Analysis, Modeling and Simulation of Multiscale Problems

Exponential Averaging of Rapid Quasiperiodic Forcing

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1 Introduction

Averaging and homogenisation principles are widely used to derive effective models for systems containing fast scales in their original description. These descriptions are usually ordinary or partial differential equations with explicit dependencies on fast variables, examples reach from celestial mechanics to elasticity and nonlinear optics. Two main approaches for the averaging of multiscale problems can be identified: one is based on weak convergence methods (see e.g. [Tar79, Tar86, Bor98, JKO94]), but which usually do not prove a quantitative error estimate for the approximation by the effective system. The other method is based on formal or rigorous asymptotic expansions in small parameters, e.g. the period of a rapid external excitation or the length scale of a microstructure. Quantitative estimates can be obtained but the class of problems is more restrictive than for weak convergence methods: The estimates are often only restricted to fast periodic forcing and are still only to a finite order in the small parameter, see e.g. [AKN97, BLP84, BP89, JKO94, LM88].

When expanding finite order procedures into a series, even for analytic ordinary differential equations one cannot expect convergence in general. But still beyond a finite asymptotic analysis there are estimates of exponential order giving upper estimates on the divergence effects for analytic ordinary differential equations. The first results of this type were by Nekhoroshev for the perturbation of fully integrable Hamiltonian equations [Nek79] and by Neishtadt for the periodic forcing of analytic differential equations [Nei84]. The approach by Neishtadt is to transform the differential equation by some periodic coordinate change such that the remainder term is small, i.e. an equation like

$$\dot{u} = f(u, t/\varepsilon)$$

is transformed to

$$\dot{v} = \bar{f}(u; \varepsilon) + r(u, t/\varepsilon; \varepsilon)$$

where the remainder is exponentially small in ε on bounded domains:

$$|r(v)| \leq C \exp(-c/\varepsilon)$$

Simó [Sim94] extended this to rapid quasiperiodic forcing

$$\begin{aligned} \dot{u} &= f(u,\theta) \\ \dot{\theta} &= \frac{1}{\varepsilon}\omega, \end{aligned}$$

where $\theta \in T^p = (\mathbb{R}/\mathbb{Z})^p$ and where the frequency vector fulfils some Diophantine conditions to control small denominators, that appear in the analysis: $|(\omega, m)| > C|m|^\tau$ for some $\tau > p-1$. Since KAM theory, Diophantine conditions appear often in the dynamical systems literature, for references see e.g. [AKN97]. Then again one can construct for analytic right-hand sides a coordinate change, such that the remainder term is exponentially small

$$\begin{aligned} \dot{v} &= \bar{f}(v;\varepsilon) + r(v,\theta;\varepsilon) \\ \dot{\theta} &= \frac{1}{\varepsilon}\omega, \end{aligned}$$

with $|r(v)| \le C\exp(-c/\varepsilon^{\frac{1}{\tau+1}})$.

Extending such results to partial differential equations has several obstacles. Considering as an example some scalar reaction-diffusion equation

$$u_t = u_{xx} + f(u, t/\varepsilon) \tag{1.1}$$

with periodic boundary condition in $[0,1]$. Firstly the right-hand side is not continuous or even bounded on any sensible phase space, whereas analyticity is crucial in all the above results. Furthermore the class of allowed transformation is much smaller, when we want to preserve the semilinear structure of the equation. Using the regularisation property of (1.1) it was possible to extend the Neishtadt results to a class of periodicly forced parabolic partial differential equations in [Mat01], where obtained a different exponential estimate of order $\exp(-c/\varepsilon^{1/3})$. In [MS03], we extended the results to a wider class of evolution equations with a rapid one-degree of freedom forcing, there the attention is restricted to highly regular initial data, instead of using the regularisation properties of (1.1). Again we obtain different exponential estimates and we also provide lower estimates for an example, showing the different exponential behaviour of ordinary and partial differential equations. For results in the direction of Nekhoroshev estimates, see e.g. [Bam99, Poe99].

In this paper we give finite order and exponential order averaging results for partial differential equations under temporal quasi-periodic forcing for highly regular initial data and for general initial data of regularising equations. We will assume Diophantine conditions on the frequency vectors, which are crucial in our estimates. Similar Diophantine conditions were also used in the spatial homogenisation of semilinear parabolic equation in [FV01] and for some low order temporal averaging results in [EZ03]. This paper does not only differ from [Mat01, MS03] in separate methods to remove and estimate periodic and quasiperiodic forcings. In contrast to these papers, we are also provide examples, where the rapid dependencies are in the main part. Furthermore we give an explicit example showing the spatial nonlocality of averaging in partial differential equations.

The paper is organised in the following way. In section 2, we state our main theorems on finite order and exponential averaging. In section 3 we first explain the general procedure underlying both proofs before giving the details of each separately. A number of examples including regularising reaction-diffusion equations and Nonlinear Schrödinger equations are discussed in section 4.

2 Main results

We state our main results on higher-order and exponential averaging of abstract infinite dimensional evolution equations with fast external quasiperiodic forcing. First we introduce notation used throughout, then we state the averaging theorems in the cases (A) of finite regularity, case (B) in the analytic setting.

We consider abstract evolution equations. Let X be a real Banach space, let A be a closed densely defined, possibly unbounded, operator with domain $D(A)$ generating a strongly continuous semigroup. We denote by $T^p = (\mathbb{R}/\mathbb{Z})^p$ the p-dimensional torus, on which the quasiperiodic motion is given by a parallel flow. On the phase space $X \times T^p$ we analyse

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}u &= Au + f(u) + g(u, \theta, \varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{2.1}$$

with initial conditions $u(0) = u_0; \theta(0) = \theta_0$ and $u \in X$, $\theta \in T^p$ and $\varepsilon > 0$ the small real parameter. The regularity assumptions on $f : X \to X$ and $g : X \times T^p \times \mathbb{R} \to X$ will be stated below.

A key assumption is that we can approximate by (not necessarily finite-dimensional) ordinary differential equations.

Hypothesis 2.1 *We assume, that there exists a sequence of (Galerkin) projections $(P_N)_{N\in\mathbb{N}}$ which satisfy the following requirements:*

(i) the sequence of projections converges strongly to the identity on X,

$$\lim_{N\to\infty} P_N u = u \textit{ in } X \textit{ for all } u \in X;$$

(ii) the projections P_N commute with A on its domain of definition

$$P_N A u = A P_N u \textit{ for all } u \in D(A);$$

(iii) the operator A is bounded on $\mathrm{Rg}\, P_N$

$$|AP_N u|_X \leq N |P_N u|_X \textit{ for all } u \in X.$$

The next assumption is needed to control small denominators and resonances.

Hypothesis 2.2 (Diophantine condition) *There exist constants $\gamma > 0$ and $\tau > p-1$ such that for all $m \in \mathbb{Z}^p$*

$$|(m,\omega)| \geq \gamma |m|^{-\tau} \tag{2.2}$$

where $(,)$ is the inner product on $\mathbb{R}^p$ and $|m| = \sum_{j=1}^{p} |m_j|$ is the norm of m. In the periodic case $p = 1$ this is $\omega \neq 0$.

Hypothesis 2.3 (Zero mean) *For all ε and $u \in X$ the quasi-periodic term has zero mean*

$$\int_{\theta \in T^p} g(u,\theta,\varepsilon) \mathrm{d}\theta = 0$$

As we will not assume fixed smoothing assumptions on the equations, we consider spaces of regular initial data. We could define them as the domains of $D(|A|^\alpha)$ or Gevrey spaces like $D(\exp(\sigma|A|^\nu)$, but it may require some work to define $|A|$, so we assume the existence of maps Λ_α or $\Gamma_{\sigma,\nu}$, which essentially behave like $|A|^\alpha$ and $\exp(\sigma|A|^\nu)$ respectively:

Hypothesis 2.4 (Higher order approximation) *Assume that there exists a closed, densely defined, boundedly invertible operator Λ_α for $\alpha \geq 1$ with domain of definition*

$$\mathcal{Y}_\alpha := D(\Lambda_\alpha) \subset D(A), \tag{2.3}$$

such that $\operatorname{Rg} P_N \subset \mathcal{Y}_\alpha$, $\Lambda_\alpha(\operatorname{Rg} P_N) = \operatorname{Rg} P_N$ for all N, and $\Lambda_\alpha A u = A \Lambda_\alpha u$, for all $u \in \operatorname{Rg} P_N$. We equip the spaces $\mathcal{Y}_\alpha$ with the graph norm

$$|u|_{\mathcal{Y}_\alpha} = |u|_X + |\Lambda_\alpha u|_X. \tag{2.4}$$

We assume that the functions in $\mathcal{Y}_\alpha$ have higher algebraic order approximations by the Galerkin projections P_N

$$|\Lambda_\alpha^{-1}(id - P_N)| \leq C_0 N^{-\alpha}, \tag{2.5}$$

for the N-independent constant $C_0(\alpha)$.

Hypothesis 2.5 (Exponential approximation) *Assume that there exists a closed, densely defined, boundedly invertible operator $\Gamma_{\sigma,\nu}$ with domain of definition*

$$\mathcal{G}_{\sigma,\nu} := D(\Gamma_{\sigma,\nu}) \subset D(A), \tag{2.6}$$

such that $\operatorname{Rg} P_m \subset \mathcal{G}_{\sigma,\nu}$, $\Gamma_{\sigma,\nu}(\operatorname{Rg} P_N) = \operatorname{Rg} P_N$ for all N, and $\Gamma_{\sigma,\nu} A u = A \Gamma_{\sigma,\nu} u$, for all $u \in \operatorname{Rg} P_N$. We equip the Gevrey spaces $\mathcal{G}_{\sigma,\nu}$ with the graph norm

$$|u|_{\mathcal{G}_{\sigma,\nu}} = |u|_X + |\Gamma_{\sigma,\nu} u|_X. \tag{2.7}$$

We assume that Gevrey-smooth functions in $G_{\sigma,\nu}$ are exponentially well approximated by the Galerkin projections P_N

$$|\Gamma_{\sigma,\nu}^{-1}(id - P_N)| \leq C_0 \exp(-c_0/N^\nu), \tag{2.8}$$

for N-independent constants $C_0(\sigma,\nu)$ and $c_0(\sigma,\nu)$.

For sectorial operators like the Laplacian $A = \Delta$ on regular domains, the higher regularity spaces $\mathcal{Y}_\alpha$ can be defined as a fractional power space, and the Gevrey space by letting $\Gamma_{\sigma,\nu} = \exp(\sigma(-A)^\nu)$. In some cases it is then possible to prove high regularity after a transient for a wide class of initial data, see section 4.1. For nonlinear Schrödinger equation we can use $\Gamma_{\sigma,\nu} = \exp(\sigma|A|^\nu)$ with $A = \mathrm{i}\Delta$ on $H^s(\mathbb{R},\mathbb{C})$.

Next we make the regularity assumptions on the nonlinearities precise

Hypothesis 2.6 (Finite regularity) *The nonlinearities $f : Y \to Y, g : Y \times T^p \times \mathbb{R} \to Y$ are C^ℓ with the C^ℓ norm bounded on balls $B_R(Y)$ of radius R independent of ε: $\|f\|_{C^\ell(B_R(Y),Y)} \leq C(R,\ell), \|g\|_{C^\ell(B_R(Y)\times T^p\times[0,\varepsilon_0],Y)} \leq C(R,\ell)$ for both $Y = X$ and $Y = \mathcal{Y}_\alpha$.*

To make analyticity precise we extend our function spaces to complex Banach spaces in the standard way. For a general Banach space Y we denote by

$$Y_\mathbb{C} = Y \times Y$$

the standard complexification $u = u_1 + \mathrm{i}u_2$ with norm $|(u_1,u_2)|^2_{Y_\mathbb{C}} = |u_1|^2_Y + |u_2|^2_Y$. Complexification of the torus is understood as the quotient of the complexification of the real space $\mathbb{R}^p$ to $\mathbb{C}^p$ by real integer translations $T^p_\mathbb{C} := (\mathbb{C}/\mathbb{Z})^p$.

Analyticity properties of functions are quantified by the help of extensions to the complexified domain. We therefore introduce a short notation. For any open subset U of a Banach space Y, we define the open complex δ-extension $U + \delta$ for any $\delta > 0$ by

$$U + \delta := \{y \in Y_\mathbb{C} | \inf_{u\in U} |u - y|_Y < \delta\}. \tag{2.9}$$

Smoothness properties of the nonlinearities can now be made precise.

Hypothesis 2.7 (Analyticity of nonlinearities) *There is a Gevrey class $Y = \mathcal{G}_{\sigma,\nu}$ with $\sigma,\nu > 0$ and a constant $\delta > 0$ for the size of the complex extension such that the following properties of the nonlinearities hold.*

The nonlinearities are analytic and bounded on bounded subsets when considered on Gevrey spaces, extended in the complex direction, $f : (Y + \delta) \to Y_\mathbb{C}; g : (Y + \delta) \times (T^p + \delta) \times \mathbb{R} \to Y_\mathbb{C}$. In addition, all of the above statements are assumed to hold when the space of Gevrey regularity $Y = \mathcal{G}_{\sigma,p}$ is replaced by $Y = X$.

To deduce results about the semigroup of solutions of equation (2.1) and, not only the equation, we will assume well-posedness

Hypothesis 2.8 (Well-posedness on $\mathcal{Y}_\alpha$) *The operator A generates a strongly continuous semigroup both on X and $\mathcal{Y}_\alpha$.*

Hypothesis 2.9 (Well-posedness on $\mathcal{G}_{\sigma,\nu}$) *The operator A generates a strongly continuous semigroup both on X and $\mathcal{G}_{\sigma,\nu}$.*

Theorem A (Finite regularity) *Assume Hypothesis 2.1 on the existence of bounded approximations, Hypothesis 2.2 on the Diophantine conditions on the frequency vector ω with constants γ and τ, Hypothesis 2.3 on the zero mean, Hypothesis 2.4 on the higher order approximation and Hypothesis 2.6 on the regularity for some fixed space $\mathcal{Y}_\alpha$ and some fixed differentiability level ℓ.*

Then, for any ball of radius R in $\mathcal{Y}_\alpha$ there exists an $\varepsilon_0 > 0$, such that for $0 < \varepsilon < \varepsilon_0$ the following holds.

There exists a C^1 transformation $u = v + \varepsilon w(v, \theta, \varepsilon)$, which is near to the identity both in X and $\mathcal{Y}_\alpha$, such that the transformed equation has the form

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} v &= Av + f(v) + \bar{g}(v, \varepsilon) + r(v, \theta, \varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{2.10}$$

with initial conditions $v(0) = u_0; \theta(0) = \theta_0$ and with $\bar{g}$ and r both bounded on balls in X, furthermore

$$|\bar{g}(v, \varepsilon)|_X \leq C_{\alpha,l}(|v|_{\mathcal{Y}_\alpha})\varepsilon^{\min\left(\frac{q(\ell)}{q(\ell)+\alpha}, \frac{\alpha}{q(\ell)+\alpha}\right)} \tag{2.11}$$

$$|r(v, \theta, \varepsilon)|_X \leq C_\alpha(|v|_{\mathcal{Y}_\alpha})\varepsilon^{\frac{q(\ell)\alpha}{q(\ell)+\alpha}}, \tag{2.12}$$

where in the exponent $q(\ell)$ is the integer part of $\ell/(\tau + p)$. Assume also Hypothesis 2.8 on well-posedness, then the solutions of the truncated equation

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} \bar{v} &= A\bar{v} + f(\bar{v}) + \bar{g}(\bar{v}, \varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{2.13}$$

with initial conditions $\bar{v}(0) = u_0; \theta(0) = \theta_0$, remain close to the solutions of the transformed equation (2.10): Suppose one of the solutions $v(t)$ or $\bar{v}(t)$ of (2.10) resp. (2.13) remains inside the ball $B_R(\mathcal{Y}_\alpha)$ for $0 \leq t \leq T$, then there exists a constant $C(T, R)$ such that

$$|v(t) - \bar{v}(t)|_X \leq C(T, R)\varepsilon^{\frac{q(\ell)\alpha}{q(\ell)+\alpha}}. \tag{2.14}$$

Theorem B (Analyticity) *Assume Hypothesis 2.1 on the existence of bounded approximations, Hypothesis 2.2 on the Diophantine conditions on the frequency vector ω with constants γ and τ, Hypothesis 2.3 on the zero mean, Hypothesis 2.5 on the exponential approximation and Hypothesis 2.7 on the analyticity regularity for some fixed space $\mathcal{G}_{\sigma,\nu}$.*

Then, for any ball of radius R in $\mathcal{G}_{\sigma,\nu}$ there exists an $\varepsilon_0 > 0$, such that for $0 < \varepsilon < \varepsilon_0$ the following holds.

There exists a C^1 near identity transformation of both $\mathcal{G}_{\sigma,\nu}$ and X such that the transformed equation has the form

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}v &= Av + f(v) + \bar{g}(v,\varepsilon) + r(v,\theta,\varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{2.15}$$

with initial conditions $v(0) = u_0; \theta(0) = \theta_0$ and with $\bar{g}$ and r both bounded on balls in X, furthermore the remainder term is exponentially small on balls of the Gevrey space.

$$|\bar{g}(v,\varepsilon)|_X \leq C\varepsilon^{(\tau+1)/(\tau+1+1/\nu)} \tag{2.16}$$

$$|r(v,\theta,\varepsilon)|_X \leq C(|v|_{\mathcal{G}_{\sigma,\nu}})\exp(-c\varepsilon^{-1/(\tau+1+1/\nu)}). \tag{2.17}$$

Assume also Hypothesis 2.9 on well-posedness in X and in the Gevrey class $\mathcal{G}_{\sigma,\nu}$, then the solutions of the truncated equation

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\bar{v} &= A\bar{v} + f(\bar{v}) + \bar{g}(\bar{v},\varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{2.18}$$

with initial condition $\bar{v}(0) = u_0; \theta(0) = \theta_0$ remain close to the solutions of the transformed equation (2.15): Suppose one of the solutions $v(t)$ or $\bar{v}(t)$ of (2.15) resp. (2.18) remains inside the ball $B_R(\mathcal{G}_{\sigma,\nu})$ for $0 \leq t \leq T$, then there exists a constant $C(T,R)$ such that

$$|v(t) - \bar{v}(t)|_X \leq C(T,R)\exp(-c\varepsilon^{-1/(\tau+1+1/\nu)}). \tag{2.19}$$

Remark 2.10 *(i) In partial differential equations with local pointwise evaluation of the nonlinearities $f(u)(x) = f(u(x))$ the corrector $\bar{g}$ and the remainder are in general nonlocal operators, mapping the phase spaces X, $\mathcal{Y}_\alpha$ and $\mathcal{G}_{\sigma,\nu}$ into themselves. We show, that the use of nonlocal transformations is already necessary for low order averaging of an example in section 4.3.*

(ii) For periodic forcing, $p = 1$, there is not a small denominator problem and it is possible to choose $\tau = 0$ and still obtain the same estimate and g then only needs to be continuous in θ, see [MS03].

(iii) The transformation w is defined iteratively and for fixed $\varepsilon > 0$, it transforms only a Galerkin approximation space of finite index. Each step in this space corresponds to the formal removing of the lowest order term in ε.

(iv) For equations with bounded A, giving an ordinary differential equation on possibly infinite dimensional spaces, it is possible with a small variation of the proof to obtain the results with formally $\alpha = \infty$ resp. $\nu = \infty$. In the analytic case we recover Simó's result [Sim94] on exponential averaging of quasiperiodic ODE with a remainder estimate of order $\exp(-c\varepsilon^{-1/(\tau+1)})$. *In the finite regularity case we obtain $|r| \le C\varepsilon^{q(\ell)}$ and $|\bar{g}| \le C\varepsilon$.*

(v) Lower exponential estimates are an intriguing problem. Some lower estimates in the periodic case $p = 1$ can be found in [MS03].

3 Approximation and Averaging

The general procedure to prove both theorems is similar. Using Hypothesis 2.1 we will use approximations by ordinary differential equations on $P_N X$. In these equations we remove the quasiperiodic part by a number of near-identity transformations of the approximation space. Formally we increase the order in ε of the remaining quasiperiodic terms by one in each transformation, but in general this process diverges even in the analytic case. Rigorous estimates depend on the regularity of the right hand side. The magnitude of the contribution by the complement of $P_N X$ is estimated using the higher regularity, that we assume on the initial conditions in Hypothesis 2.4 and 2.5. The number of transformations and the approximation space $P_N X$ will be chosen depending on the regularity class (Theorem A resp. B) and ε to simultaneously minimise the two contributions of the quasiperiodic remainder term:

- the remainder of the averaging procedure of the ordinary differential equation
- the remainder due to the Galerkin approximation.

So we will first describe the formal averaging procedure in the approximation space and its extension to the full space common in both proofs. The estimates and the choices of index N and the number of averaging steps j^* are then given separately below.

So consider equation (2.1) for $(u_N, \theta) \in P_N X \times T^p$

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} u_N &= A u_N + P_N f(u_N) + P_N g(u_N, \theta, \varepsilon) \\ \frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega \end{aligned} \tag{3.1}$$

with projected initial conditions $u_N(0) = P_N u_0; \theta(0) = \theta_0$. Suppose we already performed j transformation steps and we have an equation of the form

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t} u_N &= A u_N + P_N f(u_N) + \bar{g}_j(u_N, \varepsilon) + \tilde{g}_j(u_N, \theta, \varepsilon) \\
\frac{d}{dt}\theta &= \frac{1}{\varepsilon}\omega,
\end{aligned} \tag{3.2}$$

where $\int_{T^d} \tilde{g}_j(u_N, \theta, \varepsilon)\mathrm{d}\theta = 0$. For $j = 0$ we have $\bar{g}_j = 0$ and $\tilde{g} = P_N g$ by Hypothesis 2.3. Then the next transformation is given terms of the temporal Fourier expansion of the remainder term. Letting

$$\tilde{g}_j(u_N, \theta, \varepsilon) = \sum_{m \in \mathbb{Z}^p} \tilde{g}_{jm}(u_N, \varepsilon) \exp(\mathrm{i}2\pi(m, \theta))$$

then we transform $u_N = v_N + \varepsilon w_j(v_N, \theta, \varepsilon)$ with

$$w_j = \sum_{m \in \mathbb{Z}^p} \frac{\tilde{g}_{jm}(v_N, \varepsilon)}{2\pi \mathrm{i}(m, \omega)} \exp(\mathrm{i}2\pi(m, \theta)) \tag{3.3}$$

Then, suppressing arguments of w_j as far as possible, the transformed equation is given by

$$\begin{aligned}
&\left(id + \varepsilon \frac{\partial}{\partial v_N} w_j(v_N, \theta, \varepsilon)\right) \dot{v}_N + \varepsilon \frac{\partial}{\partial \theta} w_j(v_N, \theta, \varepsilon)\dot{\theta} \\
= \;& A v_N + P_N f(v_N) + \bar{g}_j(v_N, \varepsilon) + \tilde{g}_j(v_N, \theta, \varepsilon) \\
& + \varepsilon A w_j + P_N f(v_N + \varepsilon w_j) - P_N f(v_N) \\
& + \bar{g}_j(v_N + \varepsilon w_j, \varepsilon) - \bar{g}_j(v_N, \varepsilon) \\
& + \tilde{g}_j(v_N + \varepsilon w_j, \theta, \varepsilon) - \tilde{g}_j(v_N, \theta, \varepsilon).
\end{aligned} \tag{3.4}$$

Hence on a formal level we remove the largest quasiperiodic term $\tilde{g}_j(v_N, \theta, \varepsilon)$. Rigorously the transformed equation is then rewritten as

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t} v_N &= A u_N + P_N f(v_N) + \bar{g}_{j+1}(v_N, \varepsilon) + \tilde{g}_{j+1}(v_N, \theta, \varepsilon) \\
\frac{\mathrm{d}}{\mathrm{d}t}\theta &= \frac{1}{\varepsilon}\omega
\end{aligned}$$

with $\int_{T^p} \tilde{g}_{j+1}(u_N, \theta, \varepsilon) d\theta = 0$ for all u_N and ε. Using the cancellations due to the choice of w_j we have

$$\begin{aligned}
\bar{g}_{j+1}(v_N) &= \bar{g}_j(v_N) + \int_{T^p} r_j(v_N, \theta, \varepsilon)\mathrm{d}\theta \\
\tilde{g}_{j+1}(v_N) &= r_j(v_N, \theta, \varepsilon) - \int_{T^p} r_j(v_N, \theta, \varepsilon)\mathrm{d}\theta
\end{aligned}$$

with $(id + \varepsilon \frac{\partial}{\partial v_N} w_j)^{-1} = id - (id + \varepsilon \frac{\partial}{\partial v_N} w_j)^{-1} \varepsilon \frac{\partial}{\partial v_N} w_j$ the remainder term can be expressed as

$$\begin{aligned}
r_j = \;& (id + \varepsilon \frac{\partial}{\partial v_N} w_j)^{-1} \Big\{ \varepsilon \frac{\partial}{\partial v_N} w_j (A v_N + P f(v_N) + \bar{g}_j(v_N, \varepsilon)) \\
& + \varepsilon A w_j + P_N f(v_N + \varepsilon w_j) - P_N f(v_N) \\
& + \bar{g}_j(v_N + \varepsilon w_j, \varepsilon) - \bar{g}_j(v_N, \varepsilon) \\
& + \tilde{g}_j(v_N + \varepsilon w_j, \theta, \varepsilon) - \tilde{g}_j(v_N, \theta, \varepsilon) \Big\}
\end{aligned} \tag{3.5}$$

After performing j^* transformations

$$u_N = (id + \varepsilon w_{j^*}) \circ (id + \varepsilon w_{j^*-1}) \circ \ldots \circ (id + \varepsilon w_1) v_N = (id + \varepsilon w) v_N,$$

we obtain a transformation of equation (3.1) to

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} v_N &= A v_N + P_N f(v_N) + \bar{g}_{j^*}(v_N, \varepsilon) + \tilde{g}_{j^*}(v_N, \theta, \varepsilon) \\ \frac{\mathrm{d}}{\mathrm{d}t} \theta &= \frac{1}{\varepsilon} \omega \end{aligned} \tag{3.6}$$

still with projected initial data $v_N(0) = P_N u_0; \theta(0) = \theta_0$. We extend this to the full space by

$$u = v + \varepsilon P_N w(P_N v)$$

This yields

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} v &= A v + f(v) + \bar{g}_{j^*}(P_N v, \varepsilon) + \tilde{g}_{j^*}(P_N v, \theta, \varepsilon) + r^*(v, \theta, \varepsilon) \\ \frac{\mathrm{d}}{\mathrm{d}t} \theta &= \frac{1}{\varepsilon} \omega \end{aligned}$$

with initial data $v(0) = u_0; \theta(0) = \theta_0$, and where the additional remainder term is given by

$$\begin{aligned} r^*(v, \theta, \varepsilon) &= (id - P_N)\{f(v + \varepsilon w(P_N v)) - f(v) + g(v + \varepsilon w(P_N v), \theta, \varepsilon) - g(v, \theta, \varepsilon)\} && (3.7) \\ &\quad + P_N\{f(v + \varepsilon w(P_N v)) - f(P_N v + \varepsilon w(P_N v)) && (3.8) \\ &\qquad + g(v + \varepsilon w(P_N v), \theta, \varepsilon) - g(P_N v + \varepsilon w(P_N v), \theta, \varepsilon)\} \end{aligned}$$

Its X-norm can be estimated directly by $C|v - P_N v|_X$, which again can be estimated using the higher regularity in Hypothesis 2.4 and 2.5.

With the estimates on the right-hand side of the equation we can then prove the estimates on solution by a Gronwall argument. The difference $y(t) = v(t) - \bar{v}(t)$ satisfies the equation

$$\frac{\mathrm{d}}{\mathrm{d}t} = A(t) y + h(t) \tag{3.9}$$

with $A(t) = A + \int_0^1 (\partial_v (f + \bar{g})(s\bar{v} + (1-s)v) \mathrm{d}s$ and $h(t) = r(v(t)) - r(v(\bar{t}))$. As f, $\bar{g}$ and r possess bounded derivatives on bounded sets of $\mathcal{G}_{\sigma,\nu}$ or $\mathcal{Y}_\alpha$, the estimates follow then by the Gronwall lemma. The estimates on r hold in the X-topology only, then the Gronwall lemma only holds in X, as well.

In order to prove theorem A and B we have especially to estimate $\tilde{g}_{j^*}$ and the error term $r^*(v, \theta, \varepsilon)$

3.1 Proof of Theorem A

Before we can estimate the remainder terms, we have to ensure that the formal transformations are well-defined, i.e. that we can control the small denominator in (3.3) for $1 \leq j \leq j^*$. We will choose

$j^* = \left[\frac{\ell}{\tau+p}\right]$ independent of ε and N, where the Gaußfunction $[y]$ denotes largest integer smaller or equal y. Consider the first averaging of (3.1) then

$$w_1(v,\theta,\varepsilon) = \sum_{m\in\mathbb{Z}^p} \frac{g_m(v)}{2\pi\mathrm{i}(m,\omega)} \exp(2\pi\mathrm{i}(m,\theta)) \tag{3.10}$$

with $g_m(v) = \int_{T^p} g(v,\theta,\varepsilon)\exp(2\pi\mathrm{i}(m,\theta))\mathrm{d}\theta$. Partially integrating we obtain

$$|g_m(v)| = |\int_{T^p} (2\pi m_1)^{-1}\partial_{\theta_1} g(v,\theta,\varepsilon)\exp(2\pi\mathrm{i}(m,\theta))\mathrm{d}\theta|$$

repeating this ℓ times with the components of $\theta = (\theta_1, \dots \theta_p)$ we obtain

$$|g_m(v)| \le C|m|_\infty^{-\ell} \le C|m|^{-\ell}$$

Using the Diophantine condition of Hypothesis 2.2 we see for the ν^{th} derivative of w_1 with respect to θ:

$$|\left(\frac{\partial}{\partial\theta}\right)^\nu w_1(v,\theta,\varepsilon)| = \sum_{m\in\mathbb{Z}^p} C|m|^{-\ell+\nu+\tau} < \infty \quad \text{for } -\ell+\tau+\nu < -p.$$

Thus w_1 is $[\ell-(\tau+p)]$ times differentiable with respect to θ. Then $\tilde{g}_1$ is $[\ell-(\tau+p)]$ times differentiable and inductively w_j is $[\ell - j(\tau+p)]$ differentiable.

Assuming boundedness of g in the C^ℓ norms as in Hypothesis 2.6 by a constant $C(R)$ on both spaces $Y = X$ and $Y = \mathcal{Y}_\alpha$, there exists $\varepsilon_0 > 0$ such that for all $0 < \varepsilon < \varepsilon_0$ the first transformation is well-defined. The first remainder term and its derivatives up to $\nu = [\ell-(\tau+p)]$ can then be estimated on $P_N Y$ by

$$\begin{aligned} \|\tilde{g}_1\|_{BC^\nu(B_R(Y)\times T^p,Y)} &\le \varepsilon NC(R) + \varepsilon\|P_N f\|_{BC^\nu(B_R(Y),Y)}C(R) \\ \|\bar{g}_1\|_{BC^\nu(B_R(Y),Y)} &\le \varepsilon NC(R) + \varepsilon\|P_N f\|_{BC^\nu(B_R(Y),Y)}C(R) \end{aligned}$$

We then proceed inductively for εN small compared to $C(R)$ for a fixed C independent of ε and N. Then we obtain after j steps with $\nu = [\ell - j(\tau+p)]$

$$\begin{aligned} \|\tilde{g}_j\|_{BC^\nu(B_R(Y)\times T^p,Y)} &\le \varepsilon^j (N+C)^j C(R) \\ \|\bar{g}_j\|_{BC^\nu(B_R(Y),Y)} &\le 2\varepsilon NC(R). \end{aligned}$$

So finally we arrive for the remainder term in the Galerkin approximation space

$$\begin{aligned} \|\tilde{g}_{j^*}\|_{BC^1(B_R(Y)\times T^p,Y)} &\le \varepsilon^{\ell/(\tau+p)} (N+C)^{\ell/(\tau+p)} C(R) \\ \|\bar{g}_{j^*}\|_{BC^1(B_R(Y),Y)} &\le 2\varepsilon NC(R). \end{aligned}$$

As explained above the remainder term due to the Galerkin approximation can be controlled using hypothesis 2.4 by a term of order $N(\varepsilon)^{-\alpha}$.

Choosing a coupling of ε and N, such that we simultaneously minimise the remainder terms $\tilde{g}_{j^*}$ and $N(\varepsilon)^{-\alpha}$, gives

$$N(\varepsilon) = \varepsilon^{-q(\ell)/(q(\ell)+\alpha)}.$$

Then both remainder terms are of order $\varepsilon^{\alpha q(\ell)/(q(\ell)+\alpha)}$ with uniform constants on bounded sets in $\mathcal{Y}_\alpha$. This proves the estimates on the equation. With the general Gronwall argument in (3.9), we also obtain the estimates on the solutions. □

3.2 Proof of Theorem B

Following the argument above any fixed number of transformation steps is well-defined in the analytic setting. The number of steps, we use, will depend on ε. To estimate the remainder term we use the complex extension as in Hypothesis 2.7. In each transformation step we will estimate $\bar{g}_j$ and $\tilde{g}_j$ on slightly smaller domains $D_j = B_R(Y) + \delta_j \times T^p + \delta_j$. We set $\delta_j = \delta - j\eta(\varepsilon)$. We also introduce an intermediate domain $D_{j,\frac{1}{2}} = B_R(Y) + \delta_{j+\frac{1}{2}} \times T^p + \delta_{j+1}$. For notational convenience we denote for a function h and any complex domain D for some given ε

$$|h|_D = \sup_{(u,\theta)\in D} |h(u,\theta,\varepsilon)|_Y$$

and

$$\left\| \frac{\partial h}{\partial u} \right\|_D = \sup_{(u_0,\theta)\in D} \sup_{u\in Y, |u|_Y=1} \left| \frac{\partial h(u)}{\partial u}(u_0,\theta,\varepsilon)u \right|_Y .$$

We assume inductively

$$|\bar{g}_j|_{D_j} \le \bar{b}_j \text{ and } |\tilde{g}_j|_{D_j} \le \tilde{b}_j \tag{3.11}$$

The bound on the nonlinearity f is denoted as $|f|_{D_0} =: b$. Then we estimate w_j given in (3.3) in the intermediate domain $D_{j,\frac{1}{2}}$. Fixing a direction in the complex extension of the torus T^p with $\theta = (\theta_1, \dots, \theta_p) \in T^p$, analyticity gives estimates on the Fourier expansion of $\tilde{g}_j$:

$$\begin{aligned}
& \int_0^1 \tilde{g}_j(v,\theta_1,\dots,\theta_p)\exp(-2\pi i(m,\theta)d\theta_1 \\
= & \int_0^{i\delta_j} \tilde{g}_j(v,\theta_1,\dots,\theta_p)\exp(-2\pi i(m,\theta))d\theta_1 + \int_{i\delta_j}^{1+i\delta_j} \tilde{g}_j(v,\theta_1,\dots,\theta_p)\exp(-2\pi i(m,\theta))d\theta_1 \\
& + \int_{1+i\delta_j}^{0} \tilde{g}_j(v,\theta_1,\dots,\theta_p)\exp(-2\pi i(m,\theta))d\theta_1
\end{aligned}$$

The first and last integral cancel, then repeating this in the other directions on the torus T^p we obtain for the Fourier coefficients of index m:

$$|\tilde{g}_{jm}|_{D_{j,\frac{1}{2}}} \le \frac{\tilde{b}_j}{2\pi} \mathrm{e}^{-\delta_j|m|} \tag{3.12}$$

Then we obtain on the domain D_{j+1} for the next transformation

$$
\begin{aligned}
|\tilde{w}_j|_{D_j} &\leq \frac{\tilde{b}_j}{2\pi} \sum_{m\in\mathbb{Z}^p, m\neq 0} \frac{\mathrm{e}^{-\delta_j|m|}}{|(m,\omega)|} \mathrm{e}^{\delta_j|m|} \\
&= \frac{\tilde{b}_j}{2\pi} \sum_{m\in\mathbb{Z}^p, m\neq 0} \frac{\mathrm{e}^{-\eta(\varepsilon)|m|}}{|(m,\omega)|}. \qquad (3.13)
\end{aligned}
$$

Using the Diophantine condition hypothesis 2.2 one can prove the next lemma.

Lemma 3.1 ([Sim94, Lemma 1]) *Let $\omega \in \mathbb{R}^p$ satisfy Hypothesis 2.2 with $\tau > p-1$. Then*

$$
s_k \sum_{m\in\mathbb{Z}^p\{0\}, |m|\leq k} |(m,\omega)|^{-1} \leq \Gamma k^\tau,
$$

where Γ is positive constant depending on ω, but independent of k.

The lemma was stated in [Sim94] and a proof was given in [Sim99]. A proof is also given in the appendix. Then

$$
\begin{aligned}
|\tilde{w}_j|_{D_j} &\leq \frac{\tilde{b}_j}{2\pi} \sum_{k\in\mathbb{N}} \mathrm{e}^{-\eta(\varepsilon)k}(s_k - s_{k-1}) = \frac{\tilde{b}_j}{2\pi} \sum_{k\in\mathbb{N}} s_k(\mathrm{e}^{-\eta(\varepsilon)k} - \mathrm{e}^{-\eta(\varepsilon)k+1}) \\
&\leq \frac{\tilde{b}_j}{2\pi}(1-\mathrm{e}^{-\eta(\varepsilon)})\Gamma \sum_{k\in\mathbb{N}} \mathrm{e}^{-\eta(\varepsilon)k} k^\tau \leq \tilde{b}_j \frac{K}{\eta(\varepsilon)^\tau}, \qquad (3.14)
\end{aligned}
$$

where K is independent of $\tilde{b}_j$ and $\eta(\varepsilon)$. The transformation $id + \varepsilon w_j$ is well-defined, when we can ensure that if $v \in D_{j,\frac{1}{2}}$, then $u \in D_j$. It is enough to have

$$
\varepsilon \tilde{b}_j \frac{K}{\eta(\varepsilon)^\tau} \leq \frac{\eta(\varepsilon)}{2} \qquad (3.15)
$$

by a suitable choice of $\eta(\varepsilon)$ below.

Before giving the crucial inductive estimates on $|\tilde{g}_{j+1}|_{D_{j+1}}$ and $|\bar{g}_{j+1}|_{D_{j+1}}$ we collect some preliminary estimates. Using the Cauchy estimate, see e.g. [Mat01, Lemma7], we obtain

$$
\left\| \frac{\partial w_j(v)}{\partial v_N} \right\|_{D_{j+1}} \leq \tilde{b}_j \frac{2K}{\eta(\varepsilon)^{\tau+1}} \qquad (3.16)
$$

Then $\left\| \frac{\partial w_j(v)}{\partial v_N} \right\|_{D_{j+1}} \leq 1$ if (3.15) holds and

$$
\left\| \left(id + \frac{\partial w_j(v)}{\partial v_N} \right)^{-1} \right\|_{D_{j+1}} \leq 1 - \tilde{b}_j \frac{2K\varepsilon}{\eta(\varepsilon)^{\tau+1}}.
$$

Also using the Cauchy estimate and the mean value theorem we obtain

$$
\begin{aligned}
|(P_N f + \bar{g}_j)(v_N + \varepsilon w_j) - (P_N f + \bar{g}_j)(v_N)|_{D_{j+1}} &\leq (b + \bar{b}_j) \frac{2K\varepsilon}{\eta(\varepsilon)^{\tau+1}} \qquad (3.17) \\
|\tilde{g}_j(v_N + \varepsilon w_j) - \tilde{g}_j(v_N)|_{D_{j+1}} &\leq \tilde{b}_j + \tilde{b}_j \frac{2K\varepsilon}{\eta(\varepsilon)^{\tau+1}} \qquad (3.18)
\end{aligned}
$$

Now we are in the position to estimate $|\tilde{g}_{j+1}|_{D_{j+1}}$ and $|\bar{g}_{j+1}|_{D_{j+1}}$. We estimates the different parts in (3.5), to simplify notation we let $\psi = \frac{2K\varepsilon}{\eta(\varepsilon)^{\tau+1}}$. Then

$$\begin{aligned} |r_{j+1}|_{D_{j+1}} &= (1-\psi\tilde{b}_j)^{-1}((N+b+\bar{b}_j)\tilde{b}_j\psi + N\tilde{b}_j\psi + b\tilde{b}_j\psi + \bar{b}_j\tilde{b}_j\psi + \tilde{b}_j\tilde{b}_j\psi) \\ &= (1-\psi\tilde{b}_j)^{-1}(2(N+b+\bar{b}_j)+\tilde{b}_j)\tilde{b}_j\psi \end{aligned}$$

then we obtain $|\tilde{g}_{j+1}|_{D_{j+1}} \leq \tilde{b}_{j+1}$ and $|\bar{g}_{j+1}|_{D_{j+1}} \leq \bar{b}_{j+1}$ with

$$\bar{b}_{j+1} = \bar{b}_j + (1-\psi\tilde{b}_j)^{-1}(2(N+b+\bar{b}_j)+\tilde{b}_j)\tilde{b}_j\psi \tag{3.19}$$

$$\tilde{b}_{j+1} = 2(1-\psi\tilde{b}_j)^{-1}(2(N+b+\bar{b}_j)+\tilde{b}_j)\tilde{b}_j\psi \tag{3.20}$$

Now we will choose ε_0, the index of the Galerkin approximation $N(\varepsilon)$, the number of averaging steps j^* and the amount $\eta(\varepsilon)$, of which we change size of the complex extension such that

$$\bar{b}_j \leq 2\bar{b}_0 \text{ and } \tilde{b}_{j+1} \leq \tilde{b}_j \leq \bar{b}_0 \tag{3.21}$$

For $j = 0$ these inequalities hold by definition. We first perform a single averaging step to obtain $\bar{b}_0 = C\varepsilon N(\varepsilon)$ as in the proof of theorem A and decrease the domain by $\delta/4$. If (3.21) holds, all transformations are well-defined by (3.15), if we can ensure

$$\psi\bar{b}_0 < \frac{1}{2} \text{ for } 0 < \varepsilon < \varepsilon_0 \tag{3.22}$$

Our choice of parameter will be such that

$$2(1-\psi\tilde{b}_j)^{-1}(2(N+b+\bar{b}_j)+\tilde{b}_j)\tilde{b}_j\psi < \frac{1}{\mathrm{e}}. \tag{3.23}$$

Then we obtain from (3.19) and (3.20), that

$$\begin{aligned} \tilde{b}_j &\leq \left(\frac{1}{\mathrm{e}}\right)^j 2\bar{b}_0 \\ \bar{b}_{j+1} &< \bar{b}_j + \frac{1}{2\mathrm{e}}\tilde{b}_j \leq \bar{b}_0 + \frac{1}{2\mathrm{e}}(\tilde{b}_0 + \ldots + \tilde{b}_j)\bar{b}_0 + \frac{1}{2\mathrm{e}}\sum_{k=0}^{j}\frac{1}{\mathrm{e}^k}2\bar{b}_0 \\ &= \bar{b}_0(1+\frac{1}{\mathrm{e}-1}) < 2\bar{b}_0 \end{aligned}$$

We choose $\eta(\varepsilon) = \bar{K}(\varepsilon N(\varepsilon))^{1/(1+\tau)}$ and $\bar{K} = (2K\bar{b}_0)^{1/(1+\tau)}$. Thus (3.23) and (3.22) hold as $\psi = \frac{2\varepsilon}{\bar{b}_0}$ for $0 < \varepsilon < \varepsilon_0 = 1$. Then the number of averaging steps j^* is chosen such that the complex domain $B_R(Y) + \delta/2 \times T^p + \delta/2$ is contained in D_{j^*}, then

$$j^* = \left[\frac{\delta}{4\eta(\varepsilon)}\right] > \frac{\delta}{4\bar{K}(\varepsilon N(\varepsilon))^{1/(1+\tau)}} - 1.$$

The final transformed nonlinearities on $P_{N(\varepsilon)}Y$ are $P_{N(\varepsilon)}f(v) + \bar{g}_{j^*(\varepsilon)}(v,\varepsilon) + \tilde{g}_{j^*(\varepsilon)}(v,\theta,\varepsilon)$ with

$$|P_{N(\varepsilon)}f(.) + \bar{g}_{j^*(\varepsilon)}(.,\varepsilon)|_{D_{j^*}} < b + 2\bar{b}_0$$

and the first desired exponential estimate

$$|\tilde{g}_{j^*(\varepsilon)}(.,.,\varepsilon)|_{D_{j^*}} \leq C\exp(-c_2(\varepsilon N(\varepsilon))^{1/(1+\tau)}),$$

all estimates up to here hold both for $Y = X$ and $Y = \mathcal{G}_{\sigma,\nu}$. Another exponential estimate is obtained for the remainder terms r^* in (3.8) using the exponential approximation hypothesis 2.5 for $v \in \mathcal{G}_{\sigma,\nu}$

$$|r^*(v,\theta,\varepsilon)|_X \leq C(|v|_{\mathcal{G}_{\sigma,\nu}})\exp(-c_0/(N(\varepsilon))^\nu).$$

Balancing both exponential estimates yields an optimal choice for $(\varepsilon N(\varepsilon))^{1/(1+\tau)} = (N(\varepsilon))^{-\nu}$, i.e. $N(\varepsilon) = \varepsilon^{-1/(1+\nu(\tau+1))}$. Then we finally have the exponential estimate for the nonautonomous remainder $r = r^* - \int_{T^p} r^* + \tilde{g}_{j^*(\varepsilon)}$ as in (2.17)

$$|r(v,\theta,\varepsilon)|_X \leq C(|v|_{\mathcal{G}_{\sigma,\nu}})\exp(-c\varepsilon^{-1/(\tau+1+1/\nu)}).$$

For the autonomous correction $\bar{g} = \bar{g}_{j^*} + \int_{T^p} r^*$ we obtain as in the proof of theorem A

$$|\bar{g}|_X \leq C\varepsilon N(\varepsilon) + C(|v|_{\mathcal{G}_{\sigma,\nu}})\exp(-c\varepsilon^{-1/(\tau+1+1/\nu)}) \leq C\varepsilon^{(\tau+1)/(\tau+1+1/\nu)}.$$

The proof of theorem B is then completed using the Gronwall argument to extend the estimates from the equation to the solutions, too. □

4 Examples

In this section we give examples of equations that can be written in the form (2.1), such that theorems A and B can be applied.

4.1 Reaction-Diffusion equation

In reaction-diffusion equations an external forcing can be introduced in the reaction terms for example through light changes in a light sensitive Belousov Zhabashinsky reaction, see e.g. [SaScWu99] and references therein. Such equations with a fast quasiperiodic external forcing and with species $u_1, \ldots, u_n$ have then the form for $u = (u_1, \ldots u_n)$

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}U &= \mathrm{diag}(d_1,\ldots,d_n)\Delta U + f(u,\theta) = \mathrm{diag}(d_1,\ldots,d_n)\Delta U + \bar{f}(u) + g(u,\theta) && (4.1)\\
\dot{\theta} &= \frac{1}{\varepsilon}\omega && (4.2)\\
(u(0),\theta(0)) &= (u_0,\theta_0) \in H^s(\Omega,\mathbb{R}^n) \times T^p
\end{aligned}$$

with periodic boundary conditions on $\Omega = [0,L]^d$. If $f : \mathbb{R}^n \times T^p \to \mathbb{R}^n$ is an entire function in U and real analytic in T^p, then (4.2) has highly regular solutions. Starting with initial data

$u_0 \in X = H^s_{per}(\Omega, \mathbb{R}^n)$, with possibly noninteger $s > d/2$, the solutions are bounded in Gevrey spaces after any finite transient. If $|u(t)|_X < M$ for $0 \leq t \leq T$, then solutions gain regularity

$$\begin{aligned} |u(t)|_{\mathcal{G}_{t,1/2}} &\leq 2M \text{ for } 0 \leq t \leq t^* \\ |U(t)|_{\mathcal{G}_{t^*,1/2}} &\leq 2M \text{ for } t^* \leq t \leq T, \end{aligned}$$

with $|u|_{\mathcal{G}_{\sigma,1/2}} = |u|_X + |\exp(\sigma(-\Delta)^{1/2})u|_X$, for proofs and details see e.g. [FeTi98, Mat01]. Using a spatial Fourier decomposition of U, the hypothesis 2.1 is fulfilled, the assumptions 2.2 and 2.3 hold by assumption. The exponential approximation property 2.5 holds in $\mathcal{G}_{\sigma,1/2}$ with $c_0 = \sigma$ and for general initial data after a transient, since the Gevrey norm can be expressed in spatial Fourier modes. For $u(x) = \sum_{k \in \mathbb{Z}^d} u^k \exp(2\pi \mathrm{i}(k,x)) \in \mathcal{G}_{\sigma,1/2}$, we wave $|u|^2_{\mathcal{G}_{\sigma,1/2}} = \sum_{k\in\mathbb{Z}^d} |u^k|^2(1+\exp(\sigma|k|))^2$ and then

$$|id - P_N)U|_X = |\sum_{k \in \mathbb{Z}^d, |k| > \sqrt{N}} U^k \exp(2\pi\mathrm{i}(k,x))|_X \leq \exp(-\sigma N^{1/2})|U|_{\mathcal{G}_{\sigma,1/2}}$$

The assumption, that f is entire in U and real analytic in T^p, gives analyticity of the nonlinearities in $\mathcal{G}_{\sigma,1/2}$ and X, see [Mat01]. Using standard semigroup arguments $D\Delta$ generates a strongly continuous semigroup in X. The same arguments also apply to $\mathcal{G}_{\sigma,1/2}$.

The nonautonomous remainder can then be estimated for Gevrey initial data

$$|r(U,\theta,\varepsilon)|_X \leq C(|U|_{\mathcal{G}_{\sigma,1/2}}) \exp(-c\varepsilon^{-1/(\tau+3)})$$

and the correction term is bounded by $C\varepsilon^{(\tau+1)/(\tau+3)}$. For general initial data $U_0 \in X$ the exponent c increases in time as the regularity of the solutions increases

$$|r(U(t),\theta(t),\varepsilon)|_X \leq C(|U_0|_X)\exp(-c(t)\varepsilon^{-1/(\tau+3)})$$

with $c(t) = \min(t, t^*, c)$, where t^* is the maximal Gevrey exponent. For H^s initial data the estimates on $\bar{g}$ have to be modified, in $(id - P_N)X$, we obtain for r^* in general only boundedness.

If the nonlinearity f possesses only finite differentiability, only finite Sobolev regularity of solutions can be assumed. Theorem A can be applied with $\mathcal{Y}_\alpha = H^{s+2\alpha}_{per}$ as $|U|^2_{H^{s+2\alpha}} = \sum_{k\in\mathbb{Z}^d} |U^k|^2(1 + |k|^{s+2\alpha})^2$ and

$$|(id - P_N)U|_X \leq CN^{-\alpha}|U|_{H^{s+2\alpha}}$$

for some α depending on the differentiability ℓ of f. Again a version holds, starting with H^s initial data and using regularising to higher Sobolev spaces, as well.

For both the analytic and the finite differentiability case the correction term is given by the iterative procedure. A good approximation is the correction in the first step

$$\bar{g}(u,\varepsilon) = \int_{T^p} D_v g(v,\theta,\varepsilon) w_1(P_{N(\varepsilon)}v,\theta,\varepsilon)\mathrm{d}\theta \tag{4.3}$$

where w_1 is the first transformation as defined in (3.10) and $N(\varepsilon)$ was chosen in the proofs as for the finite regularity case $N(\varepsilon) = \varepsilon^{q(\ell)/(q(\ell)+\alpha)}$ and in the analytic setting $N(\varepsilon) = \varepsilon^{-1/(1+\nu(\tau+1))}$.

Another way to create a periodic forcing in the nonlinearity is a time-periodic change of the diffusion coefficient. As an example we consider a scalar reaction-diffusion equation

$$\frac{\mathrm{d}}{\mathrm{d}t}u = d(t\omega_1/\varepsilon)\Delta u + f(u). \tag{4.4}$$

with $d(s) = \bar{d} + \tilde{d}(s)$ and $\int_0^1 \tilde{d}(s)\mathrm{d}s = 0$. We are able to transform (4.4) into the general form of the theorems with a rescaling of time $\tau(t)$. Let $\tau(t) = \int_0^t \frac{d(s\omega_1/\varepsilon)}{\bar{d}}\mathrm{d}s$, then $\tau(l\varepsilon/\omega_1) = l\varepsilon/\omega_1$ for $l \in \mathbb{Z}$ and the derivative $\tau'(t) = d(t\omega_1/\varepsilon)/\bar{d}$ is periodic, such that this is near-identity reparametrisation of time. In the new time the equation is

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}\tau}u &= \frac{\mathrm{d}u}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}\tau} = \frac{1}{\tau'(t(\tau))}\frac{\mathrm{d}u}{\mathrm{d}t} \\ &= \frac{\bar{d}}{d(t(\tau)\omega_1/\varepsilon)}\left(d(t(\tau)\omega_1/\varepsilon)\Delta u + f(u)\right) = \bar{d}\Delta u + \frac{\bar{d}}{d(t(\tau)\omega_1/\varepsilon)}f(u)\end{aligned}$$

The nonlinearity can be understood as a periodic forcing. Let $L(T) = \int_0^T d(s)/\bar{d}\mathrm{d}s$, then

$$\frac{\bar{d}}{d(t(\tau)\omega_1/\varepsilon)}f(u, t(\tau)\omega_2/\varepsilon) = \frac{\bar{d}}{d(L(\tau\omega_1/\varepsilon))}f(u,),$$

as

$$L(\tau\omega_1/\varepsilon) = \int_0^{\omega_1\tau/\varepsilon} d(s)/\bar{d}\mathrm{d}s = \frac{\omega_1}{\varepsilon}\int_0^{\tau} d(s\omega_1/\varepsilon)/\bar{d}\mathrm{d}s = t(\tau)\frac{\omega_1}{\varepsilon}.$$

On the one-dimensional torus we add the equation

$$\dot{\theta} = \frac{1}{\varepsilon}\omega_1,$$

such that both equations together have the wanted form. Then as above the theory of the paper or alternatively of [Mat01] is applicable and there exists an autonomous equation, that exponentially close to the original system in the analytic framework.

4.2 Nonlinear Schrödinger equations

In fibre optics communications in long cables there are periodicly changing dispersion coefficients and additionally periodic amplification sites. This can be modelled by a nonlinear Schrödinger equation,

$$\mathrm{i}u_z + D(\omega_1 z/\varepsilon)u_{tt} + C(\omega_2 z/\varepsilon)|u|^2 u = 0 \tag{4.5}$$

The direction of the evolution is z. The equation describes how a temporal profile - given as a function of t - is transported along the cable described by the z-direction, see e.g. [NM92]. As phase space we use $X = H^1(\mathbb{R}, \mathbb{R}^2)$ and as Gevrey classes we consider

$$\mathcal{G}_{\sigma,1/2} = \{u \in H^1(\mathbb{R}, \mathbb{R}^2) | |u|_{H^1} + |\exp(\sigma|\partial_{tt}|^{1/2})u|_{H^1}.$$

Note that the nonlinearity is entire in $u_1 = \mathrm{Re}\, u$ and $u_2 = \mathrm{Im}\, u$. With a linear Floquet-type transformation, we are able to transform (4.5) into the general form of the theorems. The linear equation can be solved by a spatial Fourier transform. All complex Fourier modes $u_k \exp(\mathrm{i}kt)$ with $k \in \mathbb{R}$ and $u_k \in \mathbb{C}$ are invariant under the evolution defined by

$$\frac{\mathrm{d}}{\mathrm{d}z} u_k(z) = \mathrm{i}D(\omega_1 z/\varepsilon)k^2 u_k(z)$$

Then the evolution is given by

$$\begin{aligned} u_k(z) &= u_k(0)\exp(\int_0^z \mathrm{i}k^2 d(s\omega_1/\varepsilon)\mathrm{d}s) \\ &= u_k(0)\exp(\int_0^z \mathrm{i}k^2 \tilde{d}(s\omega_1/\varepsilon)\mathrm{d}s)\exp(\mathrm{i}k^2\bar{d}z) \end{aligned}$$

with $\int_0^1 \tilde{d}(s)\mathrm{d}s = 0$. Then defining a transformation of the phase space by applying the periodic transformation, $Q(z,\varepsilon)$ defined by $v_k = Q_k(z)u_k = \exp(-\int_0^z \mathrm{i}k^2\tilde{d}(s\omega_1/\varepsilon)\mathrm{d}s)u_k$ on each Fourier mode separately, we obtain the quasiperiodic equation

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}z}v(z) &= \frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{k\in\mathbb{R}} Q_k(z)u_k(z)\mathrm{d}k\right) \\ &= \int_{k\in\mathbb{R}} -\mathrm{i}k^2\tilde{d}(z\omega_1/\varepsilon)Q_k(z)u_k(z) + Q_k(z)\frac{\mathrm{d}}{\mathrm{d}z}u_k(z)\mathrm{d}k \\ &= \int_{k\in\mathbb{R}} -\mathrm{i}k^2\tilde{d}(z\omega_1/\varepsilon)Q_k(z)u_k(z) + \mathrm{i}k^2(\tilde{d}(z\omega_1/\varepsilon)+\bar{d})Q_k(z)u_k(z) + Q_k(z)\left(\widehat{C(\omega_2 z/\varepsilon)|u|^2u}\right)\mathrm{d}k \\ &= \mathrm{i}\bar{d}v_{tt} + Q(z,\varepsilon)C(\omega_2 z/\varepsilon)|Q^{-1}(z,\varepsilon)v|^2Q^{-1}(z,\varepsilon)v \end{aligned} \quad (4.6)$$

The transformation $Q(.,\varepsilon)$ has period ε/ω_1. So rewriting $\tilde{Q}(z\omega_1/\varepsilon,\varepsilon) = Q(z,\varepsilon)$, where $\tilde{Q}$ is then 1-periodic in its first argument, we obtain the wanted form of (2.1):

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}z}v(z) &= \mathrm{i}\bar{d}v_{tt} + \tilde{Q}(\theta_1,\varepsilon)C(\theta_2)|\tilde{Q}^{-1}(\theta_1,\varepsilon)v|^2\tilde{Q}^{-1}(\theta_1,\varepsilon)v \\ \dot{\theta} &= \frac{1}{\varepsilon}\begin{pmatrix}\omega_1\\ \omega_2\end{pmatrix} \end{aligned} \quad (4.7)$$

The transformation Q leaves each complex Fourier mode invariant and is an isometry on each. Thus Q leaves the spaces X and $\mathcal{G}_{\sigma,1/2}$ and furthermore $Q(z)C(\omega_2 z/\varepsilon)||Q^{-1}(z).|^2Q^{-1}(z).: Y \to Y$ for $Y = X$ and $Y = \mathcal{G}_{\sigma,1/2}$. Then the theorem is applicable when we use a truncation of the Fourier transform as a Galerkin approximation. The Diophantine conditions on (ω_1,ω_2) still has to be assumed. Then an effective autonomous description can be given for regular initial data.

4.3 Nonlocality

We give an example of a linear parabolic partial differential equation with periodic forcing, where we can see that the transformation has to be nonlocal to transform higher order terms away. Consider

$$u_t(x,t) = u_{xx}(x,t) + f(t/\varepsilon,x)u(x,t), \quad (4.8)$$

with $u(0,t) = u(1,t)$ and $x \in [0,1]$. A specific choice of f will be made later. As the equation is linear, we can restrict out attention to linear transformation – nonlinear one will create a larger error. A general linear, local and near-identity transformation has the form

$$u(x,t) = v(x,t) + \varepsilon w(t/\varepsilon, x) v(x,t),$$

where $w(\tau, x)$ is 1-periodic in τ and in a certain regularity class in X to ensure that $\mathcal{G}_{\sigma,\nu}$ resp. $\mathcal{Y}_\alpha$ is mapped to itself. Then the transformed equation is

$$v_t = v_{xx} + \frac{1}{1+\varepsilon w(t/\varepsilon,x)} \left[\varepsilon \partial_{xx} w(t/\varepsilon,x) v + 2\varepsilon \partial_x w(t/\varepsilon,x) u_x + f(t/\varepsilon,x)(v + \varepsilon w(t/\varepsilon,x)v) - \partial_\tau w(t/\varepsilon,x)\right]$$

Using the periodic boundary conditions and that w is periodic in $\tau = t/\varepsilon$, we expand w in a Fourier series simultaneously in x and t.

$$w(\tau,x) = \sum_{l\in\mathbb{Z}, m\in\mathbb{Z}} w_{lm} \exp(\mathrm{i}2\pi(l\tau + mx))$$

Letting $v = 1$, we obtain a relation between the Fourier expansion of f and w

$$w_{lm}(\mathrm{i}2\pi l + \varepsilon 4\pi^2 m^2) = f_{lm} + \varepsilon \sum_{l_1\in\mathbb{Z}, m_1\in\mathbb{Z}} w_{l_1,m_1} f_{l-l_1,m-m_1},$$

which has a unique solution for ε small by the implicit function theorem for f and w in H^s with noninteger $s > 1$, then the nonlinearity wf is differentiable as H^s is an algebra. Thus w is defined by this relation up to an error $\mathrm{O}(\varepsilon^\nu)$ in ε of some order ν, we want to achieve. In particular we have

$$\left| w_{lm} - \frac{1}{\mathrm{i}2\pi l + \varepsilon 4\pi^2 m^2} f_{lm} \right| \le \varepsilon \frac{|f||w|}{2\pi} + \mathrm{O}(\varepsilon^\nu) \le \varepsilon \frac{|f|^2}{2\pi^2} + \mathrm{O}(\varepsilon^\nu) \tag{4.9}$$

as $|w| \le |f|/\pi$ for ε small enough. If we now derive in the same way another relation for w using $v = v_k \exp(2\pi k x)$, we obtain instead

$$w_{lm}(\mathrm{i}2\pi l + \varepsilon 4\pi^2 m^2 - \varepsilon 4\pi^2 mk) = f_{lm} + \varepsilon \sum_{l_1\in\mathbb{Z}, m_1\in\mathbb{Z}} w_{l_1,m_1} f_{l-l_1,m-m_1},$$

i.e. again by the the implicit function theorem

$$\left| w_{lm} - \frac{1}{\mathrm{i}2\pi l + \varepsilon 4\pi^2 m^2 - \varepsilon 4\pi^2 mk} f_{lm} \right| \le \varepsilon \frac{|f|^2}{2\pi^2} + \mathrm{O}(\varepsilon^\nu) \tag{4.10}$$

Specialising to $f(\tau,x) = \exp(2\pi \mathrm{i}\tau)\exp(2\pi \mathrm{i}x)$ the two values for w_{11} from (4.9) and (4.10) differ by more than

$$\left| \frac{1}{\mathrm{i}2\pi l + \varepsilon 4\pi^2} - \frac{1}{\mathrm{i}2\pi l + \varepsilon 4\pi^2 - \varepsilon 4\pi^2 k} \right| \ge \varepsilon k$$

giving a direct contradiction for some fixed $k > \frac{|f|^2}{2\pi^2}$ and any choice of $\nu \ge 1$, independent of ε and the choice of function spaces $\mathcal{G}_{\sigma,\nu}$ resp. $\mathcal{Y}_\alpha$.

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Appendix

We prove lemma 3.1. For $\tau > p-1$, we can restrict our attention just to points in $\mathbb{Z}^p$, which are close to the hyperplane $\omega^\perp$, as

$$\sum_{m\in\mathbb{Z}^p, |m|\leq k, \mathrm{dist}(m,\omega^\perp)\geq 1} \frac{1}{|(m,\omega)|} \leq Ck^{p-1}\log k.$$

This can be estimated by $(\Gamma/2)k^\tau$ uniformly in k.

To discuss those points in $\mathbb{Z}^p$, which are close to $\omega^\perp$, first assume that the constant γ in the estimate $|(m,\omega)| \geq \gamma|m|^{-\tau}$ is sharp, i.e.

$$\gamma = \inf_{m\in\mathbb{Z}^p\setminus 0}\{|(m,\omega)||m|^\tau\}$$

The key idea is now to classify the $m \in \mathbb{Z}^p$, $|m| \leq k$ in how close they are to this worst case estimate for the small divisor $1/(m,\omega)$. In each case we estimate the number of m and their influence in the sum. Now fix some $\rho > 1$ and let

$$B^s = \{m \in \mathbb{Z}^p | \gamma\rho^s \leq |(m,\omega)||m|^\tau < \gamma\rho^{s+1}\}$$

First consider all those m in B^0 with $2k/3 \leq |m| \leq k$. Then we obtain lower estimates on the distance of $m_1, m_2 \in B^0, m_1 \neq m_2$ in the following way: As

$$|(m_1 - m_2,\omega)|k^\tau \leq 2(3/2)^\tau\gamma\rho$$

and using the Diophantine estimate on $m_1 - m_2$, which could be in B^0, we also have

$$|(m_1 - m_2,\omega)||m_1 - m_2|^\tau > \gamma.$$

Combining these two inequalities yields

$$\begin{aligned} |m_1 - m_2|^\tau &> \frac{2^\tau}{23^\tau\rho}k^\tau \text{ or} \\ |m_1 - m_2| &> \frac{2}{3\sqrt[\tau]{2\rho}}k \end{aligned}$$

Then the number $m \in B^0$ with $2k/3 < |m| < k$ is bounded by the number of balls of radius $2k/(3\sqrt[\tau]{2\rho})$ that can be packed into annulus $2k/3 \leq |m| \leq k$ close to the hyperplane $\omega^\perp$. This is bounded by a constant of the form $C\rho^{(p-1)/\tau}$, where C is independent of k, p, ω, r and γ. Then the contribution of B^0 to the sum

$$\sum_{2k/3 \leq |m| < k, m \in B^0} \frac{1}{|(m, \omega)|} \leq C\rho^{(p-1)/\tau} \gamma k^\tau.$$

Such an analysis is repeated for B^s with $s > 0$. As above we obtain estimates on the number of m in B^s with $2k/3 \leq |m| < k$, first we have the lower estimate on their distance

$$|m_1 - m_2| > \frac{2}{3\sqrt[\tau]{2\rho^{s+1}}} k,$$

such that the number of $m \in B^s$ is bounded by $C\rho^{(s+1)(p-1)/\tau}$ and their overall contribution is bounded by

$$C\rho^{(s+1)(p-1)/\tau} \rho^{-s} \gamma k^\tau$$

Hence the sum of all interesting B_s, i.e. $\rho^s \leq m^\tau/\gamma$, is bounded as $p - 1 < \tau$:

$$C\rho^{(p-1)/\tau} \gamma k^\tau \sum_{s=0}^{\infty} \rho^{\frac{p-1}{\tau} - 1} = C\rho^{(p-1)/\tau} \gamma k^\tau (1 - \rho^{\frac{p-1}{\tau} - 1})^{-1}$$

Then this can be extended from the annulus $2k/3 \leq |m| \leq k$ to the ball $|m| \leq k$:

$$\sum_{|m|<k} \frac{1}{|(m, \omega)|} \leq C\rho^{(p-1)/\tau} \gamma (1 - \rho^{\frac{p-1}{\tau} - 1})^{-1} k^\tau (1 + (2/3)^\tau + (2/3)^{2\tau} + (2/3)^{3\tau} + \ldots) \leq (\Gamma/2) k^\tau$$

Together with the contribution of the points with distance larger than 1 to the hyperplane $\omega^\perp$, we obtain the desired estimate.□

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