CONSTRUCTION OF CODIMENSION ONE HOMOCLINIC CYCLES

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Abstract. We give an explicit construction of families of $D_m$-equivariant polynomial vector fields in $\mathbb{R}^4$ possessing a codimension-one homoclinic cycle. The homoclinic cycle consists of $m$ homoclinic trajectories all connected to the equilibrium at the origin. The constructed vector fields can provide a setting for a (numerical) bifurcation study of these homoclinic cycles, in particular for $m$ a multiple of four, where the bifurcations form an open problem.

1. Introduction

Particularly interesting invariant sets for differential equations are heteroclinic networks built from a finite number of equilibria and heteroclinic trajectories connecting these equilibria. Such heteroclinic networks are at the heart of explanations for intermittent time series and also of studies of traveling waves and pattern formation.

In contexts of equivariant differential equations, i.e. differential equations with a symmetry, heteroclinic networks naturally occur robustly or of low codimension. Robust occurrence means that small smooth perturbations of the differential equations with a heteroclinic network admit a heteroclinic network near the one for the unperturbed differential equation. Low codimension similarly means that heteroclinic networks arise in a robust way at isolated parameter values in families of differential equations depending on a small number (the codimension) of parameters.

Of special interest in equivariant differential equations are homoclinic cycles: heteroclinic networks where the heteroclinic trajectories are symmetry related through an element of the symmetry group (precise definitions will be given below). Homburg et al [6] started a bifurcation analysis of codimension one homoclinic cycles. Under open conditions and in a wide range of cases, bifurcation scenarios were established describing how suspended hyperbolic sets appear or disappear in the bifurcation. It turned out that the analysis in [6] breaks down for homoclinic cycles with specific symmetries. The prototype bifurcation where this analysis breaks down arises for homoclinic cycles in differential equations with $D_m$-symmetry for $m$ a multiple of 4.

Homoclinic cycles consisting of $m$ homoclinic trajectories, all connected to the same equilibrium, may occur in a Takens-Bogdanov bifurcation with $D_m$-symmetry. These symmetric Takens-Bogdanov bifurcations arise for instance in convection problems, see [10] and references therein. Figure 1 displays such a network for $m = 3$. In the $D_3$-case Matthies [9] found a suspended Markov chain appearing in the bifurcation in the neighborhood of the homoclinic cycle. Matthies’ study was a motivation for and a special case in the more general study of [6]. To the best of our knowledge, it is an open problem to describe the dynamics near homoclinic cycles for $m = 4n$. Partial answers are given in [10] for $D_4$ symmetric networks near the $O(2)$-limit. These considerations are not restricted to a small neighborhood of the network.
The goal of this paper is to provide an explicit construction of polynomial vector fields in $\mathbb{R}^4$ with $D_m$-symmetry possessing a homoclinic cycle consisting of $m$ homoclinic trajectories. In fact we provide a family of polynomial vector fields unfolding the homoclinic cycle. One purpose of this would be to enable detailed numerical studies, in particular for $D_{4n}$-equivariant vector fields. The following section describes the precise set-up, contains the necessary background and definitions, and introduces notation. Section 3 specifies the properties (concerning symmetry and unfolding) that the constructed vector fields possess. Section 4 provides the actual construction of the vector fields. Equation (7) is the resulting polynomial vector field for $m = 4$. Note that the formulas depend on coefficients $a$ and $b$; bounds on them are provided for which the properties in Section 3 hold.

2. $D_m$-SYMMETRIC CODIMENSION ONE HOMOCLINIC CYCLES

Consider a family of ordinary differential equations (ODEs)
\[ \dot{x} = f(x, \lambda), \tag{1} \]
with $x \in \mathbb{R}^n$ and $\lambda \in \mathbb{R}$, that is equivariant under the linear action (representation) of a finite group $G$, [4]:
\[ gf(x, \lambda) = f(gx, \lambda), \quad \forall \lambda \in G. \]
Assume that $p$ is a hyperbolic equilibrium of (1) which is a fixed point of the group action i.e. $gp = p$, for all $g \in G$. That means that the isotropy group $G_p$ of $p$ is equal to $G$,
\[ G_q := \{ g \in G : gq = q \}. \]
In other words that means that $p$ belongs to the fixed space $\text{Fix} G$ of the group $G$. More generally, for any subgroup $H$ of $G$ the fixed space of $H$ is defined by
\[ \text{Fix} H := \{ x \in \mathbb{R}^n : hx = x, \forall h \in H \}. \]
Assume further that $\gamma$ is a homoclinic trajectory of (1) asymptotic to $p$. We stipulate that the terms “trajectory” and “solution” are reserved for ODE-flow orbits and that the term “orbit” is reserved for group orbits. Then $G\bar{\gamma}$ is an example of a homoclinic network [5]. For $h \in G$, the invariant set
\[ \Gamma = \langle h \rangle^{\bar{\gamma}}, \]
where $\langle h \rangle$ denotes the cyclic subgroup of $G$ generated by $h$, is called a homoclinic cycle. The homoclinic cycle $\Gamma$ consists of $p$ and of several homoclinic trajectories to $p$ which are $g$-images of $\gamma$. The number of these homoclinic trajectories coincides with the order of the group $\langle h \rangle$. Note that the homoclinic network $G\bar{\gamma}$ contains $G/G_{\gamma}$ homoclinic trajectories; $G_{\gamma} := G_q, \ q \in \gamma$, is the isotropy group of $\gamma$ (the isotropy groups $G_q$ are identical for all $q \in \gamma$).

We denote by $D_m$ the symmetry group of a regular $m$-gon in the plane. The group $D_m$ can be written as semidirect product of the reflection group $\mathbb{Z}_2(\zeta)$ and a rotation group $\mathbb{Z}_m(\theta_m)$, cf. [3]:
\[ D_m = \mathbb{Z}_2(\zeta) \ltimes \mathbb{Z}_m(\theta_m). \]
In this notation the reflection $\zeta$ and the rotation $\theta_m$ denote the generators of the corresponding subgroups. We write $\mathbb{R}^4 = \mathbb{R}^2 \oplus \mathbb{R}^2$, and we assume that $D_m$ acts on each $\mathbb{R}^2$ absolutely irreducibly, cf. Section 3.1. In this paper we construct $D_m$-equivariant vector fields $f_m$ in $\mathbb{R}^4$ that possess
within $\text{Fix}(\zeta)$ a homoclinic trajectory $\gamma_m$. Therefore the vector field $f_m$ has a homoclinic cycle $\Gamma_m := \langle \theta_m \rangle \gamma_m$. Figure 1 visualizes $\Gamma_3$. Further we embed this vector field in a family of vector fields $f_m(\cdot, \lambda)$ such that for $\lambda = 0$ the primary cycle does exist, and if $\lambda$ moves off zero the trajectory $\gamma_m$ splits up.

In [6] the dynamics near codimension one homoclinic networks is considered. We restrict to homoclinic cycles as introduced above. In this restricted setting, the general assumptions in [6] on the family of differential equations (1) are:

**Hypothesis (H1).**

(i) The vector fields $f(\cdot, \lambda)$ are equivariant with respect to a finite group $G$.

(ii) $\dot{x} = f(x, \lambda)$ has a hyperbolic equilibrium $p$ with real leading stable and unstable eigenvalues $\mu^s$ and $\mu^u$, with $0 < -\mu^s < \text{Re}(\mu^u)$. The isotropy group $G_p$ acts absolutely irreducibly on the eigenspace $E^s_p$ corresponding to $\mu^s$.

(iii) At $\lambda = 0$, there is a codimension one homoclinic cycle $\Gamma$ generated by a homoclinic trajectory $\gamma$ asymptotic to $p$. The trajectory $\gamma$ unfolds generically with the parameter $\lambda$.

(iv) The homoclinic trajectory $\gamma$ is nondegenerate, i.e. along $\gamma$ the intersection of the tangent spaces of the stable and unstable manifolds of $p$ is one-dimensional.

The leading eigenvalues are the eigenvalues which are closest to the imaginary axis. Since $G_p$ acts absolutely irreducibly on $E^s_p$, the eigenvalue $\mu^s$ is real.

As an extensive example in [6, Section 5] homoclinic cycles in $D_m$-equivariant systems with $m \geq 3$ are discussed. In the course of this treatment several cases are distinguished. Here we focus on one particular case which is characterized by the following assumptions:

**Hypothesis (H2).**

(i) The hyperbolic equilibrium $p$ has the isotropy group $G_p = D_m$.

(ii) The eigenspace $E^s_p$ is two-dimensional.

(iii) $G_p = D_m$ acts on $E^s_p$ as $D_m$.

(iv) The trajectory $\gamma$ has the isotropy group $G_\gamma = \mathbb{Z}_2(\zeta)$.

Due to Hypothesis (H2)(iv) the cycle $\Gamma$ consists of $m$ copies of $\gamma$. Consequently, recall our restriction to $\mathbb{R}^4$, the unstable eigenspace $E^u_p$ is also two-dimensional. Moreover, $p$ has no strong stable or strong unstable manifolds. Indeed, in [6] a few more assumptions are made. These concern mainly orbit flip and inclination flip conditions. By our restriction to $\mathbb{R}^4$ these assumptions are automatically fulfilled.
Next we review the main theorem of [6] in the context of our hypotheses. For that we have need of topological Markov chains. We simply repeat the definition given in [6]: Let

$$\Sigma_k = \{1, \ldots, k\}^\mathbb{Z}$$

denote the set of double infinite sequences $\kappa : \mathbb{Z} \to \{1, \ldots, k\}$, $i \mapsto \kappa_i$, equipped with the product topology. Let $A = (a_{ij})_{i,j \in \{1, \ldots, k\}}$ be a 0-1 matrix, that is $a_{ij} \in \{0, 1\}$. By $\Sigma_A$ we denote the topological Markov chain defined by $A$,

$$\Sigma_A = \{\kappa \in \Sigma_k \mid a_{\kappa_i\kappa_{i+1}} = 1\}.$$ 

Note that the left shift $\sigma$ operating on $\Sigma_k$ by $(\sigma\kappa)_i = \kappa_{i+1}$ leaves $\Sigma_A$ invariant.

**Theorem 2.1** ([6], Theorem 1.1). Consider the differential equations (1) in $\mathbb{R}^4$ and assume Hypotheses (H1) and (H2). Write $\gamma_1, \ldots, \gamma_m$ for the homoclinic trajectories that constitute $\Gamma$, $\gamma_i := \theta^i_m \gamma$.

There is an explicit construction of $m \times m$ matrices $A_-$ and $A_+$ with coefficients in $\{0, 1\}$ and the nonzero coefficients in mutually disjoint positions, so that the following holds for any generic family unfolding a relative homoclinic cycle as above.

Take cross sections $S_i$ transverse to $\gamma_i$ and write $\Pi_\lambda$ for the first return map on the collection of cross sections $\cup_{j=1}^m S_j$. For $\lambda > 0$ small enough, there is an invariant set $D_\lambda \subset \cup_{j=1}^m S_j$ for $\Pi_\lambda$ such that for each $\kappa \in \Sigma_A$, there exists a unique $x \in D_\lambda$ with $\Pi_\lambda^i(x) \in S_{\kappa_i}$. Moreover, $(D_\lambda, \Pi_\lambda)$ is topologically conjugate to $(\Sigma_{A_+}, \sigma)$. An analogous statement holds for $\lambda < 0$ with $\Sigma_{A_+}$ replaced by $\Sigma_{A_-}$.

This description of the dynamics provides a complete picture of the local nonwandering dynamics near $\Gamma$ if and only if

$$A_+ + A_- = 1,$$

where $1$ denotes the matrix with all coefficients equal to one.

The proof relies on Lin’s method. It turns out that this procedure imparts a relation between the geometry of $\Gamma$ and the matrices $A_{+/-}$.

Summarizing the considerations in [6] the bifurcation equations related to a given sequence $(\kappa_i)$ read

$$0 = \lambda - e^{2\mu^* (\lambda) \omega_i} \langle \eta^{+\kappa_i}_{\kappa_{i-1}}(\lambda), \eta^{-\kappa_i}(\lambda) \rangle + R_i, \quad i \in \mathbb{Z},$$

where

$$R_i = R_i(\omega, \lambda, \kappa) = O(e^{-2\mu^* (\lambda) \omega_i}) + O(e^{2\mu^* (\lambda) \omega_i \delta}), \quad \text{for some } \delta > 1.$$ 

Here $\eta^{+\kappa_i}_{\kappa_{i-1}} \in \text{Fix}(\theta^i_m \zeta) \cap E_p^+$ is a vector pointing in the direction along which $\gamma_i$ is approaching $p$. Note that due to Hypothesis (H1)(ii) and Hypothesis (H2)(iii) the intersection $\text{Fix}(\theta^i_m \zeta) \cap E_p^+$ is one-dimensional. Further, $\eta^\delta_{\kappa_i} \in \text{Fix}(\theta^i_m \zeta)$, and $\eta^\delta_{\kappa_i}$ is orthogonal to $E_p^\delta$. The matrices $A_{+/-}$ arise out of the solvability of the bifurcation equations. Define a matrix $M = (m_{ij})$ by $m_{ij} := \text{sgn}(\eta^{+\kappa_i}_{\kappa_{i-1}}, \eta^{-\kappa_i})$.

With that it follows

$$A_+ = 1/2(M + |M|), \quad A_- = 1/2(M - |M|).$$

Now it is obvious that $A_+ + A_- \neq 1$, if $m_{ij} = 0$ for some $i, j$. This is the case if $m$ is a multiple of $4$: $m = 4n$. Assume for simplicity that $E_p^\delta$ and $E_p^\delta$ are orthogonal to each other. Then $\eta^{+\kappa_i}_{\kappa_{i-1}}$ and $\eta^{-\kappa_i}$ span the same one-dimensional subspace. This situation is depicted in Figure 2 for $n = 1$. 
We construct a family of $D_4$-equivariant polynomial vector fields $f_m : \mathbb{R}^4 \times \mathbb{R} \to \mathbb{R}^4$, $(x, \lambda) \mapsto f_m(x, \lambda)$ in coordinates $x = (x_1, y_1, x_2, y_2)$. Below we describe the representation of $D_4$ on $\mathbb{R}^4$ and the properties we demand on the vector fields.

3.1. **Representations of the group $D_m$.** For information on group theory in dynamical systems contexts we refer to [3]. For our purpose only the two-dimensional absolutely irreducible representation $\vartheta_m : D_m \to GL(2, \mathbb{R})$ is of interest [8], where

$$\vartheta_m(\zeta) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \vartheta_m(\theta_m) = \begin{pmatrix} \cos(\frac{2\pi}{m}) & \sin(\frac{2\pi}{m}) \\ -\sin(\frac{2\pi}{m}) & \cos(\frac{2\pi}{m}) \end{pmatrix}.$$ 

On $\mathbb{R}^4 = \mathbb{R}^2 \oplus \mathbb{R}^2$, the state space of the desired vector field, the group $D_m$ acts as $\vartheta_m + \vartheta_m$

$$(\vartheta_m + \vartheta_m)(g)((x_1, y_1), (x_2, y_2)) \equiv (\vartheta_m(g)(x_1, y_1), \vartheta_m(g)(x_2, y_2)),$$

for all $g \in D_m$, $(x_i, y_i) \in \mathbb{R}^2$, $i = 1, 2$. For this representation we have

$$\text{Fix } \mathbb{Z}_2(\zeta) := \{(x_1, 0, x_2, 0) : x_i \in \mathbb{R}, i = 1, 2\}. \quad (2)$$

If $m$ is even, this fixed point space is invariant under $\theta_m^{m/2}$.

3.2. **Demands on the vector field $f_m$.** We construct $f_m$ with properties formulated in Properties (P1)–(P4) below.

**Property (P1).** $f_m(\cdot, \lambda)$ is $D_m$-equivariant with $m \in \mathbb{N}$, $m \geq 3$, where $D_m$ acts on $\mathbb{R}^2 \times \mathbb{R}^2$ as $\vartheta_m + \vartheta_m$.

Let $f_m(\cdot, \lambda)$ satisfy Property (P1), then the mapping $f_m(\cdot, \lambda)$ leaves $\text{Fix } \mathbb{Z}_2(\zeta)$ invariant:

$$\zeta f_m(x_1, 0, x_2, 0, \lambda) = f_m(\zeta(x_1, 0, x_2, 0, \lambda)) = f_m(x_1, 0, x_2, 0, \lambda).$$

In other words, the vector field $f_m(\cdot, \lambda)$ is tangent to $\mathbb{Z}_2(\zeta)$, and therefore this fixed point space is invariant under the flow of $f_m(\cdot, \lambda)$. Denote the restriction of $f_m$ to $\text{Fix } \mathbb{Z}_2(\zeta)$ by $\hat{f}_m$:

$$\hat{f}_m = f_m|_{\text{Fix } \mathbb{Z}_2(\zeta)}.$$ 

If $m$ is even, the vector field $\hat{f}_m$ is $\mathbb{Z}_2(\theta_m^{m/2})$-equivariant. Note that $\theta_m^{m/2}$ then acts on $\text{Fix } \mathbb{Z}_2(\zeta)$ as $-id$.

**Property (P2).** $f_m(\cdot, \lambda)$ has a hyperbolic equilibrium $p = 0$.  

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**Figure 2.** The quantities $\eta_i^{s/-}$ under the assumption of Hypothesis (H2); $m = 4$. 

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Obviously the isotropy group of $p = 0$ is equal to $D_m$: $G_p = D_m$.

**Property (P3).** $f_m(\cdot, 0)$ has in $\text{Fix} \mathbb{Z}_2(\zeta)$ a homoclinic trajectory $\gamma_m$ asymptotic to $p$.

The trajectory $\gamma_m$ has the isotropy subgroup $G_{\gamma_m} = \mathbb{Z}_2(\zeta)$. It is also a homoclinic trajectory of $\hat{f}_m(\cdot, 0)$. If $m$ is even, then by Property (P2), the vector field $\hat{f}_m(\cdot, 0)$ has two homoclinic trajectories, $\gamma_m$ and $-\gamma_m$.

Let $\mu^s$ and $\mu^u$ denote the stable and unstable eigenvalues, respectively of $p$ restricted to $\text{Fix} \mathbb{Z}_2(\zeta)$, and let $e^s$ and $e^u$ be corresponding eigenvectors. Due to the equivariance of $f_m$ we find $\theta_m D_{1f_m}(0, 0) = D_{1f_m}(0, 0) \theta_m$, and therefore $\theta_m e^s/u$ are also eigenvectors belonging to $\mu^{s/u}$. This yields that $D_{1f}(p, 0)$ has two real eigenvalues $\mu^s < 0 < \mu^u$, both of geometric multiplicity two. According to Property (P1) the group $D_m$ acts absolutely irreducibly on the stable and unstable subspaces $E^s$ and $E^u$.

**Property (P4).** Within $\text{Fix} \mathbb{Z}_2(\zeta)$ the homoclinic trajectory $\gamma$ splits up with non-zero speed at $\lambda = 0$.

With that we have the following lemma:

**Lemma 3.1.** Any vector field $f_m$ on $\mathbb{R}^4$ which satisfies Properties (P1)–(P4) satisfies the Hypotheses (H1)(i)-(iii) and (H2).

By Properties (P1)–(P4) the leading eigenvalue is not yet determined. In the constructions below we introduce freely selectable coefficients $a$ and $b$. In our construction we can choose these coefficients in such a way that the stable eigenvalue is the leading one (cf. Hypothesis (H1)(ii)). Note that Hypothesis (H1)(iv) does not follow from Properties (P1)–(P4). In Section 4.3 we make clear for which coefficients the constructed vector fields also satisfy Hypothesis (H1)(iv).

4. Construction of $D_m$-equivariant vector fields in $\mathbb{R}^4$

We build the desired $D_m$-equivariant family of vector fields $f_m$ in several steps. First we construct a single vector field $\hat{f}_m$ in $\mathbb{R}^2$ possessing a homoclinic trajectory to a hyperbolic equilibrium. In doing so we follow the idea of Sandstede [12] – we construct $\hat{f}_m$ in such a way that a (generalized) Cartesian leaf forms a homoclinic trajectory.

Next we embed the vector field $\hat{f}_m$ in a one-parameter family such that by changing the family parameter $\lambda$ (off the critical value) the homoclinic trajectory splits up with non-zero speed.

In the final step we extend this family into $\mathbb{R}^4$ and end up with a family as stated in Section 3.

4.1. Basic construction in $\mathbb{R}^2$. Sandstede used in [12] the Cartesian leaf to construct a vector field in $\mathbb{R}^2$ having a homoclinic trajectory. Here we use the slightly modified curves

$$C_m(x_1, x_2) := x_2^2(1 - x_1^{m-2}) - x_2^2.$$  

Note that $C^{-1}_3(0)$ is the Cartesian leaf, and $C^{-1}_4(0)$ is a lemniscate, cf. Figure 3. For any odd or even $m$ the curves $C^{-1}_m(0)$ resemble those for $m = 3$ or $m = 4$, respectively.

The zero level set $C^{-1}_m(0)$ of $C_m$ is invariant under the flow of a given vector field $\hat{f}$ if and only if

$$\left\langle \nabla C_m(x_1, x_2), \hat{f}(x_1, x_2) \right\rangle = 0, \quad \forall (x_1, x_2) \in C^{-1}_m(0). \quad (3)$$
Lemma 4.1. Let $m \geq 3$ and $a, b \in \mathbb{R}\setminus\{0\}$, $a^2 < b^2$. The vector field

$$\hat{f}_m(x_1, x_2) := \left( \frac{ax_1 + bx_2 - ax_1^{m-1}}{bx_1 + ax_2 - b\frac{m}{2}x_1^{m-1} - a\frac{m}{2}x_1^{m-2}x_2} \right)$$

has a homoclinic trajectory $\gamma_m$ which is a subset of $C_m^{-1}(0) \cap \{x_1 > 0\}$.

The expression of $\hat{f}_m$ follows from a general polynomial ansatz of degree $m - 1$ plugged into Equation (3). Here we confine to showing that the vector field has a homoclinic trajectory to $(x_1, x_2) = (0, 0)$.

Proof. First we show that $\hat{f}_m$ satisfies (3): let $(x_1, x_2) \in C_m^{-1}(0)$. Using

$$\nabla C_m(x_1, x_2) = \begin{pmatrix} 2x_1 - mx_1^{m-1} \\ -2x_2 \end{pmatrix},$$

compute

$$\left\langle \nabla C_m(x_1, x_2), \hat{f}_m(x_1, x_2) \right\rangle = a((2x_1 - mx_1^{m-1})(x_1 - x_1^{m-1}) - 2x_2(x_2 - \frac{m}{2}x_1^{m-2}x_2))$$

$$= a(2(\underbrace{x_1^2(1-x_1^{m-2}) - x_2^2}_{=C_m(x_1, x_2)}) - mx_1^{m-2}(\underbrace{x_1^2 - x_1^{m-2} - x_2^2}_{=C_m(x_1, x_2)}))$$

$$= 0.$$

We must verify that $\hat{f}_m(x_1, x_2) \neq 0$ for all $(x_1, x_2) \in C_m^{-1}(0)$, $x_1 > 0$: the first component $\hat{f}_m^1$ evaluated at those points equals

$$\hat{f}_m^1(x_1, \pm x_1\sqrt{1-x_1^{m-2}}) = x_1\sqrt{1-x_1^{m-2}} \left( a\sqrt{1-x_1^{m-2} \pm b} \right)$$

and becomes zero for $x_1 = 0$, $x_1^{m-2} = 1$ or $x_1^{m-2} = 1 - (b/a)^2$. With the assumption $a^2 < b^2$ the right-hand side $1 - (b/a)^2$ of the last equation is negative. Hence, if $m$ is even, this equation has no real solution. If $m$ is odd the only real solution is negative. Further, the second equation, $x_1^{m-2} = 1$, implies $|x_1| = 1$. But the second component $\hat{f}_m^2(1, 0) = b(1 - m/2)$ is different from zero, since $b \neq 0$.

Remark 4.1. Because of $a^2 < b^2$ the equilibrium $(0, 0)$ is a saddle point with eigenvalues $a + b$ and $a - b$. If one imposes $0 < a^2 < b^2$ then $|a + b| \neq |a - b|$. This implies that the vector field $\hat{f}_m$ is neither Hamiltonian nor reversible.
Remark 4.2. Let $m$ be even. The vector field $\dot{f}_m$ is equivariant with respect to $\mathbb{Z}_2(\theta_2)$, where $\theta_2$ acts on $\mathbb{R}^2$ as $-id$. Consequently, $\theta_2(\gamma_m)$ is also a homoclinic orbit of $\dot{f}_m$ asymptotic to $(x_1, x_2) = (0, 0)$. The both orbits $\dot{\gamma}_m$ and $\theta_2(\gamma_m)$ together with the equilibrium $(0, 0)$ form the “figure-eight” drawn in the right panel of Figure 3.

Remark 4.3. We can find an analytic solution for the homoclinic trajectory $\gamma_m = (\gamma^1_m, \gamma^2_m)$ by choosing the ansatz

$$\dot{\gamma}^1_m(t) = (1 - u(t)^2) \frac{m}{u}, \quad \dot{\gamma}^2_m(t) = -\dot{\gamma}^1_m(t) u(t)$$

with $u : (-\infty, \infty) \to (-1, 1)$. Then $u$ satisfies the initial value problem

$$\dot{u} = \frac{m - 2}{2}(b - au)(1 - u^2), \quad u(0) = 0.$$ 

that can be solved by separation of variables. We obtain the inverse function of $u = H(t)$ by

$$u \mapsto t = H^{-1}(u) = \frac{2a \ln(1 - \frac{a}{b} u) - (a + b) \ln(1 - u) - (a - b) \ln(1 + u)}{(m - 2)(b^2 - a^2)}.$$ 

Next we add a perturbation term to the vector field $\dot{f}_m$ that splits up the homoclinic trajectory $\gamma_m$ with non-zero speed (at $\lambda = 0$), and obtain the family of vector fields $\dot{f}_m : \mathbb{R}^2 \times \mathbb{R} \to \mathbb{R}^2$.

Lemma 4.2. Let $m \geq 3$ and $a, b \in \mathbb{R}\setminus\{0\}$, $a^2 < b^2$. Consider the family of vector fields

$$\dot{f}_m(x, \lambda) := \left( \begin{array}{c} ax_1 + bx_2 - ax_1^{m-1} \\ bx_1 + ax_2 - b^{m-1}x_1^{m-1} - a^{m-1}x_2^{m-2}x_2 \end{array} \right) + \lambda \nabla C_m(x_1, x_2).$$

In accordance with Lemma 4.1 this vector field has the homoclinic trajectory $\gamma_m$ for $\lambda = 0$. This homoclinic trajectory splits up as $\lambda$ moves off zero. Moreover, let for $\lambda$ close to zero $d(\lambda)$ denote the distance of the stable and unstable manifolds of the equilibrium $(0, 0)$, measured in a direction perpendicular to $\dot{f}_m(\gamma_m(0), 0)$. The derivative $d'(0)$ is different from zero.

Proof. The verification that the perturbation splits the homoclinic trajectory in the described way can be done by using the Melnikov integral. It can be shown that, cf. [5],

$$d'(0) = \int_{-\infty}^{\infty} \left\langle \eta(t), D_x \dot{f}_m(\gamma_m(t), 0) \right\rangle dt,$$

where $\eta(t)$ solves the adjoint variational equation $\dot{v} = -[D_x \dot{f}_m(\gamma_m(t), 0)]^T v$ with $|\eta(0)| = 1; \eta(0) \perp \gamma_m(0)$. Therefore

$$\eta(t) = \phi(t) \left( \begin{array}{c} -\dot{f}_m^2(\gamma_m(t), 0) \\ \dot{f}_m^1(\gamma_m(t), 0) \end{array} \right)$$

for a scalar function $\phi$. Simple calculations show that the function $\phi$ solves

$$\dot{\phi} = -\text{div}(\dot{f}_m)(\gamma_m(t), 0)\phi.$$ 

Combining these results yields

$$d'(0) = \int_{-\infty}^{\infty} \phi(t) \left( \begin{array}{c} -\dot{f}_m^2(\gamma_m(t), 0) \\ \dot{f}_m^1(\gamma_m(t), 0) \end{array} \right) D_x \dot{f}_m(\gamma_m(t), 0) dt.$$

By construction the scalar product within this integral is always positive or negative, and as a solution of a scalar linear differential equation $\phi(t)$ does not change sign. Hence $d'(0) \neq 0$. \qed
Remark 4.4. If \( m \) is even the entire family \( \hat{f}_m(\cdot, \lambda) \) is equivariant with respect to the representation of \( \mathbb{Z}_2(\theta_2) \) which is given in Remark 4.2. Consequently, both homoclinic trajectories \( \hat{\gamma}_m \) and \( \theta_2(\hat{\gamma}_m) \) split up as \( \lambda \) moves off zero.

Denote the stable and unstable eigenvalues by \( \mu^s \) and \( \mu^u \) respectively. Let \( a > 0 \), then \( |\mu^s| < \mu^u \).

Applying a first return map, cf. [5], yields the bifurcation diagram depicted in Figure 4. In particular this diagram reveals for which parameter values which periodic orbits do exist. \( \square \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{bifurcation_diagram.png}
\caption{Bifurcation diagram of \( f_m, a > 0 \): \( m \) is odd (top); \( m \) is even (bottom).}
\end{figure}

4.2. Extending the vector field to \( \mathbb{R}^4 \). We construct the vector field \( f_m = (f_1^m, f_2^m, f_3^m, f_4^m)^T \) such that \( f_m \big|_{\text{Fix} \mathbb{Z}_2(\zeta)} = \hat{f}_m \), or more precisely

\[
\begin{align*}
  f_m(x_1, 0, x_2, 0, \lambda) &= (\hat{f}_1^m(x_1, x_2, \lambda), 0, \hat{f}_2^m(x_1, x_2, \lambda), 0)^T.
\end{align*}
\]

(4)

We extend the perturbed vector field to \( \mathbb{R}^4 \) (see Theorem 4.1) by using a set of generators for \( D_m \)-equivariant vector fields. Such generators can be found in a paper by Matthies [9] for the case \( m = 3 \) and in a paper by Lari-Lavassani, Langford, Huseyin and Gatermann [8] for \( m = 3, 4 \).

4.2.1. \( D_m \)-equivariant vector fields in \( \mathbb{R}^4 \). In this section we first describe the structure of \( D_m \)-equivariant polynomial vector fields in \( \mathbb{R}^4 \). To this end we recall the following definitions and results from [1, 4].

Let \( G \) be a finite group acting on the vector space \( \mathbb{R}^n \). A (polynomial) function \( s : \mathbb{R}^n \to \mathbb{R} \) is called \( G \)-invariant with respect to the given representation of the group if

\[
s = s \circ g \quad \forall g \in G.
\]

The set \( \mathcal{R}_G \) of \( G \)-invariant polynomials forms a ring. This ring is finitely generated, i.e. there is a finite set \( s_1, \ldots, s_k \) of \( G \)-invariant polynomials, the generators for the ring \( \mathcal{R}_G \), such that each \( s \in \mathcal{R}_G \) is of the form

\[
s(x) = B(s_1(x), \ldots, s_k(x)),
\]
where $B : \mathbb{R}^k \to \mathbb{R}$ is polynomial. Further, the set of equivariant polynomial vector fields forms a module $M_G$ over the ring $R_G$. This module is finitely generated, i.e. there exists a set $\{h_1, \ldots, h_l\}$ of $G$-equivariant polynomial vector fields such that each $f \in M_G$ can be written as

$$f(x) = \sum_{i=1}^l B_i(s_1(x), \ldots, s_k(x))h_i(x) \quad \forall x,$$

where $B_i$ are polynomials.

Lari-Lavassani et al. [8] present a generating set for $D_3$- and $D_4$-equivariant vector fields $f : \mathbb{R}^4 \to \mathbb{R}^4$, where $D_m$ acts as $\vartheta_m + \vartheta_m$. Matthies [9] also presents a generating set for $D_3$-equivariant vector fields. Unlike Lari-Lavassani et al., he considered complex vector fields.

In what follows we identify $\mathbb{R}^2$ with $\mathbb{C}$ since it seems to be adequate to work with complex coordinates in the context of the $D_m$ representations under consideration.

The coordinates on $\mathbb{C}^2$ we denote by $z = (v, w)$ where $v = x_1 + iy_1$ and $w = x_2 + iy_2$. With the isomorphism $I : \mathbb{C}^2 \to \mathbb{R}^4$

$$I : \mathbb{C}^2 \to \mathbb{R}^4, \quad (v, w) = (x_1 + iy_1, x_2 + iy_2) \mapsto (x_1, y_1, x_2, y_2),$$

we obtain a complex vector field $f_C$ by

$$f_C := I^{-1} \circ f \circ I.$$

The vector field $f_C$ is equivariant with respect to the complex representation $(\vartheta_m + \vartheta_m)_C$ of the group $D_m$ defined by

$$g_C := I^{-1} \circ g \circ I, \quad g \in D_m.$$

In particular, the corresponding complex representations of $\zeta$ and $\theta$ read

$$\zeta_C(v, w) = (\bar{v}, \bar{w}), \quad \theta_{m,C}(v, w) = (e^{i2\pi/m}v, e^{i2\pi/m}w).$$

In the following we present sets of $D_m$-invariant functions and $D_m$-equivariant vector fields. In the cases $m = 3$ and $m = 4$ these are generator sets for the corresponding ring $R_{D_m}$ or the module $M_{D_m}$, respectively, [8, 9].

**Lemma 4.3.** Assume $D_m$ acts on $\mathbb{C}^2$ as defined in (6).

(i) The functions

$$s_0(v, w) = v\bar{v}, \quad s_1(v, w) = w\bar{w}, \quad s_2(v, w) = vw + \bar{v}\bar{w}$$

are $D_m$-invariant polynomials on $\mathbb{C}^2$.

(ii) The mappings

$$g_0(v, w) = (v, 0), \quad g_1(v, w) = (0, v), \quad g_2(v, w) = (w, 0), \quad g_3(v, w) = (0, w),$$

$$k_j(v, w) = (\bar{v}\bar{w}^{m-1-j}, 0), \quad h_j(v, w) = (0, \bar{v}\bar{w}^{m-1-j}), \quad j \in \{0, \ldots, m - 1\}.$$

are $D_m$-equivariant polynomial mappings $\mathbb{C}^2 \to \mathbb{C}^2$.

**Proof.** The invariance or equivariance of the given functions or mappings, respectively, can be verified by straightforward calculations. $\square$
4.2.2. The vector field \( f_m \). We use the mappings presented in Lemma 4.3 to extend the vector field \( \hat{f}_m \) to the desired vector field \( f_m \) in \( \mathbb{R}^3 \). In the course of this we use representations of these vector fields in complex coordinates.

In complex coordinates the fixed space of \( \mathbb{Z}_2(\zeta_C) \) reads, cf. (2) and (6),

\[
\text{Fix} \mathbb{Z}_2(\zeta_C) := \{(x_1, x_2) : x_i \in \mathbb{R}, i = 1, 2\}.
\]

According to (4) the \( \mathbb{R}^2 \)-vector field \( \hat{f}_m \) can be seen as vector field on \( \mathbb{Z}_2(\zeta) \subset \mathbb{R}^4 \) (we denote this vector field again by \( \hat{f}_m \)). The related vector field \( \hat{f}_{m,C} \) reads (in complex coordinates)

\[
\hat{f}_{m,C}(x_1, x_2, \lambda) = (\hat{f}_1^1(x_1, x_2, \lambda), \hat{f}_m^2(x_1, x_2, \lambda)).
\]

Crucial for the intended extension is the observation that the mappings (vector fields) in Lemma 4.3(ii) leave \( \text{Fix} \mathbb{Z}_2(\zeta_C) \) invariant, and the polynomials in Lemma 4.3(i) are real-valued. Further we find for \( (v, w) \in \text{Fix} \mathbb{Z}_2(\zeta_C) \), i.e. for \( (v, w) = (x_1, x_2) \),

\[
g_0(x_1, x_2) = (x_1, 0), \quad g_1(x_1, x_2) = (0, x_1), \quad g_2(x_1, x_2) = (x_2, 0), \quad g_3(x_1, x_2) = (0, x_2),
\]

\[
k_{m-1}(x_1, x_2) = (x_1^{m-1}, 0), \quad h_{m-1}(x_1, x_2) = (0, x_1^{m-1}), \quad h_{m-2}(x_1, x_2) = (0, x_1^{m-2}x_2).
\]

Consequently, the vector field \( \hat{f}_{m,C} \) can be represented by means of just these vector fields:

\[
\hat{f}_{m,C}(x_1, x_2, \lambda) = a (g_0 + g_3 - k_{m-1} - \frac{m}{2}h_{m-2}) (x_1, x_2) + b (g_1 + g_2 - \frac{m}{2}h_{m-1}) (x_1, x_2)
\]

\[
+ \lambda (2g_0 - mk_{m-1} - 2g_3) (x_1, x_2).
\]

**Theorem 4.1.** The vector field

\[
f_{m,C}(v, w, \lambda) = a (g_0 + g_3 - k_{m-1} - \frac{m}{2}h_{m-2}) (v, w) + b (g_1 + g_2 - \frac{m}{2}h_{m-1}) (v, w)
\]

\[
+ \lambda (2g_0 - mk_{m-1} - 2g_3) (v, w)
\]

is equivariant with respect to the complex representation \( (\vartheta_m + \vartheta_m)_C \).

Moreover, the vector field \( f_m := \mathcal{I} \circ f_{m,C} \circ \mathcal{I}^{-1} \) satisfies Properties (P1)–(P4).

**Proof.** The first part of the theorem is an immediate consequence of the above representation of \( \hat{f}_{m,C} \).

Further, by construction the vector field \( f_m \) leaves \( \text{Fix} \mathbb{Z}_2(\zeta_C) \) invariant and its restriction to this fixed space coincides with \( \hat{f}_m \). So the properties concerning the homoclinic trajectory \( \gamma_m \) follow from the considerations in Section 4.1. \( \square \)

**Remark 4.5.** Not any vector field \( \hat{f}_C \) on \( \text{Fix} \mathbb{Z}_2(\zeta_C) \) can be extended to an \( \vartheta_m \times \vartheta_m \)-equivariant vector field \( f_C \) on \( \mathbb{C}^2 \); if \( m \) is even, the components of all vector fields in Lemma 4.3 are monomials of odd degree, whereas all functions in Lemma 4.3 are homogeneous polynomials of even degree. Hence, the components of all polynomial vector fields \( f_C \) that can be generated by those functions and vector fields, cf. (5), are sums of homogeneous polynomials of odd degree. This must be true already for the restricted vector field \( \hat{f}_C \).

Recall that for \( m = 4 \), Lemma 4.3 presents a set of generators for the module \( \mathcal{M}_{D_m} \). \( \square \)
For the real vector fields \( f_m \) the polynomial structure is getting more and more complicated as \( m \) increases. For that reason we confine ourselves to present the representation of \( f_4 \),

\[
\begin{align*}
f_4(x, \lambda) &= \begin{pmatrix} ax_1 + bx_2 - ax_1^3 + 3ax_1y_1^2 \\ ay_1 + by_2 + 3ax_1^2y_1 - ay_1^3 \\ bx_1 + ax_2 - 2bx_1^3 + 6bx_1y_1^2 - 2ax_1^2x_2 + 2ay_1^3x_2 + 4ax_1y_1y_2 \\ by_1 + ay_2 + 6bx_1^2y_1 - 2by_1^3 + 4ax_1y_1x_2 + 2ay_2(x_1^2 - y_1^2) \end{pmatrix} \\
&\quad + \lambda \begin{pmatrix} 2x_1 - 4x_1^3 + 12x_1y_1^2 \\ 2y_1 + 12x_1^2y_1 - 4y_1^3 \\ -2x_2 \\ -2y_2 \end{pmatrix}.
\end{align*}
\]

4.3. Verification of Hypothesis (H1)(iv). We show that for \( |a| \ll |b| \) the constructed vector field \( f_m \) satisfies the minimal intersection condition Hypothesis (H1)(iv). This condition is equivalent to the fact that the adjoint of the variational equation along \( \gamma_m \),

\[
\dot{\psi} = -(D_{(x,y)}f_m(\gamma_m(t),0))^T \psi,
\]

has (up to multiples) only one solution which is bounded on \( \mathbb{R} \). According to the construction, see also in the proof of Lemma 4.2, one such bounded solution lies in \( \text{Fix} \mathbb{Z}_2(\zeta) \). With that said it remains to show that (8) has no bounded solution outside of \( \text{Fix} \mathbb{Z}_2(\zeta) \). Recall that exactly those solutions of (8) are bounded on \( \mathbb{R} \) which start in the orthogonal complement of the sum of the tangent spaces of the stable and unstable manifolds of the equilibrium \( p = 0 \) along \( \gamma_m \).

As before we drop the dependence of the vector field on \( a \) and \( b \) in our notation.

With \( H_1 : \mathbb{R}^4 \to \mathbb{R}^4 \), \( H_i = (H^1_i, H^2_i, H^3_i, H^4_i)^T \) defined by

\[
H_1(x,0) := (0, a + (m - 1)ax_1^{m-2}, 0, b + \frac{m(m - 1)}{2}bx_1^{m-2} + \frac{m(m - 2)}{2}ax_1^{m-3}x_2)^T,
\]

\[
H_2(x,0) := (0, b, 0, a + \frac{m}{2}ax_1^{m-2})^T,
\]

we write

\[
f_m(x,y,0) = \left( f^1_m(x,0), 0, f^2_m(x,0), 0 \right)^T + y_1H_1(x,y) + y_2H_2(x,y).
\]

Note that the \( y \)-components of \( \gamma_m(t) \) are zero. Therefore the Jacobian of \( f_m \) at \( \gamma_m(t) \) reads

\[
D_{(x,y)}f_m(\gamma_m(t),0) = D_{(x,y)}\left( f^1_m(\gamma_m(t),0), 0, f^2_m(\gamma_m(t),0), 0 \right)^T + H_1(\gamma_m(t))(0,1,0,0) + H_1(\gamma_m(t))(0,0,0,1).
\]

Within \( \text{Fix} \mathbb{Z}_2(\zeta) \) a solution \( w \) of (8) is bounded on \( \mathbb{R} \) if and only if \( w(t) \perp \gamma_m(t) \) for all \( t \). Using the inner unit normal \( \nu \) of \( C^1_m(0) \cap \{ x_1 > 0 \} \) within \( \text{Fix} \mathbb{Z}_2(\zeta) \) we decompose a bounded solution \( w \) of (8) as follows:

\[
w(t) = w_1(t)\nu(t) + w_2(t)(0,1,0,0)^T + w_4(t)(0,0,0,1)^T,
\]

where \( \nu(t) = (\nu^1(t), 0, \nu^2(t), 0)^T, |\nu(t)| = 1, \langle \gamma_m(t), \nu(t) \rangle = 0 \). With that we find

\[
\dot{w}(t) = \dot{w}_1(t)\nu(t) + w_1(t)\dot{\nu}(t) + \dot{w}_2(t)(0,1,0,0)^T + \dot{w}_4(t)(0,0,0,1)^T.
\]
We plug this expression into (8) and take the inner product with \((0,1,0,0)^T\) or \((0,0,0,1)^T\) to get differential equations for \(w_2\) or \(w_4\), respectively. Here we take into consideration that, because of \(\langle \nu(t), \nu(t) \rangle \equiv 1\), the derivative \(\dot{\nu}(t)\) is perpendicular to \(\nu(t)\). Moreover, \(\dot{\nu}(t)\) is also perpendicular to \((0,1,0,0)^T\) and \((0,0,0,1)^T\). Further we exploit that \(H^1_i(\gamma_m(t)) \equiv H^2_i(\gamma_m(t)) \equiv 0, i = 1, 2\). Thus it follows

\[
\begin{align*}
\dot{w}_2 &= -H^2_1(\gamma_m(t))w_2 - H^1_1(\gamma_m(t))w_4, \\
\dot{w}_4 &= -H^2_2(\gamma_m(t))w_2 - H^1_2(\gamma_m(t))w_4.
\end{align*}
\]

In more detail this equation is written as

\[
\begin{pmatrix}
\dot{w}_2 \\
\dot{w}_4
\end{pmatrix} = -\left( aA(t) + bB(t) \right) \begin{pmatrix} w_2 \\ w_4 \end{pmatrix},
\]

with

\[
A(t) = \begin{pmatrix}
1 + (m-1)(\gamma^1_m(t))^{m-2} \frac{m(m-2)}{2}(\gamma^1_m(t))^{m-3}\gamma^2_m(t) & \frac{m(m-2)}{2}(\gamma^1_m(t))^{m-2} \\
0 & 1 + \frac{m(m-2)}{2}(\gamma^1_m(t))^{m-2}
\end{pmatrix},
\]

\[
B(t) = \begin{pmatrix}
0 & 1 + \frac{m(m-1)}{2}(\gamma^1_m(t))^{m-2} \\
1 & 0
\end{pmatrix} = \begin{pmatrix}
0 & 1 \\
1 & 0
\end{pmatrix} + \begin{pmatrix}
0 & \frac{m(m-1)}{2}(\gamma^1_m(t))^{m-2} \\
0 & 0
\end{pmatrix}.
\]

Instead of (9) we first consider the truncated equation

\[
\begin{pmatrix}
\dot{w}_2 \\
\dot{w}_4
\end{pmatrix} = -bB(t) \begin{pmatrix} w_2 \\ w_4 \end{pmatrix}.
\]

With \(v := w_4\) this equation can be rewritten as second order equation

\[
\ddot{v} = b^2 \left( 1 + \frac{m(m-1)}{2}(\gamma^1_m(t))^{m-2} \right) v.
\]

This equation can be treated as a similar problem in [13, Lemma 2.2, Lemma 2.3]. Recall that \(\gamma^1_m(t) > 0\) for all \(t \in \mathbb{R}\). Suppose (12) has a nontrivial bounded solution \(v\). Then both \(v\) and \(\dot{v}\) are square-integrable over \(\mathbb{R}\), moreover \(v\) decays exponentially fast as \(t \to \pm \infty\). Keeping this in mind we find by multiplying (12) by \(v\) and integrating that

\[
0 > -\int_{-\infty}^{\infty} (\dot{v}(t))^2 \, dt = \int_{-\infty}^{\infty} b^2 \left( 1 + \frac{m(m-1)}{2}(\gamma^1_m(t))^{m-2} \right) v(t)^2 \, dt > 0.
\]

This contradicts the assumption of a bounded solution.

Summarizing, Equation (11) has no bounded solution. Further, \(B(t)\) can be seen as an exponentially decaying perturbation of a hyperbolic matrix. By the roughness theorem [2, Lecture 4, Proposition 1], this equation has exponential dichotomies on both \(\mathbb{R}^+\) and \(\mathbb{R}^-\). Altogether this implies that (11) has an exponential dichotomy on \(\mathbb{R}\).

Finally, by [7, Theorem 3.2], Equation (9) still has an exponential dichotomy for \(a\) satisfying

\[
|a| \sup_{t \in \mathbb{R}} \|A(t)\| \left( \frac{K_1}{\alpha} + \frac{K_2}{\beta} \right) < 1.
\]
Here \( \| \cdot \| \) is the operator norm, and \( K_1, K_2, \alpha \) and \( \beta \) are constants related to the exponential dichotomy of the truncated equation (11):

\[
\| \Phi(t, \tau)P(\tau) \| \leq K_1 e^{-\alpha(t-\tau)}, \quad t \geq \tau, \\
\| \Phi(\tau, t)(id - P(t)) \| \leq K_2 e^{\beta(\tau-t)}, \quad t \geq \tau,
\]

where \( \Phi(\cdot, \cdot) \) denotes the transition matrix of (11).

In what follows we give an estimate of the constant \( a \) such that (13) holds true. To that end we need estimates of the constants \( K_1, K_2, \alpha \) and \( \beta \). First we consider exponential dichotomies of (11) on subintervals \([t_0^+, \infty)\) and \(( -\infty, t_0^-)\) with corresponding constants \( \tilde{K}_1^+, \tilde{K}_2^+ \) and \( \tilde{K}_1^-, \tilde{K}_2^- \), respectively. Somewhat lengthy computations which we don’t include here, show that for

\[
t_0^+ = \frac{1}{(m-2)\mu^*} \ln \left( \frac{-2(m-2)\mu^*}{3m(m-1)|b|} \right) = \frac{1}{(m-2)|a-b|} \ln \left( \frac{2(m-2)(|b|-a)}{3m(m-1)|b|} \right), \\
t_0^- = \frac{1}{(m-2)\mu^*} \ln \left( \frac{2(m-2)\mu^*}{3m(m-1)|b|} \right) = \frac{1}{(m-2)|a+b|} \ln \left( \frac{2(m-2)(a+b)}{3m(m-1)|b|} \right),
\]

one may take constants \( \tilde{K}_1^+ = \tilde{K}_2^+ = \frac{a}{2} \) and \( \alpha = \beta = |b| \). We indicate the approach to these computations. As in (10), treat \( B(t) \) as a perturbation of the constant hyperbolic matrix \( \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \). Observe that the perturbation term tends to zero exponentially fast as \( t \) tends to \( \pm \infty \). The values of the constants are now derived from an inspection of the proof of the roughness statement as in [11, Lemma 1.1], incorporating the exponential decay of the perturbation term.

By [2, Lecture 2] all constants \( K_{1/2}^{\pm} \) satisfying

\[
K_1^+ \geq \tilde{K}_1^+ N_1^+ e^{\pm |b|/|t_0^+|}, \quad K_2^+ \geq \tilde{K}_2^+ N_2^+ e^{\pm |b|/|t_0^+|},
\]

with

\[
N_1^\pm = e^{\frac{t_0^+}{|b|} \| B(\tau) \| d\tau}
\]

are suitable constants for the exponential dichotomy of (11) on \( \mathbb{R}^+ \) and \( \mathbb{R}^- \), respectively. The right-hand side in (14) can be estimated by

\[
e^{\frac{t_0^+}{|b|} \| B(\tau) \| d\tau} \leq e^{\pm |b|/|t_0^+|} e^{\frac{m(m-1)}{2} |b| \int \frac{1}{(\gamma_m(\tau))^{m-2} d\tau}},
\]

Using the representation of \( \gamma_m \) given in Remark 4.3 we find

\[
\int_0^0 (\gamma_m(\tau))^{m-2} d\tau = - \int_0^1 H^{-1} (-\text{sgn}(b) \sqrt{1-s}) d\tau = \frac{2\ln(1+\frac{|b|}{m})}{a(m-2)}, \\
\int_0^\infty (\gamma_m(\tau))^{m-2} d\tau = \int_0^1 H^{-1} (\text{sgn}(b) \sqrt{1-s}) d\tau = \frac{-2\ln(1-\frac{|b|}{m})}{a(m-2)}
\]

For \( a > 0 \) we have

\[
\int_0^0 (\gamma_m(\tau))^{m-2} d\tau \leq \int_0^\infty (\gamma_m(\tau))^{m-2} d\tau \quad \text{and} \quad -t_0^- \leq t_0^+.
\]

For \( a < 0 \) the relation signs are reversed.

For our further analysis we assume \( a > 0 \), and define

\[
K(a, b) := \frac{9}{2} e^{\frac{3|b|}{|t_0^+|}} e^{m(m-1)|b|} \int_0^0 (\gamma_m(\tau))^{m-2} d\tau = \frac{9}{2} e^{\frac{3|b|}{|a-b|}} \ln \left( \frac{2(m-2)(|b|-a)}{3m(m-1)|b|} \right) e^{-\frac{2m(m-1)|b|}{|a|} \ln(1-\frac{|b|}{m})}.
\]
According to our above considerations we may choose
\[ K^\pm_1 = K^\pm_2 = K(a,b). \]
Further, using \(|\gamma_i(t)| \leq 1, 1 = 1, 2,\) we find
\[ \sup_{t \in \mathbb{R}} \|A(t)\| \leq \frac{m^2}{\sqrt{2}}. \]
Summarizing, from (13) with \( \alpha = \beta = |b|, \) \( K_1 = K_2 = K(a,b) \) and the above estimate of \( \|A(t)\| \) we obtain
\[ a \leq \frac{|b|}{\sqrt{2}m^2 K(a,b)}. \]  
First we realize that \( K(a,b) \) decreases monotonically as \( a \to 0. \) Consequently we find that for \( a \leq \frac{|b|}{r}, r \gg 1 \)
\[ \frac{|b|}{\sqrt{2}m^2 K\left(\frac{|b|}{r}, b\right)} \leq \frac{|b|}{\sqrt{2}m^2 K(a,b)}. \]
Hence, any \( a > 0 \) with
\[ a \leq |b| \min \left\{ \frac{1}{r}, \frac{1}{\sqrt{2}m^2 K\left(\frac{|b|}{r}, b\right)} \right\}, \quad r \gg 1 \]
satisfies the inequality (15). Indeed \( K\left(\frac{|b|}{r}, b\right) = \frac{9}{2} e^{\frac{3r}{2(m-2)} \ln\left(\frac{2(m-2)}{m(m-1)(1-\frac{1}{r})}\right)} e^{\frac{2m(m-1)r \ln(1-\frac{1}{r})}{(m-2)}} \) does not depend on \( b. \)
Consider for instance the case \( m = 4. \) With \( r = 1000 \) we then find
\[ a \leq |b| \cdot 0.221 \cdot 10^{-8}. \]
In order to assess the quality of this estimate we remark that \( \frac{|b|}{\sqrt{2}m^2 K}, \) where
\[ K := \lim_{a \to +0} K(a,b) = \frac{9}{2} \left( \frac{3m(m-1)}{2(m-2)} \right)^{\frac{m-2}{m-1}} e^{\frac{2m(m-1)}{m-2}}. \]
is an upper bound for \( a. \) For \( m = 4 \) we find \( \frac{|b|}{\sqrt{2}m^2 K} \approx |b| \cdot 0.223 \cdot 10^{-8}. \)

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