



EXPONENTIAL DICHOTOMY AND STABLE MANIFOLDS FOR DIFFERENTIAL-ALGEBRAIC EQUATIONS ON THE HALF-LINE

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10 **EXPONENTIAL DICHOTOMY AND STABLE MANIFOLDS FOR**
11 **DIFFERENTIAL-ALGEBRAIC EQUATIONS ON THE HALF-LINE**

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15
16 ABSTRACT. We study linear and semi-linear differential-algebraic equations (DAEs) on the half-line \mathbb{R}_+ .
17 Firstly, we characterize the existence of exponential dichotomy for linear DAEs based on the Lyapunov-
18 Perron method. Then, we prove the existence of local and global, invariant, stable manifolds for semi-linear
19 DAEs in the case that the evolution family corresponding to linear DAE admits an exponential dichotomy
20 and the nonlinear forcing function fulfills the non-uniform φ -Lipschitz condition, in which the Lipschitz
function φ belongs to wide classes of admissible function spaces such as L_p , $1 \leq p \leq \infty$, $L_{p,q}$, etc.

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23 4 1. INTRODUCTION AND PRELIMINARIES

24
25 5 The present paper focuses on the existence of invariant (local and global) stable manifolds for semi-linear
26 6 non-autonomous differential-algebraic equations (DAEs) of the form

27
28 d rows
$$\underbrace{\begin{bmatrix} E_1(t) \\ 0 \end{bmatrix}}_{E(t)} \dot{x}(t) = \underbrace{\begin{bmatrix} A_1(t) \\ A_2(t) \end{bmatrix}}_{A(t)} x(t) + \underbrace{\begin{bmatrix} f_1(t, x(t)) \\ f_2(t, x(t)) \end{bmatrix}}_{f(t, x(t))}, \quad t \in \mathbb{R}_+ := [0, +\infty). \quad (1.1)$$

29
30 7 To do that, we start by investigating the exponential dichotomy of the associated linear system

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$$E(t)\dot{x}(t) = A(t)x(t), \quad t \in [0, +\infty). \quad (1.2)$$

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34 8 Here $E = \begin{bmatrix} E_1(t) \\ 0 \end{bmatrix}$, $A = \begin{bmatrix} A_1(t) \\ A_2(t) \end{bmatrix}$ are assumed to be matrix-valued functions acting on \mathbb{R}_+ to $\mathbb{R}^{n,n}$, $x : \mathbb{R}_+ \rightarrow$
35 9 \mathbb{R}^n , $f : \mathbb{R}_+ \times \mathbb{R}^n \rightarrow \mathbb{R}^n$. Furthermore, we assume that for all t , the matrices $E_1(t)$, $A_2(t)$ have full row rank.

36
37 10 DAE systems of the forms (1.1), (1.2) arise in many applications, include multibody dynamics, electrical
38 11 circuits, chemical engineering, and many other applications. Due to the rank-deficiency of $E(t)$, the
39 12 qualitative behavior of DAEs is much richer, in comparison to ordinary differential equations (ODEs). We
40 13 refer the reader to recent monographs [2, 11–13] and the references therein. In particular, even though the
41 14 stability analysis for DAEs have been intensively discussed (see the survey [11, Chapter 2]), there are only
42 15 few papers on the spectral theory of DAEs and in particular, the exponential dichotomy for DAEs. We refer
43 16 to [14] for the concept of exponential dichotomy and its relation to the well conditioning of the associated
44 17 boundary value problem, to [16] for Lyapunov and other spectra for linear DAEs, to [4, 7] for the robustness
45 18 of exponential stability and Bohl exponents.

46
47 19 On the other hand, whenever the exponential dichotomy of the linear, homogeneous system (1.2) is
48 20 characterized, the next important question in the qualitative theory of DAEs is to study the existence of
49 21 integral manifolds (e.g., stable, unstable, center, center-stable, center-unstable) for the semi-linear DAE (1.1)
50 22 [3, 5]. Unfortunately, till now this question is essentially open for DAEs. In order to shorten these gaps,
51 23 this paper is devoted to investigation of the exponential dichotomy of (1.2) and stable manifolds of (1.1).

52
53 Key words and phrases. Exponential dichotomy, semilinear, differential-algebraic equation, admissibility of function spaces,
54 stable manifold.

Our method is based on the classical "Lyapunov-Perron method" ([5, 24]) and the admissibility of function spaces ([9, 10]).

The outline of this paper is as follows. In the rest of this first section we recall some basic concepts for later use, including the notion of the exponential dichotomy and its properties, as well as some important features of admissible function spaces. In Section 2 we give a characterization for the existence of exponential dichotomy for the DAE (1.2). Section 3 contains our main results on the existence and properties of local stable manifold for the semi-linear DAE (1.1). The global version of these results will be presented in Section 4. Finally, we illustrate our results by studying a spatial discretization of Navier-Stokes equations, and we conclude this research by a summary and some open problems.

1.1. Evolution Families and Exponential Dichotomies. Let us now recall some basic notions. By $(\mathbb{R}^n, \|\cdot\|)$ we denote the n-dimensional real vector space equipped with the Euclidean norm. For any matrix V , by V^T we denote its transpose. For any $p \in \mathbb{N}$, by $C^p([0, \infty), \mathbb{R}^n)$ we denote the space of p -times continuously differentiable functions acting on $[0, \infty)$ with values in \mathbb{R}^n . By $C_b([0, \infty), \mathbb{R}^n)$ we denote the space of continuous and bounded functions mapping from $[0, \infty)$ into \mathbb{R}^n . This space is a Banach space with the *ess sup*-norm $\|f\|_\infty := \sup\{\|f(t)\|, t \geq 0\}$.

It is well-known (e.g. [3]), that for ordinary differential equations (ODEs), if the Cauchy problem

$$\begin{aligned} \frac{dx(t)}{dt} &= A(t)x(t), \quad t \geq s \geq 0, \\ x(s) &= x_s \in \mathbb{R}^n, \end{aligned} \tag{1.3}$$

is well-posed, then there exists a pointwise nonsingular matrix-valued function $(t, s) \mapsto X(t, s) \in \mathbb{R}^{n,n}$ such that the solution of (1.3) is given by $x(t) = X(t, s)x_s$. This fact motivates the existence of an evolution family $(X(t, s))_{t \geq s \geq 0}$ associated with the matrix function $A(t)$. This family satisfies the condition $X(t, t) = Id$ and the so-called *semi-group property*

$$X(t, r)X(r, s) = X(t, s), \quad \text{for all } t \geq r \geq s \geq 0. \tag{1.4}$$

Furthermore, the solution of the corresponding semi-linear ODE

$$\frac{dx(t)}{dt} = A(t)x(t) + f(t, x(t)), \quad \text{for all } t \geq s \geq 0,$$

is given by the so-called *variation-of-constant formula*

$$x(t) = X(t, s)x(s) + \int_s^t X(t, \tau)f(\tau, x(\tau))d\tau, \quad \text{for all } t \geq s \geq 0. \tag{1.5}$$

For more details on the notion and discussion on properties and applications of evolution families we refer the readers to Pazy [20].

Definition 1.1. A given evolution family $\{X(t, s)\}_{t \geq s \geq 0}$ of the ODE (1.3) is said to have an *exponential dichotomy* on the half-line if there exist a family of projection matrices $\{P(t)\}_{t \geq 0}$ and two positive constants N, ν such that the following conditions are satisfied.

- i) $P(t)X(t, s) = X(t, s)P(s)$ for all $t \geq s \geq 0$,
- ii) the restriction $X(t, s)| : \ker P(s) \rightarrow \ker P(t)$ is an isomorphism and we denote the inverse of $X(s, t)|$,
- iii) $\|X(t, s)P(s)x\| \leq N e^{-\nu(t-s)} \|P(s)x\|$, for all $t \geq s \geq 0$, $x \in \mathbb{R}^n$,
- iv) $\|X(t, s)| (I - P(s))x\| \leq N e^{\nu(t-s)} \|(I - P(s))x\|$, for all $s \geq t \geq 0$, $x \in \mathbb{R}^n$.

Here $\{P(t)\}_{t \geq 0}$ (resp. N, ν) are called *dichotomy projections* (resp. *dichotomy constants*).

Next we recall some basic concepts and properties for DAEs, starting with *fundamental solution matrix* as below.

Definition 1.2. (i) Consider the DAE (1.2). A matrix function $X \in C([0, \infty), \mathbb{R}^{n,k})$, $d \leq k \leq n$, is called a *fundamental solution matrix* of (1.2) if each of its columns is a solution to (1.2) and $\text{rank } X(t) = d$, for all $t \geq 0$.

(ii) A fundamental solution matrix is said to be *maximal* if $k = n$ and *minimal* if $k = d$, respectively. A maximal fundamental solution is called *principal* if it satisfies the *projected initial condition*

$$E(0)(X(0) - Id) = 0. \quad (1.6)$$

We can easily see that, the fundamental solution matrices for DAEs are not necessarily square or of full rank. Furthermore, each fundamental solution matrix has exactly d -linear independent columns, and a minimal fundamental solution matrix can be made maximal by adding $n - d$ zero columns. This is the major difference between ODEs and DAEs. Consequently, we are unable to define the evolution family for a DAE in the classical sense. The modified concept, but still capture the essence of an original one, has been proposed and carefully discussed in [16]. We recall it below, and notice that this concept is equivalent to the one proposed by Lentini and März in [14] within the context of the matrix chains approach and tractability index. Throughout this paper, we will assume the following.

Assumption 1.3. Consider the DAEs (1.1), (1.2). We assume that the function pair (E, A) in these DAEs is *strangeness-free*, i.e.,

$$\text{rank} \begin{bmatrix} E_1(t) \\ A_2(t) \end{bmatrix} = n,$$

for all $t \geq 0$. Furthermore, we assume that $E \in C^1([0, \infty), \mathbb{R}^{n,n})$ and $A \in C^0([0, \infty), \mathbb{R}^{n,n})$.

It should be important to note, that for general linear, homogeneous DAE of the form (1.2), one can transform it to the strangeness-free form without alternating the solution space. For further details, see [12, Chap. 3].

By making use of some smooth factorizations, for example QR or SVD ([6] or [12], Theorem 3.9), we can decouple and then exploit the structure of the DAE (1.2) in the following lemma.

Lemma 1.4. Consider the DAE (1.2) and assume that it satisfies Assumption 1.3. Then, there exist pointwise-orthogonal matrix-valued functions U and $V \in C^1([0, \infty), \mathbb{R}^{n,n})$, such that after changing variable $x(t) = V(t)y(t)$, and scaling (1.2) with $U(t)$, we can transform it to the so-called decoupled system of the following form

$$\begin{bmatrix} \Sigma(t) & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{y}_1(t) \\ \dot{y}_2(t) \end{bmatrix} = \begin{bmatrix} \tilde{A}_1(t) & \tilde{A}_2(t) \\ \tilde{A}_3(t) & \tilde{A}_4(t) \end{bmatrix} \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix}, \quad (1.7)$$

with pointwise nonsingular matrix-valued functions $\Sigma(t) \in \mathbb{R}^{d,d}$ and $\tilde{A}_4(t) \in \mathbb{R}^{a,a}$.

Proof. Applying an SVD factorization for $E_1(t)$ we can find pointwise-orthogonal matrix functions $U_1(t) \in C^1([0, \infty), \mathbb{R}^{d,d})$ and $V \in C^1([0, \infty), \mathbb{R}^{n,n})$ such that $U_1(t)E_1(t)V(t) = [\Sigma(t) \ 0]$, where $\Sigma(t)$ is a continuous, pointwise nonsingular function with values in $\mathbb{R}^{d,d}$. Changing the variable $x(t) = V(t)y(t)$ and scaling (1.2) with $U(t) := \begin{bmatrix} U_1(t) & 0 \\ 0 & I_a \end{bmatrix}$, we obtain a new system

$$U(t)E(t)V(t)y(t) = U(t) \left(A(t)V(t) - E(t)\dot{V}(t) \right) y(t),$$

which is exactly of the form (1.7). Furthermore, notice that

$$\begin{bmatrix} \Sigma(t) & 0 \\ \tilde{A}_3(t) & \tilde{A}_4(t) \end{bmatrix} = \begin{bmatrix} U_1(t) & 0 \\ 0 & I_a \end{bmatrix} \begin{bmatrix} E_1(t) \\ A_2(t) \end{bmatrix} V,$$

then Assumption 1.3 yields that both Σ and \tilde{A}_4 are nonsingular. This completes the proof. \square

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7 Let $\hat{A}_3 := -\tilde{A}_4^{-1}(t)\tilde{A}_3(t)$, $\hat{A}_1 := \Sigma^{-1}(t)\tilde{A}_1(t) + \Sigma^{-1}(t)\tilde{A}_2(t)\tilde{A}_4^{-1}(t)\tilde{A}_3(t)$, we rewrite the transformed
8 system (1.7) as
9

$$\dot{y}_1(t) = \hat{A}_1(t)y_1(t), \quad (1.8)$$

$$y_2(t) = \hat{A}_3(t)y_1(t). \quad (1.9)$$

10 Since $V(t)$ is orthogonal for all $t \geq 0$, we see that all important qualitative properties of $x(t)$, such as
11 boundedness, exponential stability, contractivity, expansiveness, etc., can be carried out for the function
12 $y(t)$. Clearly, we see that (1.9) gives an *algebraic constraint* that the solution to (1.7) must obey, while (1.8)
13 gives the dynamic of (1.7). For this reason, we call it *an underlying ODE* to (1.7).

14 Let $\{\hat{Y}_1(t, s)\}_{t \geq s \geq 0}$ be the evolution family associated with the matrix function $\hat{A}_1(t)$, then we can define
15 the corresponding evolution families for two DAEs (1.7), (1.2) consecutively as follows.
16

$$17 \hat{Y}(t, s) := \begin{bmatrix} \hat{Y}_1(t, s) & 0 \\ \hat{A}_3(t)\hat{Y}_1(t, s) & 0 \end{bmatrix}, \quad \hat{X}(t, s) = V(t)\hat{Y}(t, s)V^T(s), \text{ for all } t \geq s \geq 0. \quad (1.10)$$

18 Nevertheless, since $X(t, s)$ is not invertible, we will define the *reflexive generalized inverse matrix function*
19 as in [16] by
20

$$21 \hat{Y}^-(t, s) := \begin{bmatrix} \hat{Y}_1^{-1}(t, s) & 0 \\ \hat{A}_3(s)\hat{Y}_1^{-1}(t, s) & 0 \end{bmatrix}, \quad \hat{X}^-(t, s) := V(s)\hat{Y}^-(t, s)V^T(t), \text{ for all } t \geq s \geq 0. \quad (1.11)$$

22 Furthermore, we can directly verify the semigroup properties, i.e.
23

$$24 \hat{X}(t, r) = \hat{X}(t, s)\hat{X}(s, r), \text{ for all } t \geq s \geq r \geq 0,$$

$$25 \hat{X}(t, s) = \hat{X}(t, 0)\hat{X}^-(s, 0), \text{ for all } t \geq s \geq 0.$$

26 Now we give a solution formula for system (1.1), in comparison to (1.5).
27

28 **Lemma 1.5.** Consider the DAE (1.1) and the evolution family $(X(t, s))_{t \geq s \geq 0}$ defined by (1.10). Then the
29 solution to (1.1), if exists, also satisfies the so-called mild equation
30

$$31 \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \hat{X}(t, s) \begin{bmatrix} x_1(s) \\ x_2(s) \end{bmatrix} + \int_s^t \hat{X}(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, x_1(\tau), x_2(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, x_1(t), x_2(t)) \end{bmatrix},$$

32 for all $t \geq s \geq 0$, where $\hat{f}_1 := \Sigma^{-1}(t)f_1$ and $\hat{f}_2 := -\tilde{A}_4^{-1}(t)f_2$.
33

34 *Proof.* The proof can be obtained directly by using Lemma 1.4. Thus, in order to keep the brevity we will
35 omit the details here. \square
36

37 In the following, for ease of notation, we will use the abbreviation $\hat{X}(t) := \hat{X}(t, 0)$, $\hat{X}^-(t) := \hat{X}^-(t, 0)$,
38 $\hat{Y}(t) := \hat{Y}(t, 0)$ and $\hat{Y}^-(t) := \hat{Y}^-(t, 0)$. The concept of exponential dichotomy for the DAE (1.7) is given as
39 below.
40

41 **Definition 1.6.** ([16]) The DAE (1.7) is said to have an *exponential dichotomy* if there exist a family of
42 projection matrices $\{P_y(t)\}_{t \geq 0}$ in $\mathbb{R}^{d,d}$ and positive constants N, ν such that
43

$$44 \left\| \hat{Y}(t) \begin{bmatrix} P_y(t) & 0 \\ 0 & 0 \end{bmatrix} \hat{Y}^-(s) \right\| \leq N e^{-\nu(t-s)}, \text{ for all } t \geq s \geq 0,$$

$$45 \left\| \hat{Y}(t) \begin{bmatrix} I_d - P_y(t) & 0 \\ 0 & 0 \end{bmatrix} \hat{Y}^-(s) \right\| \leq N e^{\nu(t-s)}, \text{ for all } s \geq t \geq 0, \quad (1.12)$$

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Since the Euclidean norm is preserved under orthogonal transformations, due to (1.10)-(1.12) we see that

$$\left\| \hat{X}(t)V^T(0) \begin{bmatrix} P_y(t) & 0 \\ 0 & 0 \end{bmatrix} V(0)\hat{X}^-(s) \right\| \leq Ne^{-\nu(t-s)}, \text{ for all } t \geq s \geq 0.$$

and

$$\left\| \hat{X}(t)V^T(0) \begin{bmatrix} Id - P_y(t) & 0 \\ 0 & 0 \end{bmatrix} V(0)\hat{X}^-(s) \right\| \leq Ne^{\nu(t-s)}, \text{ for all } s \geq t \geq 0.$$

In addition, since $V^T(0) \begin{bmatrix} Id - P_y(t) & 0 \\ 0 & 0 \end{bmatrix} V(0)$ is also a projection matrix for any $t \geq 0$, we can interpret the exponential dichotomy of (1.2) as the one of (1.7).

1.2. Function Spaces and Admissibility. In this subsection we recall some notions of function spaces that play a fundamental role in the study of differential equations and refer to Nguyen [9], Massera and Schäffer [17, Chap. 2] and Räbiger and Schnaubelt [21, §1] for various applications.

Let E (endowed with the norm $\|\cdot\|_E$) be Banach function space of real-valued functions defined as in [9]. We then recall the Banach space corresponding to the space E as follows.

Definition 1.7 ([9]). Consider the Banach space $(\mathbb{R}^n, \|\cdot\|)$. For a Banach function space E we set

$$\mathcal{E} := \mathcal{E}(\mathbb{R}_+, \mathbb{R}^n) := \{f : \mathbb{R}_+ \rightarrow \mathbb{R}^n : f \text{ is strongly measurable and } \|f(\cdot)\| \in E\}$$

endowed with the norm $\|f\|_{\mathcal{E}} := \|f(\cdot)\|_E$. Thus, one can directly see that $(\mathcal{E}, \|\cdot\|_{\mathcal{E}})$ is a Banach space. We call it *the Banach space corresponding to E* .

We now introduce the notion of admissibility in the following definition.

Definition 1.8 ([9]). The Banach function space E is called *admissible* if for any $\varphi \in E$ the following conditions hold.

(i) There exists a constant $M \geq 1$ such that for every compact interval $[a, b] \subset \mathbb{R}_+$ we have

$$\int_a^b |\varphi(t)| dt \leq \frac{M(b-a)}{\|\chi_{[a,b]}\|_E} \|\varphi\|_E \text{ for all } \varphi \in E. \quad (1.13)$$

(ii) The function $\Lambda_1 \varphi$ defined by $\Lambda_1 \varphi(t) := \int_t^{t+1} \varphi(\tau) d\tau$ belongs to E .

(iii) For any $\tau \geq 0$, the space E is T_{τ}^+ -invariant and T_{τ}^- -invariant, where T_{τ}^+ and T_{τ}^- are defined as

$$T_{\tau}^+ \varphi(t) := \begin{cases} \varphi(t-\tau) & \text{for } t \geq \tau \geq 0, \\ 0 & \text{for } 0 \leq t \leq \tau, \end{cases} \quad T_{\tau}^- \varphi(t) := \varphi(t+\tau) \text{ for } t \geq 0. \quad (1.14)$$

Furthermore, there exist constants N_1, N_2 such that $\|T_{\tau}^+\|_E \leq N_1$, $\|T_{\tau}^-\|_E \leq N_2$ for all $\tau \in \mathbb{R}_+$.

Example 1.9. Besides the spaces $L_p(\mathbb{R}_+)$, $1 \leq p \leq \infty$, and the space

$$\mathbf{M}_{\alpha}(\mathbb{R}_+) := \{h \in L_{1,loc}(\mathbb{R}_+) : \sup_{t \geq 0} \int_t^{t+\alpha} |h(\tau)| d\tau < \infty\},$$

(for any fixed $\alpha > 0$), endowed with the norm $\|h\|_{\mathbf{M}_{\alpha}} := \sup_{t \geq 0} \int_t^{t+\alpha} |h(\tau)| d\tau$, many other function spaces occurring in interpolation theory, e.g. the Lorentz spaces $L_{p,q}$, $1 < p < \infty$, $1 \leq q < \infty$ (see [3], [23]) and, more general, the class of rearrangement invariant function spaces (see [15]) are admissible.

128 *Remark 1.10.* Following directly from Definition 1.8 we have that

$$129 \quad \sup_{t \geq 0} \int_t^{t+1} |\varphi(\tau)| d\tau \leq \frac{M}{\inf_{t \geq 0} \|\chi_{[t,t+1]}\|_E} \|\varphi\|_E,$$

11 and hence, $E \hookrightarrow \mathbf{M}_1(\mathbb{R}_+)$. Furthermore, $C_b(\mathbb{R}^+)$ is dense in \mathbf{M}_1 .

12 We present here some important features of admissible spaces in the following proposition (see [9, Proposition 13 2.6] and originally in [17, 23.V.(1)]).

15 **Proposition 1.11** ([9]). Let E be an admissible Banach function space. Then the following assertions hold.

16 a) Let $\varphi \in L_{1,loc}(\mathbb{R}_+)$ such that $\varphi \geq 0$ and $\Lambda_1 \varphi \in E$, where, Λ_1 is defined as in definition 1.8 (ii). For $\sigma > 0$
17 we define functions $\Lambda'_\sigma \varphi$ and $\Lambda''_\sigma \varphi$ by

$$18 \quad \Lambda'_\sigma \varphi(t) := \int_0^t e^{-\sigma(t-s)} \varphi(s) ds,$$

$$19 \quad \Lambda''_\sigma \varphi(t) := \int_t^\infty e^{-\sigma(s-t)} \varphi(s) ds.$$

23 Then, $\Lambda'_\sigma \varphi$ and $\Lambda''_\sigma \varphi$ belong to E . In particular, if $\sup_{t \geq 0} \int_t^{t+1} \varphi(\tau) d\tau < \infty$ (this will be satisfied if $\varphi \in E$ (see
24 remark 1.10)) then $\Lambda'_\sigma \varphi$ and $\Lambda''_\sigma \varphi$ are bounded. Moreover, denoted by $\|\cdot\|_\infty$ for *ess sup*-norm, we have

$$26 \quad \|\Lambda'_\sigma \varphi\|_\infty \leq \frac{N_1}{1 - e^{-\sigma}} \|\Lambda_1 T_1^+ \varphi\|_\infty \quad \text{and} \quad \|\Lambda''_\sigma \varphi\|_\infty \leq \frac{N_2}{1 - e^{-\sigma}} \|\Lambda_1 \varphi\|_\infty \quad (1.15)$$

28 for operator T_1^+ and constants N_1, N_2 defined as in Definition 1.8.

29 b) E contains exponentially decaying functions $\psi(t) = e^{-\alpha t}$ for any constant $\alpha > 0$.

30 c) E does not contain exponentially growing functions $f(t) := e^{bt}$ for any constant $b > 0$.

31 137 2. EXPONENTIAL DICHOTOMY FOR LINEAR DAEs

33 In the qualitative analysis of ODEs, one of the central topic is to find sufficient and necessary conditions
34 for the considered systems to admit exponential dichotomy. Many researches have been devoted to this
35 topic, and critical results have been achieved for ODEs in finite and infinite dimensional phase spaces (e.g.
36 [5, Chap. 4], [24]). For DAEs, the only result that we are aware of is recalled below.

37 **Proposition 2.1.** ([16]) The DAE (1.2) has exponential dichotomy if and only if the matrix function $\hat{A}_3(t)$
38 is bounded, and the corresponding underlying ODE (1.8) also has exponential dichotomy. Moreover, the
39 existence of exponential dichotomy implies that $\sup_{t \geq 0} \|P_y(t)\| < \infty$.

41 Notice that, even for ODEs, Proposition 2.1 is only valid for finite-dimensional systems but not for infinite
42 dimensional systems. For this reason, we recall another important result below.

44 **Proposition 2.2.** ([5]) The ODE (1.3) has an exponential dichotomy if and only if for any continuous,
45 bounded function $f(t)$ on $[0, \infty)$, there exists a continuous, bounded solution $x(t)$ to (1.3).

46 In view of Proposition 2.2, comparable conditions for the existence of exponential dichotomy have not
47 been considered for DAEs, and hence, this will be our main aim in this section.

48 **Definition 2.3.** Consider the matrix functions E, A in system (1.2). Then, a function $f : \mathbb{R}_+ \rightarrow \mathbb{R}^n$
49 satisfying the condition

$$51 \quad \sup_{t \geq 0} \left\{ \left\| \begin{bmatrix} \Sigma^{-1}(t) & -\Sigma^{-1}(t) \tilde{A}_2(t) \tilde{A}_4^{-1}(t) \\ 0 & \tilde{A}_4^{-1}(t) \end{bmatrix} f(t) \right\| \right\} < +\infty,$$

53 153 is called (E, A) -bounded. We denote the set of all continuous and (E, A) -bounded functions by $\mathcal{B}^{EA}(\mathbb{R}_+, \mathbb{R}^n)$.

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The main result of this section is to prove a characterization of the exponential dichotomy for DAEs. Roughly speaking, the DAE (1.2) admits exponential dichotomy if and only if the mapping $\mathcal{L} := E \frac{d}{dt} - A$ is surjective on the space $\mathcal{B}^{EA}(\mathbb{R}_+, \mathbb{R}^n)$. In connection with the solvability of the corresponding linear and inhomogeneous DAE

$$\begin{array}{ll} d \text{ rows} & \left[\begin{array}{c} E_1(t) \\ 0 \end{array} \right] \dot{x}(t) = \underbrace{\left[\begin{array}{c} A_1(t) \\ A_2(t) \end{array} \right]}_{A(t)} + \underbrace{\left[\begin{array}{c} f_1(t) \\ f_2(t) \end{array} \right]}_{f(t)}, & t \in [0, +\infty). \end{array} \quad (2.1)$$

We formulate our main result in this section as follows.

Theorem 2.4. *Consider the linear, strangeness-free DAE (1.2) and the associated inhomogeneous DAE (2.1). Then the following assertions hold.*

- (i) *If the DAE (1.2) admits exponential dichotomy then for any continuous, (E, A) -bounded function $f(t)$ on $[0, \infty)$, there exists a continuous, bounded solution $x(t)$ to the DAE (2.1).*
- (ii) *If the matrix function $\hat{A}_3(t)$ is bounded, then the converse of assertion (i) holds true.*

Proof. Firstly, we notice that, since $\hat{f} = U(t) \begin{bmatrix} \Sigma^{-1}(t) & -\Sigma^{-1}(t)\tilde{A}_2(t)\tilde{A}_4^{-1}(t) \\ 0 & -\hat{A}_4^{-1} \end{bmatrix} f(t)$, the (E, A) -boundedness of f is equivalent to the boundedness of \hat{f} . Recall that the decoupled system (1.7) reads

$$\dot{y}_1(t) = \hat{A}_1(t)y_1(t) + \hat{f}_1(t), \quad (2.2)$$

$$y_2(t) = \hat{A}_3(t)y_1(t) + \hat{f}_2(t). \quad (2.3)$$

(i) Assuming that the DAE (1.2) admits exponential dichotomy, then (1.7) also has an exponential dichotomy. Proposition 2.1 implies that equation (2.2) has an exponential dichotomy, and the function \hat{A}_3 is bounded. Therefore, Proposition 2.2 implies that y_1 is bounded, and consequently, y_2 is also bounded.

(ii) From Proposition 2.2, it follows that (2.2) has exponential dichotomy. On the other hand, the boundedness of \hat{A}_3 implies that (1.2) admits exponential dichotomy. \square

3. LOCAL STABLE MANIFOLDS FOR SEMI-LINEAR DAEs

In this section we study the existence of a local stable manifold for the semi-linear DAE (1.1). Throughout this section we assume that the evolution family $(X(t, s))_{t \geq s \geq 0}$ associated with the linear, homogeneous DAE (1.2) admits an exponential dichotomy on \mathbb{R}_+ .

From Lemma 1.4, by using orthogonal transformation $x(t) = V(t)y(t)$, where $y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} \in \mathbb{R}^{d+a}$ we can transform (1.1) to the coupled system

$$\dot{y}_1(t) = \hat{A}_1(t)y_1(t) + \hat{f}_1(t, y(t)), \quad (3.1)$$

$$y_2(t) = \hat{A}_3(t)y_1(t) + \hat{f}_2(t, y(t)), \quad (3.2)$$

where

$$\hat{f}(t, y(t)) = \begin{bmatrix} \hat{f}_1(t, y(t)) \\ \hat{f}_2(t, y(t)) \end{bmatrix} := \begin{bmatrix} \Sigma^{-1}(t)f_1(t, x(t)) - \Sigma^{-1}(t)\tilde{A}_2(t)\tilde{A}_4^{-1}(t)f_2(t, x(t)) \\ -A_4^{-1}(t)f_2(t, x(t)) \end{bmatrix}. \quad (3.3)$$

Notice that, unlike the DAEs (1.2) and (2.1), equation (3.2) only gives an implicit algebraic constraint in terms of y_1 and y_2 . In order to guarantee the strangeness-free of system (1.1), we need the following assumption.

Assumption 3.1. Assume that for some $\rho > 0$, the function $A_4^{-1}(t)f_2(t, x)$ is a contraction mapping in the ball $B_\rho := \{x \in \mathbb{R}^n | \|x\| \leq \rho\}$ (uniformly in time), i.e.,

$$\|A_4^{-1}(t)f_2(t, x) - A_4^{-1}(t)f_2(t, \tilde{x})\| \leq L\|x - \tilde{x}\|,$$

for a.e. $t \in \mathbb{R}_+$, and for all $x, \tilde{x} \in B_\rho$ where the Lipschitz constant L satisfies that $L < 1$.

Lemma 3.2. Under Assumption 3.1 and given $y_1 \in B_r h o$, there exists a unique function $y_2 \in B_r h o$ satisfying (3.2).

Proof. Firstly, notice that Assumption 3.1 implies that $\hat{f}_2(t, y)$ is also Lipschitz in y with the same constant L . Then, the desired claim is obtained directly by making use of [18, Lem. 2.7]. \square

Remark 3.3. Lemma 3.2 leads to one important fact, that under Assumption 3.1, the coupled system (3.1)-(3.2) is still strangeness-free, as defined in [12, Chap. 4]. Therefore, in analogue to the linear case, (3.2) is called *an algebraic constraint*, whereas (3.1) is called *an underlying ODE*.

To obtain the existence of a stable manifold we need the following property of the nonlinear part f_1 defined as follows.

Definition 3.4. Let φ be a positive function belonging to an admissible Banach function space E . A function $h : \mathbb{R}_+ \times \mathbb{R}^d \rightarrow \mathbb{R}^d$ is said to belong to the class (M, φ, ρ) for some positive constant M , ρ if h satisfies

- (i) $\|h(t, x)\| \leq M\varphi(t)$ for a.e. $t \in \mathbb{R}_+$ and for all $x \in B_\rho$,
- (ii) $\|h(t, x) - h(t, \tilde{x})\| \leq \varphi(t)\|x - \tilde{x}\|$ for a.e. $t \in \mathbb{R}_+$, for all $x, \tilde{x} \in B_\rho$.

Assumption 3.5. Assume that the function $t \mapsto \Sigma^{-1}(t) f_1(t, x(t)) - \Sigma^{-1}(t) \tilde{A}_2(t) \tilde{A}_4^{-1}(t) f_2(t, x(t))$ belongs to class (M, φ, ρ) for some positive constants M , ρ and a positive function $\varphi \in E$.

For the simplicity of presentation, we will study the existence of a local stable manifold for system (3.1)-(3.2). Moreover, we consider the mild/integral-algebraic system which reads

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \hat{Y}(t, s) \begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} + \int_s^t \hat{Y}(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix}, \quad (3.4)$$

for all $t \geq s \geq 0$.

Lemma 3.6. Let Assumptions 3.1 and 3.5 hold true. Then, for all $y, \tilde{y} \in B_\rho$ the following assertions hold.

- (i) $\|\hat{f}_1(t, y)\| \leq M\varphi(t)$ for a.e. $t \in \mathbb{R}_+$,
- (ii) $\|\hat{f}_1(t, y) - \hat{f}_1(t, \tilde{y})\| \leq \varphi(t)\|y - \tilde{y}\|$ for a.e. $t \in \mathbb{R}_+$,
- (iii) $\|\hat{f}_2(t, y) - \hat{f}_2(t, \tilde{y})\| \leq L\|y - \tilde{y}\|$ for a.e. $t \in \mathbb{R}_+$.

Proof. The proof is trivially followed from Assumptions 3.1 and 3.5 due to the fact that $\|y\| = \|Qy\|$ for any orthogonal matrix V . \square

Let $(\hat{Y}(t, s))_{t \geq s \geq 0}$ has an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$ as in Definition 1.6. Furthermore, as in Proposition 2.1, let us denote by $H_1 := \sup_{t \geq 0} \|\hat{A}_3(t)\|$ and $H_2 := \sup_{t \geq 0} \|P_y(t)\|$. Then, we can define the Green function on the half-line as follows

$$G(t, \tau) := \begin{cases} \hat{Y}(t, \tau) \begin{bmatrix} P_y(\tau) & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \hat{Y}_1(t, \tau)P_y(\tau) & 0 \\ \hat{A}_3(t)\hat{Y}_1(t, \tau)P_y(\tau) & 0 \end{bmatrix}, & \text{for all } t \geq \tau \geq 0, \\ -\hat{Y}(t, \tau) \begin{bmatrix} I_d - P_y(\tau) & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \hat{Y}_1(t, \tau)(I_d - P_y(\tau)) & 0 \\ \hat{A}_3(\tau)\hat{Y}_1(t, \tau)(I_d - P_y(\tau)) & 0 \end{bmatrix}, & \text{for all } 0 \leq t < \tau. \end{cases} \quad (3.5)$$

EXPONENTIAL DICHOTOMY AND STABLE MANIFOLD FOR DAES

209 Then, we have

$$\|G(t, \tau)\| \leq (1 + H_1)(1 + H_2) Ne^{-\nu|t-\tau|} \quad \text{for all } t \neq \tau \geq 0. \quad (3.6)$$

210 In the following lemma, we give an explicit form for bounded solutions to system (3.4).

211 **Lemma 3.7.** *Let the evolution family $(\hat{Y}(t, s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumptions 3.1, 3.5 hold true. Let $y(t)$ be any solution to (3.4) such that $\text{ess sup}_{t \geq t_0} \|y(t)\| \leq \rho$ for fixed $t_0 \geq 0$ and some $\rho > 0$. Then, for $t \geq t_0 \geq 0$, we can rewrite $y(t)$ in the form*

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = Y(t, t_0) \begin{bmatrix} v_0 \\ 0 \end{bmatrix} + \int_{t_0}^{\infty} G(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix}, \quad (3.7)$$

215 for some $v_0 \in \text{Im}P_y(t_0)$, where $G(t, \tau)$ is the Green function defined by (3.5).

20 Proof. Put

$$z(t) = \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} := \int_{t_0}^{\infty} G(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix}.$$

216 By direct computation, we can verify that z satisfies the integral equation

$$z(t) = \hat{Y}(t, t_0) \begin{bmatrix} z_1(t_0) \\ z_2(t_0) \end{bmatrix} + \int_{t_0}^t \hat{Y}(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix},$$

217 for all $t \geq t_0$. Now let us estimate $\|z(t)\|$. Making use of Lemma 3.6 and (3.6), we see that

$$\|z(t)\| \leq (1 + H_1)(1 + H_2) Ne^{-\nu|t-t_0|} M\varphi(\tau) d\tau + L\rho,$$

218 and then, from (1.15) it follows that

$$\|z(t)\| \leq M (1 + H_1)(1 + H_2) \frac{N}{1 - e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) + L\rho,$$

219 for all $t \geq t_0$. Thus, $z(t) - y(t)$ is also bounded. Moreover, since

$$z(t) - y(t) = \hat{Y}(t, t_0) (z(t_0) - y(t_0)) = \begin{bmatrix} \hat{Y}_1(t, t_0) (z_1(t_0) - y_1(t_0)) \\ \hat{A}_3(t) \hat{Y}_1(t, t_0) (z_1(t_0) - y_1(t_0)) \end{bmatrix},$$

220 we see that $v_0 := z_1(t_0) - y_1(t_0) \in \text{Im}P_y(t_0)$. Finally, since $z(t) = y(t) + \hat{Y}(t, t_0) \begin{bmatrix} v_0 \\ 0 \end{bmatrix}$ for all $t \geq t_0$, equality 221 (3.7) follows. \square

222 *Remark 3.8.* By computing directly, we can see that the converse of Lemma 3.7 is also true. It means, that 223 all solutions to (3.7) also satisfy equation (3.4) for all $t \geq t_0$.

224 Let us denote by

$$H_3 := (1 + H_1)(1 + H_2) \frac{N}{1 - e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) \quad \text{and} \quad \tilde{\rho} := \frac{1 - L}{2N(1 + H_1)} \rho. \quad (3.8)$$

225 **Lemma 3.9.** *Under the assumptions of Lemma 3.7, let $y(t)$, $\tilde{y}(t)$ be any two functions lying in the ball B_ρ 226 and satisfy (3.7) for $v_0, \tilde{v}_0 \in \text{Im}P_y(t_0)$. If H_3 defined as in (3.8) satisfies $H_3 + L < 1$ then the following 227 estimate holds true:*

$$\|y - \tilde{y}\|_\infty \leq \frac{N}{1 - H_3 - L} \|v_0 - \tilde{v}_0\|. \quad (3.9)$$

Proof. Using the same arguments as in the proof of Lemma 3.6, we see that

$$\begin{aligned} \|y(t) - \tilde{y}(t)\| &\leq N\|v_0 - \tilde{v}_0\| + \int_{t_0}^{\infty} (1+H_1)(1+H_2) Ne^{-\nu|t-\tau|} |\varphi(\tau)| \|y(\tau) - \tilde{y}(\tau)\| d\tau + L\|y(t) - \tilde{y}(t)\|, \\ &\leq N\|v_0 - \tilde{v}_0\| + (1+H_1)(1+H_2) \frac{N}{1-e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) \|y - \tilde{y}\|_\infty + L\|y(t) - \tilde{y}(t)\|, \\ &\leq N\|v_0 - \tilde{v}_0\| + (H_3 + L) \|y - \tilde{y}\|_\infty, \end{aligned}$$

which directly implies (3.9). \square

In the following theorem, we exploit the local structure of bounded solutions to (3.4).

Theorem 3.10. *Let the evolution family $(\hat{Y}(t,s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumptions 3.1, 3.5 hold true, and constant H_3 defined as in (3.8). Then, the following assertions hold true.*

(i) If

$$H_3 < \min \left\{ 1 - L, \frac{(1-L)\rho}{2M} \right\}, \quad (3.10)$$

then there corresponds to each $v_0 \in B_{\tilde{\rho}} \cap \text{Im}P_y(t_0)$ one and only one solution $y(t)$ to (3.4) on $[t_0, \infty)$ satisfying $P_y(t_0)y_1(t_0) = v_0$ and $\text{esssup}_{t \geq t_0} \|y(t)\| \leq \rho$.

(ii) Moreover, any two solutions $y(t), \tilde{y}(t)$ corresponding to different v_0, \tilde{v}_0 in $B_{\tilde{\rho}} \cap \text{Im}P_y(t_0)$ attract each other exponentially, i.e.,

$$\|y(t) - \tilde{y}(t)\| \leq H_4 e^{-\mu(t-t_0)} \|v_0 - \tilde{v}_0\| \quad \text{for all } t \geq t_0, \quad (3.11)$$

for some positive constants H_4, μ .

Proof. (i) Consider in the space $L_\infty(\mathbb{R}_+, \mathbb{R}^n)$ the ball $\mathcal{B}_\rho := \{y \in L_\infty(\mathbb{R}_+, \mathbb{R}^n) : \|y(\cdot)\|_\infty := \text{esssup}_{t \geq 0} \|y(t)\| \leq \rho\}$.

For each fixed $v_0 \in B_{\tilde{\rho}}$ we will prove the transformation T defined by

$$(Ty)(t) = \begin{cases} Y(t, t_0) \begin{bmatrix} v_0 \\ 0 \end{bmatrix} + \int_{t_0}^{\infty} G(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix} & \text{for all } t \geq t_0, \\ 0 & \text{for all } t < t_0, \end{cases} \quad (3.12)$$

is a contraction mapping from \mathcal{B}_ρ to itself. Using the same argument as in the proof of Lemma 3.6, we see that

$$\begin{aligned} \|(Ty)(t)\| &\leq (1+H_1)Ne^{-\nu(t-t_0)} \|v_0\| + M(1+H_1)(1+H_2) \frac{N}{1-e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) + L\rho, \\ &\leq (1+H_1)N\|v_0\| + MH_3 + L\rho \quad \text{for all } t \geq 0, \end{aligned}$$

and by (3.10) we see that

$$\|(Ty)(t)\| \leq (1+H_1)N\tilde{\rho} + \frac{(1-L)\rho}{2} + L\rho = \rho \quad \text{for all } t \geq 0.$$

Therefore, T is a mapping from \mathcal{B}_ρ to itself. Now we prove its contraction property. Indeed, making use of (3.6), we obtain the following estimate:

$$\begin{aligned} \|Ty(t) - T\tilde{y}(t)\| &\leq \int_{t_0}^{\infty} \|G(t, \tau)\| \|\hat{f}_1(\tau, y(\tau)) - \hat{f}_1(\tau, \tilde{y}(\tau))\| d\tau + \|\hat{f}_2(t, y(t)) - \hat{f}_2(t, \tilde{y}(t))\|, \\ &\leq \int_{t_0}^{\infty} (1 + H_1)(1 + H_2) Ne^{-\nu|t-\tau|} \varphi(\tau) \|y(\tau) - \tilde{y}(\tau)\| d\tau + L \|y(t) - \tilde{y}(t)\|, \\ &\leq (H_3 + L) \|y(\cdot) - \tilde{y}(\cdot)\|_{\infty} \text{ for all } t \geq 0. \end{aligned}$$

Consequently, due to (3.10), we see that T is a contraction mapping with the contraction constant $H_3 + L$. Thus, there exist a unique function $y \in \mathcal{B}_\rho$ such that $y = Ty$, and hence, due to the definition of T , y is the solution to the mild/integral-algebraic system (3.4).

(ii) The proof of the estimate (3.11) can be done in a similar way as in [10, Thm 3.7]. We present here for seek of completeness. Let $y(t)$ and $\tilde{y}(t)$ be two essentially bounded solutions of (3.4) corresponding to different values $v_0, \tilde{v}_0 \in B_{\bar{\rho}} \cap \text{Im } P_y(t_0)$. Then, we have that

$$\begin{aligned} \|y(t) - \tilde{y}(t)\| &\leq Y(t, t_0) \|v_0 - \tilde{v}_0\| + \int_{t_0}^{\infty} \|G(t, \tau)\| \|\hat{f}_1(\tau, y(\tau)) - \hat{f}_1(\tau, \tilde{y}(\tau))\| d\tau + \|\hat{f}_2(t, y(t)) - \hat{f}_2(t, \tilde{y}(t))\|, \\ &\leq (1 + H_1) Ne^{-\nu(t-t_0)} + \int_{t_0}^{\infty} (1 + H_1)(1 + H_2) Ne^{-\nu|t-\tau|} \varphi(\tau) \|y(\tau) - \tilde{y}(\tau)\| d\tau + L \|y(t) - \tilde{y}(t)\|, \end{aligned}$$

and hence,

$$\|y(t) - \tilde{y}(t)\| \leq \frac{1 + H_1}{1 - L} Ne^{-\nu(t-t_0)} + \int_{t_0}^{\infty} \frac{(1 + H_1)(1 + H_2)}{1 - L} Ne^{-\nu|t-\tau|} \varphi(\tau) \|y(\tau) - \tilde{y}(\tau)\| d\tau.$$

Then, due to the Cone Inequality, [5, Theorem 1.9.3], in analogue to [19, Theorem 3.7], we obtain the estimation (3.11) with H_4, μ are given by

$$0 < \mu < \nu + \ln \left(1 - \frac{H_3(1 - e^{-\nu})}{1 - L} \right), \quad H_4 := \frac{(1 + H_1)N}{1 - L - \frac{H_3(1 - e^{-\nu})}{1 - e^{\mu - \nu}}}.$$

Furthermore, notice that from (3.10) it follows that $\mu < \nu$ implying the positivity of H_4 . This completes the proof. \square

Under Assumption 3.1, we then define the so-called *constrained manifold*, which all solutions to (3.1)-(3.2) must belong to

$$\mathbb{L}(t, y) := \{(t, y_1, y_2) \in \mathbb{R}_+ \times \mathbb{R}^d \times \mathbb{R}^a \mid y_2 = \hat{A}_3(t)y_1 + \hat{f}_2(t, y_1, y_2)\}. \quad (3.13)$$

We further notice that this manifold is of dimension d , which is the degree of freedom to the DAE (3.4). Now, we are able to introduce the concept of a local stable manifold for the solutions of the integral-algebraic system (3.4).

Definition 3.11. A subset \mathbb{M} of the constrained manifold $\mathbb{L}(t, y)$ is said to be a *local stable manifold* for solutions to (3.4) if for every $t \in \mathbb{R}_+$ the phase subspace \mathbb{R}^d splits into a direct sum $\mathbb{R}^d = W_1(t) \oplus W_2(t)$ such that

$$\inf_{t \in \mathbb{R}_+} Sn(W_1(t), W_2(t)) := \inf_{t \in \mathbb{R}_+} \inf\{\|w_1 + w_2\|, w_i \in W_i(t), \|w_i\| = 1, i = 0, 1\} > 0,$$

and if there exist positive constants ρ, ρ_1, ρ_2 and a family of Lipschitz continuous mappings

$$g_t : B_{\rho_1} \cap W_1(t) \rightarrow B_{\rho_2} \cap W_2(t), \quad t \in \mathbb{R}_+,$$

with a common Lipschitz constant independent of t such that

- (i) $\mathbb{M} = \{(t, y_1 = w_1 + g_t(w_1), y_2) \in \mathbb{R}_+ \times (W_1(t) \oplus W_2(t)) \times \mathbb{R}^a \mid w_1 \in B_{\rho_1} \cap W_1(t)\}$, and we denote by
 $\mathbb{M}_t := \{(y_1 = w_1 + g_t(w_1), y_2) \mid (t, y_1 = w_1 + g_t(w_1), y_2) \in \mathbb{M}\}$,
(ii) \mathbb{M}_t is homeomorphic to $B_{\rho_1} \cap W_1(t)$ for all $t \geq 0$,
(iii) to each $\tilde{w} \in \mathbb{M}_{t_0}$ there corresponds one and only one solution y to (3.4) satisfying $y_1(t_0) = \tilde{w}$ and
 $\text{ess sup}_{t \geq t_0} \|y(t)\| \leq \rho$.

We now state and prove our main result on the existence of a local stable manifold for DAEs.

Theorem 3.12. *Let the evolution family $(\hat{Y}(t, s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumptions 3.1, 3.5 hold true. If*

$$H_3 < \min \left\{ 1 - L, \frac{(1 - L)(1 + H_1)\rho}{2M}, \frac{(1 - L)(1 + H_1)(1 + H_2)}{N + (1 + H_1)(1 + H_2)} \right\},$$

then there exists a local stable manifold for the solutions of (3.4). Moreover, every two solutions $y(t), \tilde{y}(t)$ on the manifold \mathbb{M} attract each other exponentially in the sense that there exist positive constants H_4 and μ independent of $t_0 \geq 0$ such that

$$\|y(t) - \tilde{y}(t)\| \leq H_4 e^{-\mu(t-t_0)} \|P(t_0)y_1(t_0) - P(t_0)\tilde{y}_1(t_0)\|, \quad \text{for all } t \geq t_0. \quad (3.14)$$

Proof. First we notice that the phase subspace \mathbb{R}^d splits into the direct sum $\mathbb{R}^d = \text{Im}P_y(t) \oplus \text{kernel} P_y(t)$ for all $t \geq 0$. We set $W_1(t) := \text{Im}P_y(t)$ and $W_2(t) := \text{kernel} P_y(t)$, then due to Proposition 2.1, we see that $\sup_{t \geq 0} \|P_y(t)\| < \infty$, and hence, $\inf_{t \in \mathbb{R}_+} \text{Sn}(W_1(t), W_2(t)) > 0$.

For any $\rho > 0$ defined as in Assumptions 3.1, 3.5, let $\rho_1 := \tilde{\rho} = \frac{1 - L}{2N(1 + H_1)}\rho$ and $\rho_2 := \frac{(1 - L)\rho}{2}$. For each $t \geq 0$ we define the mapping g_t acts on $B_{\rho_1} \cap W_1(t)$ as

$$g_t(w_1) := \int_t^\infty \hat{Y}_1(t, \tau)(I_d - P_y(\tau))f_1(\tau, y(\tau))d\tau,$$

where the function $y(t)$ is uniquely defined via Theorem 3.10 i). Clearly, $g_t(w_1) \in \text{ker} P_y(t) = W_2(t)$.

Now, we prove that $\|g_t(w_1)\| \leq \rho_2$. Due to Theorem 3.10 (i) and Lemma 3.6 (i), we have that $\|y(t)\| \leq \rho$ and $\|f_1(\tau, y(\tau))\| \leq M\varphi(\tau)$ for a.e. $t \geq 0$. Therefore,

$$\begin{aligned} \|g_t(w_1)\| &\leq \int_t^\infty N e^{-\nu(\tau-t)} \|f_1(\tau, y(\tau))\| d\tau \leq \int_t^\infty N e^{-\nu(\tau-t)} M\varphi(\tau) d\tau, \\ &\leq M(1 + H_2) \frac{N}{1 - e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) = \frac{MH_3}{1 + H_1} \leq \frac{(1 - L)\rho}{2}, \end{aligned}$$

and hence, $g_t : B_{\rho_1} \cap W_1(t) \rightarrow B_{\rho_2} \cap W_2(t)$.

Notice that both part (iii) in Definition 3.11 and estimation (3.14) are followed directly from Theorem 3.10. We now only need to prove that \mathbb{M}_t is homeomorphic to $B_{\rho_1} \cap W_1(t)$. We first prove that g_t is a Lipschitz mapping. This fact can be seen from the following estimation.

$$\begin{aligned} \|g_t(w_1) - g_t(\tilde{w}_1)\| &\leq \int_t^\infty N e^{-\nu(\tau-t)} \|f_1(\tau, y(\tau)) - f_2(\tau, \tilde{y}(\tau))\| d\tau \leq \int_t^\infty N e^{-\nu(\tau-t)} \varphi(\tau) \|y(\tau) - \tilde{y}(\tau)\| d\tau, \\ &\leq \frac{N}{1 - e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) \|y - \tilde{y}\|_\infty = \frac{H_3}{(1 + H_1)(1 + H_2)} \|y - \tilde{y}\|_\infty, \end{aligned}$$

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278 and hence, (3.9) implies that

$$\|g_t(w_1) - g_t(\tilde{w}_1)\| \leq \frac{NH_3}{(1+H_1)(1+H_2)(1-H_3-L)} \|w_1 - \tilde{w}_1\|.$$

279 Finally, $H_3 < \frac{(1-L)(1+H_1)(1+H_2)}{N+(1+H_1)(1+H_2)}$ yields that $\frac{NH_3}{(1+H_1)(1+H_2)(1-H_3-L)} < 1$, and hence, g_t is a contraction mapping for all $t \geq 0$. Then, applying the Implicit Function Theorem for Lipschitz continuous mappings ([18, Lem. 2.7]), we see that the mapping $Id + g_t : \mathbb{M}_t \rightarrow B_{\rho_1} \cap W_1(t)$ is a homeomorphism. This implies the condition (ii) of Definition 3.11 finishing the proof. \square

4. GLOBAL INVARIANT STABLE MANIFOLDS FOR SEMI-LINEAR DAES

284 In this section we study the existence of global stable manifolds for semi-linear DAEs of the form (1.1).
 285 We begin with the concept of φ -Lipschitz functions.

286 **Definition 4.1.** Let E be an admissible Banach function space and $\varphi \in E$ be a positive function. A function $287 h : \mathbb{R}_+ \times \mathbb{R}^n \rightarrow \mathbb{R}^d$ is said to be φ -Lipschitz if the following conditions hold true.

- 288 (i) $\|h(t, 0)\| = 0$ for a.e. $t \in \mathbb{R}_+$,
- 289 (ii) $\|h(t, x) - h(t, \tilde{x})\| \leq \varphi(t) \|x - \tilde{x}\|$ for a.e. $t \in \mathbb{R}_+$ and all $x, \tilde{x} \in \mathbb{R}^n$.

290 In comparability to Assumptions 3.1, 3.5, we also need some global properties of the nonlinear term f .

291 **Assumption 4.2.** Assume that the following hypotheses hold true.

- 292 (i) The function $\Sigma^{-1}(t) f_1(t, x(t)) - \Sigma^{-1}(t) \tilde{A}_2(t) \tilde{A}_4^{-1}(t) f_2(t, x(t))$ is φ -Lipschitz.
- 293 (ii) The function $\tilde{A}_4^{-1}(t) f_2(t, x(t))$ is a contraction mapping with the Lipschitz constant $L < 1$ for all $(t, x(t))$ lying on the constraint-manifold associated with (1.1) defined by

$$\mathbb{L}(t, x) := \{(t, x) \in \mathbb{R}_+ \times \mathbb{R}^n \mid A_2(t)x + f_2(t, x) = 0\}.$$

294 We can directly verify that orthogonal transformations of the form $x = Vy$ preserves the φ -Lipschitz property, and hence, function \hat{f}_1 in (3.1) is also φ -Lipschitz. Besides that, function \hat{f}_2 in (3.2) is also a contraction mapping with the Lipschitz constant $L < 1$. For notational simplicity, now we will study the transformed system (1.7) and the integral-algebraic system (3.4).

295 **Definition 4.3.** A subset \mathbb{M} of the constrained manifold $\mathbb{L}(t, y)$ is said to be a *global, invariant stable manifold* for solutions to (3.4) if for every $t \in \mathbb{R}_+$ the phase subspace \mathbb{R}^d splits into a direct sum $\mathbb{R}^d = W_1(t) \oplus W_2(t)$ such that

$$\inf_{t \in \mathbb{R}_+} Sn(W_1(t), W_2(t)) := \inf_{t \in \mathbb{R}_+} \inf \{\|w_1 + w_2\|, w_i \in W_i(t), \|w_i\| = 1, i = 0, 1\} > 0,$$

296 and if there exists a family of Lipschitz continuous mappings

$$g_t : W_1(t) \rightarrow W_2(t), \quad t \in \mathbb{R}_+,$$

297 with the Lipschitz constants independent of t such that

- 298 (i) $\mathbb{M} = \{(t, w_1 + g_t(w_1), y_2) \in \mathbb{R}_+ \times (W_1(t) \oplus W_2(t)) \times \mathbb{R}^a \mid w_1 \in W_1(t)\}$, and we denote by
 $\mathbb{M}_t := \{(y_1, y_2) \mid (t, y_1, y_2) \in \mathbb{M}\},$
- 299 (ii) \mathbb{M}_t is homeomorphic to $W_1(t)$ for all $t \geq 0$,
- 300 (iii) to each $\tilde{w} \in \mathbb{M}_{t_0}$ there corresponds one and only one solution y to (3.4) satisfying $y_1(t_0) = \tilde{w}$ and
 $ess\sup_{t \geq t_0} \|y(t)\| < \infty$,
- 301 (iv) \mathbb{M} is invariant under system (3.4), i.e., if y is a solution to (3.4), and $ess\sup_{t \geq t_0} \|y(t)\| < \infty$, then
 $y(s) \in \mathbb{M}_s$ for all $s \geq t_0$.

302 Analogously to Lemma 3.7, we give the explicit form of bounded solutions to system (3.4) as below.

Lemma 4.4. Let the evolution family $(\hat{Y}(t, s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumption 4.2 holds true. Let $y(t)$ be any solution to (3.4) such that $\text{ess sup}_{t \geq t_0} \|y(t)\| < \infty$ for a fixed $t_0 \geq 0$. Then, for all $t \geq t_0 \geq 0$, we can rewrite $y(t)$ in the form

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = Y(t, t_0) \begin{bmatrix} v_0 \\ 0 \end{bmatrix} + \int_{t_0}^{\infty} G(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix}, \quad (4.1)$$

for some $v_0 \in \text{Im}P_y(t_0)$, where $G(t, \tau)$ is the Green function defined by (3.5).

Proof. The proof can be done by using similar arguments as in the proof of Lemma 3.2. \square

In the following two theorems, we present the global versions of Theorems 3.10 and 3.12, where we construct the structure of bounded solutions to (3.4) and prove the existence of a global, stable manifold, respectively.

Theorem 4.5. Let the evolution family $(\hat{Y}(t, s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumption 4.2 holds true.

(i) For any fixed $t_0 \geq 0$, if

$$H_3 < 1 - L,$$

then there corresponds to each $v_0 \in \text{Im}P_y(t_0)$ one and only one solution $y(t)$ to (3.4) on $[t_0, \infty)$ satisfying $P_y(t_0)y_1(t_0) = v_0$ and $\text{ess sup}_{t \geq t_0} \|y(t)\| < \infty$.

(ii) Any two solutions $y(t), \tilde{y}(t)$ corresponding to different initial conditions v_0, \tilde{v}_0 in $\text{Im}P_y(t_0)$, are exponentially attracted to each other, i.e.,

$$\|y(t) - \tilde{y}(t)\| \leq H_4 e^{-\mu(t-t_0)} \|v_0 - \tilde{v}_0\| \text{ for all } t \geq t_0,$$

with some positive constants H_4, μ satisfying

$$0 < \mu < \nu + \ln \left(1 - \frac{H_3(1 - e^{-\nu})}{1 - L} \right), \quad H_4 := \frac{(1 + H_1)N}{1 - L - \frac{H_3(1 - e^{-\nu})}{1 - e^{\mu - \nu}}}. \quad (4.2)$$

Proof. The proof of this theorem is essentially the same as the proof of Theorem 3.10. The only change is, that instead of considering the ball B_ρ we will work with the space $L_\infty(\mathbb{R}_+, \mathbb{R}^n)$ itself. Then, we can prove (without any difficulty) that for each fixed $v_0 \in \text{Im}P_y(t_0)$, the transformation T defined by

$$(Ty)(t) = \begin{cases} Y(t, t_0) \begin{bmatrix} v_0 \\ 0 \end{bmatrix} + \int_{t_0}^{\infty} G(t, \tau) \begin{bmatrix} \hat{f}_1(\tau, y(\tau)) \\ 0 \end{bmatrix} d\tau + \begin{bmatrix} 0 \\ \hat{f}_2(t, y(t)) \end{bmatrix}, & \text{for all } t \geq t_0, \\ 0, & \text{for all } t < t_0, \end{cases}$$

is a contraction mapping, and therefore, all the assertions of the theorem follows. \square

Theorem 4.6. Let the evolution family $(\hat{Y}(t, s))_{t \geq s \geq 0}$ of system (1.7) have an exponential dichotomy with the corresponding projection matrices $\{P_y(t)\}_{t \geq 0}$ and the dichotomy constants $N, \nu > 0$. Furthermore, assume that Assumption 4.2 holds true. If

$$H_3 < \min \left\{ 1 - L, \frac{(1 - L)(1 + H_1)(1 + H_2)}{N + (1 + H_1)(1 + H_2)} \right\},$$

then there exists a global invariant stable manifold for the solutions of (3.4). Moreover, every two solutions $y(t), \tilde{y}(t)$ on the manifold \mathbb{M} attract each other exponentially in the sense that there exist positive constants H_4 and μ independent of $t_0 \geq 0$ such that

$$\|y(t) - \tilde{y}(t)\| \leq H_4 e^{-\mu(t-t_0)} \|P(t_0)y_1(t_0) - P(t_0)\tilde{y}_1(t_0)\| \text{ for all } t \geq t_0.$$

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Proof. Analogous to the proof of Theorem 3.12, we consider the decomposition $\mathbb{R}^d = \text{Im}P_y(t) \oplus \text{kernel } P_y(t)$ and set $W_1(t) := \text{Im}P_y(t)$ and $W_2(t) := \text{kernel } P_y(t)$. Thus, we see that $\inf_{t \in \mathbb{R}_+} S_n(W_1(t), W_2(t)) > 0$. Now we define the family of mappings $(g_t)_{t \geq 0}$ acting on W_1 as

$$g_t(w_1) := \int_t^\infty \hat{Y}_1(t, \tau)(I_d - P_y(\tau))f_1(\tau, y(\tau))d\tau,$$

where the function $y(t)$ is bounded and be uniquely defined via Theorem 4.5 i). Clearly, $g_t(w_1) \in \text{ker } P_y(t) = W_2(t)$. To verify the Lipschitz property of g_t , let us consider two arbitrary elements w_1 and \tilde{w}_1 in W_1 and let y and \tilde{y} be the corresponding functions defined via Theorem 4.5 i). Then, we see that

$$\begin{aligned} \|g_t(w_1) - g_t(\tilde{w}_1)\| &\leq \int_t^\infty N e^{-\nu(\tau-t)} \|f_1(\tau, y(\tau)) - f_2(\tau, \tilde{y}(\tau))\| d\tau \leq \int_t^\infty N e^{-\nu(\tau-t)} \varphi(\tau) \|y(\tau) - \tilde{y}(\tau)\| d\tau, \\ &\leq \frac{N}{1 - e^{-\nu}} (\|\Lambda_1 T_1^+ \varphi\|_\infty + \|\Lambda_1 \varphi\|_\infty) \|y - \tilde{y}\|_\infty = \frac{H_3}{(1 + H_1)(1 + H_2)} \|y - \tilde{y}\|_\infty, \end{aligned}$$

and hence, (3.9) implies that

$$\|g_t(w_1) - g_t(\tilde{w}_1)\| \leq \frac{NH_3}{(1 + H_1)(1 + H_2)(1 - H_3 - L)} \|w_1 - \tilde{w}_1\|.$$

Finally, $H_3 < \frac{(1-L)(1+H_1)(1+H_2)}{N+(1+H_1)(1+H_2)}$ yields that $\frac{NH_3}{(1+H_1)(1+H_2)(1-H_3-L)} < 1$, and hence, g_t is a contraction mapping for all $t \geq 0$. Then, applying the Implicit Function Theorem for Lipschitz continuous mapping ([18, Lem. 2.7]), we see that the mapping $Id + g_t : \mathbb{M}_t \rightarrow W_1(t)$ is a homeomorphism. This implies the condition ii) of Definition 3.11, and hence, the proof is finished. \square

Now let us illustrate our results by the following examples.

Example 4.7. The dynamical behavior of a system in fluid mechanics and turbulence modeling is often described by the incompressible Navier-Stokes equation on an open, bounded domain $\Omega \subset \mathbb{R}^k$, $k = 2$ or 3 , of the form

$$\begin{aligned} \frac{\partial u}{\partial t} &= \nu \Delta u - \nabla p - (u \cdot \nabla) u + f(t, u, p), \\ \nabla \cdot u &= 0, \\ u|_{\partial\Omega} &= 0, \\ u|_{t=0} &= u_0, \end{aligned}$$

where $\nu > 0$ is the viscosity, $u = u(t, \xi)$ is the velocity field which is a function of the time t and the position ξ , p is the pressure, f is the external force. Then, discretizing the space variable by finite difference, finite volumes, or finite element methods [8], one obtains a differential-algebraic system of the following form.

$$\begin{aligned} M \dot{U} &= (K + N(U)) U - CP + F(t, U, P), \\ C^T U &= 0, \end{aligned}$$

where $U(t)$, $P(t)$ approximate the velocity $u(t, \xi)$ and the pressure $p(t, \xi)$, respectively. Here the leading matrix M is either an identity matrix or a symmetric positive definite matrix depending on the spatial discretization scheme. Furthermore, in many applications, the matrix $C^T M^{-1} \left(C - \frac{\partial F}{\partial P} \right)$ is nonsingular. We notice, see e.g. [1], that the differentiation index of this system is two, and hence, it is not strangeness-free,

so Assumption 1.3 is violated. Thus, one needs to transform it first in order to obtain a DAE

$$\begin{aligned} M\dot{U} &= -(K + N(U)) U - CP + F(t, U, P), \\ 0 &= C^T M^{-1} C P - C^T M^{-1} (F - (K + N(U)) U) . \end{aligned} \quad (4.2)$$

Clearly, we still need to linearize (4.2) to obtain system of the form (1.1). Fortunately, in this case the linearization procedure around a trajectory yields the decoupled form (1.7)

$$\begin{aligned} M\dot{U} &= \tilde{A}_1(t)U + \tilde{A}_2(t)P + g_1(t, U, P), \\ 0 &= C^T M^{-1} \left(C - \frac{\partial F}{\partial P} \right) P - C^T M^{-1} \left(\frac{\partial F}{\partial U} - A(t) \right) U + C^T M^{-1} g_2(t, U, P) . \end{aligned} \quad (4.3)$$

We further notice that since $C^T M^{-1} \left(C - \frac{\partial F}{\partial P} \right)$ is nonsingular, from the second equation we can uniquely determine P in term of U , and hence, system (4.2) is indeed strangeness-free. Let

$$\tilde{A}_3(t) := -C^T M^{-1} \left(\frac{\partial F}{\partial U} - A(t) \right), \quad \tilde{A}_4(t) := C^T M^{-1} \left(C - \frac{\partial F}{\partial P} \right)$$

Consequently, if the homogenous DAE

$$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{U} \\ \dot{V} \end{bmatrix} = \begin{bmatrix} \tilde{A}_1(t) & \tilde{A}_2(t) \\ \tilde{A}_3(t) & \tilde{A}_4(t) \end{bmatrix} \begin{bmatrix} U \\ P \end{bmatrix}$$

admits an exponential dichotomy, and g_1 satisfies the φ -Lipschitz condition, and g_2 is a contraction mapping (uniformly in time), then there exists a stable manifold for the solution to (4.2).

Example 4.8. Consider the nonlinear electrical circuit with Josephson junction in Figure 1 below. The Josephson junction device on the right hand side, consisting of two super conductors separated by an oxide barrier, is characterized by the sinusoidal relation $i_2 = I_0 \sin(k\phi_2)$, where I_0 and k are positive constants depend on the device itself. Moreover, the resistance R , inductance L and conductance G are positive. Furthermore, i_1 is the current going through the inductance, v_1 and v_2 are voltage drops across the inductance and the Josephson junction, respectively. It is important to note that we will consider nonlinear instead

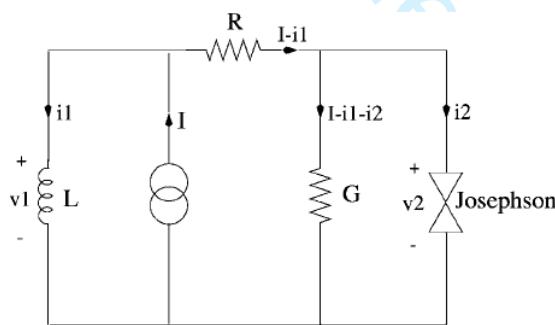


FIGURE 1. Electric circuit with Josephson junction, [22]

of linear resistance, inductance and conductance as in [22], and hence, we see that for the inductance $i_1 = i_L(L, \phi_1)$, for the resistance $v_R = v_R(R, i_1)$, and for the conductance $i_G = i_G(G, v_2)$. Therefore, we

obtain the following system, which completely describes the behavior of this circuit.

$$\dot{\phi}_1 = v_1, \quad (4.4a)$$

$$\dot{\phi}_2 = v_2, \quad (4.4b)$$

$$i_1 = i_L(L, \phi_1), \quad (4.4c)$$

$$i_2 = I_0 \sin(k\phi_2), \quad (4.4d)$$

$$0 = v_1 - v_R(R, i_1) + v_2, \quad (4.4e)$$

$$0 = -i_G(G, v_2) + I - i_1 - i_2. \quad (4.4f)$$

From (4.4c)-(4.4f) we obtain an explicit form of v_1 in terms of ϕ_1 , i_1 and v_2 , so we can compress the system to obtain

$$\dot{\phi}_1 = v_R(R, i_L(L, \phi_1)) + v_2, \quad (4.5a)$$

$$\dot{\phi}_2 = v_2, \quad (4.5b)$$

$$i_1 = i_L(L, \phi_1), \quad (4.5c)$$

$$0 = -i_G(G, v_2) + I - i_L(L, \phi_1) - I_0 \sin(k\phi_2). \quad (4.5d)$$

The linearized version of this system along equilibrium points defined by $v_2 = 0$, $i_1 = I$, $\phi_1 = LI$, $\phi_2 = n\pi/k$, reads

$$\dot{\phi}_1 = RI - (R/L)\phi_1 + v_2,$$

$$\dot{\phi}_2 = v_2,$$

$$i_1 = \phi_1/L,$$

$$0 = -Gv_2 + I - \phi_1/L - I_0 \sin(k\phi_2),$$

will have a positive eigenvalue and a negative one (e.g. [22]). Hence, it admits exponential dichotomy for any odd number n . Thus, for φ -Lipschitz function v_R and contraction mapping i_G , we obtain a stable manifold for (4.5).

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