omega(1-\lambda(t_{i-1}+\frac{h}{3}))x_{2,i-1} \\ -x_{1,i-1}+(1+\omega(t_{i-1}+\frac{h}{3}))x_{2,i-1} \\ \lambda x_{1,i-1}+\omega(1-\lambda t_i)x_{2,i-1} \\ -x_{1,i-1}+(1+\omega t_i)x_{2,i-1} \end{bmatrix}.$$

Since the Radau IIa methods are stiffly accurate, they yield consistent approximations. Using therefore $x_{1,i-1} = (1+\omega t_{i-1})x_{2,i-1}$ shows that all quantities are multiples of $x_{2,i-1}$. Gaussian elimination and simplification finally leads to

$$x_{2,i} = X_{2,2} = -\frac{2(2h\omega h\lambda + 2h\omega - h\lambda - 3)}{2h\lambda h\omega + (h\lambda)^2 - 4h\omega - 4h\lambda + 6} x_{2,i-1}.$$

Thus, the DAE stability function for the 2-stage Radau IIa method reads

$$R(z,w) = \frac{6-4w+2z-2zw}{6-4z-4w+z^2+2zw}.$$

A plot of this function is given in Figure 2.

5.3 Implicit midpoint rule

Applying the implicit midpoint rule, i.e. the Gauß method with $s = 1$, given by the Butcher tableau

$$\begin{array}{c|c} \frac{1}{2} & \frac{1}{2} \\ \hline & 1 \end{array}$$

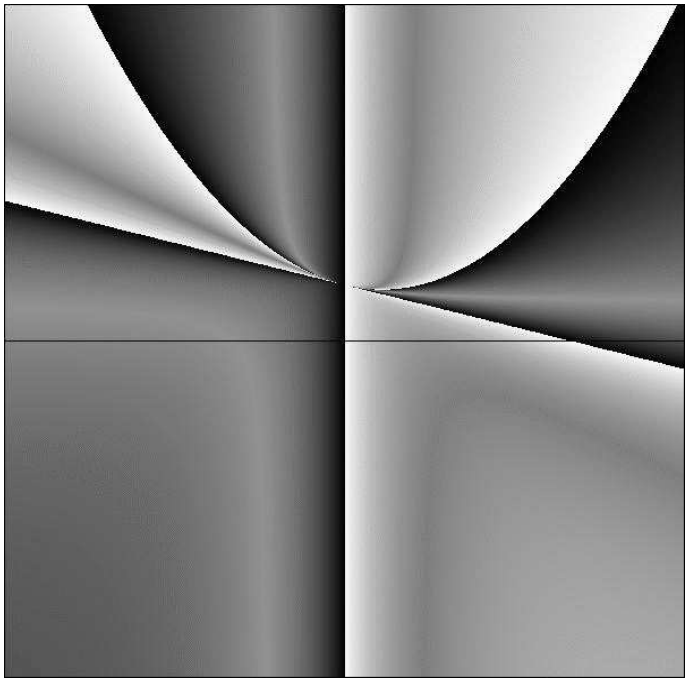

Figure 2: DAE stability function for the Radau IIa method with two stages

see [13], to (27), we obtain the following iteration for the stage values and stage derivatives

$$\begin{aligned}
\dot{X}_1 - \omega(t_{i-1} + \tfrac{1}{2}h)\dot{X}_2 &= \lambda X_1 + \omega(1 - \lambda(t_{i-1} + \tfrac{1}{2}h))X_2,\\
0 &= -X_1 + (1 + \omega(t_{i-1} + \tfrac{1}{2}h))X_2,\\
X_1 &= x_{i-1,1} + \tfrac{1}{2}h\dot{X}_1,\\
X_2 &= x_{i-1,2} + \tfrac{1}{2}h\dot{X}_2,\\
x_{i,1} &= x_{i-1,1} + h\dot{X}_1,\\
x_{i,2} &= x_{i-1,2} + h\dot{X}_2.
\end{aligned}$$

Elimination of the stage values gives the linear system

$$\begin{bmatrix} 1 - \frac{1}{2}h\lambda & -\omega(t_{i-1} + \frac{1}{2}h) - \frac{1}{2}h\omega(1 - \lambda(t_{i-1} + \frac{1}{2}h)) \\ \frac{1}{2}h & -\frac{1}{2}h(1 + \omega(t_{i-1} + \frac{1}{2}h)) \end{bmatrix} \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} \lambda x_{i-1,1} + \omega(1 - \lambda(t_{i-1} + \frac{1}{2}h))x_{i-1,2} \\ -1 + (1 + \omega(t_{i-1} + \frac{1}{2}h))x_{i-1,2} \end{bmatrix}.$$

Using $x_{1,i-1} = (1+\omega t_{i-1})x_{2,i-1}$ and, hence, assuming that we work with consistent approximations (e.g. by projecting in every step), one derives that $x_{2,i} = R(z,w)x_{2,i-1}$ with

$$R(z,w) = \frac{2 + z - w}{2 - z - w}. \tag{30}$$

A plot of this function is given in Figure 3.

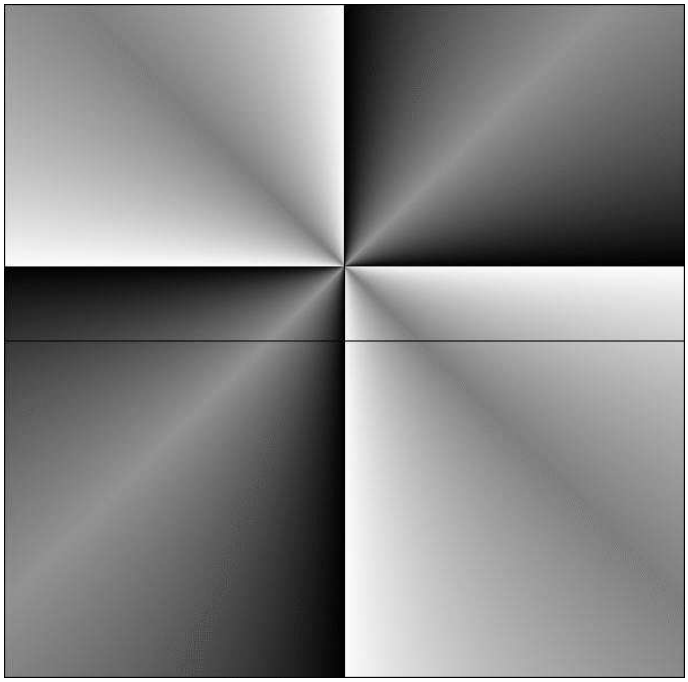

Figure 3: DAE stability function for the implicit midpoint rule

5.4 Implicit trapezoidal rule

Applying the implicit trapezoidal rule, i.e. the 2-stage Lobatto method, see [13], given by the Butcher tableau

$$\begin{array}{c|cc} 0 & 0 & 0 \\ 1 & \frac{1}{2} & \frac{1}{2} \\ \hline & \frac{1}{2} & \frac{1}{2} \end{array}$$

to (27), we obtain the relations

$$\begin{aligned} \dot{X}_{1,1} - \omega t_{i-1}\dot{X}_{1,2} &= \lambda X_{1,1} + \omega(1-\lambda t_{i-1})X_{1,2}, \\ 0 &= -X_{1,1} + (1+\omega t_{i-1})X_{1,2}, \\ \dot{X}_{2,1} - \omega t_i \dot{X}_{2,2} &= \lambda X_{2,1} + \omega(1-\lambda t_i)X_{2,2}, \\ 0 &= -X_{2,1} + (1+\omega t_i)X_{2,2}, \\ X_{1,1} &= x_{1,i-1}, \\ X_{1,2} &= x_{2,i-1}, \\ X_{2,1} &= x_{1,i-1} + \tfrac{1}{2}h\dot{X}_{1,1} + \tfrac{1}{2}h\dot{X}_{2,1}, \\ X_{2,2} &= x_{2,i-1} + \tfrac{1}{2}h\dot{X}_{1,2} + \tfrac{1}{2}h\dot{X}_{2,2} \end{aligned}$$

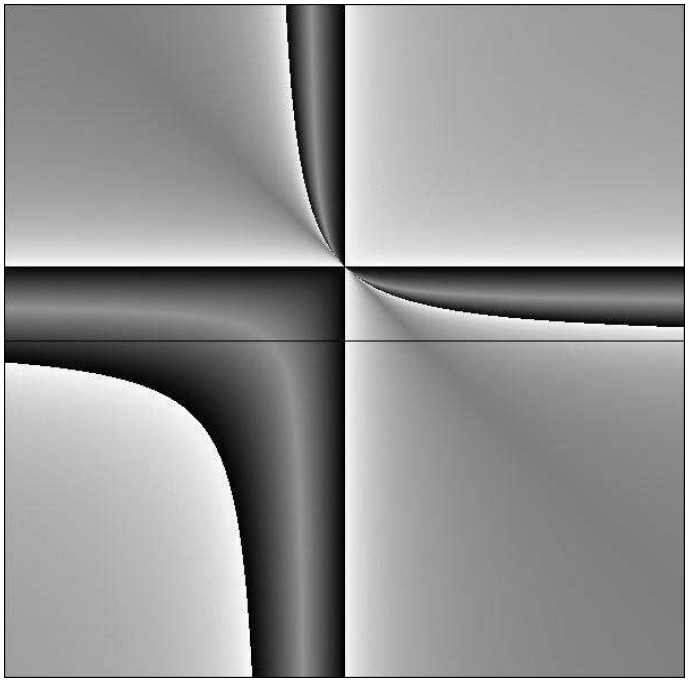

Figure 4: DAE stability function for the implicit trapezoidal rule

for the stage values and derivatives. Eliminating the stage values, it remains to solve the linear system

$$\begin{bmatrix} 1 & -\omega t_{i-1} & 0 & 0 \\ 1 & -1-\omega(t_{i-1} & 0 & 0 \\ -\frac{1}{2}h\lambda & -\frac{1}{2}h\omega(1-\lambda t_i) & 1-\frac{1}{2}h\lambda & -\omega t_i - \frac{1}{2}h\omega(1-\lambda t_i) \\ \frac{1}{2}h\lambda & -\frac{1}{2}h(1+\omega t_i) & \frac{1}{2}h & -\frac{1}{2}h(1+\omega t_i) \end{bmatrix} \begin{bmatrix} \dot{X}_{1,1} \\ \dot{X}_{1,2} \\ \dot{X}_{2,1} \\ \dot{X}_{2,2} \end{bmatrix}$$
$$= \begin{bmatrix} \lambda x_{1,i-1} + \omega(1-\lambda t_{i-1})x_{2,i-1} \\ \omega x_{2,i-1} \\ \lambda x_{1,i-1} + \omega(1-\lambda t_i)x_{2,i-1} \\ -x_{1,i-1} + (1+\omega t_i)x_{2,i-1} \end{bmatrix}.$$

Using as before $x_{1,i-1} = (1+\omega t_{i-1})x_{2,i-1}$ under the assumption that we work with consistent approximations, one derives that $x_{2,i} = X_{2,2} = R(z,w)x_{2,i-1}$ with

$$R(z,w) = \frac{2+z-w-zw}{2-z-w}.$$

A plot of this function is given in Figure 4.

5.5 Stiffly accurate Runge-Kutta methods

Applying a general stiffly accurate Runge-Kutta method, see [13], given by the Butcher tableau

$$\begin{array}{c|c} c & \mathcal{A} \\ \hline & b^T \end{array}$$

with $\mathcal{A}$ invertible and $b^T\mathcal{A}^{-1}e = 1$, $e = [\,1\ \cdots\ 1\,]^T$, to (27), we obtain the relations

$$\begin{array}{ll} \text{(a)} & \dot{X}_{j,1} - \omega(t_{i-1}+c_jh)\dot{X}_{j,2} = \lambda X_{j,1} + \omega(1-\lambda(t_{i-1}+c_jh))X_{j,2}, \\ \text{(b)} & 0 = -X_{j,1} + (1+\omega(t_{i-1}+c_jh))X_{j,2}, \\ \text{(c)} & X_{j,1} = x_{1,i-1} + h\sum_{l=1}^s a_{j,l}\dot{X}_{l,1}, \\ \text{(d)} & X_{j,2} = x_{2,i-1} + h\sum_{l=1}^s a_{j,l}\dot{X}_{l,2} \end{array} \tag{31}$$

for $j = 1, \ldots, s$. Obviously, all stage values are consistent due to

$$X_{j,1} = (1+\omega(t_{i-1}+c_jh))X_{j,2}$$

and so all numerical approximations due to $x_{1,i-1} = (1+\omega t_{i-1})x_{2,i-1}$. Using the vectors of stage values and derivatives defined by

$$X_1 = \begin{bmatrix} X_{1,1} \\ \vdots \\ X_{s,1} \end{bmatrix}, \quad X_2 = \begin{bmatrix} X_{1,2} \\ \vdots \\ X_{s,2} \end{bmatrix}, \quad \dot{X}_1 = \begin{bmatrix} \dot{X}_{1,1} \\ \vdots \\ \dot{X}_{s,1} \end{bmatrix}, \quad \dot{X}_2 = \begin{bmatrix} \dot{X}_{1,2} \\ \vdots \\ \dot{X}_{s,2} \end{bmatrix},$$

the relations (31c,d) yield

$$\dot{X}_1 = \tfrac{1}{h}\mathcal{A}^{-1}(X_1 - e\,x_{1,i-1}), \quad \dot{X}_2 = \tfrac{1}{h}\mathcal{A}^{-1}(X_2 - e\,x_{2,i-1}).$$

Eliminating then $\dot{X}_1$, $\dot{X}_2$ in (31a) and multiplying by h gives

$$\begin{aligned} \mathcal{A}^{-1}(X_1 - e\,x_{1,i-1}) - \begin{bmatrix} \omega\hat{t}_1 & & \\ & \ddots & \\ & & \omega\hat{t}_s \end{bmatrix} \mathcal{A}^{-1}(X_2 - e\,x_{2,i-1}) \\ = \lambda X_1 + \begin{bmatrix} \omega(1-\lambda\hat{t}_1) & & \\ & \ddots & \\ & & \omega(1-\lambda\hat{t}_s) \end{bmatrix} X_2, \end{aligned}$$

with $\hat{t}_j = t_{i-1} + c_jh$, $j = 1, \ldots, s$. Utilizing finally the consistency relations, we obtain the linear equation

$$\begin{bmatrix} v_{1,1}-z-w & v_{1,2}(1+w(c_2-c_1)) & \ldots & v_{1,s}(1+w(c_s-c_1)) \\ v_{2,1}(1+w(c_1-c_2)) & v_{2,2}-z-w & \ldots & v_{2,s}(1+w(c_s-c_2)) \\ \vdots & & \ddots & \vdots \\ v_{s,1}(1+w(c_1-c_s)) & v_{s,2}(1+w(c_2-c_s)) & \cdots & v_{s,s}-z-w \end{bmatrix} \begin{bmatrix} X_{1,2} \\ X_{2,2} \\ \vdots \\ X_{s,2} \end{bmatrix}$$
$$= \begin{bmatrix} d_1(1-c_1w)x_{2,i-1} \\ d_2(1-c_2w)x_{2,i-1} \\ \vdots \\ d_s(1-c_sw)x_{2,i-1} \end{bmatrix},$$

with $\mathcal{A}^{-1} = (v_{j,l})$ and $d_j = v_{j,1} + \cdots + v_{j,s}$. Since $x_{2,i} = X_{2,s}$ this in particular shows that $x_{2,i} = R(z,w)x_{2,i-1}$ with a rational stability function $R(z,w)$ only depending on the parameters defining the Runge-Kutta method.

5.6 Gauß-Lobatto methods

Applying the Gauß-Lobatto method collocation method, see [23, 24], with $k = 1$ to (27), we obtain the iteration

$$\begin{aligned} \frac{x_{1,i}-x_{1,i-1}}{h} - \omega(t_i - \tfrac{1}{2}h)\frac{x_{2,i}-x_{2,i-1}}{h} = \lambda\frac{x_{1,i}+x_{1,i-1}}{2} + \omega(1-\lambda(t_i-\tfrac{1}{2}h))\frac{x_{2,i}+x_{2,i-1}}{2}, \\ 0 = -x_{1,i} + (1+\omega t_i)x_{2,i}, \end{aligned}$$

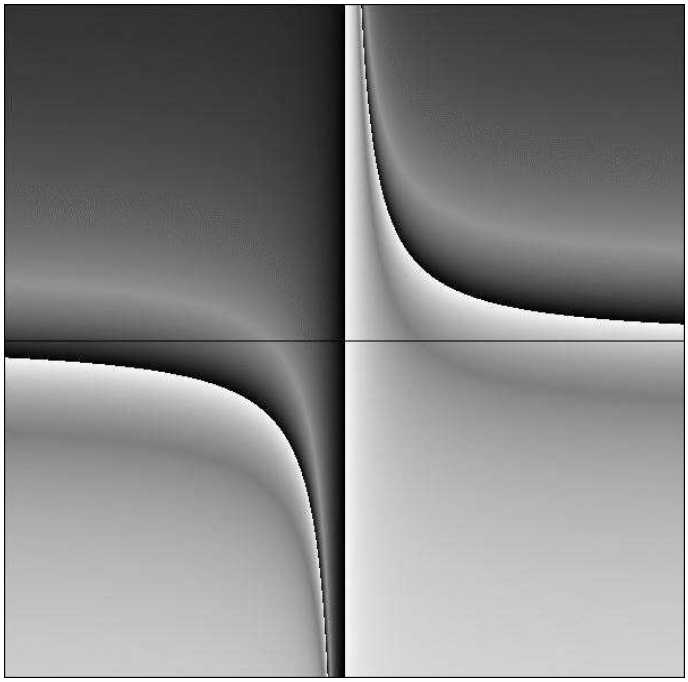

Figure 5: DAE stability function for the Gauß-Lobatto method with $k = 1$

which yields

$$\begin{aligned}&\left[(1+\omega t_i) - \omega(t_i - \tfrac{1}{2}h) - \tfrac{1}{2}h\lambda(1+\omega t_i) - \tfrac{1}{2}h\omega(1-\lambda(t_i - \tfrac{1}{2}h))\right] x_{2,i} \\ &\qquad = \left[(1+\omega t_{i-1}) - \omega(t_{i-1} + \tfrac{1}{2}h) + \tfrac{1}{2}h\lambda(1+\omega t_{i-1}) + \tfrac{1}{2}h\omega(1-\lambda(t_{i-1} - \tfrac{1}{2}h))\right] x_{2,i-1}.\end{aligned}$$

Simplifying the bracketed expressions, we obtain $x_{2,i} = R(z,w)x_{2,i-1}$ with the DAE stability function

$$R(z,w) = \frac{4+2z-zw}{4-2z-zw}.$$

A plot of this function is given in Figure 5.

For the general Gauß-Lobatto collocation method applied to (27), we obtain the relations

$$\begin{aligned}\frac{1}{h}\sum_{l=0}^{k} v_{j,l}(X_{l,1} - \omega(t_{i-1}+\varrho_j h)X_{l,2} - \sum_{l=0}^{k} u_{j,l}(\lambda X_{l,1} + \omega(1-\lambda(t_{i-1}+\varrho_j h))X_{l,2}) = 0,\\ -X_{j,1} + (1+\omega(t_{j-1}+\sigma_j h))X_{j,2} = 0,\end{aligned}$$

for $j = 1, \ldots, k$. Here, $\varrho_1, \ldots, \varrho_k$ denote the Gauß nodes and $\sigma_0, \ldots, \sigma_k$ the Lobatto nodes with the corresponding number of stages. If L_l denote the Lagrange polynomials in the Lobatto nodes, then $v_{j,l} = \dot{L}_l(\varrho_j)$ and $u_{j,l} = L_l(\varrho_j)$ for $l = 0, \ldots, k$. Furthermore, $x_{2,i} = X_{k,2}$, $X_{0,1} = x_{1,i-1}$, and $X_{0,2} = x_{2,i-1}$. Since these methods yield consistent approximations, we have that $x_{1,i-1} = (1+\omega t_{i-1})x_{2,i-1}$. Combining all these, we obtain the following equivalent formulations.

$$\begin{aligned}&\sum_{l=0}^{k}(v_{j,l} - u_{j,l}h\lambda)X_{l,1} - \sum_{l=0}^{k}\Big[v_{j,l}\omega(t_{i-1}+\varrho_j h) + u_{j,l}h\omega(1-\lambda(t_{i-1}+\varrho_j h))\Big]X_{l,2} = 0,\\ &\sum_{l=0}^{k}\Big[(v_{j,l} - u_{j,l}h\lambda)(1+\omega(t_{i-1}+\sigma_l h)) - v_{j,l}\omega(t_{i-1}+\varrho_j h) - u_{j,l}h\omega(1-\lambda(t_{i-1}+\varrho_j h))\Big]X_{l,2} = 0,\\ &\sum_{l=0}^{k}\Big[(v_{j,l} - u_{j,l}h(\lambda+\omega) + v_{j,l}h\omega(\sigma_l - \varrho_j) - u_{j,l}h\omega h\lambda(\sigma_l - \varrho_j)\Big]X_{l,2} = 0.\end{aligned}$$

The latter relation shows that the values $X_{l,2}$, $l = 1, \ldots, k$, satisfy a linear system of equations with a right hand side containing the factor $X_{0,2} = x_{2,i-1}$. Moreover, besides the quantities (z, w) the relation only contains coefficients describing the specific method. Hence, $x_{2,i} = R(z, w)x_{2,i-1}$ with a rational stability function $R(z, w)$.

5.7 BDF methods

Applying a BDF method, see e.g. [2, 13], to (27), we obtain the iteration

$$\frac{1}{h}\sum_{l=0}^{k} \alpha_{k-l} x_{1,i-l} - \omega t_i \frac{1}{h}\sum_{l=0}^{k} \alpha_{k-l} x_{2,i-l} = \lambda x_{1,i} + \omega(1 - \lambda t_i)x_{2,i},$$
$$0 = -x_{1,i} + (1 + \omega t_i)x_{2,i}.$$

Due to the latter relation, the BDF method yields consistent approximations. Utilizing, therefore, that all past approximations are consistent, we obtain

$$\sum_{l=0}^{k} \alpha_{k-l}[(1 + \omega t_{i-l}) - \omega t_i]x_{2,i-l} = [h\lambda(1 + \omega t_i) + h\omega(1 - \lambda t_i)]x_{2,i}.$$

On an equidistant grid, this yields the homogeneous difference equation

$$(\alpha_k - h\lambda)x_{2,i} + \sum_{l=1}^{k} \alpha_{k-l}(1 - lh\omega)x_{2,i-l} = 0.$$

Requiring that all solution of the difference equations are bounded is equivalent to requiring that the associated polynomial

$$(\alpha_k - h\lambda)\varrho^i + \sum_{l=1}^{k} \alpha_{k-l}(1 - lh\omega)\varrho^{i-l} = 0.$$

satisfies the so-called root condition, namely that all roots are bounded by one in modulus and those of modulus one are simple, see again [2, 13]. Note that this property only depends on (z, w). The dark regions in Figure 6 for $k = 2$ are those points (z, w) where the root condition holds. The shading is related to the largest modulus of the roots.

5.8 Summary of DAE stability functions

Table 1 summarizes all DAE stability functions that we have obtained by applying classical DAE one-step methods to the test equation (27). Moreover, we have included some DAE stability functions for higher order methods which were obtained with the help of a formula manipulation package.

Obviously, for $w = 0$ the obtained DAE stability function reduces to the classical stability function for this method applied to the standard test function (3) for ODEs. As λ describes eigenvalues in the system, one is interested in complex values of $z = h\lambda$. Of course, the above results are still valid for a parameter $z \in \mathbb{C}$. Instead of the plots given in the previous sections, we can think of stability regions in the complex z-plane parameterized by a real parameter w. Such objects can be visualized by movies. For the methods discussed here such movies can be found at

`http://www.math.uni-leipzig.de/~kunkel/stab.html`.

They show the z-plane in the range $\operatorname{Re} z, \operatorname{Im} z \in [-9, 9]$ with the time running over $w \in [-5, 5]$.

Comparing the stability domains of the various methods, one recognizes that they behave differently with the sign of w. In the case of a negative eigenvalue λ in (27), the Radau IIa method with $s = 2$ for example stays stable for arbitrary negative w but may exhibit difficulties for a certain positive w, whereas for the Gauß-Lobatto method with $k = 1$ it is just the other way around. It remains, however, unclear how this behavior can be exploited in applications.

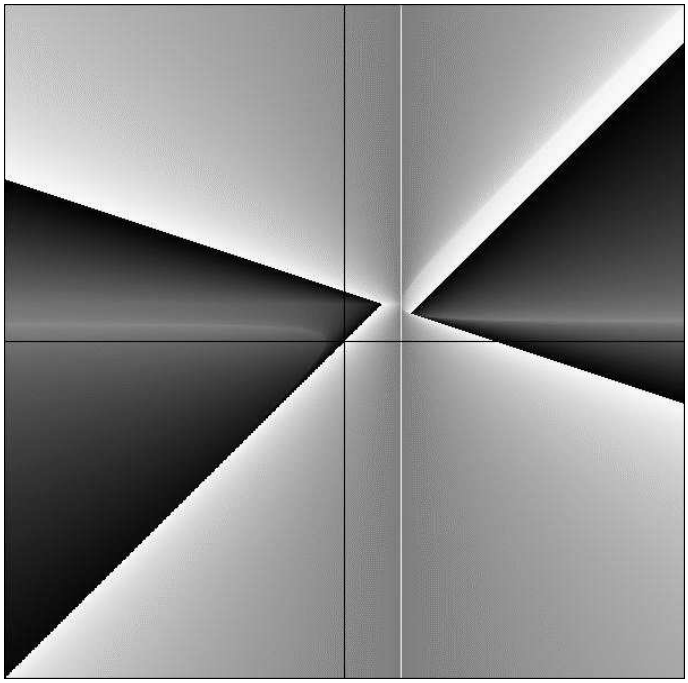

Figure 6: DAE stability function for the BDF method with $k = 2$

Table 1: DAE stability functions

Method	DAE-stability function $R(z, w)$
Implicit Euler	$R(z,w) = \dfrac{1-w}{1-z-w}$
Radau IIa $s = 2$	$R(z,w) = \dfrac{6-4w+2z-2zw}{6-4z-4w+z^2+2zw}$
Radau IIa $s = 3$	$R(z,w) = \dfrac{60-36w+24z-18zw+3z^2-3z^2w}{60-36w-36z+18zw+9z^2-z^3-3z^2w}$
Implicit midpoint rule	$R(z,w) = \dfrac{2+z-w}{2-z-w}$
Gauß $s = 2$	$R(z,w) = \dfrac{12-6w+6z-4zw+z^2}{12-6w-6z+2zw+z^2}$
Gauß-Lobatto $k = 1$	$R(z,w) = \dfrac{4+2z-zw}{4-2z-zw}$
Gauß-Lobatto $k = 2$	$R(z,w) = \dfrac{24+12z-2zw+2z^2-z^2w}{24-12z-2zw+2z^2+z^2w}$
Implicit trapezoidal rule	$R(z,w) = \dfrac{2+z-w-zw}{2-z-w}$

6 Spin-stabilized discretizations

As we have seen in Section 4, numerical schemes may become unstable when they are applied to DAEs with a spinning kernel of $\hat{E}$, where $\hat{E}$ in general is the linearization of a reduced formulation of the given DAE with respect to $\dot{x}$. In particular, we expect such effects, when the transformation Q involved in (12) yields a large term $[I_d\, 0]Q^T\dot{Q}$. Example 1 for $\eta = 0$ shows that discretizing a given DAE with the implicit Euler methods actually results in discretizing the inherent ODE with the explicit Euler method. If in such a case the inherent ODE is stiff, then it is necessary to apply stable discretization methods. A possibility to overcome these difficulties would be to determine a smooth transformation Q to get rid of the spinning kernel. Although this could be performed numerically, see e.g. [3, 6, 18, 32, 40] or [21, Cor. 3.10], such a procedure in general would be too costly. In the following, we therefore present an alternative approach.

As in the treatment of stiff ODEs, where it is assumed that the stiffness is contained in the linearized equation, we assume that the spin-effect is covered by the linearization of Q. The idea then is to use a linear approximation

$$\tilde{Q}(t) = Q(t_{i+k}) + (t - t_{i+k})\dot{\tilde{Q}}, \quad \dot{\tilde{Q}} \in \mathbb{R}^{n,n} \tag{32}$$

to Q in the i-th step of a k-step method in order to transform the given DAE before we discretize it. A suitable matrix $\dot{\tilde{Q}}$ can for example be obtained by finite differences

$$\dot{\tilde{Q}} = \frac{1}{h}(Q(t_{i+k}) - Q(t_{i+k-1})).$$

In the numerical computations, one must be aware that Q is not unique and that we therefore do not get a smooth representation of Q. This can be avoided e.g. by freezing the pivoting and all other decisions performed during the computation of $Q(t_{i+k})$ say by QR-decomposition, when we determine $Q(t_{i+k-1})$.

According to [21], we are allowed to restrict ourselves to the case of strangeness-free DAEs. In the following we also concentrate mainly on linear problems.

6.1 A general convergence result

In the following, we study the convergence properties of methods that are obtained by including a transformation before a given convergent method is applied. We use the notation of [21, Ch. 5] but have to slightly modify the general approach given there. As usual we restrict ourselves to equidistant grids.

Let $\tilde{\mathfrak{X}}_i$ represent the numerical approximation and let $\tilde{\mathfrak{X}}(t_i)$ represent the corresponding true solution at time $t_i = t_0 + ih$. We start with a basic numerical method given by

$$\tilde{\mathfrak{X}}_{i+1} = \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}_i; h) \tag{33}$$

representing any classical integration method for DAEs. We assume that (33) is *consistent of order p* according to

$$\|\tilde{\mathfrak{X}}(t_{i+1}) - \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h)\| \le Ch^{p+1} \tag{34}$$

and *stable* according to

$$\|\mathfrak{R}_{i+1}(\tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h) - \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}_i; h))\| \le (1 + hK)\|\mathfrak{R}_i(\tilde{\mathfrak{X}}(t_i) - \tilde{\mathfrak{X}}_i)\|. \tag{35}$$

In the latter estimate, the quantities $\mathfrak{R}_i$ are matrices which are required to satisfy

$$\begin{array}{ll} \text{(a)} & \|\mathfrak{R}_i\|,\ \|\mathfrak{R}_i^{-1}\| \le M, \\ \text{(b)} & \mathfrak{R}_{i+1}\mathfrak{R}_i^{-1} = I + \mathcal{O}(h). \end{array} \tag{36}$$

Moreover, all involved constants are assumed to be independent of i and h. Then, the estimate

$$\begin{aligned} &\|\mathfrak{R}_{i+1}(\tilde{\mathfrak{X}}(t_{i+1}) - \tilde{\mathfrak{X}}_{i+1})\| \\ &\quad = \|\mathfrak{R}_{i+1}(\tilde{\mathfrak{X}}(t_{i+1}) - \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h) + \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h) - \tilde{\mathfrak{X}}_{i+1})\| \\ &\quad \le MCh^{p+1} + (1 + hK)\|\mathfrak{R}_i(\tilde{\mathfrak{X}}(t_i) - \tilde{\mathfrak{X}}_i)\| \end{aligned}$$

holds and, hence, the method is convergent.

With the help of this basic method, we define a new method by applying in each step first a transformation, then the integration step by the basic method in the transformed system, and finally a back-transformation. Thus, the so obtained new method has the form

$$\mathfrak{X}_{i+1} = \mathfrak{F}(t_i, \mathfrak{X}_i; h),$$

with

$$\mathfrak{F}(t_i, \mathfrak{X}_i; h) = \mathfrak{Q}_{i+1}\tilde{\mathfrak{F}}(t_i, \mathfrak{Q}_i^{-1}\mathfrak{X}_i; h).$$

The quantities $\mathfrak{Q}_i$ will describe the mentioned spin-stabilization but at the moment they may represent any suitable transformations. Note that we omit a subscript i although $\mathfrak{F}$ is defined differently in each integration step. According to (36) we require that

$$\begin{array}{ll} \text{(a)} & \|\mathfrak{Q}_i\|,\ \|\mathfrak{Q}_i^{-1}\| \le M, \\ \text{(b)} & \mathfrak{Q}_{i+1}\mathfrak{Q}_i^{-1} = I + \mathcal{O}(h). \end{array} \tag{37}$$

With the relations $\tilde{\mathfrak{X}}_i = \mathfrak{Q}_i^{-1}\mathfrak{X}_i$ and $\tilde{\mathfrak{X}}(t_i) = \mathfrak{Q}_i^{-1}\mathfrak{X}(t_i)$, we then have that

$$\begin{aligned} &\|\mathfrak{X}(t_{i+1}) - \mathfrak{F}(t_i, \mathfrak{X}(t_i); h)\| \\ &\quad = \|\mathfrak{X}(t_{i+1}) - \mathfrak{Q}_{i+1}\tilde{\mathfrak{F}}(t_i, \mathfrak{Q}_i^{-1}\mathfrak{X}(t_i); h)\| = \|\mathfrak{Q}_{i+1}\tilde{\mathfrak{X}}(t_{i+1}) - \mathfrak{Q}_{i+1}\tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h)\| \\ &\quad \le \|\mathfrak{Q}_{i+1}\|\,\|\tilde{\mathfrak{X}}(t_{i+1}) - \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h)\| \le MCh^{p+1} \end{aligned}$$

and that

$$\begin{aligned} &\|\mathfrak{R}_{i+1}\mathfrak{Q}_{i+1}^{-1}(\mathfrak{F}(t_i, \mathfrak{X}(t_i); h) - \mathfrak{F}(t_i, \mathfrak{X}_i; h))\| \\ &\quad = \|\mathfrak{R}_{i+1}(\tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}(t_i); h) - \tilde{\mathfrak{F}}(t_i, \tilde{\mathfrak{X}}_i; h))\| \\ &\quad \le (1 + hK)\|\mathfrak{R}_i(\tilde{\mathfrak{X}}(t_i) - \tilde{\mathfrak{X}}_i; h)\| = (1 + hK)\|\mathfrak{R}_i\mathfrak{Q}_i^{-1}(\mathfrak{X}(t_i) - \mathfrak{X}_i)\|. \end{aligned}$$

Hence, if the basic method is convergent, then the new method that first transforms, then applies the basic method, and finally transforms back is convergent as well.

In the special case of the DAE integration methods that we will consider together with the spin-stabilization according to (32) for the transformations, we will be in the situation that

$$\mathfrak{X}_i = \begin{bmatrix} x_{i+k-1} \\ x_{i+k-2} \\ \vdots \\ x_i \end{bmatrix}, \quad \mathfrak{X}(t_i) = \begin{bmatrix} x(t_{i+k-1}) \\ x(t_{i+k-2}) \\ \vdots \\ x(t_i) \end{bmatrix} \tag{38}$$

and

$$\mathfrak{Q}_i = \begin{bmatrix} \tilde{Q}(t_{i+k-1}) & & & \\ & \tilde{Q}(t_{i+k-2}) & & \\ & & \ddots & \\ & & & \tilde{Q}(t_i) \end{bmatrix},$$

where we again omit a subscript i at $\tilde{Q}$, which also differs from step to step. Since we stay close to a (continuous) path $Q(t)$ of orthogonal matrices on a compact interval when we deal with convergence, it is clear that the properties (37) hold.

The numerical method given by $\tilde{\mathfrak{F}}$ in (33) is then applied to integrate the transformed DAE with coefficient functions

$$\tilde{E} = E\tilde{Q}, \quad \tilde{A} = A\tilde{Q} - E\dot{\tilde{Q}}.$$

In the following section we discuss the spin-stabilization approach for two classes of standard DAE integrators.

6.2 Spin-stabilized stiffly accurate Runge-Kutta methods

In this section we discuss the use of spin-stabilization within stiffly accurate Runge-Kutta methods possessing an invertible coefficient matrix $\mathcal{A}$. For this, let a linear DAE (10) be given which is already strangeness-free such that we do not need to perform an index reduction.

A Runge-Kutta method for the integration of (10) has the form

$$\begin{array}{lll} \text{(a)} & x_{i+1} = x_i + h\sum_{j=1}^{s} \beta_j \dot{X}_j, & \\ \text{(b)} & X_j = x_i + h\sum_{l=1}^{s} \alpha_{j,l} \dot{X}_l, & j = 1,\ldots,s, \\ \text{(c)} & E_j \dot{X}_j = A_j X_j + f_j, & j = 1,\ldots,s, \end{array} \tag{39}$$

with

$$E_j = E(t_i + \gamma_j h), \quad A_j = A(t_i + \gamma_j h), \quad f_j = f(t_i + \gamma_j h).$$

For convenience, we use the short hand notation

$$\operatorname{diag}(E_j) = \begin{bmatrix} E_1 & & \\ & \ddots & \\ & & E_s \end{bmatrix}, \quad \operatorname{col}(f_j) = \begin{bmatrix} f_1 \\ \vdots \\ f_s \end{bmatrix}$$

which also applies to other arguments. Using the Kronecker product, as it is common in the treatment of Runge-Kutta methods, we can solve (39b) according to

$$\dot{X} = \frac{1}{h}(\mathcal{A}^{-1} \otimes I_n)(X - (e \otimes x_i)),$$

where $X = \operatorname{col}(X_j)$ and $\dot{X} = \operatorname{col}(\dot{X}_j)$. Writing (39c) as

$$\operatorname{diag}(E_j)\dot{X} = \operatorname{diag}(A_j)X + \operatorname{col}(f_j),$$

we can eliminate $\dot{X}$ to obtain

$$\operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n)(X - (e \otimes x_i)) = h\operatorname{diag}(A_j)X + h\operatorname{col}(f_j)$$

and thus

$$[\operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n) - h\operatorname{diag}(A_j)]X = \operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n)(e \otimes x_i) + h\operatorname{col}(f_j). \tag{40}$$

Observing that the leading matrix is invertible for sufficiently small h and that the numerical solution x_{i+1} is given by the last block entry of X in the case of stiffly accurate Runge-Kutta schemes, we obtain

$$x_{i+1} = (e_s^T \otimes I_n)[\operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n) - h\operatorname{diag}(A_j)]^{-1}[\operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n)(e \otimes x_i) + h\operatorname{col}(f_j)],$$

where $e_s = [\,0\ \cdots\ 0\ 1\,]^T \in \mathbb{R}^s$. In view of (35), we must consider the matrix

$$W = (e_s^T \otimes I_n)[\operatorname{diag}(E_j)(\mathcal{A}^{-1} \otimes I_n) - h\operatorname{diag}(A_j)]^{-1}\operatorname{diag}(E_j)(d \otimes I_n),$$

where $d = \mathcal{A}^{-1}e$ as in Section 5.5. Let P_j, Q_j denote matrices that transform (E_j, A_j) to Weierstraß canonical form, see [2, 21], according to

$$P_j E_j Q_j = \begin{bmatrix} I_d & 0 \\ 0 & 0 \end{bmatrix}, \quad P_j A_j Q_j = \begin{bmatrix} C_j & 0 \\ 0 & I_a \end{bmatrix}.$$

Then W can represented as

$$\begin{aligned} W = (e_s^T \otimes I_n)&\operatorname{diag}(Q_j) \\ &\cdot [\operatorname{diag}(P_j E_j)(\mathcal{A}^{-1} \otimes I_n)\operatorname{diag}(Q_j) - h\operatorname{diag}(P_j A_j Q_j)]^{-1} \\ &\cdot \operatorname{diag}(P_j E_j Q_j)\operatorname{diag}(Q_j^{-1})(d \otimes I_n). \end{aligned}$$

Utilizing that P_jE_j has already a vanishing second block row, we see that

$$\begin{aligned}
&\operatorname{diag}(P_jE_j)(\mathcal{A}^{-1}\otimes I_n)\operatorname{diag}(Q_j) - h\operatorname{diag}(P_jA_jQ_j)\\
&= \left[\begin{array}{c|c|c} v_{1,1}P_1E_1Q_1 - hP_1A_1Q_1 & \cdots & v_{1,s}P_1E_1Q_s \\ \hline \vdots & \ddots & \vdots \\ \hline v_{s,1}P_sE_sQ_1 & \cdots & v_{s,s}P_sE_sQ_s - hP_sA_sQ_s \end{array}\right]\\
&= \left[\begin{array}{cc|c|cc} v_{1,1}I_d - hC_1 & 0 & \cdots & v_{1,1}I_d + \mathcal{O}(h) & \mathcal{O}(h) \\ 0 & -hI_a & \cdots & 0 & 0 \\ \hline \vdots & \vdots & \ddots & \vdots & \vdots \\ \hline v_{s,1}I_d + \mathcal{O}(h) & \mathcal{O}(h) & \cdots & v_{s,s}I_d - hC_s & 0 \\ 0 & 0 & \cdots & 0 & -hI_a \end{array}\right].
\end{aligned} \tag{41}$$

The inverse of this matrix must be applied to

$$\operatorname{diag}(P_jE_jQ_j) = \operatorname{diag}(J), \quad J = \begin{bmatrix} I_d & 0 \\ 0 & 0 \end{bmatrix}.$$

Because of its zero block rows, in (41) we can replace the entries consisting only of $\mathcal{O}(h)$ by zero and the entries $-hI_a$ by $v_{j,l}I_a$ without altering the resulting W. Hence,

$$\begin{aligned}
W &= (e_s^T\otimes I_n)\operatorname{diag}(Q_j)((\mathcal{A}^{-1}\otimes I_n) + \mathcal{O}(h))^{-1}\operatorname{diag}(J)\operatorname{diag}(Q_j^{-1})(d\otimes I_n)\\
&= Q_s(e_s^T\otimes I_n)((\mathcal{A}\otimes I_n) + \mathcal{O}(h))\operatorname{diag}(J)\operatorname{diag}(Q_j^{-1})(d\otimes I_n).
\end{aligned}$$

Observing, furthermore, that

$$\begin{aligned}
&\operatorname{diag}(J)\operatorname{diag}(Q_j^{-1})(d\otimes I_n) = \operatorname{diag}(J)\operatorname{diag}(Q_j^{-1})\operatorname{col}(d_jQ_jQ_0^{-1} + \mathcal{O}(h))\\
&\quad = \operatorname{diag}(J)\operatorname{diag}(d_jI_n)\operatorname{col}(Q_0^{-1} + \mathcal{O}(h)) = (d\otimes I_n)\operatorname{diag}(J)\operatorname{col}(I_n + \mathcal{O}(h))Q_0^{-1},
\end{aligned}$$

with Q_0 belonging to the transformation of $(E(t_i), A(t_i))$ to Weierstraß canonical form and using that $e_s^T\mathcal{A}d = e_s^T\mathcal{A}\mathcal{A}^{-1}e = 1$, we finally arrive at

$$\begin{aligned}
W &= Q_s(e_s^T\otimes I_n)((\mathcal{A}\otimes I_n) + \mathcal{O}(h))(d\otimes I_n)\operatorname{diag}(J)\operatorname{col}(I_n + \mathcal{O}(h))Q_0^{-1}\\
&= Q_s((e_s^T\mathcal{A}d\otimes I_n) + \mathcal{O}(h))\operatorname{diag}(J)\operatorname{col}(I_n + \mathcal{O}(h))Q_0^{-1}\\
&= Q_s(I_n + \mathcal{O}(h))\operatorname{diag}(J)\operatorname{col}(I_n + \mathcal{O}(h))Q_0^{-1}.
\end{aligned}$$

Comparing with (35) we have stability with

$$\mathfrak{R}_i = Q_0^{-1}, \quad \mathfrak{R}_{i+1} = Q_0^{-1}.$$

Together with the known consistency, we get convergence of any transformation method that is based on stiffly accurate Runge-Kutta methods, in particular of the spin-stabilized stiffly accurate Runge-Kutta methods.

Theorem 19 *A spin-stabilized stiffly accurate Runge-Kutta method based on a stiffly accurate Runge-Kutta method of order p with invertible $\mathcal{A}$ as $\widetilde{\mathfrak{F}}$ together with the transformation (32) is convergent of order p.*

In order to study the stability properties of a spin-stabilized stiffly accurate Runge-Kutta method concerning its long-time behavior, we apply it to the test equation (27). Let (E, A) denote the coefficients of the test equation, let P, Q denote matrix functions that transform (E, A) to the canonical form of (29), and let $\tilde{Q}$ be the stabilizing transformation according to

$$\tilde{Q}(t) = Q(t_{i+1}) + (t - t_{i+1})\dot{\tilde{Q}}.$$

Setting $x = \tilde{Q}\tilde{x}$, we have to integrate the DAE

$$E(t)\tilde{Q}(t)\dot{\tilde{x}} = (A(t)\tilde{Q}(t) - E(t)\dot{\tilde{Q}})\tilde{x}.$$

Using, furthermore, the quantities $\hat{t}_j = t_i + \gamma_j h$ and $\tilde{Q}_j = \tilde{Q}(\hat{t}_j)$, the spin-stabilized Runge-Kutta method has the form

$$\begin{aligned}
&\text{(a)} && \tilde{Q}(t_{i+1})^{-1} x_{i+1} = \tilde{Q}(t_i)^{-1} x_i + h \textstyle\sum_{j=1}^{s} \beta_j \dot{X}_j, \\
&\text{(b)} && X_j = Q(t_i)^{-1} x_i + h \textstyle\sum_{l=1}^{s} \alpha_{j,l} \dot{X}_l, \quad j = 1, \ldots, s, \\
&\text{(c)} && E_j \tilde{Q}_j \dot{X}_j = (A_j \tilde{Q}_j - E_j \dot{\tilde{Q}}) X_j, \quad j = 1, \ldots, s,
\end{aligned} \tag{42}$$

Due to (42c) and the special form of the test equation, the scaled stage values $\tilde{Q}_j X_j$ are consistent at time $\hat{t}_j$. Writing down (40) for the present situation, we obtain that

$$\begin{aligned}
\Big[\operatorname{diag}(E_j \tilde{Q}_j)(\mathcal{A}^{-1} \otimes I_n) - h \operatorname{diag}(A_j \tilde{Q}_j - E_j \dot{\tilde{Q}})\Big] \operatorname{diag}(\tilde{Q}_j^{-1}) \operatorname{col}(\tilde{Q}_j X_j) \\
= \Big[\operatorname{diag}(E_j \tilde{Q}_j)(\mathcal{A}^{-1} \otimes I_n)(e \otimes I_n)\Big] \tilde{Q}(t_i)^{-1} x_i
\end{aligned}$$

or

$$\Big[\operatorname{diag}(E_j \tilde{Q}_j)(\mathcal{A}^{-1} \otimes I_n) \operatorname{diag}(\tilde{Q}_j^{-1}) - h \operatorname{diag}(A_j - E_j \dot{\tilde{Q}} \tilde{Q}_j^{-1})\Big] \operatorname{col}(\tilde{Q}_j X_j) = \operatorname{col}(d_j E_j \tilde{Q}_j \tilde{Q}(t_i)^{-1} x_i).$$

The diagonal entries of the leading block matrix are given by $v_{j,j} E_j - h(A_j - E_j \dot{\tilde{Q}} \tilde{Q}_j^{-1})$, whereas the off-diagonal entries have the form $v_{j,l} E_j \tilde{Q}_j \tilde{Q}_l^{-1}$. The third term, which has to be considered is $E_j \tilde{Q}_j \tilde{Q}(t_i)^{-1}$ in the right hand side. In the treatment of these three terms, we incorporate the elimination of the first components of x_i and $\tilde{Q}_j X_j$ due to the consistency of these quantities at the corresponding points. We also make use of the transformation (28) to the canonical form (29).

Because of

$$\begin{aligned}
\tilde{Q}_j \tilde{Q}(t_i)^{-1} &= (\tilde{Q}(t_i) + \gamma_j h \dot{\tilde{Q}}(t_i) + \mathcal{O}(h^2)) \tilde{Q}(t_i)^{-1} \\
&= I + \gamma_j h \dot{Q}(t_i) Q(t_i)^{-1} + \mathcal{O}(h^2) \\
&= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \gamma_j h \frac{\omega}{(1+\omega^2 t_i^2)^2} \begin{bmatrix} -\omega t_i & 1 \\ -1 & -\omega t_i \end{bmatrix} \begin{bmatrix} 1 & -\omega t_i \\ \omega t_i & 1 \end{bmatrix} + \mathcal{O}(h^2) \\
&= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \gamma_j h \frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} + \mathcal{O}(h^2),
\end{aligned}$$

we obtain that

$$\begin{aligned}
&E_j \tilde{Q}_j \tilde{Q}(t_i)^{-1} \begin{bmatrix} 1+\omega t_i \\ 1 \end{bmatrix} \\
&\quad = \begin{bmatrix} 1 & -\omega \hat{t}_j \\ 0 & 0 \end{bmatrix} \left(\begin{bmatrix} 1+\omega t_i \\ 1 \end{bmatrix} + \gamma_j h \frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 1 \\ -(1+\omega t_i) \end{bmatrix} + \mathcal{O}(h^2) \right) \\
&\quad = \begin{bmatrix} 1 + \omega t_i + \gamma_j h \frac{\omega}{1+\omega^2 t_i^2} + \omega \hat{t}_j \gamma_j h \frac{\omega}{1+\omega^2 t_i^2} (1+\omega t_i) - \omega \hat{t}_j \\ 0 \end{bmatrix} + \mathcal{O}(h^2).
\end{aligned}$$

As $t_i \to \infty$, the third term in the first component of the latter matrix vanishes, whereas the fourth term tends to $\gamma_j h \omega$ which cancels $\omega t_i - \omega \hat{t}_j$. Hence, the first component tends to one.

Observing that

$$\begin{aligned}
\tilde{Q}_j \tilde{Q}_l^{-1} &= (Q(t_{i+1} - (1-\gamma_j) h \dot{\tilde{Q}})(Q(t_{i+1} - (1-\gamma_l) h \dot{\tilde{Q}})^{-1} \\
&= (I - (1-\gamma_j) h \dot{\tilde{Q}} Q(t_{i+1})^{-1})(I - (1-\gamma_l) h \dot{\tilde{Q}} Q(t_{i+1})^{-1})^{-1} \\
&= (I - (1-\gamma_j) h \dot{\tilde{Q}} Q(t_{i+1})^{-1})(I + (1-\gamma_l) h \dot{\tilde{Q}} Q(t_{i+1})^{-1} + \mathcal{O}(h^2)) \\
&= I + (\gamma_j - \gamma_l) h \dot{\tilde{Q}} Q(t_{i+1})^{-1} + \mathcal{O}(h^2) \\
&= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + (\gamma_j - \gamma_l) h \frac{\omega}{(1+\omega^2 \hat{t}_j^2)^2} \begin{bmatrix} -\omega \hat{t}_j & 1 \\ -1 & -\omega \hat{t}_j \end{bmatrix} \begin{bmatrix} 1 & -\omega \hat{t}_j \\ \omega \hat{t}_j & 1 \end{bmatrix} + \mathcal{O}(h^2) \\
&= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + (\gamma_j - \gamma_l) h \frac{\omega}{1+\omega^2 \hat{t}_j^2} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} + \mathcal{O}(h^2),
\end{aligned}$$

we find that

$$\begin{aligned} E_j\tilde{Q}_j\tilde{Q}_l^{-1}&\begin{bmatrix} 1+\omega\hat{t}_l \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -\omega\hat{t}_j \\ 0 & 0 \end{bmatrix}\left(\begin{bmatrix} 1+\omega\hat{t}_l \\ 1 \end{bmatrix} + (\gamma_j-\gamma_l)h\frac{\omega}{1+\omega^2\hat{t}_j^2}\begin{bmatrix} 1 \\ -(1+\omega\hat{t}_l) \end{bmatrix} + \mathcal{O}(h^2)\right) \\ &= \begin{bmatrix} 1+\omega\hat{t}_l - \omega\hat{t}_j + (\gamma_j-\gamma_l)h\frac{\omega}{1+\omega^2\hat{t}_j^2}(1+\omega\hat{t}_j(1+\omega\hat{t}_l)) \\ 0 \end{bmatrix} + \mathcal{O}(h^2). \end{aligned}$$

As above it follows that the first component also tends to one when $t_i \to \infty$. Finally, with

$$\dot{\tilde{Q}}Q_j^{-1} = \frac{\omega}{1+\omega^2\hat{t}_j^2}\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} + \mathcal{O}(h)$$

by a similar computation, we get that

$$\begin{aligned} \Big(v_{j,j}E_j - h(A_j - E_j\dot{\tilde{Q}}Q_j^{-1})\Big)&\begin{bmatrix} 1+\omega\hat{t}_j \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} v_{j,j} - h(\lambda+\omega) + h\frac{\omega}{1+\omega^2\hat{t}_j^2}(1+\omega\hat{t}_j+\omega^2\hat{t}_j^2) \\ 0 \end{bmatrix} + \mathcal{O}(h^2). \end{aligned}$$

Here, the third term in the first component tends to $h\omega$ as $t_i \to \infty$.

Since x_{i+1} coincides with $\tilde{Q}_sX_s$, we altogether have derived the representation

$$x_{i+1,2} = (e_s^T(\mathcal{A}^{-1} - h\lambda I)^{-1}d + \mathcal{O}(h^2))x_{i,2}.$$

Comparing with Section 5.5, we immediately see that

$$e_s^T(\mathcal{A}^{-1} - h\lambda I)^{-1}d = R(z,0),$$

where $R(z,w)$ is the stability function derived there. Moreover, $R(z,0)$ is nothing else than the classical stability function for ODEs. Hence, under the assumption that the constant in the remainder term is small, we see that the influence of the parameter ω on the stability of the discretization has been removed.

6.3 Spin-stabilized BDF methods

In this section we discuss the use of spin-stabilization within BDF methods. As in the previous section, we consider a strangeness-free DAE (10).

A BDF method for the integration of (10) has the form

$$\frac{1}{h}E_i\sum_{l=0}^{k}\alpha_{k-l}x_{i-l} = A_ix_i + f_i, \tag{43}$$

with

$$E_i = E(t_i), \quad A_i = A(t_i), \quad f_i = f(t_i).$$

We assume that the method is normalized to have the leading coefficient $\alpha_k = 1$. The relation (43) then yields

$$x_i = (E_i - h\beta_kA_i)^{-1}\Big[h\beta_kf_i - E_i\sum_{l=1}^{k}\alpha_{k-l}x_{i-l}\Big].$$

In view of (35), we must consider the matrix

$$W = \begin{bmatrix} -\alpha_{k-1}D_i & \cdots & -\alpha_1D_i & -\alpha_0D_i \\ I_n & & & \\ & \ddots & & \\ & & I_n & \end{bmatrix}$$

with

$$D_i = (E_i - h\beta_k A_i)^{-1} E_i.$$

Let P_i, Q_i transform (E_i, A_i) to Weierstraß canonical form. Then D_i has the form

$$\begin{aligned} D_i &= Q_i (P_i E_i Q_i - k\beta_k P_i A_i Q_i)^{-1} P_i E_i Q_i Q_i^{-1} \\ &= Q_i \begin{bmatrix} I_d - h\beta_k C_i & 0 \\ 0 & -hI_a \end{bmatrix} \begin{bmatrix} I_d & 0 \\ 0 & 0 \end{bmatrix} Q_i^{-1} \\ &= Q_i \begin{bmatrix} I_d + \mathcal{O}(h) & 0 \\ 0 & 0 \end{bmatrix} Q_i^{-1}, \end{aligned}$$

implying that

$$\begin{aligned} &\operatorname{diag}(Q_i^{-1}, \dots, Q_i^{-1}) W \operatorname{diag}(Q_i, \dots, Q_i) \\ &= \left[\begin{array}{cc|cc|cc|cc} -\alpha_{k-1} I_d & 0 & \cdots & \cdots & -\alpha_1 I_d & 0 & -\alpha_0 I_d & 0 \\ 0 & 0 & \cdots & \cdots & 0 & 0 & 0 & 0 \\ \hline I_d & 0 & & & & & & \\ 0 & I_a & & & & & & \\ \hline & & \ddots & & & & & \\ & & & \ddots & & & & \\ \hline & & & & I_d & & & \\ & & & & & I_a & & \end{array}\right] + \mathcal{O}(h). \end{aligned}$$

Hence, if the BDF method is D-stable, see [13], then there is a vector norm such that the latter matrix is bounded by $1 + hK$ in the corresponding matrix norm with a suitable constant K. Comparing with (35) and observing (38) we have stability with

$$\mathfrak{R}_i = \operatorname{diag}(Q_{i+k}, \dots, Q_{i+k}).$$

Thus, we have the following theorem.

Theorem 20 *A spin-stabilized BDF method based on a BDF method of order k, $1 \le k \le 6$ together with the transformation (32) is convergent of order k.*

In order to study the stability properties of a spin-stabilized BDF method concerning its long-time behavior, we apply it to the test equation (27). Let (E, A) denote the coefficients of the test equation, let P, Q denote matrix functions that transform (E, A) to the canonical form of (29), and let $\tilde{Q}$ be the stabilizing transformation according to

$$\tilde{Q}(t) = Q(t_i) + (t - t_i)\dot{\tilde{Q}}.$$

Setting $x = \tilde{Q}\tilde{x}$ and $x_{i-l} = \tilde{Q}_{i-l}\tilde{x}_{i-l}$ with $\tilde{Q}_{i-l} = \tilde{Q}(t_{i-l})$, we have to integrate the DAE

$$E(t)\tilde{Q}(t)\dot{\tilde{x}} = (A(t)\tilde{Q}(t) - E(t)\dot{\tilde{Q}})\tilde{x}.$$

Hence, the spin-stabilized BDF method has the form

$$\frac{1}{h} E_i \tilde{Q}_i \sum_{l=0}^{k} \alpha_{k-l} \tilde{Q}_{i-l}^{-1} x_{i-l} = (A_i \tilde{Q}_i - E_i \dot{\tilde{Q}}) \tilde{Q}_i^{-1} x_i,$$

leading to the difference equation

$$\Big[E_i - hA_i + hE_i \dot{\tilde{Q}} \tilde{Q}_i^{-1}\Big] x_i + E_i \tilde{Q}_i \sum_{l=1}^{k} \alpha_{k-l} \tilde{Q}_{i-l}^{-1} x_{i-l} = 0. \tag{44}$$

Since the BDF methods yield consistent numerical approximations, we know that

$$x_i = \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} = \begin{bmatrix} 1+\omega t_i \\ 1 \end{bmatrix} x_{2,i},$$

which we assume to hold for every numerical approximation. As already mentioned, we also assume that $\dot{\tilde{Q}} = \dot{Q}(t_i) + \mathcal{O}(h)$ with a small involved constant. Using (28) we then have that

$$\begin{aligned}(\dot{Q}(t_i) + \mathcal{O}(h))\tilde{Q}_i^{-1} &= \frac{\omega}{(1+\omega^2 t_i^2)^{3/2}} \begin{bmatrix} -\omega t_i & 1 \\ -1 & -\omega t_i \end{bmatrix} \frac{1}{(1+\omega^2 t_i^2)^{1/2}} \begin{bmatrix} 1 & -\omega t_i \\ \omega t_i & 1 \end{bmatrix} + \mathcal{O}(h) \\ &= \frac{\omega}{(1+\omega^2 t_i^2)^2} \begin{bmatrix} 0 & 1+\omega^2 t_i^2 \\ -1-\omega^2 t_i^2 & 0 \end{bmatrix} + \mathcal{O}(h) \\ &= \frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} + \mathcal{O}(h),\end{aligned}$$

and, thus,

$$\begin{aligned}E_i(\dot{Q}_i + \mathcal{O}(h))\tilde{Q}_i^{-1} x_i &= \left(\frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ -(1+\omega t_i) \end{bmatrix} + \mathcal{O}(h) \right) x_{2,i} \\ &= \left(\frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 1+\omega t_i(1+\omega t_i) \\ 0 \end{bmatrix} + \mathcal{O}(h) \right) x_{2,i}.\end{aligned}$$

Furthermore, we observe that

$$\begin{aligned}\tilde{Q}_i \tilde{Q}_{i-l}^{-1} &= Q(t_i)(Q(t_i) + (t_{i-l} - t_i)\dot{\tilde{Q}})^{-1} \\ &= Q(t_i)Q(t_i)^{-1}(I + lh\dot{Q}(t_i)Q(t_i)^{-1}) + \mathcal{O}(h^2) \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + lh\frac{\omega}{1+\omega^2 t_i^2} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} + \mathcal{O}(h^2)\end{aligned}$$

such that

$$\begin{aligned}E_i \tilde{Q}_i \tilde{Q}_{i-l}^{-1} x_{i-l} &= \left(\begin{bmatrix} 1 & -\omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & lh\frac{\omega}{1+\omega^2 t_i^2} \\ -lh\frac{\omega}{1+\omega^2 t_i^2} & 1 \end{bmatrix} \begin{bmatrix} 1-\omega t_i - l\omega h \\ 1 \end{bmatrix} + \mathcal{O}(h^2) \right) x_{2,i-l} \\ &= \left(\begin{bmatrix} 1 + lh\frac{\omega^2 t_i}{1+\omega^2 t_i^2} & lh\frac{\omega}{1+\omega^2 t_i^2} - \omega t_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1-\omega t_i - l\omega h \\ 1 \end{bmatrix} + \mathcal{O}(h^2) \right) x_{2,i-l} \\ &= \left(\begin{bmatrix} 1 - l\omega h + lh\frac{\omega^2 t_i(1+\omega t_i)}{1+\omega^2 t_i^2} + lh\frac{\omega}{1+\omega^2 t_i^2} \\ 0 \end{bmatrix} + \mathcal{O}(h^2) \right) x_{2,i-l}.\end{aligned}$$

Inserting all relations into the first block row of (44) and utilizing the consistency of all approximations gives a difference equation for the second components only. In the limit $t_i \to \infty$ this difference equation reads

$$\begin{aligned}\Big[(1+\omega t_i) - \omega t_i - h\lambda(1+\omega t_i) - h\omega(1-\lambda t_i) + h\omega + \mathcal{O}(h^2)\Big] x_{2,i} \\ + \sum_{l=1}^{k} \alpha_{k-l}(1+\mathcal{O}(h^2)) x_{2,k-l} = 0\end{aligned}$$

which reduces to

$$(1 - z + \mathcal{O}(h^2)) x_{2,i} + \sum_{l=1}^{k} \alpha_{k-l}(1+\mathcal{O}(h^2)) x_{2,k-l} = 0.$$

But this is nothing else than a perturbation of the difference equation which we obtain when we apply the BDF method to the standard ODE test equation. Thus, provided the constants involved in the remainder terms are small, we can expect the same stability properties of the spin-stabilized BDF methods as in the ODE case.

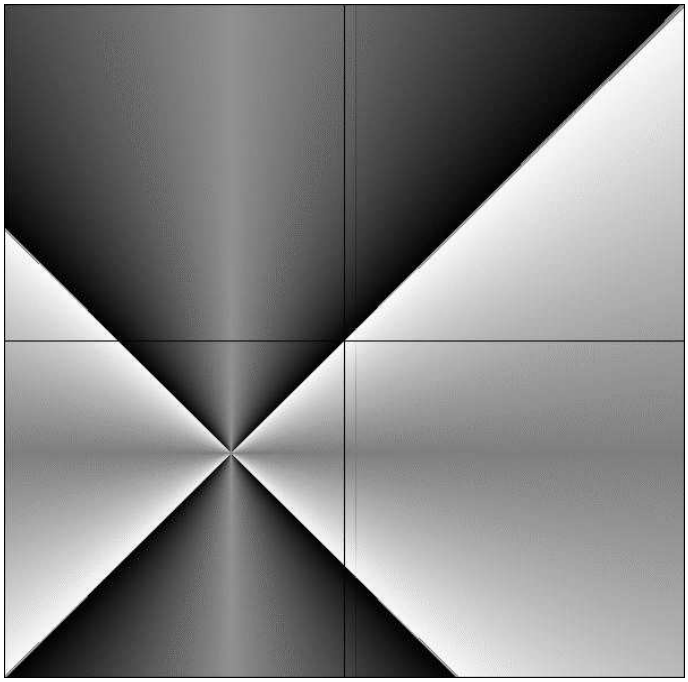

Figure 7: Numerical stability region for the standard implicit Euler method

6.4 A numerical experiment

We have implemented the standard implicit Euler method and its spin-stabilized version as presented in this paper. Using a constant stepsize, we applied both methods to the problem of Example 1 for a range of parameter values (δ, η) and checked numerically the stability of the numerical solutions. The results can be seen in Figure 7 for the standard implicit Euler method and in Figure 8 for the spin-stabilized implicit Euler method. Both figures were obtained with a stepsize of $h = 0.1$ and cover the range $(\delta, \eta) \in [-3, 3]^2$. The shading is based on a numerical estimate of the limit factor between the norms of x_i and x_{i+1}.

In Figure 7, one can recognize the stability restriction $|1 + h\delta| < |1 + h\eta|$, whereas Figure 8 shows that the spin-stabilized implicit Euler method is stable in the region $\delta < \eta$, where the actual solution is stable. We also see the superstability of the implicit Euler method, i. e. the stability of the numerical solution of the implicit Euler method in regions where the actual solution is not stable.

7 Conclusion

We have analyzed the stability properties of general differential-algebraic equations of arbitrary index and related them to those of the corresponding inherent ordinary differential equation.

We have presented a new test equation for differential-algebraic equations that takes into account that the kernel of $F_{\dot{x}}$ may spin along the solution. We have analyzed the stability of classical numerical integration methods for differential-algebraic equations on the basis of this new test equation and introduced the concept of DAE stability functions.

In order to deal with rapidly spinning kernels we have derived a new stabilization method that can be used together with all classical integrators. We have shown that this approach which in every integration step first transforms the equation, then carries out the integration step by the given method, and finally transforms back, leads to the same convergence results for stiffly

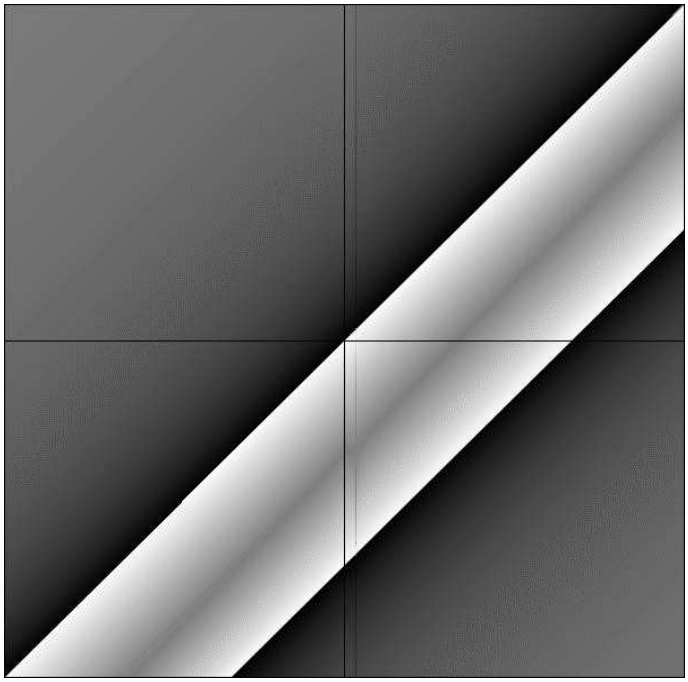

Figure 8: Numerical stability region for the spin-stabilized implicit Euler method

accurate Runge-Kutta and BDF methods as for the unstabilized methods, while getting more appropriate regions of numerical stability. Moreover, we have demonstrated our new approach with a numerical example.

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