

Stable foliations near a traveling front for reaction diffusion systems

Yuri Latushkin, Roland Schnaubelt, Xinyao Yang

CRC Preprint 2016/18, July 2016

KARLSRUHE INSTITUTE OF TECHNOLOGY

CRC 1173



Participating universities



Universität Stuttgart

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN



Funded by

DFG

ISSN 2365-662X

STABLE FOLIATIONS NEAR A TRAVELING FRONT FOR REACTION DIFFUSION SYSTEMS

YURI LATUSHKIN, ROLAND SCHNAUBELT AND XINYAO YANG

ABSTRACT. We establish the existence of a stable foliation in the vicinity of a traveling front solution for systems of reaction diffusion equations in one space dimension that arise in the study of chemical kinetics and solid fuel combustion. In this way we complement the orbital stability results from earlier papers by A. Ghazaryan, S. Schechter and Y. Latushkin. The essential spectrum of the differential operator obtained by linearization at the front touches the imaginary axis. In spaces with exponential weights, one can shift the spectrum to the left. We study the nonlinear equation on the intersection of the unweighted and weighted spaces. Small translations of the front form a center unstable manifold. For each small translation we prove the existence of a stable manifold containing the translated front and show that the stable manifolds foliate a small ball centered at the front.

1. INTRODUCTION

Traveling fronts are solutions to partial differential equations which move with constant speed without changing their shapes and which are asymptotic to spatially constant steady states. Traveling fronts are important by many reasons and have intensively been studied. We refer to the books and review papers [F, VVV, X] and to more recent sources such as [KP, LW, RM1, RM2, RM3, Sa, TZKS] that contain further bibliography.

In this paper we study the dynamics in the vicinity of traveling fronts for a class of reaction diffusion equations in one space dimension. A typical example arising in combustion theory for solid fuels, cf. [BLR, GLSS, MS], is given by

$$u_t = u_{xx} + ug(v), \quad v_t = \epsilon v_{xx} + \kappa ug(v), \quad (1.1)$$

where $u, v \in \mathbb{R}$, $\epsilon \geq 0$, $\kappa \in \mathbb{R}$, and $g(v) = e^{-1/v}$ for $v > 0$ and $g(v) = 0$ for $v \leq 0$. These and more general equations covered by our hypotheses often appear in the work on chemical reaction models and in combustion models, see, e.g., [GSM, SMS, SKMS, T, VV]. In such systems the spectrum of the linearization of the equation at the front touches the imaginary axis, cf. [Sa, SS]. To shift the spectrum to the left, one employs exponentially weighted spaces. This idea goes back to [S] and [PW]. However, in weighted spaces one can lose the Lipschitz properties of the nonlinearity. We shall study reaction terms with a certain "product" structure as in (1.1) which allows one to overcome these difficulties. The investigation of this class of nonlinearities was initiated by A. Ghazaryan in [G] and then continued in

Partially supported by the US National Science Foundation under Grants NSF DMS-1067929, DMS-1311313, by the Research Board and Research Council of the University of Missouri, and by the Simons Foundation. This research was funded by the IRSES program of the European Commission (PIRSES-GA-2012-318910). RS gratefully acknowledges financial support by the Deutsche Forschungsgemeinschaft (DFG) through CRC 1173.

[GLS1, GLSS, GLS2], see also the review paper [GLS3]. In particular, it was proved in [GLS2] that under appropriate assumptions on the nonlinearity the traveling front is orbitally stable; that is, any solution originating in a small vicinity of the front converges exponentially in the weighted norm to a translation of the front.

In this paper we continue the work in [GLS2] now utilizing the theory of invariant manifolds, cf. [BJ, CHT, Lu]. We analyze the dynamics in greater detail by proving in Theorem 4.1 the existence of a stable foliation near the front. Specifically, we observe that the set of all translations of the front serves as a local central unstable manifold consisting of fixed points. Next, using the Lyapunov-Perron method, cf. e.g. [LL, LPS1, LPS2], we establish the existence and the fundamental properties of a locally invariant stable manifold going through each translation of the front. We also show that these manifolds foliate a small neighborhood of the front and therefore each point in the neighborhood belongs to one of them, cf. [BLZ, CHT]. Moreover, the orbit of the point converges to the translation of the front along the stable manifold as proved in [GLS2].

In the construction of the local stable manifolds we have to face the problem that the linearization enjoys good decay properties only in weighted spaces on which the nonlinearity is not locally Lipschitz. To overcome this difficulty, we use both the product structure of the nonlinearity (cf. Hypothesis 2.2) and additional decay properties of the linearization at the limit of the traveling front as $\xi \rightarrow -\infty$, see Lemmas 3.1 and 3.3.

The paper is organized as follows. In Section 2 we formulate our assumptions and prove several preliminary results. In Section 3 we study the Lyapunov-Perron operator whose fixed points define the stable manifolds. In Section 4 we formulate and prove our main result on the existence of the stable manifolds and discuss two examples.

Notation. Throughout the paper, $|\cdot|$ and $\langle \cdot, \cdot \rangle$ are the Euclidean norm and the scalar product in \mathbb{R}^n . For a given map $f : \mathbb{R}^m \rightarrow \mathbb{R}^k$, its differential with respect to y is written as $\partial_y f : \mathbb{R}^m \rightarrow \mathcal{B}(\mathbb{R}^m, \mathbb{R}^k)$. We let $\mathcal{B}(\mathcal{E}, \mathcal{F})$ be the set of linear bounded operators between Banach spaces \mathcal{E} and \mathcal{F} , and abbreviate $\mathcal{B}(\mathcal{E}) = \mathcal{B}(\mathcal{E}, \mathcal{E})$. We denote by C a generic constant that may change from one estimate to another, and use T to designate transposition. For a Banach space with norm $\|\cdot\|$, we write $\mathbb{B}_\delta(\|\cdot\|)$ for the closed ball of radius δ centered at 0.

We denote by \mathcal{E}_0 with norm $|\cdot|_0$ either the Sobolev space H^1 or the space BUC of bounded uniformly continuous functions on \mathbb{R} with vector values, and by \mathcal{E}_α with norm $|\cdot|_\alpha$ the respective space of (exponentially) weighted functions, see (2.12). Let $|\cdot|_\beta$ be the norm on the intersection space $\mathcal{E}_\beta := \mathcal{E}_0 \cap \mathcal{E}_\alpha$; i.e., $|y|_\beta := \max\{|y|_0, |y|_\alpha\}$.

2. THE SETTING

We consider the system of reaction diffusion equations

$$Y_t = DY_{xx} + R(Y), \quad x \in \mathbb{R}, t \geq 0, \quad (2.1)$$

where $D = \text{diag}(d_1, \dots, d_n)$, $d_j \geq 0$, $Y(t, x) \in \mathbb{R}^n$, and $R : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a C^3 function satisfying additional properties listed below.

Passing in (2.1) to the moving coordinate frame $\xi = x - ct$ and redenoting ξ again by x , we arrive at the nonlinear equation

$$Y_t = DY_{xx} + cY_x + R(Y), \quad x \in \mathbb{R}, t \geq 0. \quad (2.2)$$

We discuss the wellposedness of this system in Remark 2.3.

Hypothesis 2.1. We assume that for some velocity $c \in \mathbb{R}$ the system (2.2) admits a stationary solution $Y_0 \in C^3(\mathbb{R})$; i.e., (2.1) possesses the traveling front solution $Y(t, x) = Y_0(x - ct)$. It is also required that $Y_0(x)$ converges to the end states Y_\pm as $x \rightarrow \pm\infty$ exponentially; i.e.,

$$\begin{aligned} |Y_0(x) - Y_-| &\leq Ce^{-\omega_- x}, & x \leq 0, \\ |Y_0(x) - Y_+| &\leq Ce^{-\omega_+ x}, & x \geq 0, \end{aligned} \quad (2.3)$$

for some $\omega_- < 0 < \omega_+$ and $C > 0$. Replacing R by $\tilde{R}(Y) := R(Y + Y_-)$, we can and will assume that $Y_- = 0$ (and we then drop the tilde).

We further assume that the nonlinear term R in (2.1) and (2.2) has the following product structure.

Hypothesis 2.2. The nonlinear term R belongs to $C^3(\mathbb{R}^n, \mathbb{R}^n)$. In appropriate variables $Y = (U, V)^T$ with $U \in \mathbb{R}^{n_1}$, $V \in \mathbb{R}^{n_2}$ and $n_1 + n_2 = n$, we have

$$R(U, 0) = (A_1 U, 0) \quad (2.4)$$

for a constant $n_1 \times n_1$ matrix A_1 .

In other words, we suppose that

$$R(U, V) = \begin{pmatrix} A_1 U + R_1(U, V) \\ R_2(U, V) \end{pmatrix},$$

where the maps R_j belong to $C^2(\mathbb{R}^n, \mathbb{R}^{n_j})$ and satisfy $R_j(U, 0) = 0$ for $j \in \{1, 2\}$ and $U \in \mathbb{R}^{n_1}$. Note that condition (2.4) yields $R(0, 0) = R(Y_-) = 0$. We also split

$$D = \begin{pmatrix} D_1 & 0 \\ 0 & D_2 \end{pmatrix}, \quad \text{where } D_1 = \text{diag}(d_1, \dots, d_{n_1}), \quad D_2 = \text{diag}(d_{n_1+1}, \dots, d_n).$$

Let $q \in \mathbb{R}$. We write $Y_q(x) = Y_0(x - q)$ for the shifted wave. Since (2.2) is translationally invariant, Y_q is again a steady state solution of (2.2) and thus yields a traveling wave solution for (2.1). Linearizing (2.2) at Y_q (that is, substituting $Y_q + Y$ instead of Y in (2.2)), we arrive at the equation

$$Y_t = L_q Y + F_q(Y), \quad \text{where } L_q Y = DY_{xx} + cY_x + \partial_Y R(Y_q)Y. \quad (2.5)$$

Here, ∂_Y is the differential with respect to $Y \in \mathbb{R}^n$ and the nonlinear term $F_q : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is written as

$$F_q(Y) = \int_0^1 (\partial_Y R(Y_q + tY) - \partial_Y R(Y_q)) Y dt. \quad (2.6)$$

The linearization of (2.2) at $Y_- = (0, 0)^T$ is given by

$$Y_t = L^- Y + G(Y), \quad \text{where } L^- Y = DY_{xx} + cY_x + \partial_Y R(0)Y \quad (2.7)$$

and $G : \mathbb{R}^n \rightarrow \mathbb{R}^n$; $G(Y) = R(Y) - \partial_Y R(0)Y$. We remark that

$$(L_q - L^-)Y = B_q Y \quad \text{with } B_q(x) = \partial_Y R(Y_q(x)) - \partial_Y R(0). \quad (2.8)$$

Below we impose conditions on L_0 at $q = 0$; i.e., on the linearization at the original traveling wave Y_0 . We further consider L_q for $|q| \leq q_0$ with some $q_0 > 0$, which will be fixed sufficiently small in the final theorem. The shifted wave Y_q decays as in Hypothesis 2.2 with the same exponents ω_\pm and constants C only depending on q_0 . Assumption (2.4) also yields the formulas

$$\partial_Y R(0, 0) = \begin{pmatrix} A_1 & \partial_V R_1(0, 0) \\ 0 & \partial_V R_2(0, 0) \end{pmatrix}, \quad L^- = \begin{pmatrix} L^{(1)} & \partial_V R_1(0, 0) \\ 0 & L^{(2)} \end{pmatrix} \quad (2.9)$$

with the differential expressions

$$\begin{aligned} L^{(1)}U &= D_1U_{xx} + cU_x + A_1U, \\ L^{(2)}V &= D_2V_{xx} + cV_x + \partial_V R_2(0, 0)V. \end{aligned} \quad (2.10)$$

Remark 2.3. We consider the equations (2.2) and (2.5) on the space \mathcal{E}_0 which is either the Sobolev space $H^1(\mathbb{R})^n$ or the space of bounded uniformly continuous functions $BUC(\mathbb{R})^n$. It is straightforward to check that the nonlinearities R and F_q are Lipschitz on bounded subsets of \mathcal{E}_0 .

For the differential expressions L_q and L^- defined in (2.5) and (2.7), respectively, we denote by \mathcal{L}_q and \mathcal{L}^- the differential operators on \mathcal{E}_0 on their natural domain \mathcal{D} defined as follows. For $\mathcal{E}_0 = H^1(\mathbb{R})^n$, the domain \mathcal{D} of \mathcal{L}_q and of \mathcal{L}^- consists of the vector functions $Y = (Y_j)_{j=1}^n$ whose components Y_j belong to $H^3(\mathbb{R})$ if $d_j > 0$ and to $H^2(\mathbb{R})$ if $d_j = 0$. For $\mathcal{E}_0 = BUC(\mathbb{R})^n$, we choose the domain analogously with $H^3(\mathbb{R})$ replaced by $BUC^2(\mathbb{R})$ and $H^2(\mathbb{R})$ replaced by $BUC^1(\mathbb{R})$, the spaces of differentiable functions which are bounded and have bounded, uniformly continuous derivatives. The operators \mathcal{L}_q and \mathcal{L}^- generate strongly continuous semigroups $\{T_q(t)\}_{t \geq 0}$ and $\{S(t)\}_{t \geq 0}$ on \mathcal{E}_0 , respectively, cf. e.g. [GLS1, §2.2].

Standard results then show the local wellposedness of (2.5) in \mathcal{E}_0 for initial values y_0 in the domain of \mathcal{L}_q , where the (classical) solutions belong to $C^1([0, t_0], \mathcal{E}_0)$ and take values in \mathcal{D} . They are given by Duhamel's formula

$$Y(t) = T_q(t)y_0 + \int_0^t T_q(t-\tau)F_q(Y(\tau))d\tau, \quad t \geq 0. \quad (2.11)$$

See e.g. Theorems 6.1.4 and 6.1.6 in [P]. A function $Y \in C([0, t_0], \mathcal{E}_0)$ satisfying (2.11) is called a *mild solution* of (2.5). This concept is strictly weaker than that of classical solvability. We mostly work with mild solutions. Similar remarks apply to (2.2) and the differential expression $D\partial_{xx} + c\partial_x$ equipped the same domain \mathcal{D} . Approximating a given initial value $y_0 \in \mathcal{E}_0$ in \mathcal{E}_0 by functions in \mathcal{D} , we see that all mild solutions of (2.2) are given by $Y_q + Y(t)$ where $Y(t)$ solves (2.11). \diamond

Let $\alpha = (\alpha_-, \alpha_+) \in \mathbb{R}^2$. We say that $\gamma_\alpha : \mathbb{R} \rightarrow \mathbb{R}$ is a weight function of class α if γ_α is C^2 , $\gamma_\alpha(x) > 0$ for all $x \in \mathbb{R}$, and $\gamma_\alpha(x) = e^{\alpha_- x}$ for $x \leq -x_0$ and $\gamma_\alpha(x) = e^{\alpha_+ x}$ for $x \geq x_0$ for some $x_0 > 0$. We shall always assume that

$$0 < \alpha_- < -\omega_- \quad \text{and} \quad 0 \leq \alpha_+ < \omega_+, \quad (2.12)$$

where ω_\pm are the exponents mentioned in (2.3). Given such a pair $\alpha = (\alpha_-, \alpha_+)$, we introduce the weighted space $\mathcal{E}_\alpha = \{u : \mathbb{R} \rightarrow \mathbb{R}^n : \gamma_\alpha u \in \mathcal{E}_0\}$ with the norm $|u|_\alpha = |\gamma_\alpha u|_0$. (Recall that \mathcal{E}_0 with norm $|\cdot|_0$ is either $H^1(\mathbb{R})^n$ or $BUC(\mathbb{R})^n$.) The intersection space $\mathcal{E}_\beta = \mathcal{E}_0 \cap \mathcal{E}_\alpha$ is endowed with the norm $|u|_\beta = \max\{|u|_0, |u|_\alpha\}$. The differential expressions L_q, L^- etc. equipped with their natural domains define operators in \mathcal{E}_α which are denoted by $\mathcal{L}_{q,\alpha}, \mathcal{L}_\alpha^-$ etc. (cf. Remark 2.3). On the spectrum of $\mathcal{L}_{0,\alpha}$, we impose the following assumptions.

Hypothesis 2.4. *In addition to Hypotheses 2.1 and 2.2, we assume that there exists $\alpha = (\alpha_-, \alpha_+) \in \mathbb{R}^2$ such that (2.12) with ω_\pm from (2.3) and the following assertions hold.*

- (a) $\sup\{\operatorname{Re} \lambda : \lambda \in \operatorname{Sp}_{\text{ess}}(\mathcal{L}_{0,\alpha})\} < 0$ for the differential expression L_0 defined in (2.5).
- (b) The only element of $\operatorname{Sp}(\mathcal{L}_{0,\alpha})$ in $\{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \geq 0\}$ is a simple eigenvalue at $\lambda = 0$ with Y_0' being the respective eigenfunction.

Here the essential spectrum $\text{Sp}_{\text{ess}}(A)$ of a closed densely defined operator contains all points in the spectrum $\text{Sp}(A)$ which are not isolated eigenvalues of finite algebraic multiplicity. We discuss various consequences of the above hypothesis which are important for our proofs.

Remark 2.5. We claim that assertions (a) and (b) in Hypothesis 2.4 are satisfied for $\mathcal{E}_0 = H^1(\mathbb{R})^n$ or $\mathcal{E}_0 = BUC(\mathbb{R})^n$ if and only if they hold when \mathcal{E}_0 is replaced by the space $L^2(\mathbb{R})^n$ and \mathcal{E}_α by the space $L_\alpha^2(\mathbb{R})^n$ of functions u with $\gamma_\alpha u \in L^2(\mathbb{R})$ which is endowed with the norm $|u|_\alpha = |\gamma_\alpha u|_{L^2}$.

Indeed, the “if” part of the claim above is proved in Lemma 3.8 of [GLS2]. So we assume Hypothesis 2.4 for $\mathcal{E}_0 = H^1(\mathbb{R})^n$ or $\mathcal{E}_0 = BUC(\mathbb{R})^n$. Then assertion (a) of this hypothesis for $\mathcal{E}_0 = L^2(\mathbb{R})^n$ is true since the right-hand boundary of the essential spectra of $\mathcal{L}_{0,\alpha}$ is the same for all three spaces by [GLS2, Lemma 3.5]. To show assertion (b) for $\mathcal{E}_0 = L^2(\mathbb{R})^n$, we assume that $\mathcal{L}_{0,\alpha}$ on $L_\alpha^2(\mathbb{R})^n$ has an isolated eigenvalue λ of finite algebraic multiplicity with $\text{Re } \lambda \geq 0$. By means of the isomorphism $u(\cdot) \mapsto \gamma(\cdot)u(\cdot)$ between $L_\alpha^2(\mathbb{R})^n$ and $L^2(\mathbb{R})^n$ we obtain a differential operator $\hat{\mathcal{L}}$ in $L^2(\mathbb{R})^n$ which is similar to $\mathcal{L}_{0,\alpha}$ in $L_\alpha^2(\mathbb{R})^n$, cf. [GLS2, Eqn. (3.2)], and hence possesses the unstable isolated eigenvalue λ , too. Palmer’s Dichotomy Theorem in [Pa] says that the first order system corresponding to the second order eigenvalue problem for $\hat{\mathcal{L}}$ admits exponential dichotomies on \mathbb{R}_- and \mathbb{R}_+ . Arguing as in the proof of Lemma 3.8 of [GLS2], we see that the respective eigenfunction Z decays exponentially as $x \rightarrow \pm\infty$. It thus belongs to $BUC(\mathbb{R})^n$, and also to $H^1(\mathbb{R})^n$ since Z_x can be bounded by Z itself due to the eigenvalue equation, see (3.3) in [GLS2]. As a result, $\hat{\mathcal{L}}$ in $H^1(\mathbb{R})^n$ or $BUC(\mathbb{R})^n$ has the unstable eigenvalue λ and therefore also $\mathcal{L}_{0,\alpha}$ in \mathcal{E}_α . Hypothesis 2.4 now shows that $\lambda = 0$, completing the proof of the claim. \diamond

Lemma 2.6. *Assume that Hypothesis 2.4 holds. Then assertions (a) and (b) in Hypothesis 2.4 are satisfied by the operator $\mathcal{L}_{q,\alpha}$ instead of $\mathcal{L}_{0,\alpha}$ and by the function Y'_q instead of Y'_0 .*

Proof. The operators $\mathcal{L}_{q,\alpha}$ and $\mathcal{L}_{0,\alpha}$ are similar via the transformation $Y \mapsto Y(\cdot - q)$ which also maps Y' into Y'_q . The assertions then easily follow. \square

Remark 2.7. Assume Hypothesis 2.4. Lemma 2.6 says that $\lambda = 0$ is an isolated simple eigenvalue for $\mathcal{L}_{q,\alpha}$. We let P_q^c denote the spectral projection for $\mathcal{L}_{q,\alpha}$ in \mathcal{E}_α onto $\ker \mathcal{L}_{q,\alpha} = \text{span}\{Y'_q\}$. Basic operator theory (see, e.g., [DL, Lemma 2.13]) yields that

$$\text{ran}(I_{\mathcal{E}_\alpha} - P_q^c) = \ker P_q^c = \text{ran}(\mathcal{L}_{q,\alpha}).$$

Moreover, the one-dimensional projection P_q^c is given by

$$P_q^c Y = \zeta_q(Y) Y'_q, \quad \zeta_q(Y'_q) = 1, \quad (2.13)$$

for an element ζ_q in $\ker \mathcal{L}_{q,\alpha}^*$ which is also one dimensional, cf. [K, Theorem IV.5.13]. As in the proof of Lemma 2.6, the operators $\mathcal{L}_{q,\alpha}^*$ and $\mathcal{L}_{0,\alpha}^*$ are similar and therefore the norms of $\zeta_q \in \mathcal{E}_\alpha^*$ are bounded uniformly for $|q| \leq q_0$. Also, in view of Lemma 3.3 in [GLS2], the first three derivatives of the shifted wave Y_q are bounded by $Ce^{-\omega-\xi}$ for $\xi \leq 0$ and by $Ce^{-\omega+\xi}$ for $\xi \geq 0$ with ω_\pm from Hypothesis 2.2 and constants C only depending on q_0 . We conclude that

$$\begin{aligned} |P_q^c Y|_\alpha &= |\zeta_q(Y)| |Y'_q|_\alpha \leq C |Y|_\alpha |Y'_q|_\alpha \leq C |Y|_\beta |Y'_q|_\alpha, \\ |P_q^c Y|_0 &= |\zeta_q(Y)| |Y'_q|_0 \leq C |Y|_\alpha |Y'_q|_0 \leq C |Y|_\beta |Y'_q|_0. \end{aligned}$$

As a consequence, P_q^c induces maps

$$P_q^c \in \mathcal{B}(\mathcal{E}_\alpha) \cap \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_\alpha) \cap \mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_\beta) \cap \mathcal{B}(\mathcal{E}_\beta) \cap \mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0) \cap \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)$$

The complementary projection $P_q^s = I - P_q^c$ thus satisfies

$$P_q^s \in \mathcal{B}(\mathcal{E}_\alpha) \cap \mathcal{B}(\mathcal{E}_\beta) \cap \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_\alpha) \cap \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0).$$

We use the same notation P_q^c and P_q^s on all these spaces and their norms are uniformly bounded for $|q| \leq q_0$. The projections further satisfy

$$\|P_q^c - P_p^c\|_{\mathcal{B}(\mathcal{E}_\beta)} \leq C|q - p|, \quad \|P_q^c - P_p^c\|_{\mathcal{B}(\mathcal{E}_\alpha)} \leq C|q - p| \quad (2.14)$$

for $|p|, |q| \leq q_0$ and a constant independent of p and q . In fact, (2.5) yields

$$\begin{aligned} L_q - L_p &= \partial_Y R(Y_0(\cdot - q)) - \partial_Y R(Y_0(\cdot - p)) \\ &= \int_0^1 \partial_{YY} R(sY_q + (1-s)Y_p) ds [Y_0(\cdot - q) - Y_0(\cdot - p)], \\ Y_0(x - q) - Y_0(x - p) &= - \int_0^1 Y_0'(x - p - s(q - p))(q - p) ds. \end{aligned} \quad (2.15)$$

For $\mathcal{E}_0 = BUC$ we deduce

$$\begin{aligned} \|\mathcal{L}_{q,\alpha} - \mathcal{L}_{p,\alpha}\|_{\mathcal{B}(\mathcal{E}_\alpha)} &= \sup_{x \in \mathbb{R}} |\partial_Y R(Y_0(x - q)) - \partial_Y R(Y_0(x - p))| \leq C|q - p|, \\ \|\mathcal{L}_q - \mathcal{L}_p\|_{\mathcal{B}(\mathcal{E}_0)} &= \sup_{x \in \mathbb{R}} |\partial_Y R(Y_0(x - q)) - \partial_Y R(Y_0(x - p))| \leq C|q - p|, \end{aligned} \quad (2.16)$$

and similarly for $\mathcal{E}_0 = H^1$. These estimates can easily be transferred to the resolvents on a sufficiently small circle around 0 which implies the claim (2.14). \diamond

Remark 2.8. To provide extra information, we now determine ζ_q from (2.13) as a solution of a differential equation. Remark 2.5 yields that Hypothesis 2.4 is also true if we replace \mathcal{E}_0 by $L^2(\mathbb{R})$. We first determine ζ_q for the operator $\mathcal{L}_{q,\alpha}^*$ acting on the dual $L_\alpha^2(\mathbb{R})^*$ of the space $L_\alpha^2(\mathbb{R})$ of functions with the exponential weight γ_α . We recall that the operator $\gamma_\alpha : L_\alpha^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$; $Y(\cdot) \mapsto \gamma_\alpha(\cdot)Y(\cdot)$, is an isometric isomorphism. Moreover, $L_\alpha^2(\mathbb{R})^*$ can be identified with L^2 space with the weight $1/\gamma_\alpha$, where the duality map between $L_\alpha^2(\mathbb{R})$ and $L_\alpha^2(\mathbb{R})^*$ is given by the usual (real) L^2 scalar product. Hence, the adjoint operator $\gamma_\alpha^* : L^2(\mathbb{R}) \rightarrow L_\alpha^2(\mathbb{R})^*$ coincides with the multiplication operator by γ_α .

The operator $\gamma_\alpha \mathcal{L}_{q,\alpha} \gamma_\alpha^{-1}$ in $L^2(\mathbb{R})$ is Fredholm since it is similar to the Fredholm operator $\mathcal{L}_{q,\alpha}$ in $L_\alpha^2(\mathbb{R})$. The adjoint of $\gamma_\alpha \mathcal{L}_{q,\alpha} \gamma_\alpha^{-1}$ in $L^2(\mathbb{R})$ is also Fredholm, and it is equal to $\gamma_\alpha^{-1} \mathcal{L}_{q,\alpha}^* \gamma_\alpha$ since $\gamma_\alpha^* = \gamma_\alpha$. We note that the dimension of the kernels is preserved by similarity and duality. The functional $\zeta_q \in \ker \mathcal{L}_{q,\alpha}^*$ from (2.13) is then represented by $\zeta_q = \gamma_\alpha Z_q$ where $Z_q \in L^2(\mathbb{R})$ belongs to $\ker(\gamma_\alpha^{-1} \mathcal{L}_{q,\alpha}^* \gamma_\alpha)$. In other words, $Z_q \in L^2(\mathbb{R})$ is the unique (up to a normalization) solution on \mathbb{R} of the differential equation $(\gamma_\alpha^{-1} \mathcal{L}_{q,\alpha}^* \gamma_\alpha) Z_q = 0$. Reasoning as in the proof of Lemma 3.8 in [GLS2] or in Remark 2.5 we conclude that the solution Z_q decays exponentially to zero as $x \rightarrow \pm\infty$. Moreover, Z_q is the translation $Z_0(\cdot - q)$ of Z_0 , and the decay of the function Z_q is thus uniform in q for $|q| \leq q_0$. Formula (2.13) now yields

$$P_q^c Y = \pi_q(Y) Y_q' \quad \text{with} \quad \pi_q(Y) = \int_{\mathbb{R}} \langle Z_q(x), \gamma_\alpha(x) Y(x) \rangle dx \quad (2.17)$$

for all $Y \in L_\alpha^2(\mathbb{R})$, where Z_q is the exponentially decaying function normalized such that $\pi_q(Y_q') = 1$.

Finally, returning to the cases $\mathcal{E}_0 = H^1(\mathbb{R})^n$ or $\mathcal{E}_0 = BUC(\mathbb{R})^n$, we notice that $\pi_q(\cdot)$ is a bounded functional on \mathcal{E}_α in both cases. Using also the decay properties of Y'_q recalled in Remark 2.7, we confirm from (2.17) once again that P_q^c is a bounded operator from both \mathcal{E}_β and \mathcal{E}_α into \mathcal{E}_β , with uniform constants for $q \in [-q_0, q_0]$. \diamond

Remark 2.9. Let B_q be multiplication operator induced by the matrix valued function $B_q(\cdot)$ from (2.8). Lemma 8.2 of [GLS2] says that B_q belongs to $\mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)$. As in assertion (3) of this lemma, one also sees that $\|B_q - B_p\|_{\mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)} \leq C|q - p|$ for $q, p \in [-q_0, q_0]$. Inspecting the proofs, we see that the constants do not depend on p and q , but on q_0 . \diamond

The operators \mathcal{L}_q and $\mathcal{L}_{q,\alpha}$ generate strongly continuous semigroups on \mathcal{E}_0 and \mathcal{E}_α , respectively, which are both denoted by $\{T_q(t)\}_{t \geq 0}$, see e.g. [GLS1, §2.2]. By Lemma 2.6, there are numbers

$$0 > -\nu > \sup\{\operatorname{Re} \lambda : \lambda \in \operatorname{Sp}(\mathcal{L}_{q,\alpha}) \setminus \{0\}\},$$

Lemma 3.13 of [GLS2] then yields the exponential decay

$$\|T_q(t)P_q^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} \leq Ce^{-\nu t}, \quad t \geq 0, \quad (2.18)$$

see also [GLS1]. The constant C can be chosen uniform in q because of the transformation used in the proof of Lemma 2.6.

Also the operators \mathcal{L}^- and \mathcal{L}_α^- generate strongly continuous semigroups on \mathcal{E}_0 and \mathcal{E}_α , designated by $\{S(t)\}_{t \geq 0}$. Since the multiplication operator B_q is bounded on these spaces, formula (2.8) implies the variation of constant formula

$$T_q(t - \tau) = S(t - \tau) + \int_\tau^t S(t - s)B_q T_q(s - \tau) ds, \quad t \geq \tau \geq 0, \quad q \in \mathbb{R}. \quad (2.19)$$

The upper triangular structure of the operator \mathcal{L}^- indicated in (2.9) implies an analogous representation of the semigroup

$$S(t) = \begin{pmatrix} S_1(t) & Q(t) \\ 0 & S_2(t) \end{pmatrix} \quad \text{and} \quad Q(t) = \int_0^t S_1(t - s) \partial_V R_1(0, 0) S_2(s) ds. \quad (2.20)$$

Here $\{S_1(t)\}_{t \geq 0}$ and $\{S_2(t)\}_{t \geq 0}$ are the semigroups generated by the operators $\mathcal{L}^{(1)}$ and $\mathcal{L}^{(2)}$ from (2.10), respectively. On these semigroups we impose the following assumptions.

Hypothesis 2.10. *The strongly continuous semigroup $\{S_1(t)\}_{t \geq 0}$ is bounded and the semigroup $\{S_2(t)\}_{t \geq 0}$ is uniformly exponentially stable on \mathcal{E}_0 ; that is,*

$$\|S_1(t)\|_{\mathcal{B}(\mathcal{E}_0)} \leq C, \quad \|S_2(t)\|_{\mathcal{B}(\mathcal{E}_0)} \leq Ce^{-\rho t}$$

for some $\rho > 0$ and all $t \geq 0$.

Hypothesis 2.10 and (2.20) imply the boundedness of $\{S(t)\}_{t \geq 0}$ on \mathcal{E}_0 ; i.e.,

$$\|S(t)\|_{\mathcal{B}(\mathcal{E}_0)} \leq C, \quad t \geq 0. \quad (2.21)$$

We next show that the semigroup $\{T_q(t)\}_{t \geq 0}$ is bounded on the space \mathcal{E}_β , too

Lemma 2.11. *Assume Hypotheses 2.4 and 2.10. Take $q_0 > 0$ and let $\alpha = (\alpha_-, \alpha_+)$ satisfy (2.12). Then we have*

$$\sup_{|q| \leq q_0} \sup_{t \geq 0} \|T_q(t)\|_{\mathcal{B}(\mathcal{E}_\beta)} < \infty. \quad (2.22)$$

Proof. The variation of constant formula (2.19) yields on \mathcal{E}_β

$$T_q(t)P_q^s = S(t)P_q^s + \int_0^t S(t-s)B_qT_q(s)P_q^s ds. \quad (2.23)$$

As noted in Remark 2.7 and (2.21), the projection P_q^s belongs to $\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)$ and to $\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_\alpha)$ while the semigroup $S(t)$ is uniformly bounded in \mathcal{E}_0 for $|q| \leq q_0$ and $t \geq 0$, respectively. Using (2.23), these facts, Remark 2.9 and the exponential decay in (2.18), we can estimate

$$\begin{aligned} \|T_q(t)P_q^s\|_{\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)} &\leq C\|P_q^s\|_{\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)} \\ &\quad + C \int_0^t \|B_q\|_{\mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)} \|T_q(s)P_q^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} \|P_q^s\|_{\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_\alpha)} ds \\ &\leq C + C \int_0^t e^{-\nu t} ds \leq C \end{aligned}$$

for all $t \geq 0$ and $|q| \leq q_0$, with uniform constants. In view of the inequality $\|T_q(t)P_q^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} \leq Ce^{-\nu t}$ from (2.18), we have proved (2.22) with $T_q(t)$ replaced by $T_q(t)P_q^s$. Writing the semigroup as $T_q(t) = T_q(t)P_q^s + T_q(t)P_q^c$ on \mathcal{E}_β , it remains to show (2.22) with $T_q(t)$ replaced by $T_q(t)P_q^c$. Recall from Remark 2.7 that $P_q^c = I - P_q^s \in \mathcal{B}(\mathcal{E}_\beta)$ projects \mathcal{E}_β onto the kernel of the generators $\mathcal{L}_{q,0}$ and $\mathcal{L}_{q,\alpha}$ of the semigroup $\{T_q(t)\}_{t \geq 0}$ on \mathcal{E}_0 and \mathcal{E}_α . We conclude that $T_q(t)P_q^c Y = P_q^c Y$ for all $Y \in \mathcal{E}_\beta$ and $t \geq 0$. Therefore, $\|T_q(t)P_q^c\|_{\mathcal{B}(\mathcal{E}_\beta)} \leq C$ for $t \geq 0$, completing the proof of (2.22). \square

3. THE LYAPUNOV-PERRON OPERATOR

In this section we introduce the Lyapunov-Perron operator associated with the nonlinear equation (2.5) and show that it is a contraction of a small ball in a certain space of functions $u : \mathbb{R} \rightarrow \mathcal{E}_0 \cap \mathcal{E}_\alpha$. First, we establish the main technical estimates for the nonlinearity $F_q : \mathbb{R}^n \rightarrow \mathbb{R}^n$ defined in (2.6).

Lemma 3.1. *Assume that $\alpha = (\alpha_-, \alpha_+)$ satisfies (2.12) and that the nonlinearity $R \in C^3(\mathbb{R}^n, \mathbb{R}^n)$ fulfills (2.4). Let $\delta_1 > 0$ and choose a radius $\delta \in (0, \delta_1]$. Then for all functions $y = (u, v)$ and $\bar{y} = (\bar{u}, \bar{v})$ from \mathcal{E}_β with $|y|_\beta, |\bar{y}|_\beta \leq \delta$ the estimates*

$$|F_q(y)|_0 \leq C|y|_0 (|y|_\alpha + |v|_0), \quad (3.1)$$

$$|F_q(y)|_\alpha \leq C|y|_0 |y|_\alpha, \quad (3.2)$$

$$|F_q(y) - F_q(\bar{y})|_0 \leq C(|y - \bar{y}|_0 (|y|_\alpha + |\bar{y}|_\alpha) + |y - \bar{y}|_0 |v|_0 + |\bar{y}|_0 |v - \bar{v}|_0), \quad (3.3)$$

$$|F_q(y) - F_q(\bar{y})|_\alpha \leq |y - \bar{y}|_\alpha (|y|_0 + |\bar{y}|_0) \quad (3.4)$$

are true, where $C = C(\delta_1, q_0)$ and $|q| \leq q_0$.

Proof. Let $|y|_\beta, |\bar{y}|_\beta \leq \delta \leq \delta_1$. From the proof of Lemma 8.3 in [GLS2] we recall the representation

$$F_q(y) = I_1(y) + I_2(y) + I_3(y) + I_4(y) + I_5(y),$$

where $Y_q = (U_q, V_q)$, $y = (u, v)$,

$$I_1(y) = \int_0^1 (\partial_{ur}(Y_q + ty) - \partial_{ur}(Y_q)) u V_q dt,$$

$$I_2(y) = \int_0^1 (\partial_{ur}(Y_q + ty)u) tv dt,$$

$$\begin{aligned}
I_3(y) &= \int_0^1 (\partial_v r(Y_q + ty) - \partial_v r(Y_q)) v V_q dt, \\
I_4(y) &= \int_0^1 (\partial_v r(Y_q + ty) v) t v dt, \\
I_5(y) &= \int_0^1 (r(Y_q + ty) - r(Y_q)) v dt,
\end{aligned}$$

and the function $r \in C^2(\mathbb{R}^n, \mathbb{R}^{n \times n})$ is given by

$$r(u, v) = \int_0^1 \partial_v R(u, tv) dt.$$

We note that r is only applied to functions which are uniformly bounded by $C(1 + \delta_1)$. It is then straightforward to check the inequalities $|I_j(y)|_0 \leq C|y|_0 |v|_0$ for $j \in \{2, \dots, 5\}$ and $|I_j(y)|_\alpha \leq C|y|_0 |y|_\alpha$ for $j \in \{1, 2, \dots, 5\}$. Since $uV_q = (\gamma_\alpha u)(\gamma_\alpha^{-1} V_q)$ and $(\gamma_\alpha^{-1} V_q) \in BUC^1(\mathbb{R}^{n_1})$ by Lemma 3.7 of [GLS2], we can further estimate $|I_1(y)|_0 \leq C|y|_0 |y|_\alpha$, finishing the proof of (3.1) and (3.2). Here and below the constants only depend on δ_1 and q_0 .

To show (3.3) and (3.4), we deal with each integral I_j separately. The terms $|y - \bar{y}|_0 (|y|_\alpha + |\bar{y}|_\alpha)$ and $|y - \bar{y}|_\alpha (|y|_0 + |\bar{y}|_0)$ come from I_1 while the remaining ones originate from I_2 through I_5 . We first represent $I_1(y) - I_1(\bar{y})$ as

$$\begin{aligned}
I_1(y) - I_1(\bar{y}) &= \int_0^1 \int_0^1 \partial_y \partial_u r(Y_q + st(y - \bar{y}) + t\bar{y}) u V_q t (y - \bar{y}) ds dt \\
&\quad + \int_0^1 \int_0^1 \partial_y \partial_u r(Y_q + st\bar{y}) (u - \bar{u}) V_q t \bar{y} ds dt.
\end{aligned} \tag{3.5}$$

Using $uV_q(y - \bar{y}) = (\gamma_\alpha u)(\gamma_\alpha^{-1} V_q)(y - \bar{y})$ and $(u - \bar{u})V_q \bar{y} = (u - \bar{u})\gamma_\alpha^{-1} V_q \gamma_\alpha \bar{y}$ as above, we conclude that $|I_1(y) - I_1(\bar{y})|_0 \leq C|y - \bar{y}|_0 (|y|_\alpha + |\bar{y}|_\alpha)$. If we multiply (3.5) by γ_α , we directly estimate $|I_1(y) - I_1(\bar{y})|_\alpha \leq C(|y|_0 + |\bar{y}|_0) |y - \bar{y}|_\alpha$ since $|u| \leq |y|$. Likewise, we write $I_5(y) - I_5(\bar{y})$ as

$$\begin{aligned}
I_5(y) - I_5(\bar{y}) &= \int_0^1 \int_0^1 (\partial_y r(Y_q + sty) - \partial_y r(Y_q + st\bar{y})) t y v ds dt \\
&\quad + \int_0^1 \int_0^1 \partial_y r(Y_q + ts\bar{y}) t v (y - \bar{y}) ds dt \\
&\quad + \int_0^1 \int_0^1 \partial_y r(Y_q + st\bar{y}) t \bar{y} (v - \bar{v}) ds dt
\end{aligned} \tag{3.6}$$

and obtain the bounds $|I_5(y) - I_5(\bar{y})|_0 \leq C(|y - \bar{y}|_0 |v|_0 + |\bar{y}|_0 |v - \bar{v}|_0)$, recalling that $|y|_0 \leq \delta_1$ by assumption. After multiplying (3.6) by γ_α , it also follows that $|I_5(y) - I_5(\bar{y})|_\alpha \leq C(|y|_0 |y - \bar{y}|_\alpha + |\bar{y}|_0 |v - \bar{v}|_\alpha)$ since $|v| \leq |y|$. Similarly, the formulas

$$\begin{aligned}
I_2(y) - I_2(\bar{y}) &= \int_0^1 (\partial_u r(Y_q + ty) - \partial_u r(Y_q + t\bar{y})) t v dt \\
&\quad + \int_0^1 \partial_u r(Y_q + t\bar{y}) (u - \bar{u}) t v dt + \int_0^1 \partial_u r(Y_q + t\bar{y}) \bar{u} t (v - \bar{v}) dt,
\end{aligned} \tag{3.7}$$

$$I_4(y) - I_4(\bar{y}) = \int_0^1 (\partial_v r(Y_q + ty) - \partial_v r(Y_q + t\bar{y})) t v dt \tag{3.8}$$

$$+ \int_0^1 \partial_v r(Y_q + t\bar{y})(v - \bar{v})tv \, dt + \int_0^1 \partial_v r(Y_q + t\bar{y})\bar{v}t(v - \bar{v}) \, dt$$

imply the inequalities

$$\begin{aligned} |I_2(y) - I_2(\bar{y})|_0 &\leq C(|y - \bar{y}|_0 |v|_0 + |\bar{y}|_0 |v - \bar{v}|_0), \\ |I_4(y) - I_4(\bar{y})|_0 &\leq C(|y - \bar{y}|_0 |v|_0 + |\bar{y}|_0 |v - \bar{v}|_0). \end{aligned}$$

Multiplying (3.7) and (3.8) by γ_α , we also derive

$$\begin{aligned} |I_2(y) - I_2(\bar{y})|_\alpha &\leq C(|y|_0 |y - \bar{y}|_\alpha + |\bar{y}|_0 |v - \bar{v}|_\alpha), \\ |I_4(y) - I_4(\bar{y})|_\alpha &\leq C(|y|_0 |y - \bar{y}|_\alpha + |\bar{y}|_0 |v - \bar{v}|_\alpha). \end{aligned}$$

We finally compute

$$\begin{aligned} I_3(y) - I_3(\bar{y}) &= \int_0^1 \int_0^1 \partial_y \partial_v r(Y_q + st(y - \bar{y}) + t\bar{y})vV_q t(y - \bar{y}) \, ds \, dt \\ &\quad + \int_0^1 \int_0^1 \partial_y \partial_v r(Y_q + st\bar{y})(v - \bar{v})V_q t\bar{y} \, ds \, dt. \end{aligned}$$

Again we infer that

$$\begin{aligned} |I_3(y) - I_3(\bar{y})|_0 &\leq C(|y - \bar{y}|_0 |v|_0 + |\bar{y}|_0 |v - \bar{v}|_0), \\ |I_3(y) - I_3(\bar{y})|_\alpha &\leq C(|y|_0 |y - \bar{y}|_\alpha + |\bar{y}|_0 |v - \bar{v}|_\alpha). \end{aligned}$$

This completes the proof of the lemma. \square

Remark 3.2. It follows from the observations after Remark 2.9 that the realization of L_q in $\mathcal{E}_\beta = \mathcal{E}_0 \cap \mathcal{E}_\alpha$ generates a strongly continuous semigroup. The Lipschitz properties proved in the above lemma thus imply that the semilinear equation (2.5) is locally wellposed also in \mathcal{E}_β , cf. Remark 2.3. \diamond

We next establish basic properties of the Lyapunov-Perron operator $\Phi_q(y, z_0)$ defined by

$$\Phi_q(y, z_0)(t) = T_q(t)P_q^s z_0 + \int_0^t T_q(t - \tau)P_q^s F_q(y(\tau)) \, d\tau - \int_t^\infty P_q^c F_q(y(\tau)) \, d\tau, \quad (3.9)$$

where $|q| \leq q_0$ and $z_0 \in \mathcal{E}_0 \cap \mathcal{E}_\alpha = \mathcal{E}_\beta$ satisfies

$$|z_0|_\beta = \max\{|z_0|_0, |z_0|_\alpha\} \leq \delta_0, \quad (3.10)$$

for some $\delta_0 > 0$. Here we use that P_q^c maps into the kernel of the generator of $\{T_q(t)\}_{t \geq 0}$, see Remark 2.7, so that the semigroup is just the identity on the range of P_q^c and we can omit it in the second integral in (3.9).

For a continuous map $y = (u, v) : \mathbb{R} \rightarrow \mathcal{E}_\beta = \mathcal{E}_0 \cap \mathcal{E}_\alpha$ we define the norms

$$\|y\|_{\omega, \alpha} = \sup_{t \geq 0} e^{\omega t} |y(t)|_\alpha, \quad \|y\|_{0,0} = \sup_{t \geq 0} |y(t)|_0, \quad \|v\|_{\omega,0} = \sup_{t \geq 0} e^{\omega t} |v(t)|_0,$$

where $\omega > 0$ is specified below and $\alpha = (\alpha_-, \alpha_+)$ is given by (2.12). Let $\delta > 0$. Then $(\mathbb{B}_\delta, \|\cdot\|)$ is the set of continuous functions $y : \mathbb{R} \rightarrow \mathcal{E}_0 \cap \mathcal{E}_\alpha$ such that

$$\|y\| := \max(\|y\|_{\omega, \alpha}, \|y\|_{0,0}, \|v\|_{\omega,0}) \leq \delta. \quad (3.11)$$

We recall from Hypothesis 2.10 and (2.18) the exponential estimates

$$\|S_2(t)\|_{\mathcal{B}(\mathcal{E}_0)} \leq Ce^{-\rho t}, \quad \|T_q(t)P_q^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} \leq Ce^{-\nu t} \quad (3.12)$$

for $t \geq 0$. For technical reasons (see the next proof), if necessary we have to modify these exponents such that

$$0 < \omega < \rho < \nu. \quad (3.13)$$

This is always possible, though one may lose information here. By Lemma 2.11, the semigroup $\{T_q(t)\}_{t \geq 0}$ is bounded in \mathcal{E}_β . The above constants do not depend on $|q| \leq q_0$.

Lemma 3.3. *Take $q_0 > 0$. Let $\delta > 0$ and $\delta_0 = \delta_0(\delta) > 0$ be small enough. For each $z_0 \in \mathbb{B}_{\delta_0}(|\cdot|_\beta)$ the Lyapunov-Perron operator $y \mapsto \Phi_q(y, z_0)$ leaves $\mathbb{B}_\delta(\|\cdot\|)$ invariant and is a strict contraction on this ball for all $|q| \leq q_0$. Moreover, for the norm $\|\cdot\|$ defined in (3.11) one has*

$$\|\Phi_q(y, z_0) - \Phi_q(\bar{y}, \bar{z}_0)\| \leq C|z_0 - \bar{z}_0|_\beta + C\delta\|y - \bar{y}\| \quad (3.14)$$

for some $C > 0$ and all $z_0, \bar{z}_0 \in \mathbb{B}_{\delta_0}(|\cdot|_\beta)$, $y, \bar{y} \in \mathbb{B}_\delta(\|\cdot\|)$, and $|q| \leq q_0$.

Proof. Let $t \geq 0$, $\delta, \delta_0 > 0$, $z_0, \bar{z}_0 \in \mathbb{B}_{\delta_0}(|\cdot|_\beta)$, $y, \bar{y} \in \mathbb{B}_\delta(\|\cdot\|)$, and $|q| \leq q_0$. Below the constants are uniform for δ, δ_0 and q in bounded subsets. By $\pi_1 y = u$ and $\pi_2 y = v$, we denote the projection of $y = (u, v)$ onto its first and second components. Formulas (2.19) and (2.20) yield

$$\pi_2 T_q(t - \tau) = S_2(t - \tau)\pi_2 + \int_\tau^t S_2(t - s)\pi_2 B_q T_q(s - \tau) ds, \quad 0 \leq \tau \leq t. \quad (3.15)$$

1a) Using (3.15), (3.12), and Remarks 2.7 and 2.9, the second component of the first integral in (3.9) can be estimated by

$$\begin{aligned} e^{\omega t} \left| \pi_2 \int_0^t T_q(t - \tau) P_q^s F_q(y(\tau)) d\tau \right|_0 & \\ \leq C e^{\omega t} \int_0^t \left(e^{-\rho(t-\tau)} |F_q(y(\tau))|_\beta + \int_\tau^t e^{-\rho(t-s)} e^{-\nu(s-t)} |F_q(y(\tau))|_\alpha ds \right) d\tau, & \end{aligned} \quad (3.16)$$

since

$$|S_2(t - \tau)\pi_2 P_q^s F_q(y(\tau))|_0 \leq \|S_2(t - \tau)\pi_2\|_{\mathcal{B}(\mathcal{E}_0)} \|P_q^s\|_{\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)} |F_q(y(\tau))|_\beta, \quad (3.17)$$

$$\begin{aligned} |S_2(t - s)\pi_2 B_q T_q(s - \tau) P_q^s F_q(y(\tau))|_0 & \\ \leq \|S_2(t - s)\pi_2\|_{\mathcal{B}(\mathcal{E}_0)} \|B_q\|_{\mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)} \|T_q(s - \tau) P_q^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} |F_q(y(\tau))|_\alpha. & \end{aligned} \quad (3.18)$$

Because of (3.1) and (3.2), the formulas (3.16) and (3.13) yield

$$\begin{aligned} e^{\omega t} \left| \pi_2 \int_0^t T_q(t - \tau) P_q^s F_q(y(\tau)) d\tau \right|_0 & \\ \leq C e^{\omega t} \int_0^t \left(e^{-\rho(t-\tau)} e^{-\omega\tau} e^{\omega\tau} (|y(\tau)|_\alpha + |v(\tau)|_0) |y(\tau)|_0 \right. & \\ \quad \left. + \int_\tau^t e^{-\rho(t-s)} e^{-\nu(s-t)} e^{-\omega\tau} e^{\omega\tau} |y(\tau)|_\alpha |y(\tau)|_0 ds \right) d\tau & \\ \leq C (\|y\|_{\omega, \alpha} + \|v\|_{\omega, 0}) \|y\|_{0, 0} \int_0^t e^{(\omega - \rho)(t-\tau)} d\tau & \\ \quad + C \|y\|_{\omega, \alpha} \|y\|_{0, 0} \int_0^t e^{\omega(t-\tau)} \left(\int_\tau^t e^{-\rho(t-s)} e^{-\nu(s-\tau)} ds \right) d\tau & \\ \leq C \|y\|^2 \leq C\delta^2. & \end{aligned}$$

We next employ (3.12), (3.2) and (3.13) to bound

$$\begin{aligned} e^{\omega t} \left| \int_0^t T_q(t-\tau) P_q^s F_q(y(\tau)) d\tau \right|_{\alpha} &\leq C \int_0^t e^{\omega t} e^{-\nu(t-\tau)} e^{-\omega\tau} e^{\omega\tau} |y(\tau)|_0 |y(\tau)|_{\alpha} d\tau \\ &\leq C \|y\|_{0,0} \|y\|_{\omega,\alpha} \leq C\delta^2. \end{aligned}$$

To finish with the first integral in (3.9), it remains to control the $|\cdot|_0$ norm of its first component. Here (2.19), (2.21), Remark 2.7 (in particular, that $P_q^s \in \mathcal{B}(\mathcal{E}_{\beta}, \mathcal{E}_0)$), Remark 2.9, (3.1), (3.12), (3.2) and (3.13) imply the inequalities

$$\begin{aligned} &\left| \pi_1 \int_0^t T_q(t-\tau) P_q^s F_q(y(\tau)) d\tau \right|_0 \\ &= \left| \pi_1 \int_0^t S(t-\tau) P_q^s F_q(y(\tau)) d\tau + \pi_1 \int_0^t \int_{\tau}^t S(t-s) B_q T_q(s-\tau) P_q^s F_q(y(\tau)) ds d\tau \right|_0 \\ &\leq C \int_0^t |F_q(y(\tau))|_{\beta} d\tau + C \|B_q\|_{\mathcal{B}(\mathcal{E}_{\alpha}, \mathcal{E}_0)} \int_0^t \int_{\tau}^t |T_q(s-\tau) P_q^s F_q(y(\tau))|_{\alpha} ds d\tau \\ &\leq C \int_0^t e^{-\omega\tau} |y(\tau)|_0 e^{\omega\tau} (|y(\tau)|_{\alpha} + |v(\tau)|_0) d\tau + C \int_0^t \int_{\tau}^t e^{-\nu(s-\tau)} |y(\tau)|_0 |y(\tau)|_{\alpha} ds d\tau \\ &\leq C \|y\|_{0,0} (\|y\|_{\omega,\alpha} + \|v\|_{\omega,0}) \int_0^t e^{-\omega\tau} d\tau + C \|y\|_{0,0} \|y\|_{\omega,\alpha} \int_0^t \int_{\tau}^t e^{-\nu(s-\tau)} ds e^{-\omega\tau} d\tau \\ &\leq C\delta^2. \end{aligned}$$

1b) We now treat the term $T_q(t) P_q^s z_0$ in (3.9). From (3.12) and (3.13) we infer

$$e^{\omega t} |T_q(t) P_q^s z_0|_{\alpha} \leq C e^{\omega t} e^{-\nu t} |z_0|_{\alpha} \leq C\delta_0.$$

By means of (2.19), (2.21), Remark 2.7 (in particular, that $P_q^s \in \mathcal{B}(\mathcal{E}_{\beta}, \mathcal{E}_0)$) and Remark 2.9, as well as (3.12), we next compute

$$\begin{aligned} |\pi_1 T_q(t) P_q^s z_0|_0 &\leq |S(t) P_q^s z_0|_0 + \int_0^t |S(t-s) B_q T_q(s) P_q^s z_0|_0 ds \\ &\leq C |z_0|_{\beta} + C \int_0^t \|B_q\|_{\mathcal{B}(\mathcal{E}_{\alpha}, \mathcal{E}_0)} e^{-\nu s} |z_0|_{\alpha} ds \leq C\delta_0. \end{aligned}$$

Finally, formulas (3.15), (3.12), Remarks 2.7 and 2.9, as well as inequality (3.13) imply

$$\begin{aligned} e^{\omega t} |\pi_2 T_q(t) P_q^s z_0|_0 &\leq e^{\omega t} |S_2(t) \pi_2 P_q^s z_0|_0 + \int_0^t |S_2(t-s) \pi_2 B_q T_q(s) P_q^s z_0|_0 ds \\ &\leq C e^{(\omega-\rho)t} |z_0|_{\beta} + C \int_0^t e^{\omega t} e^{-\rho(t-s)} e^{-\nu s} |z_0|_{\alpha} ds \\ &\leq C\delta_0. \end{aligned}$$

1c) To show the invariance, it remains to bound the norms of the last integral in (3.9). Remark 2.7 (in particular, that $P_q^c \in \mathcal{B}(\mathcal{E}_{\alpha}, \mathcal{E}_{\beta})$) and estimate (3.2) yield

$$\begin{aligned} e^{\omega t} \left| \int_t^{\infty} P_q^c F_q(y(\tau)) d\tau \right|_{\beta} &\leq C \int_t^{\infty} e^{\omega t} |F_q(y(\tau))|_{\alpha} d\tau \\ &\leq C \int_t^{\infty} e^{\omega t} e^{-\omega\tau} e^{\omega\tau} |y(\tau)|_0 |y(\tau)|_{\alpha} d\tau \\ &\leq C \|y\|_{0,0} \|y\|_{\omega,\alpha} \leq C\delta^2. \end{aligned}$$

We thus have shown that $\Phi_q(\cdot, z_0)$ leaves the ball $\mathbb{B}_\delta(\|\cdot\|)$ invariant if first $\delta > 0$ and then $\delta_0 > 0$ are chosen small enough.

2) For the contractivity we have to estimate the difference

$$\begin{aligned} \Phi_q(y, z_0) - \Phi_q(\bar{y}, z_0) &= \int_0^t T_q(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau \\ &\quad - \int_t^\infty P_q^c(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau. \end{aligned} \quad (3.19)$$

2a) Using (2.19), (2.21), (3.12), Remark 2.7 (in particular, that $P_q^s \in \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)$) and Remark 2.9, we bound the first integral by

$$\begin{aligned} &\left| \int_0^t T_q(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau \right|_0 \\ &\leq \left| \int_0^t S(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau \right|_0 \\ &\quad + \left| \int_0^t \int_\tau^t S(t-s) B_q T_q(s-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, ds \, d\tau \right|_0 \\ &\leq C \int_0^t |F_q(y(\tau)) - F_q(\bar{y}(\tau))|_\beta \, d\tau \\ &\quad + C \int_0^t \int_\tau^t \|B_q\|_{\mathcal{B}(\mathcal{E}_0, \mathcal{E}_\alpha)} e^{-\nu(s-\tau)} |F_q(y(\tau)) - F_q(\bar{y}(\tau))|_\alpha \, ds \, d\tau. \end{aligned}$$

The inequalities (3.3) and (3.4) then lead to

$$\begin{aligned} &\left| \int_0^t T_q(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau \right|_0 \\ &\leq C \int_0^t e^{-\omega\tau} \left[|y(\tau) - \bar{y}(\tau)|_0 e^{\omega\tau} (|y(\tau)|_\alpha + |\bar{y}(\tau)|_\alpha + |v(\tau)|_0) \right. \\ &\quad \left. + |\bar{y}(\tau)|_0 e^{\omega\tau} |v(\tau) - \bar{v}(\tau)|_0 + e^{\omega\tau} |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) \right] \, d\tau \\ &\quad + C \int_0^t e^{-\omega\tau} e^{\omega\tau} |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) \, d\tau \\ &\leq C \|y - \bar{y}\|_{0,0} (\|y\|_{\omega,\alpha} + \|\bar{y}\|_{\omega,\alpha} + \|v\|_{\omega,0}) + C \|\bar{y}\|_{0,0} \|v - \bar{v}\|_{\omega,0} \\ &\quad + C \|y - \bar{y}\|_{\omega,\alpha} (\|y\|_{0,0} + \|\bar{y}\|_{0,0}) \\ &\leq C\delta \|y - \bar{y}\|. \end{aligned}$$

The $|\cdot|_\alpha$ -norm of the first integral in (3.19) is estimated by

$$\begin{aligned} &e^{\omega t} \left| \int_0^t T_q(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) \, d\tau \right|_\alpha \\ &\leq C \int_0^t e^{\omega t} e^{-\nu(t-\tau)} e^{-\omega\tau} e^{\omega\tau} |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) \, d\tau \\ &\leq C \int_0^t e^{(\omega-\nu)(t-\tau)} \, d\tau \|y - \bar{y}\|_{\omega,\alpha} (\|y\|_{0,0} + \|\bar{y}\|_{0,0}) \\ &\leq C\delta \|y - \bar{y}\|, \end{aligned}$$

employing (3.12), (3.4), and (3.13). As in (3.17) and (3.18), for the second component we use formulas (3.15) and (3.12), Remark 2.7 (in particular, that $P_q^s \in$

$\mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)$) and Remark 2.9, as well as inequalities (3.3), (3.4) and (3.13) to derive the estimates

$$\begin{aligned}
& e^{\omega t} \left| \pi_2 \int_0^t T_q(t-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) d\tau \right|_0 \\
& \leq e^{\omega t} \left| \int_0^t S_2(t-\tau) \pi_2 P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) d\tau \right|_0 \\
& \quad + e^{\omega t} \left| \int_0^t \int_\tau^t S_2(t-s) \pi_2 B_q T_q(s-\tau) P_q^s(F_q(y(\tau)) - F_q(\bar{y}(\tau))) ds d\tau \right|_0 \\
& \leq C \int_0^t e^{\omega(t-\tau)} e^{-\rho(t-\tau)} e^{\omega\tau} \left[|y(\tau) - \bar{y}(\tau)|_0 (|y(\tau)|_\alpha + |\bar{y}(\tau)|_\alpha + |v(\tau)|_0) \right. \\
& \quad \left. + |\bar{y}(\tau)|_0 |v(\tau) - \bar{v}(\tau)|_0 + |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) \right] d\tau \\
& \quad + C \int_0^t \int_\tau^t e^{\omega t - \rho(t-s)} \|B_q\|_{\mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)} e^{-\nu(s-\tau) - \omega\tau} e^{\omega\tau} |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) d\tau \\
& \leq C \left(\|y - \bar{y}\|_{0,0} (\|y\|_{\omega,\alpha} + \|\bar{y}\|_{\omega,\alpha} + \|v\|_{\omega,0}) + \|\bar{y}\|_{0,0} \|v - \bar{v}\|_{\omega,0} \right. \\
& \quad \left. + \|y - \bar{y}\|_{\omega,\alpha} (\|y\|_{0,0} + \|\bar{y}\|_{0,0}) \right) \\
& \leq C\delta \|y - \bar{y}\|.
\end{aligned}$$

As a result, the $\|\cdot\|$ -norm of the first integral in (3.19) is dominated by $C\delta \|y - \bar{y}\|$.

2b) For the second integral in (3.19), Remark 2.7 and inequality (3.4) yield

$$\begin{aligned}
& e^{\omega t} \left| \int_t^\infty P_q^c(F_q(y(\tau)) - F_q(\bar{y}(\tau))) d\tau \right|_\beta \\
& \leq C \int_t^\infty e^{\omega(t-\tau)} e^{\omega\tau} |y(\tau) - \bar{y}(\tau)|_\alpha (|y(\tau)|_0 + |\bar{y}(\tau)|_0) d\tau \\
& \leq C \|y - \bar{y}\|_{\omega,\alpha} (\|y\|_{0,0} + \|\bar{y}\|_{0,0}) \\
& \leq C\delta \|y - \bar{y}\|.
\end{aligned}$$

We have thus established

$$\|\Phi_q(y, z_0) - \Phi_q(\bar{y}, z_0)\| \leq C\delta \|y - \bar{y}\|, \quad (3.20)$$

finishing the proof of the first part of Lemma 3.3.

3) It remains to show the estimate

$$\|\Phi_q(y, z_0) - \Phi_q(y, \bar{z}_0)\| = \|T_q(\cdot) P_q^s(z_0 - \bar{z}_0)\| \leq C |z - \bar{z}_0|_\beta. \quad (3.21)$$

The inequalities (3.12) and (3.13) first imply that

$$\|T_q(\cdot) P_q^s(z_0 - \bar{z}_0)\|_{\omega,\alpha} \leq C |z - z_0|_\alpha.$$

To treat the norm $\|\cdot\|_{0,0}$, from (2.19), (2.21), Remark 2.7 (in particular, that $P_q^s \in \mathcal{B}(\mathcal{E}_\beta, \mathcal{E}_0)$), Remark 2.9 and (3.12), we conclude

$$\begin{aligned}
|T_q(t) P_q^s(z_0 - \bar{z}_0)|_0 & \leq |S(t) P_q^s(z_0 - \bar{z}_0)|_0 + \int_0^t |S(t-s) B_q T_q(s) P_q^s(z_0 - \bar{z}_0)|_0 ds \\
& \leq C |z_0 - \bar{z}_0|_\beta + C \int_0^t e^{-\nu s} ds |z_0 - \bar{z}_0|_\alpha \\
& \leq C |z_0 - \bar{z}_0|_\beta.
\end{aligned}$$

In a similar way, formula (3.15), Remarks 2.7 and 2.9, as well as inequalities (3.12) and (3.13) yield the remaining bound for $\|\pi_2 T_q(\cdot) P_q^s(z_0 - \bar{z}_0)\|_{\omega,0}$ so that (3.21) follows. \square

4. STABLE MANIFOLDS

For a small $q_0 > 0$ and each $q \in [-q_0, q_0]$, we now construct a function $\phi_q : \text{ran}(P_q^s) \rightarrow P_q^c$ whose graph contains Y_q and it is a stable manifold \mathcal{M}_q^s for the system (2.2). We further prove that the sets \mathcal{M}_q^s satisfy the standard properties of stable manifolds and that they foliate a small neighborhood of Y_0 .

Let $\delta, \delta_0 > 0$ be sufficiently small and $q_0 > 0$. Take $|q| \leq q_0$ and $z_0 \in \text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)$. Lemma 3.3 then yields a unique function $y_{z_0}^q : \mathbb{R}_+ \rightarrow \mathcal{E}_\beta$ which belongs to $\mathbb{B}_\delta(\|\cdot\|)$ and is a fixed point of the Lyapunov-Perron operator $\Phi_q(\cdot, z_0)$; that is,

$$y_{z_0}^q(t) = T_q(t)z_0 + \int_0^t T_q(t-\tau)P_q^s F_q(y_{z_0}^q(\tau)) d\tau - \int_t^\infty P_q^c F_q(y_{z_0}^q(\tau)) d\tau \quad (4.1)$$

for $t \geq 0$. At $t = 0$ we obtain the identity

$$y_{z_0}^q(0) = z_0 - \int_0^\infty P_q^c F_q(y_{z_0}^q(\tau)) d\tau$$

for all $z_0 \in \text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)$. We define the function $\phi_q : \text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta) \rightarrow \text{ran}(P_q^c)$ by

$$\phi_q(z_0) = - \int_0^\infty P_q^c F_q(y_{z_0}^q(\tau)) d\tau. \quad (4.2)$$

In this notation, we have $y_{z_0}^q(0) = z_0 + \phi_q(z_0)$ so that $y_{z_0}^q(0)$ belongs to the graph $\text{graph}_{\delta_0} \phi_q$ of ϕ_q over the small neighborhood $\text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)$ of 0. Adding and subtracting the term $\int_0^t P_q^c F_q(y_{z_0}^q(\tau)) d\tau$, we deduce from (4.1) that the fixed point $y = y_{z_0}^q$ of the Lyapunov-Perron operator satisfies the equation

$$y(t) = T_q(t)y(0) + \int_0^t T_q(t-\tau)F_q(y(\tau)) d\tau, \quad t \geq 0. \quad (4.3)$$

Consequently, $y = y_{z_0}^q$ is the mild solution of the nonlinear equation (2.5) in $\mathbb{B}_\delta(\|\cdot\|)$, and the function $Y_q + y$ solves (2.2) in the mild sense, cf. Remark 2.3. By uniqueness, y_0^q is the 0 function. Let also \bar{z}_0 belong to $\text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)$. Taking a sufficiently small $\delta > 0$ in (3.14), we deduce the estimates

$$\|y_{z_0}^q - y_{\bar{z}_0}^q\| \leq C|z_0 - \bar{z}_0|_\beta, \quad \|y_{z_0}^q\| \leq C|z_0|_\beta. \quad (4.4)$$

For a number $\eta > 0$ to be fixed below, the stable manifold \mathcal{M}_q^s is then defined by

$$\mathcal{M}_q^s = \{Y_q + z_0 + \phi_q(z_0) : z_0 \in \text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)\} \cap (Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)), \quad (4.5)$$

where $|q| \leq q_0$ and $Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ is the closed ball in $\mathcal{E}_\beta = \mathcal{E}_\alpha \cap \mathcal{E}_0$ with radius η and centered at the original traveling wave Y_0 .

Theorem 4.1. *Assume Hypotheses 2.4 and 2.10. Let $q_0, \delta, \delta_0, \eta > 0$ be sufficiently small, $|q| \leq q_0$, and $\omega > 0$ be given by (3.13). Then the ball $Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ is foliated by the stable manifolds \mathcal{M}_q^s from (4.5) for the nonlinear equation (2.2) and the following assertions hold.*

- (i) *Each \mathcal{M}_q^s is a Lipschitz manifold in \mathcal{E}_β . If $Y(0) \in \mathcal{M}_q^s$ and the mild solution $Y(t; Y(0))$ of (2.2) belongs to $Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ for some $t \geq 0$, then $Y(t; Y(0))$ is contained in \mathcal{M}_q^s .*

- (ii) For each $Y(0) \in \mathcal{M}_q^s$ there exists a solution $Y(t; Y(0))$ of (2.2) which exists for all $t \geq 0$ and satisfies $|Y(t; Y(0)) - Y_q|_\beta \leq \delta$ as well as
- (a) $|Y(t; Y(0)) - Y_q|_\alpha \leq Ce^{-\omega t} |Y(0) - Y_q|_\beta$,
 - (b) $|\pi_1(Y(t; Y(0)) - Y_q) - U_q|_0 \leq C |Y(0) - Y_q|_\beta$,
 - (c) $|\pi_2(Y(t; Y(0)) - Y_q) - V_q|_0 \leq Ce^{-\omega t} |Y(0) - Y_q|_\beta$
- for all $t \geq 0$. Here, $Y_q = (U_q, V_q) = Y_0(\cdot - q)$ is the shifted traveling wave, $\pi_1 : Y = (U, V) \rightarrow U$, and $\pi_2 : Y = (U, V) \rightarrow V$.
- (iii) If $Y(t; Y(0))$, $t \geq 0$, is a mild solution of (2.2) with $Y(0) \in Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ that satisfies properties (a)–(c) in item (ii), then $Y(0)$ belongs to \mathcal{M}_q^s .
- (iv) For $q \neq \bar{q}$, we have $\mathcal{M}_q^s \cap \mathcal{M}_{\bar{q}}^s = \emptyset$. Moreover, $Y_0 + \mathbb{B}_\eta(|\cdot|_\beta) = \bigcup_{|q| \leq q_0} \mathcal{M}_q^s$.
- (v) The map $[-q_0, q_0] \rightarrow \text{ran}(P_q^c)$; $q \mapsto \phi_q(P_q^s z_0)$, is Lipschitz for each $z_0 \in \mathbb{B}_{\delta_0}(|\cdot|_\beta)$.

As a result, for each $Y(0) \in Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ there exists exactly one shift $q \in [-q_0, q_0]$ such that $Y(0) \in \mathcal{M}_q^s$.

The following lemma will be used in the proof of Theorem 4.1. Recall the definition of the ball $\mathbb{B}_\delta(\|\cdot\|)$ in (3.11).

Lemma 4.2. *Assume Hypotheses 2.4 and 2.10. Let $\delta, \delta_0 > 0$ be chosen small enough, $q_0 > 0$, and let $|q| \leq q_0$. Take $y_0 \in \mathcal{E}_\beta = \mathcal{E}_\alpha \cap \mathcal{E}_0$. Let $y = Y(\cdot; y_0) \in C([0, t_0], \mathcal{E}_0 \cap \mathcal{E}_\alpha)$ be the mild solution of the nonlinear equation (2.5) with the initial value $y(0) = y_0$, where $t_0 \in (0, \infty]$. Set $z_0 = P_q^s y_0$ and assume that $|z_0|_\beta \leq \delta_0$. Then the following assertions are equivalent.*

- (a) $y_0 = z_0 + \phi_q(z_0) \in \text{graph}_{\delta_0} \phi_q$.
- (b) y can be extended to a global mild solution of (2.5) in $\mathbb{B}_\delta(\|\cdot\|)$, and it is the fixed point $y_{z_0}^q$ of the Lyapunov-Perron operator $\Phi_q(\cdot, z_0)$ from (3.9).
- (c) y can be extended to a global mild solution of (2.5) in $\mathbb{B}_\delta(\|\cdot\|)$.

Proof. (a) \Rightarrow (b): Assertion (a) and the equations (4.2) and (4.1) yield

$$y_0 = z_0 + \phi_q(z_0) = z_0 - \int_0^\infty P_q^c F_q(y_{z_0}^q(\tau)) d\tau = y_{z_0}^q(0),$$

where $y_{z_0}^q \in \mathbb{B}_\delta(\|\cdot\|)$ is the fixed point of $\Phi_q(\cdot, z_0)$. Since their initial values are the same, the mild solutions y and $y_{z_0}^q$ coincide by uniqueness of (4.3); i.e., (b) holds.

(b) \Rightarrow (c): This implication is obvious.

(c) \Rightarrow (a): In view of (c), Lemma 3.3 shows that the integral

$$z_c := P_q^c y_0 + \int_0^\infty P_q^c F_q(y(\tau)) d\tau \in \text{ran}(P_q^c).$$

exists. Since y solves (4.3) and $T_q(t - \tau)$ is the identity on $\text{ran}(P_q^c)$, we can write

$$\begin{aligned} y(t) &= T_q(t)y_0 + \int_0^t T_q(t - \tau)F_q(y(\tau)) d\tau \\ &= T_q(t)P_q^s y_0 + \int_0^t T_q(t - \tau)P_q^s F(y(\tau)) d\tau - \int_t^\infty P_q^c F(y(\tau)) d\tau \\ &\quad + P_q^c y_0 + \int_t^\infty P_q^c F(y(\tau)) d\tau + \int_0^t P_q^c F(y(\tau)) d\tau, \end{aligned}$$

using again Lemma 3.3 and (c). The definition of $\Phi_q(y, z_0)$ in (3.9) then yields

$$y(t) = \Phi_q(y, z_0)(t) + z_c, \quad t \geq 0. \quad (4.6)$$

Due to (c) and (3.11), the functions y and $\Phi_q(y, z_0)$ tend to 0 in \mathcal{E}_α as $t \rightarrow \infty$, and hence $z_c = 0$. Equation (4.6) thus implies $y = \Phi_q(y, z_0)$ so that (a) is a consequence of the observations after (4.2). \square

Proof of Theorem 4.1. Recall from Remark 2.3 that all mild solutions of (2.2) are given by $y + Y_q$ for a mild solution y of (2.5).

(i) and (ii). Equations (4.1) and (4.2) show that $z_0 + \phi_q(z_0)$ is the value of $\Phi(z_0, \phi_q(z_0))$ at $t = 0$. From (4.4) we then deduce that ϕ_q and hence \mathcal{M}_q^s are Lipschitz in $\mathcal{E}_\beta = \mathcal{E}_0 \cap \mathcal{E}_\alpha$.

Let $y_0 + Y_q$ belong to \mathcal{M}_q^s , where $z_0 = P_q^s y_0 \in \text{ran}(P_q^s) \cap \mathbb{B}_{\delta_0}(|\cdot|_\beta)$. By Lemma 4.2, the fixed point $y_{z_0}^q$ is the mild solution $Y(\cdot; y_0)$ of (2.5) in $\mathbb{B}_\delta(\|\cdot\|)$ of (2.5) with the initial value y_0 . Combined with (4.4) and Remark 2.7, these facts imply (ii).

Take $t_0 > 0$ such that $|y(t_0) + Y_q - Y_0|_\beta \leq \eta$. It is easy to see that $y(t_0 + \cdot)$ still belongs to $\mathbb{B}_\delta(\|\cdot\|)$ and that it is the mild solution of (2.5) with the initial value $y(t_0)$. Moreover, Remark 2.7 (in particular, that $P_q^s \in \mathcal{B}(\mathcal{E}_\beta)$) and (2.15) yield

$$|P_q^s y(t_0)|_\beta \leq C(|y(t_0) + Y_q - Y_0|_\beta + |Y_0 - Y_q|_\beta) \leq C(\eta + q) \leq \delta_0, \quad (4.7)$$

if we choose $\eta > 0$ and q_0 small enough. (Note that the constants are uniform for q in compact intervals and independent of η .) Therefore, $y(t_0) + Y_q$ is contained in \mathcal{M}_q^s thanks to Lemma 4.2. So (i) is shown.

(iii). Take $Y(0) \in Y_0 + \mathbb{B}_\eta(|\cdot|_\beta)$ that satisfies properties (a)–(c) in item (ii). The function $y(t) = Y(t; Y(0)) - Y_q$ is a mild solution of (2.5) with initial value $Y(0) - Y_q$. Using again (2.15), we can estimate

$$|Y(0) - Y_q|_\beta \leq |Y(0) - Y_0|_\beta + |Y_q - Y_0|_q \leq \eta + Cq.$$

Possibly decreasing $\eta, q_0 > 0$, we deduce from conditions (a)–(c) the inequality (3.11) for y and from Remark 2.7 the estimate $|P_q^s(Y(0) - Y_q)|_\beta \leq \delta_0$. Lemma 4.2 now yields that $y(0) \in \text{graph}_{\delta_0} \phi_q$, proving (iii).

(iv). By Theorem 3.14 in [GLS2], we can fix a sufficiently small radius $\eta > 0$ such that for each point $Y(0)$ in the ball $Y_0 + \mathbb{B}_\eta(|\cdot|_\beta; Y_0)$ there exists a shift $q = q(Y(0))$ such that the solution $Y(\cdot; Y(0))$ of (2.2) satisfies properties (a)–(c) of item (ii). We remark that in Theorem 3.14 we can choose the same number $\delta > 0$ as in the current proof and exponents¹ $\nu, \rho > \omega$ which are different from our exponents ν and ρ in (3.13). Item (iii) then implies that $Y(0)$ is contained in \mathcal{M}_q^s . If $Y(0)$ is also an element of $\mathcal{M}_{\bar{q}}^s$ for some $\bar{q} \in [-q_0, q_0]$, then the corresponding solution y would converge both to Y_q and $Y_{\bar{q}}$ as $t \rightarrow \infty$, and so $q = \bar{q}$. Hence, (iv) holds.

(v). Let $|q|, |\bar{q}| \leq q_0$ and $z_0 \in \mathbb{B}_{\delta_0}(|\cdot|_\beta)$. The maps $q \mapsto P_q^c \in \mathcal{B}(\mathcal{E}_\kappa, \mathcal{E}_\beta)$, $q \mapsto P_q^s \in \mathcal{B}(\mathcal{E}_\kappa)$ and $q \mapsto B_q \in \mathcal{B}(\mathcal{E}_\alpha, \mathcal{E}_0)$ are Lipschitz for $\kappa \in \{\beta, \alpha\}$ due to (2.14) and Remark 2.9. Lemma 3.7 of [GLS2] implies that $\gamma_\alpha Y_0'$ and $\gamma_\alpha^{-1} Y_0'$ are bounded. Using (2.6) and (2.15), we then deduce the estimate

$$|F_q(Y) - F_{\bar{q}}(Y)|_\beta \leq C|Y|_\kappa |q - \bar{q}|$$

for all $Y \in \mathcal{E}_\kappa$ and $\kappa \in \{0, \alpha\}$. In view of (4.2), for (v) it remains to check that the map $q \mapsto y_{z_0}^q =: y_q$ is Lipschitz for $\|\cdot\|$. Since y_q is the fixed point, we infer from (3.9) the identity

$$y_q - y_{\bar{q}} = \Phi_q(y_q, z_0) - \Phi_{\bar{q}}(y_q, z_0) + \Phi_{\bar{q}}(y_q, z_0) - \Phi_{\bar{q}}(y_{\bar{q}}, z_0).$$

¹In (7) of Theorem 3.14 there is a misprint, one has to replace ν by ρ .

By (3.20), the second difference on the right hand side is bounded by $C\delta \|y_q - y_{\bar{q}}\|$ and can thus be absorbed by the left hand side possibly after decreasing $\delta > 0$ once more. To control the other difference, we note that the bounded perturbation theorem and (2.16) imply that $q \mapsto T_q(t) \in \mathcal{B}(\mathcal{E}_\kappa)$ is Lipschitz for $\kappa \in \{0, \alpha\}$ and uniformly for $t \geq 0$ in compact sets, see Corollary 3.1.3 of [P]. To extend this property to \mathbb{R}_+ , let $t \in (n, n+1]$. We write

$$\begin{aligned} T_q(t)P_q^s - T_{\bar{q}}(t)P_{\bar{q}}^s &= (T_q(t-n) - T_{\bar{q}}(t-n))T_q(n)P_q^s + T_{\bar{q}}(t-n)T_q(n)P_q^s (P_q^s - P_{\bar{q}}^s) \\ &\quad + T_{\bar{q}}(t-n) \sum_{k=0}^{n-1} T_q(n-k-1)P_q^s (T_q(1) - T_{\bar{q}}(1))T_{\bar{q}}(k)P_{\bar{q}}^s \\ &\quad + T_{\bar{q}}(t-n)(P_q^s - P_{\bar{q}}^s)T_{\bar{q}}(n)P_{\bar{q}}^s. \end{aligned}$$

In the exponential decay estimate (2.18) for $T_q(t)P_q^s$ we can replace ν by a slightly larger number, see Lemma 3.13 of [GLS2]. This and the above mentioned facts lead to the inequality

$$\|T_q(t)P_q^s - T_{\bar{q}}(t)P_{\bar{q}}^s\|_{\mathcal{B}(\mathcal{E}_\alpha)} \leq Ce^{-\nu t} |q - \bar{q}|, \quad t \geq 0.$$

As in Lemma 3.3 one can now show that

$$\|\Phi_q(z_0, y_q) - \Phi_{\bar{q}}(z_0, y_q)\| \leq C|q - \bar{q}|.$$

Summing up, (v) is true. \square

To conclude, we briefly mention two motivating examples borrowed from [GLS3] that fit our setting. More details can be found in the papers [GLSS] and [GLS2], respectively. We stress, however, that for this type of examples the Hypotheses 2.1, 2.2 and 2.4 (a) can rigorously be verified not in all cases while the absence of the unstable eigenvalues required in Hypothesis 2.4 (b) is usually checked only numerically for certain ranges of the parameter values.

Example 4.3. Gasless combustion. A simple combustion model in one space dimension has been mentioned in the Introduction and is given by the system

$$\partial_t u = \partial_{xx} u + vg(u), \quad \partial_t v = -\beta vg(u),$$

where $g(u) = e^{-\frac{1}{u}}$ if $u > 0$ and $g(u) = 0$ if $u \leq 0$. In this system, u is the temperature, v is the concentration of unburned fuel, g is the unit reaction rate, and $\beta > 0$ is a constant parameter. This system was a primary guiding example in [G, GLS1, GLSS, GLS2, GLS3]. One motivation for looking at this well-studied problem, in which the reactant does not diffuse, was heat-enhanced methods of oil recovery in which the reactant is coke contained in the rock formation, see [AY]. The value $u = 0$ represents the ignition temperature and is also taken to be the background temperature, at which the reaction does not take place.

Clearly, Hypothesis 2.2 is satisfied here. One looks for traveling waves $Y_0 = (u_0, v_0)$ such that $Y_- = (u_-, 0)$ with $u_- > 0$, $Y_+ = (0, 1)$, and $(u_0(x), v_0(x))$ approaches these end states exponentially as $x \rightarrow \pm\infty$. For each $\beta > 0$ there is a unique $c > 0$ for which such a wave exists, cf. [GLS3, §3.2]. This wave represents a combustion front that leaves behind of it high temperature $u_- = 1/\beta$ and no fuel, while in front of it temperature is 0 and there is fuel, with concentration normalized to 1. As discussed in Paragraph 3.2 of [GLS3], Hypothesis 2.10 is true and Hypothesis 2.4 can be verified (partly numerically) for small $\beta > 0$.

We note the lack of diffusion in the second equation which inspired the linear Lemma 3.13 in [GLS2] used to derive the exponential decay (2.18) from the spectral assumptions in Hypothesis (2.4), and the form of the nonlinear term in this and related problems which inspired the triangular and product structure of the nonlinearity in the current paper that follows from Hypothesis 2.2.

Example 4.4. Exothermic-endothermic chemical reactions. A model in which two chemical reactions occur at rates determined by temperature was studied in [SMS, SKMS], see also [GLS2]. One reaction is exothermic (produces heat), the other is endothermic (absorbs heat). The system reads

$$\partial_t y_1 = \partial_{xx} y_1 + y_2 f_2(y_1) - \sigma y_3 f_3(y_1), \quad (4.8)$$

$$\partial_t y_2 = d_2 \partial_{xx} y_2 - y_2 f_2(y_1), \quad (4.9)$$

$$\partial_t y_3 = d_3 \partial_{xx} y_3 - \tau y_3 f_3(y_1). \quad (4.10)$$

Here y_1 is the temperature, y_2 is the quantity of an exothermic reactant, and y_3 is the quantity of an endothermic reactant. The parameters σ and τ are positive, and there are positive constants a_i and b_i such that $f_i(u) = a_i e^{-\frac{b_i}{u}}$ for $u > 0$ and $f_i(u) = 0$ for $u \leq 0$. In [SMS, SKMS] it is shown numerically that in certain parameter regimes there exist traveling wave solutions Y_0 of (4.8)–(4.10) with speed $c > 0$ and the end states $Y_- = (1 - \frac{\sigma}{\tau}, 0, 0)$ and $Y_+ = (0, 1, 1)$. Moreover, both end states are approached at an exponential rate, the zero eigenvalue of the linearization is simple, and there are no other eigenvalues in the right half plane. A rigorous motivation for the existence of such traveling wave is also given in [GLS2, Section 9.2]. Assuming the existence of the traveling wave with these properties, the remaining hypotheses of the current paper are easy to verify.

REFERENCES

- [AY] I. Y. Akkutlu and Y. C. Yortsos, *The dynamics of in-situ combustion fronts in porous media*. Combustion and Flame **134** (2003), 229–247.
- [BJ] P.W. Bates and C.K.R.T. Jones, *Invariant Manifolds for Semilinear Partial Differential Equations*, In: *Dynamics Reported Vol. 2*, Vieweg-Teubner Verlag, 1989, pp. 1–38.
- [BLZ] P. Bates, K. Lu and C. Zeng, *Invariant foliations near normally hyperbolic invariant manifolds for semiflows*. Trans. Amer. Math. Soc. **352** (2000), 4641–4676.
- [BLR] H. Berestycki, B. Larrouturou and J. Roquejoffre, *Mathematical investigation of the cold boundary difficulty in flame propagation theory*. In: *Dynamical Issues in Combustion Theory*, Vol. 35 (Minneapolis, MN, 1989) IMA Vol. Math. Appl., Springer, New York, pp. 37–61, 1991.
- [CHT] X.-Y. Chen, J. Hale and B. Tan, *Invariant foliations for C^1 semigroups in Banach spaces*. J. Differential Equations **139** (1997), 283–318.
- [DL] M. Das and Y. Latushkin, *Derivatives of the Evans function and (modified) Fredholm determinants for first order systems*. Math. Nachr. **284** (2011), 1592–1638.
- [F] P. Fife, *Pattern formation in gradient systems*. In: *Handbook of Dynamical Systems Vol. 2*, North-Holland, Amsterdam, 2002, pp. 677–722.
- [G] A. Ghazaryan, *Nonlinear stability of high Lewis number combustion fronts*. Indiana Univ. Math. J. **58** (2009), 181–212.
- [GLS1] A. Ghazaryan, Y. Latushkin and S. Schechter, *Stability of traveling waves for degenerate systems of reaction diffusion equations*. Indiana Univ. Math. J. **60** (2011), 443–472.
- [GLSS] A. Ghazaryan, Y. Latushkin, S. Shechter and A. de Souza, *Stability of gasless combustion fronts in one-dimensional solids*. Archive Rational Mech. Anal. **198** (2010), 981–1030.
- [GLS2] A. Ghazaryan, Y. Latushkin and S. Shechter, *Stability of traveling waves for a class of reaction-diffusion systems that arise in chemical reaction models*. SIAM J. Math. Anal. **42** (2010), 2434–2472.

- [GLS3] A. Ghazaryan, Y. Latushkin and S. Shechter, *Stability of traveling waves in partly hyperbolic systems*. Math. Model. Nat. Phenom. **8** (2013), 32–48.
- [GSM] V.V. Gubernov, H.S. Sidhu and G.N. Mercer, *Combustion waves in a model with chain branching reaction and their stability*. Combust. Theory Model. **12** (2008), 407–431.
- [KP] T. Kapitula and K. Promislow, *Spectral and dynamical stability of nonlinear waves*. Appl. Math. Sci. **185**, Springer, New York, 2013.
- [K] T. Kato, *Perturbation Theory for Linear Operators*. Springer-Verlag, New York, 1966.
- [LL] Y. Latushkin and B. Layton, *The optimal gap condition for invariant manifolds*. Discrete Contin. Dyn. Syst. **5** (1999), 233–268.
- [LPS1] Y. Latushkin, J. Prüss and R. Schnaubelt, *Stable and unstable manifolds for quasilinear parabolic systems with fully nonlinear boundary conditions*. J. Evol. Equ. **6** (2006), 535–576.
- [LPS2] Y. Latushkin, J. Prüss and R. Schnaubelt, *Center manifolds and dynamics near equilibria of quasilinear parabolic systems with fully nonlinear boundary conditions*. Discrete Contin. Dyn. Syst. Ser. B **9** (2008), 595–633.
- [LW] Y. Li and Y. Wu, *Stability of traveling front solutions with algebraic spatial decay for some autocatalytic chemical reaction systems*. SIAM J. Math. Anal. **44** (2012), 1474–1521.
- [Lu] A. Lunardi, *Analytic semigroups and optimal regularity in parabolic problems*. Birkhäuser, Basel, 1995.
- [MS] B. Matkowsky and G. Sivashinsky, *Propagation of a pulsating reaction front in solid fuel combustion*. SIAM J. Appl. Math. **35** (1978), 465–478.
- [Pa] K. Palmer, *Exponential dichotomy and Fredholm operators*, Proc. Amer. Math. Soc. **104** (1988), 149–156.
- [P] P. Pazy, *Semigroups of Linear Operators and Applications to Partial Differential Equations*. Springer-Verlag, New York, 1983.
- [PW] R.L. Pego and M.I. Weinstein, *Asymptotic stability of solitary waves*. Comm. Math. Phys. **164** (1994), 305–349.
- [RM1] J. Rottmann-Matthes, *Computation and Stability of Patterns in Hyperbolic-Parabolic Systems*. Shaker Verlag, Aachen, 2010.
- [RM2] J. Rottmann-Matthes, *Linear stability of travelling waves in first-order hyperbolic PDEs*. J. Dynam. Differential Equations **23** (2011), 365–393.
- [RM3] J. Rottmann-Matthes, *Stability of parabolic-hyperbolic traveling waves*. Dynamics of Part. Diff. Eqns. **9** (2012), 29–62.
- [Sa] B. Sandstede, *Stability of travelling waves*, In: *Handbook of Dynamical Systems Vol. 2*, North-Holland, Elsevier, Amsterdam, 2002, pp. 983–1055.
- [SS] B. Sandstede and A. Scheel, *Absolute and convective instabilities of waves on unbounded and large bounded domains*. Phys. D **145** (2000), 233–277.
- [S] D. H. Sattinger, *On the stability of waves of nonlinear parabolic systems*. Adv. Math. **22** (1976), 312–355.
- [SMS] P. Simon, J. Merkin and S. Scott, *Bifurcations in non-adiabatic flame propagation models*, Focus on Combustion Research (2006), 315–357.
- [SKMS] P. Simon, S. Kalliadasis, J.H. Merkin and S.K. Scott, *On the structure of the spectra for a class of combustion waves*. J. Math. Chem. **35** (2004), 309–328.
- [T] D. Terman, *Traveling wave solutions arising from a two-step combustion model*. SIAM J. Math. Anal. **19** (1988), 1057–1080.
- [VV] F. Varas and J. Vega, *Linear stability of a plane front in solid combustion at large heat of reaction*. SIAM J. Appl. Math. **62** (2002), 1810–1822.
- [VVV] A. Volpert, V. Volpert and V. Volpert, *Traveling Wave Solutions of Parabolic Systems*. American Mathematical Society, Providence (RI), 1994.
- [TZKS] J.-C. Tsai, W. Zhang, V. Kirk and J. Sneyd, *Traveling waves in a simplified model of calcium dynamics*. SIAM J. Appl. Dyn. Systems **11** (2012), 1149–119.
- [X] J. Xin, *Front propagation in heterogeneous media*. SIAM Review **42** (2000), 161–230.

RS, DEPARTMENT OF MATHEMATICS, KARLSRUHE INSTITUTE OF TECHNOLOGY, 76128 KARLSRUHE, GERMANY

E-mail address: `schnaubelt@kit.edu`

URL: `http://www.math.kit.edu/iana3/~schnaubelt/`

XY, DEPARTMENT OF MATHEMATICS, UNIVERSITY OF MISSOURI, COLUMBIA, MO 65211, USA

E-mail address: `xywp8@mail.mizzou.edu`