A NOTE ON THE REDUCIBILITY OF LINEAR DIFFERENTIAL EQUATIONS WITH QUASIPERIODIC COEFFICIENTS

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The system $\dot{x} = (A + \epsilon Q(t))x$, where $A$ is a constant matrix whose eigenvalues are not necessarily simple and $Q$ is a quasiperiodic analytic matrix, is considered. It is proved that, for most values of the frequencies, the system is reducible.

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1. Introduction and results. Consider the quasiperiodic linear differential equation

$$\dot{x} = (A + \epsilon Q(t))x \quad (1.1)$$

with $x$ an $n$-dimensional vector, $A$ a constant square matrix of order $n$, and $Q$ a square matrix of order $n$, quasiperiodic in time $t$. We say that a change of variables $x = P(t)y$ is a Lyapunov-Perron (LP) transformation if $P(t)$ is nonsingular and $P(t), P^{-1}(t)$, and $\dot{P}(t)$ are bounded for all $t \in \mathbb{R}$. Moreover, if $P$, $P^{-1}$, and $\dot{P}$ are quasiperiodic in time $t$, we refer to $x = P(t)y$ as a quasiperiodic LP transformation. If there is a quasiperiodic LP transformation $x = P(t)y$ such that $y$ satisfies the equation

$$\dot{y} = By \quad (1.2)$$

with $B$ a constant matrix, then we say that (1.1) is reducible.

The concept of the reducibility was first considered by Lyapunov (see [5]). There are several authors who investigated the reducibility of (1.1) (see, e.g., [1, 2, 6]). The present paper complements the results obtained by Jorba and Simó [2], which we will briefly recall. To this end, we will introduce some notation and definitions that will be used throughout the paper.

We say that a function $F$ is a quasiperiodic function in time $t$, with the basic frequencies $\omega = (\omega_1, \ldots, \omega_r)$, if there exists a function $\mathcal{F}(\theta_1, \ldots, \theta_r)$ which is $2\pi$-periodic in all its arguments $\theta_j$, $j = 1, \ldots, r$, and such that $F(t) = \mathcal{F}(\omega_1 t, \ldots, \omega_r t)$. We call $\mathcal{F}$ the hull of $F(t)$. The function $F$ will be called analytic quasiperiodic in a strip of width $\delta$ if, furthermore, $\mathcal{F}$ is analytic in the complex strip $|\text{Im}\theta| < \delta$. 
Let $\lambda = (\lambda_1, \ldots, \lambda_n)$ be the eigenvalues of $A$ and $\lambda^0(\epsilon) = (\lambda^0_1(\epsilon), \ldots, \lambda^0_n(\epsilon))$ the eigenvalues of $\bar{A} := A + \epsilon \bar{Q}$, where $\bar{Q}$ is the average of $Q(t)$,

$$\bar{Q} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} Q(t) dt.$$  \hspace{1cm} (1.3)

Assume that $Q(t)$ is analytic on the strip of width $\delta_0 > 0$ and that the vector $(\lambda, \sqrt{-1} \omega)$ satisfies the nonresonance conditions

$$| \sqrt{-1} k \cdot \omega + l \cdot \lambda | \geq \frac{c}{|k|^\gamma},$$  \hspace{1cm} (1.4)

where $l \in \mathbb{Z}^n$ with $|l| = 0, 2$ and $0 \neq k \in \mathbb{Z}^r$. It was shown by Jorba and Simó [2] that (1.1) is reducible for $\epsilon$ in some Cantorian set $\mathcal{E} \subset (0, \epsilon_0)$, with $\epsilon_0$ sufficiently small, provided that

1. the eigenvalues $\lambda_1, \ldots, \lambda_n$ of $A$ are different;
2. the eigenvalues $\lambda^0_i(\epsilon), \ldots, \lambda^0_n(\epsilon)$ of $\bar{A}$ satisfy

$$\left| \frac{d}{d\epsilon} (\lambda^0_i(\epsilon) - \lambda^0_j(\epsilon)) \right|_{\epsilon=0} > 2 \rho > 0$$  \hspace{1cm} (1.5)

for some constant $\rho$ and any $1 \leq i < j \leq n$.

In [2], the basic idea is to kill the small perturbation $\epsilon Q(t)$ by KAM iteration. Condition (2) is used to overcome the problem arising from the frequency shift which comes up in this procedure. By a well-known theorem [3, pages 113–115], condition (1) guarantees that the eigenvalues $\lambda^0_j(\epsilon)$ of $\bar{A} = A + \epsilon \bar{Q}$ are differentiable in $\epsilon$, and that therefore condition (2) can be imposed.

A natural question is: what happens when condition (1) or (2) is not satisfied? The main result of the present paper is the following theorem which gives an answer to this question.

**Theorem 1.1.** Let $\Omega_0 \subset \mathbb{R}^r$ be a compact set with positive Lebesgue measure and assume that $Q(t)$ is quasiperiodic with frequency $\omega \in \Omega_0$ and analytic in the strip of width $\delta_0 > 0$. Then, for a sufficiently small positive constant $\gamma$, there exist a subset $\Omega \subset \Omega_0$ with $\text{Meas}(\Omega_0 \setminus \Omega) = \text{Meas}(\Omega_0)(1 - O(\gamma^{1/n^2}))$ and a sufficiently small constant $\epsilon^* = \epsilon^*(\delta_0, \gamma) > 0$ such that for any $\epsilon \in (0, \epsilon^*)$, system (1.1) is reducible. More exactly, there is an analytic quasiperiodic transformation $x = P(t) y$ such that (1.1) is changed into

$$\dot{y} = By,$$  \hspace{1cm} (1.6)

where $B$ is a constant matrix with $\|A - B\| = O(\epsilon)$.

The proof is based on the construction of an iterative lemma, Lemma 2.1. In this construction, a finite number of terms in the Fourier expansion of the perturbation are killed in each iteration, and the remainder is included in the higher-order perturbation. The averaged perturbation is included in the time-independent term. To solve the homological equation, avoiding the problem
of small divisors, certain frequencies must be removed from the original frequency set $\Omega_0$ at each iteration step. Showing that the remaining frequencies form a big subset of $\Omega_0$ through the estimates of Section 3 concludes the proof.

**Remark 1.2.** When one of $\lambda_j$ is not simple, the functions $\lambda_0^j(\epsilon)$ are not necessarily differentiable in $\epsilon$. Therefore, in the hypothesis of Theorem 1.1, we have to regard the tangent frequencies $\omega$, instead of $\epsilon$, as the parameters used to overcome the frequency shift in KAM iterative steps. Thus, we cannot find explicitly a tangent frequency vector $\omega$ satisfying some Diophantine conditions such that Theorem 1.1 holds true. On the other hand, in Theorem 1.1 it is not necessary to excise a subset of small measure from $(0, \epsilon^*)$. In this sense, Theorem 1.1 complements the results of [2]. Yet another complementary approach is that of [1], where $\omega$ is fixed and reducibility is proved for “most” matrices $A$.

2. Proof of Theorem 1.1. The proof of Theorem 1.1 is based on Newton iteration. Before we state the main iterative lemma, we need to introduce some notation.

In the following, we denote by $C$, $C_1$, $C_2$, ... positive constants which arise in the estimates, by $\mathfrak{D}$ the hull of a quasiperiodic function $Q(t)$, and by $\overline{\mathfrak{D}}$ the average of $\mathfrak{D}$ on the $r$-torus. For a matrix-valued function $Q(t)$, define

$$\|Q\| := \sup_{t \in D} \|Q(t)\|,$$

where $\|\cdot\|$ is the sup-norm of the matrix.

Denote by $m$ the number of the iterative step, and let

1. $\epsilon_m$ be the sequence that bounds the size of the perturbation before the $m$th iteration step with $\epsilon_m = \epsilon(1 + \rho)^{m-1}$ and $\rho = 1/3$, for example;
2. $\delta_m$ be the sequence that measures the size of the analyticity domain in the angular variables after $m$ iteration steps with

$$\delta_m = \delta_0 - \frac{\delta_0}{2} (1 + \cdots + m^{-2}) \sum_{j=1}^{\infty} j^{-2} \quad \text{for } m \geq 1;$$

3. $U_m = U(\delta_m) = \{ \theta \in (\mathbb{C}/2\pi\mathbb{Z})^N : |\text{Im}\theta| < \delta_m \};$
4. $q_m$ be the sequence that measures the width of the analyticity domain in the frequency space after $m$ iteration steps with $q_m = \epsilon_1^{1/4n^2}$, where $n$ is the dimensional number of system (1.1);
5. $C(m)$ be a constant of the form $C_1 m^{C_2}$.

Let $\Omega_0 = \Pi_0 \supset \Pi_1 \supset \cdots \supset \Pi_{m-1}$ be the closed sets in $\mathbb{R}_r^T$ and let $\Pi_m \subset \Pi_{m-1}$ be as defined inductively in Section 3. Let $\mathcal{G}_l$ be the complex $q_l$-neighborhood of $\Pi_l$ for $l = 0, 1, \ldots, m$. Assume that, after $m - 1$ steps of Newton iteration, we
get a quasiperiodic linear differential equation
\[ \dot{x} = (A_{m-1} + \epsilon_m Q_m(t; \omega))x, \quad (2.3) \]
where the following conditions are satisfied:

(H1) \( A_{m-1} = A + \epsilon_1 \hat{\omega}_1(\omega) + \cdots + \epsilon_{m-1} \hat{\omega}_{m-1}(\omega), \) \( m \geq 2, \) \( A_0 = A \) with \( \hat{\omega}_l(\omega) \) analytic in \( \mathcal{C}_l, \) and \( \| \hat{\omega}_l \|_{\mathcal{C}_l} \leq 1 \) for \( l = 1, \ldots, m - 1; \)

(H2) the hull \( \mathcal{H}_m \) of \( Q_m(t; \omega) \) is analytic in \( U_{m-1} \times \mathcal{C}_{m-1} \) and
\[ \| \mathcal{H}_m(\theta, \omega) \|_{U_{m-1} \times \mathcal{C}_{m-1}} \leq 1. \] 

Let
\[ A_m = A_{m-1} + \epsilon_m \hat{\omega}_m. \] 

Then (2.3) can be rewritten as
\[ \dot{x} = (A_m + \epsilon_m Q^*_m(t))x, \quad (2.6) \]
where \( Q^*_m(t) = Q_m(t) - \hat{\omega}_m. \) Following [2], we will find a change of variables
\[ x = (E + \epsilon_m P_m(t))y, \quad (2.7) \]
where \( E \) is the unit matrix such that (2.3) is changed into
\[ \dot{y} = (A_m + O(\epsilon_{m+1}))y \quad (2.8) \]
verifying conditions (H1)\(_{m+1}\) and (H2)\(_{m+1}\). This change of variables is given by the following lemma.

**Lemma 2.1** (iterative lemma). Assume that (H1)\(_m\) and (H2)\(_m\) are fulfilled. Then there is a quasiperiodic LP transformation
\[ x = (E + P_m(t))y, \quad (2.9) \]
where \( P_m(t) \) is quasiperiodic with frequency \( \omega \) and its hull \( \mathcal{P}_m(\theta; \omega) \) is analytic in \( U_m \times \mathcal{C}_m \) such that (2.3) is changed into
\[ \dot{y} = (A_m + \epsilon_{m+1} Q_{m+1}(t))y, \quad (2.10) \]
where \( A_m \) and \( Q_{m+1} \) satisfy the conditions (H1)\(_{m+1}\) and (H2)\(_{m+1}\).

**Proof.** Rewrite (2.3) as
\[ \dot{x} = (A_m + \epsilon_m Q^*_m(t))x, \quad (2.11) \]
where \( Q^*_m(t) = Q_m(t) - \hat{\omega}_m \) and \( A_m = A_{m-1} + \hat{\omega}_m. \) Hence, we can write
\[ \mathcal{H}_m^*(\theta, \omega) = \sum_{0 \neq k \in \mathbb{Z}} \hat{\omega}_m^*(k; \omega)e^{\sqrt{-1}k \cdot \theta}, \quad (2.12) \]
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where \( \hat{\varphi}^*_m(k; \omega) \) is the \( k \) Fourier coefficient of \( \varphi^*_m(\theta, \omega) \) in \( \theta \). Let \( M_m = (1/b_m)|\ln \epsilon_m| \), where \( b_m = \delta_{m-1} - \delta_m \), and let

\[
\varphi^*_1_m(\theta, \omega) = \sum_{|k| \leq M_m} \hat{\varphi}^*_m(k; \omega) e^{\sqrt{-1} k \cdot \theta},
\]

and

\[
\varphi^*_2_m(\theta, \omega) = \sum_{|k| > M_m} \hat{\varphi}^*_m(k; \omega) e^{\sqrt{-1} k \cdot \theta},
\]

so that

\[
\varphi^*_m(\theta, \omega) = \varphi^*_1_m(\theta, \omega) + \varphi^*_2_m(\theta, \omega).
\]

We claim that

\[
\left\| \varphi^*_2_m(\theta, \omega) \right\|_{U_m \times C_m} \leq C(m) \epsilon_m,
\]

where \( C(m) \) is a constant of the form \( C_1 m^C_2 \). In fact,

\[
\left\| \varphi^*_2_m(\theta, \omega) \right\|_{U_m \times C_m} \leq \sum_{|k| > M_m} \left\| \hat{\varphi}^*_m(k; \omega) \right\|_{C_m} |e^{\sqrt{-1} k \cdot \theta}|_{U_m} \\
\leq \sum_{|k| > M_m} \left\| \hat{\varphi}^*_m(\theta; \omega) \right\|_{U_m-1 \times C_m} e^{-|k| \delta_{m-1-\delta_m}} \\
\leq \sum_{|k| > M_m} e^{-|k| \delta_{m-1-\delta_m}} = \epsilon_m \sum_{|k| > 0} e^{-|k| \delta_{m-1-\delta_m}} \\
\leq C(m) \epsilon_m.
\]

Next, we perform the change of variables as in (2.7), where \( E \) is the unit matrix in \( \mathbb{R}^n \), to transform (2.10) into

\[
\dot{y} = \left( (E + \epsilon_m P_m)^{-1} (A_m + \epsilon_m (A_m P_m - \dot{P}_m + Q^{*1}_m) + \epsilon_m Q^{*1}_{m+1}) \right) y,
\]

where

\[
\epsilon_m Q^{*1}_{m+1} = \epsilon_m Q^{*2}_m + \epsilon_m^2 (E + \epsilon_m P_m)^{-1} Q^{*}_m P_m.
\]

We would like to have

\[
(E + \epsilon_m P_m)^{-1} (A_m + \epsilon_m (A_m P_m - \dot{P}_m + Q^{*1}_m)) = A_m
\]

and this implies that

\[
\dot{P}_m = A_m P_m - P_m A_m + Q^{*1}_m.
\]

In order to solve this equation, we consider

\[
\omega \cdot \frac{\partial \varphi_m}{\partial \theta} = A_m \varphi_m - \varphi_m A_m + \varphi^{*1}_m,
\]
where $\mathcal{P}$ is the hull of $P(t)$. Write
\begin{equation}
\mathcal{P}_m(\theta, \omega) = \sum_{0 \leq |k| \leq M_m} \hat{\mathcal{P}}_m(k; \omega)e^{ik \cdot \theta}. \tag{2.22}
\end{equation}

Then we get
\begin{equation}
\sqrt{-1}(k \cdot \omega)\hat{\mathcal{P}}_m(k) = A_m\hat{\mathcal{P}}_m(k) - \hat{\mathcal{P}}_m(k)A_m + \hat{\mathcal{P}}^*_m(k), \quad 0 < |k| \leq M_m, \tag{2.23}
\end{equation}
where we omit the dependence on $\omega$ to simplify the notation. That is,
\begin{equation}
(\sqrt{-1}(k \cdot \omega)E - A_m)\hat{\mathcal{P}}_m(k) + \hat{\mathcal{P}}_m(k)A_m = \hat{\mathcal{P}}^*_m(k), \quad 0 < |k| \leq M_m. \tag{2.24}
\end{equation}

By Lemmas A.2 and 3.1, (2.24) is solvable for $\omega \in \mathbb{C}_m$ and
\begin{equation}
\|\hat{\mathcal{P}}_m(k; \omega)\|_{\mathbb{C}_m} \leq \|((\sqrt{-1}k \cdot \omega)E_n^2 - E_n \otimes A_m + A^T_\mathbb{C}_m \otimes E_n)^{-1}\|^\mathbb{C}_m \|\hat{\mathcal{P}}^*_m(k)\|_{\mathbb{C}_m} \\
\leq \frac{C|k|^\tau}{\gamma_m} \|\hat{\mathcal{P}}^*_m(k)\|_{U_m} \|\omega_m\|_{U_m} \|\omega_m\|_{C_m-1} e^{-|k|\gamma_m} \\
\leq \frac{C|k|^\tau}{\gamma_m} \|\omega_m\|_{U_m} \|\omega_m\|_{C_m-1} e^{-|k|\gamma_m}, \tag{2.25}
\end{equation}
where in the last inequality we have used $(H2)_m$. Therefore,
\begin{equation}
\|\mathcal{P}_m(\theta, \omega)\|_{U_m \times C_m} \leq \sum_{0 < |k| \leq M_m} \|\hat{\mathcal{P}}_m(k; \omega)\|_{\mathbb{C}_m} e^{\sqrt{-1}k \cdot \theta} \|\omega_m\|_{U_m} \\
\leq \sum_{k \in \mathbb{Z}_r} \frac{C|k|^\tau}{\gamma_m} e^{-|k|(|\gamma_m - \gamma_m|)} \\
\leq \frac{C}{\gamma_m} \sum_{k \in \mathbb{Z}_r} |k|^\tau e^{-C_k |k|(|\gamma_m - \gamma_m|)} \leq C(m), \tag{2.26}
\end{equation}
where the last inequality follows from Lemma A.1. Then, the function
\begin{equation}
P_m(t) = \mathcal{P}_m(\omega_1 t, \ldots, \omega_r t; \omega) \tag{2.27}
\end{equation}
solves (2.20). By (2.26) and (2.18), it is easy to show that $\|\mathcal{P}_{m+1}\|_{U_m \times C_m} \leq 1$. We omit the details.

**Proof of Theorem 1.1.** Obviously, (1.1) satisfies the conditions $(H)_m$ with $m = 1$. In fact, condition $(H2)_1$ may always be fulfilled by a suitable rescaling of $\epsilon$. Thus, by Lemma 2.1, there exists a sequence of transformations $x = (E + \epsilon_m P_m(t))y$, $m = 1, 2, \ldots$, such that the hulls $\mathcal{P}_m$ of the $P_m(t)$ are analytic in the domains $U_m \times \mathbb{C}_m$, and
\begin{equation}
\|\mathcal{P}_m\|_{U_m \times \mathbb{C}_m} \leq C(m). \tag{2.28}
\end{equation}
Let
\[ U_\infty \times \mathcal{C}_\infty = \bigcap_{m=1}^{\infty} U_m \times \mathcal{C}_m. \]  
(2.29)

Then, all the \( P_m, m = 1,2,\ldots, \) are well defined in the domain \( U_\infty \times \mathcal{C}_\infty \). Set
\[ \Phi(\theta,\omega) = \cdots \circ (E + \epsilon_m P_m(\theta;\omega)) \circ \cdots \circ (E + \epsilon_2 P_2(\theta;\omega)) \circ (E + \epsilon_1 P_1(\theta;\omega)), \]
and
\[ \Phi(t;\omega) = \cdots \circ (E + \epsilon_m P_m(t;\omega)) \circ \cdots \circ (E + \epsilon_2 P_2(t;\omega)) \circ (E + \epsilon_1 P_1(t;\omega)). \]
(2.30)

Note that \( \| E + \epsilon_m P_m(\theta;\omega) \|_{U_\infty \times \mathcal{C}_\infty} \leq 1 + \epsilon_m C(m) \leq 1 + 2^{-m}. \) We see that \( \Phi, \) and thus \( \Phi, \) are well defined. Let
\[ x = \Phi(t)y. \]
(2.31)

Since \( \epsilon_m \sup_{l \in \mathbb{N}} \| \mathcal{H}_l \|_{U_\infty \times \mathcal{C}_\infty} \leq \epsilon_m \to 0 \) as \( m \to \infty, \) the transformation \( x = \Phi(t)y \) changes (1.1) into
\[ \dot{y} = By, \]
(2.32)

where \( B = A + \sum_{j=1}^{\infty} \epsilon_m \mathcal{H}_m. \) This, together with Lemma 3.3, completes the proof of Theorem 1.1. \( \square \)

3. Estimates on the allowed frequencies set. Let \( \Pi_l (0 \leq l \leq m - 1) \) be a sequence of compact subsets of \( \mathbb{R}^l \) with \( \Omega = \Pi_0 \supset \Pi_1 \supset \cdots \supset \Pi_{m-1} \) and denote by \( \mathcal{C}_l \) the complex \( q_l \)-neighborhood of \( \Pi_l, l = 0,\ldots,m-1. \) Recall that
\[ A_m(\omega) = A + \epsilon_1 \mathcal{H}_1(\omega) + \cdots + \epsilon_m \mathcal{H}_m(\omega), \]
(3.1)

where, for \( l = 1,\ldots,m - 1, \) the \( \mathcal{H}_l(\omega) \) are analytic, and real for real arguments in the domain \( \mathcal{C}_l, \) and \( \| \mathcal{H}_l(\omega) \|_{\mathcal{C}_l} \leq 1; \) and \( \mathcal{H}_m(\omega) \) is analytic, and real for real arguments in the domain \( \mathcal{C}_{m-1}, \) and \( \| \mathcal{H}_m(\omega) \|^{e_{m-1}} \leq 1. \) Denote by \( \cdot \) the determinant of a matrix. Let
\[ \mathcal{R}_k(m) := \left\{ \omega \in \Pi_{m-1} : \left\| (\sqrt{-1} k \cdot \omega) E_{n^2} - E_n \otimes A_m + A_m^T \otimes E_n \right\|_d < \frac{\gamma_m}{|k|^\tau_1} \right\}, \]
(3.2)

where \( \gamma_m = \gamma/m^{2n^2} \) and \( \tau_1 = (r + 1)n^2, \)
\[ \Pi_m = \Pi_{m-1} \setminus \bigcup_{0 < |k| \leq M_m} \mathcal{R}_k(m), \]
(3.3)

where \( M_m = |\ln \epsilon_m|/(\delta_{m-1} - \delta_m) \) is the number of Fourier coefficients we must consider at the \( m \)th step of the iteration, and denote by \( \mathcal{C}_m \) the complex \( q_m \)-neighborhood of \( \Pi_m. \)
Lemma 3.1. Let \( \tau = \tau_1 + n^2 - 1 \) and

\[
G(\omega) = (\sqrt{-1} k \cdot \omega) E_{n^2} - E_n \otimes A_m(\omega) + A_m^T(\omega) \otimes E_n.
\]

Then, for \( \omega \in \mathscr{C}_m \) and \( 0 < |k| \leq M_m \), the inverse of \( G(\omega) \) exists and it is analytic in the domain \( \mathscr{C}_m \) with

\[
||G^{-1}(\omega)||^{\mathcal{C}_m} \leq C_y^{-1}_m |k|^\tau.
\]

Proof. By the definition of \( \Pi_m \), we get that for \( \omega \in \Pi_m \) and \( 0 < |k| \leq M_m \),

\[
|\mathcal{M}_k(\omega)| \geq \frac{y_m}{|k|^\tau_1}.
\]

It is easy to see that

\[
||G(\omega)||^{\mathcal{C}_m} \leq C_5 |k|, \quad k \neq 0,
\]

where \( C_5 = 2(\max\{ |\omega| : \omega \in \Pi \} + \|A\| + 1) \). Since \( \det G(\omega) = \mathcal{M}_k(\omega) \), \( G^{-1}(\omega) \) exists for \( \omega \in \Pi_m \) and

\[
G^{-1}(\omega) = \frac{\text{adj}G(\omega)}{\mathcal{M}_k(\omega)},
\]

where adj is the adjoint of a matrix. Thus, for \( 0 < |k| \leq M_m \),

\[
||G^{-1}(\omega)||^{\Pi_m} \leq C_6 \frac{|k|^{n^2-1}}{y_m / |k|^\tau_1} = C_6 y_m^{-1} |k|^\tau.
\]

Now, we assume that \( \omega \in \mathscr{C}_m \). Then there is an \( \omega_0 \in \Pi_m \) such that \( |\omega - \omega_0| < q_m \). Thus,

\[
||G^{-1}(\omega_0)|| \cdot ||G(\omega) - G(\omega_0)||
\]

\[
\leq ||G^{-1}(\omega)||^{\Pi_m} ||\nabla_{\omega} G(\omega) ||^{\mathcal{C}_m} |\omega - \omega_0|
\]

\[
\leq C_6 y_m^{-1} |k|^\tau ||G(\omega)||^{\mathcal{C}_m-1} \frac{q_m}{q_m - q_m}
\]

\[
\leq C_6 y_m^{-1} |k|^\tau + 1 \frac{q_m}{q_m - q_m}
\]

\[
\leq C_6 M_m^{\tau+1} y_m^{-1} \frac{q_m}{q_m - q_m}
\]

\[
\leq C_6 m^{(6+2r)n^2} |\ln \epsilon_m| |\tau+1/4n^2 (y_0)^{-1} \epsilon_m^{1/4n^2} - \epsilon_m^{1/4n^2}| < \frac{1}{2}.
\]
Therefore, \( E + G^{-1}(\omega_0)(G(\omega) - G(\omega_0)) \) has its inverse which is analytic in \( \mathcal{O}_m \) since

\[
(E + G^{-1}(\omega_0)(G(\omega) - G(\omega_0)))^{-1} = \sum_{j=0}^{\infty} (-G^{-1}(\omega_0)(G(\omega) - G(\omega_0)))^j.
\] (3.11)

So, \( G(\omega) \) has its inverse for \( \omega \in \mathcal{O}_m \) and

\[
\|G^{-1}(\omega)\| = \| (E + G^{-1}(\omega_0)(G(\omega) - G(\omega_0)))^{-1} \cdot G^{-1}(\omega_0) \|
\leq \| (E + G^{-1}(\omega_0)(G(\omega) - G(\omega_0)))^{-1} \| \cdot \|G^{-1}(\omega_0)\|
\leq C Y_m |k|^\tau. \quad (3.12)
\]

**Lemma 3.2.** Let \( K = n^2(n+1)^2(\text{diam}\Pi_0)^{r-1} \). Then the Lebesgue measure of \( \mathcal{R}_k(m) \) verifies

\[
\text{Meas}\mathcal{R}_k(m) \leq \frac{K Y^{1/n^2}}{|k|^{r+1}} \frac{1}{m^2}. \quad (3.13)
\]

**Proof.** Recall that \( q_l = \epsilon_l^{1/n^2} \), let \( q^l_1 = (5/6)q_l + (1/6)q_{l+1} \), and denote by \( \mathcal{O}^l_1 \) the complex \( q^l_1 \)-neighborhood of \( \Pi_l \). Obviously, \( \mathcal{O}^l_1 \subset \mathcal{O}^l_1 \subset \mathcal{O}_l \) and \( \text{dist}(\partial \mathcal{O}^l_1, \partial \mathcal{O}_l) = (1/6)(q_l - q_{l+1}) > (1/12)q_l \). Noting that \( \|\tilde{\partial}_l\|\epsilon_l \leq 1 \) and using Cauchy’s theorem, we get for \( 1 \leq s \leq n^2 \) and \( 0 \leq l \leq m - 1 \),

\[
\epsilon_l \|\tilde{\partial}_l A_m(\omega)\|^{2^{l-1}} \leq \epsilon_l (12q_l^{-1})^{s}\|\tilde{\partial}_l\|^{\epsilon_l} \leq \epsilon_l^{1/2}. \quad (3.14)
\]

The combination of (3.1) and (3.14) leads to

\[
\|\tilde{\partial}_l A_m(\omega)\|^{2^{l-1}} \leq \epsilon^{1/2}. \quad (3.15)
\]

Let

\[
B(\omega) := -E_n \otimes A_m(\omega) + A_m^T \otimes E_n. \quad (3.16)
\]

Then

\[
\|\tilde{\partial}_l B(\omega)\|^{2^{l-1}} \leq \epsilon^{1/2}. \quad (3.17)
\]

Set

\[
\mathcal{M}_k(\omega) = \left| (\sqrt{-1}k \cdot \omega)E_{n^2} + B(\omega) \right|_d. \quad (3.18)
\]

We are now in a position to estimate \( \tilde{\partial}_l^g \mathcal{M}_k \). To this end, write \( B(\omega) = (b_{ij}) \). Then

\[
\mathcal{M}_k(\omega) = (\sqrt{-1})^{n^2}(k \cdot \omega)^{n^2} + \sum_{1 \leq l \leq n^2 - 1} \phi_l(\omega)(k \cdot \omega)^{n^2-l}, \quad (3.19)
\]
where

\[ \phi_l(\omega) = \sum_{1 \leq j_l \leq n^2} \sigma_{j_1 \cdots j_l} b_{1j_1} \cdots b_{lj_l} \]  

(3.20)

and \( \sigma_{j_1 \cdots j_l} \in \{-1, +1, -\sqrt{-1}, +\sqrt{-1}\} \).

Observe that for \( 1 \leq l \leq n^2 \) and \( \omega \in \mathcal{C}_{m-1}^l \),

\[ |\partial_{\omega^l_i} b_{ij} | \leq \| \partial_{\omega^l_i} B(\omega) \|^{m-1} \leq \epsilon^{1/2}. \]  

(3.21)

Thus, for \( \omega \in \mathcal{C}_{m-1}^l \) and \( 1 \leq s \leq n^2 \),

\[ \left| \frac{d^s}{d\omega_1^s} (b_{1j_1} \cdots b_{lj_l}) \right| \leq \left| \sum_{s_1 + \cdots + s_l = s} \left( \frac{d^{s_1}}{d\omega_1^{s_1}} b_{1j_1} \right) \cdots \left( \frac{d^{s_l}}{d\omega_1^{s_l}} b_{lj_l} \right) \right| \]

\[ \leq \epsilon^{(1/2)(s_1 + \cdots + s_l)} \sum_{s_1 + \cdots + s_l = s} 1 \]

\[ \leq (2\epsilon^{1/2})^s, \]  

(3.22)

and therefore,

\[ \left| \frac{d^s}{d\omega_1^s} \phi_l(\omega) \right| \leq \left( \frac{n^2}{l} \right) (2\epsilon^{1/2})^s. \]  

(3.23)

Without loss of generality, assume that \( |k| = |k_1| + \cdots + |k_r| \leq r|k_1| \). Hence, for every \( \omega \in \mathcal{C}_{m-1}^l \),

\[ \left| \frac{d^{n^2}}{d\omega_1^{n^2}} \sum_{1 \leq s \leq n^2-1} \phi_l(\omega)(k \cdot \omega)^{n^2-1} \right| \]

\[ \leq \sum_{1 \leq s \leq n^2-1} \left| \frac{d^{n^2}}{d\omega_1^{n^2}} (\phi_l(\omega)(k \cdot \omega)^{n^2-1}) \right| \]

\[ \leq \sum_{1 \leq l \leq n^2-1} \sum_{1 \leq s \leq n^2} \left( \frac{n^2}{s} \right) \left| \frac{d^s}{d\omega_1^s} \phi_l(\omega) \right| \left| \frac{d^{n^2-s}}{d\omega_1^{n^2-s}} (k \cdot \omega)^{n^2-1} \right| \]

\[ \leq \sum_{1 \leq l \leq n^2-1} \sum_{1 \leq s \leq n^2} \left( \frac{n^2}{l} \right) \left( \frac{n^2}{s} \right) (2\epsilon^{1/2})^s |k_1| |n^2-s| |k \cdot \omega|^{s-1} n^2! \]

\[ \leq C_4 \epsilon^{1/2} |k_1|^{n^2-1} n^2!, \]  

(3.24)

where \( C_4 \) is some constant which depends only on \( n, r \), and on the maximum of \( |\omega| \) in \( \Pi_0 \). Obviously,

\[ \frac{d^{n^2}}{d\omega_1^{n^2}} (k \cdot \omega)^{n^2} = n^2! |k_1|^{n^2}. \]  

(3.25)
Thus, in $C^1_{m-1}$, we have

$$\left| \frac{d^{n^2}}{d\omega_1^{n^2}} M_k(\omega) \right| \geq n^2 |k_1| |n^2 (1 - C_4 \epsilon^{1/2} |k_1|^{-1}) > \frac{1}{2} n^2 |k_1|^{n^2}$$

(3.26)

provided that $\epsilon$ is small enough so that $C_4 \epsilon^{1/2} < 1/2$. Using (3.26) and Lemma A.3, we get

$$\text{Meas} \mathcal{B}_k(m) \leq n^2 (n^2 + 1) \left( \frac{Y_m}{|k|^r} \right)^{1/n^2} (\text{diam} \Pi_0)^{r^{-1}} \leq K y^{1/n^2} \cdot \frac{1}{m^2}.$$  

(3.27)

This completes the proof.

By Lemma 2.1, the nested sequence of closed sets

$$\Omega_0 = \Pi_0 \supset \Pi_1 \supset \cdots \supset \Pi_m \supset \cdots$$  

(3.28)

is defined inductively. The following lemma is a corollary of Lemma 3.2.

**Lemma 3.3.** Let

$$\Pi_\infty = \bigcap_{m=0}^{\infty} \Pi_m.$$  

(3.29)

Then $\text{Meas} \Pi_\infty = (\text{Meas} \Pi_0)(1 - O(y^{1/n^2}))$.

**Appendix**

**Lemma A.1.** For $\delta > 0$ and $\nu > 0$, the following inequality holds true:

$$\sum_{k \in \mathbb{Z}^N} e^{-2|k|\delta} |k|^\nu \leq \left( \frac{\nu}{e} \right)^\nu \frac{1}{\delta^{\nu+N}} (1 + e)^N.$$  

(A.1)

**Proof.** This lemma can be found in [1]. We will find the value of $z \geq 1$ yielding a maximum value for the expression $\nu \ln z - \delta z$. Differentiating it in $z$ and equating the result to zero, we get that $\nu/z = \delta$ and $z = \nu/\delta > 1$. From this it follows that

$$\nu \ln z - \delta z \leq \nu \left( \ln \frac{\nu}{\delta} - 1 \right).$$  

(A.2)

This expression yields

$$z^\nu \leq \exp(\delta z) \exp \left( \nu \left( \ln \frac{\nu}{\delta} - 1 \right) \right) = \left( \frac{\nu}{e} \right)^\nu \frac{\exp(\delta z)}{\delta^\nu}.$$  

(A.3)
Thus,
\[
\sum_{k \in \mathbb{Z}^N} e^{-2|k|\nu} \leq \left(\frac{\nu}{e}\right)^\nu \frac{1}{\delta^\nu} \sum_k e^{-|k|\delta} = \left(\frac{\nu}{e}\right)^\nu \frac{1}{\delta^\nu} \left(\frac{1 + \exp(-\nu)}{1 - \exp(-\nu)}\right)^N \leq \left(\frac{\nu}{e}\right)^\nu \frac{1}{\delta^\nu} \left(\frac{1 + e^{-\delta}}{\delta}\right)^N.
\] (A.4)

**Lemma A.2.** Let $A$, $B$, and $C$ be $r \times r$, $s \times s$, and $r \times s$ matrices, respectively; and let $X$ be an $r \times s$ unknown matrix. Then the matrix equation
\[
AX + XB = C
\] (A.5)
is solvable if and only if the vector equation
\[
(E_s \otimes A + B^T \otimes E_r)X' = C' \quad \text{(A.6)}
\]
is solvable, where $X' = (X_1^T, \ldots, X_s^T)^T$, $C' = (C_1^T, \ldots, C_s^T)^T$ if we write $X = (X_1, \ldots, X_s)$ and $C = (C_1, \ldots, C_s)$. Moreover,
\[
\|X\| \leq \left\| (E_s \otimes A + B^T \otimes E_r)^{-1} \right\| \|C\| \quad \text{(A.7)}
\]
if the inverse exists.

**Proof.** This lemma can be found in many textbooks on matrix theory; for example, [4, page 256].

The following lemma can be found in [7, page 23].

**Lemma A.3.** Let $\mathcal{I}$ be an interval in $\mathbb{R}^1$ and $\mathcal{I}$ its closure. Suppose that $g : \mathcal{I} \to \mathbb{C}$ is $k$ times continuously differentiable. Let $\mathcal{I}_h = \{x \in \mathcal{I} : |g(x)| \leq h\}$, $h > 0$. If, for some constant $d > 0$, $|d^{k}g(x)/dx^k| \geq d$ for any $x \in \mathcal{I}$, then $\text{Meas} I_h \leq c h^{1/k}$ with $c = 2(2 + 3 + \cdots + k + d^{-1})$.

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