Local behaviour of the error in the Bergman kernel method for numerical conformal mapping *

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Abstract


Let Ω be a simply-connected domain in the complex plane, let ζ ∈ Ω and let K(z, ζ) denote the Bergman kernel function of Ω with respect to ζ. Also, let K_n(z, ζ) denote the nth-degree polynomial approximation to K(z, ζ), given by the classical Bergman kernel method, and let π_n denote the corresponding nth-degree Bieberbach polynomial approximation to the conformal map f of Ω onto a disc. Finally, let B be any subdomain of Ω. In this paper we investigate the two local errors ∥K(·, ζ) - K_n(·, ζ)∥_L^2(Ω), ∥f(·) - π_n∥_L^2(Ω), and compare their rates of convergence with those of the corresponding global errors with respect to L^2(Ω).

Our results show that if ∂B contains a subarc of ∂Ω, then the rates of convergence of the local errors are not substantially different from those of the global errors.

Keywords: Bergman kernel function; Bergman kernel method; Bieberbach polynomials; conformal mapping; local and global errors.

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1. Introduction

Let $\Omega$ be a simply-connected domain of the complex plane $\mathbb{C}$, whose boundary $\Gamma$ is a closed Jordan curve, and let $\zeta \in \Omega$. Then, by the Riemann mapping theorem, there exists a unique conformal mapping $w = f_\zeta(z)$ of $\Omega$ onto a disc $\{w: |w| < r_\zeta\}$, such that

$$f_\zeta(\zeta) = 0, \quad f_\zeta'(\zeta) = 1.$$  

The radius $r_\zeta$ of this disc is called the conformal radius of $\Omega$ with respect to $\zeta$. (To avoid the study of uninteresting cases we shall assume throughout this paper that $f_\zeta(z)$ is not a polynomial function.)

For the inner product

$$(g, h) := \int_{\Omega} g(z)\overline{h(z)} \, dm,$$

where $dm$ is the two-dimensional Lebesgue measure, we consider the Hilbert space

$$L^2(\Omega) := \{g: g \text{ analytic in } \Omega, \|g\|_{L^2(\Omega)} = (g, g)^{1/2} < \infty\}.$$

Let $K(z, \zeta)$ denote the Bergman kernel function of $\Omega$ which has the reproducing property

$$g(\zeta) = (g, K(\cdot, \zeta)), \quad \forall g \in L^2(\Omega). \quad (1.1)$$

(cf. [1–3, 6]). Then it is known (cf. [3, p.341]) that $r_\zeta = (\pi K(\zeta, \zeta))^{-1/2}$ and that for $z \in \Omega$,

$$f_\zeta'(z) = \frac{K(z, \zeta)}{K(\zeta, \zeta)}, \quad f_\zeta(z) = \frac{1}{K(\zeta, \zeta)} \int_{\Omega} K(t, \zeta) \, dt. \quad (1.2)$$

Next let $Q_n(z) = \gamma_n z^n + \cdots$, $\gamma_n > 0$, be the sequence of orthonormal polynomials for the inner product $(\cdot, \cdot)$, i.e.,

$$\int_{\Omega} Q_k(z)\overline{Q_l(z)} \, dm = \delta_{k,l}. \quad (1.3)$$

Since $\Omega$ is a Jordan region, it is known (cf. [3, p.17]) that $\{Q_n\}_{n=0}^\infty$ forms a complete orthonormal system for $L^2(\Omega)$ and, from the reproducing property (1.1), it follows that (with respect to this system) the Fourier coefficients of $K(\cdot, \zeta)$ are given by $Q_n(\zeta)$, $n = 0, 1, \ldots$. Thus, for the partial sums

$$K_n(z, \zeta) := \sum_{j=0}^n Q_j(\zeta)Q_j(z) \quad (1.3)$$

we have

$$E_n(K, \Omega) := \|K(\cdot, \zeta) - K_n(\cdot, \zeta)\|_{L^2(\Omega)} \to 0, \quad \text{as } n \to \infty. \quad (1.4)$$

From the least-squares property of the Fourier sections, we also have that

$$E_n(K, \Omega) \leq \|K(\cdot, \zeta) - p_n\|_{L^2(\Omega)}, \quad \forall p_n \in \Pi_n, \quad (1.5)$$

where $\Pi_n$ denotes the collection of all polynomials having degree at most $n$. 
In the classical Bergman kernel method (BKM) for numerically computing the conformal mapping \( f_{\z} \), we replace \( K \) by \( K_{n-1} \) in (1.2) and obtain the polynomial approximations
\[
\pi_n(z) = \frac{K_{n-1}(z, \z)}{K_{n-1}(\z, \z)} \quad \text{and} \quad \pi_n(z) := \frac{1}{K_{n-1}(\z, \z)} \int_{\z}^{z} K_{n-1}(t, \z) \, dt,
\]
to \( f'_{\z} \) and \( f_{\z} \), respectively. The polynomials \( \pi_n \) are the Bieberbach polynomials for \( \Omega \), and it is easily seen from (1.4) that they satisfy
\[
e_n(f'_{\z}, \Omega) := \| f'_{\z} - \pi_n' \|_{L^2(\Omega)} \to 0, \quad \text{as } n \to \infty,
\]
and
\[
e_n(f_{\z}, \Omega) := \| f_{\z} - \pi_n \|_{L^2(\Omega)} \to 0, \quad \text{as } n \to \infty.
\]
Roughly speaking, the rates of convergence in (1.4), (1.7) and (1.8) are governed by the smoothness properties of the boundary \( \Gamma \) or, equivalently, by the nature and location of the singularities of \( f_{\z} \) in \( \Omega \). For example, if \( \Gamma \) is an analytic Jordan curve, then these rates are geometric, i.e.,
\[
\limsup_{n \to \infty} \left[ E_n(K, \Omega) \right]^{1/n} < 1
\]
(and similarly for \( e_n(f'_{\z}, \Omega) \) and \( e_n(f_{\z}, \Omega) \)), while for piecewise analytic boundaries these rates are typically of the form \( 1/n^\gamma \), for some constant \( \gamma > 0 \) (cf. [3, 4, 9, 10]).

The purpose of this paper is to investigate local rates of convergence in the BKM. To be more precise, let \( B \) be any (arbitrarily small) Jordan subdomain of \( \Omega \) and consider the norm
\[
\| g \|_{L^2(B)} := \left( \int_B \int_B |g|^2 \, dm \right)^{1/2}.
\]
Then our goal is to investigate the rates of convergence of the following two errors:
\[
E_n(K, B) := \| K(\cdot, \z) - K_n(\cdot, \z) \|_{L^2(B)},
\]
and
\[
e_n(f_{\z}, B) := \| f_{\z} - \pi_n \|_{L^2(B)}.
\]
If the closure \( \overline{B} \) is contained in \( \Omega \), then it is indeed possible for the local errors (1.10), (1.11) to tend to zero geometrically faster than the corresponding global errors with respect to \( L^2(\Omega) \) (see Example 3.1). If, however, the boundary \( \partial B \) of \( B \) contains a subarc of \( \Gamma \) (and \( \Gamma \) satisfies certain smoothness conditions), then we shall show that the rates of convergence of the local errors are not “substantially” different from those of the corresponding global errors. This fact is somewhat surprising, because it implies that the BKM errors in small subregions of \( \Omega \) that are near to the singularities of \( f_{\z} \) are “essentially” the same as those in small subregions that are far from these singularities. This behaviour is, however, consistent with the second author’s principle of contamination in best approximation (cf. [8]).

2. Statements of results

Our results will be established by assuming that the boundary curve \( \Gamma \) satisfies certain smoothness conditions. In particular, we shall assume that \( \Gamma \) belongs to a class \( C(p, \alpha) \). This class is defined as follows (cf. [10, p.5]).
Definition 2.1. A rectifiable Jordan curve $\gamma$ is said to belong to the class $C(p, \alpha)$, where $p$ is a positive integer and $0 < \alpha \leq 1$, if $\gamma$ has a parametrization $z = z(s)$, where $s$ is arc length, and the function $z(s)$ is $p$ times continuously differentiable with $z^{(p)}(s) \in \text{Lip } \alpha$.

Our principal result is as follows.

Theorem 2.2. With the notations of Section 1, suppose that $\Gamma \in C(p + 1, \alpha)$, $p \geq 0$, $0 < \alpha \leq 1$. If $B \subset \Omega$ is any Jordan domain such that its boundary $\partial B$ contains a subarc of $\Gamma$, then

$$\sum_{n=0}^{\infty} \left( \frac{\|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(\Omega)}}{\|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(B)}} \right)^2 = \infty. \quad (2.1)$$

An immediate consequence of Theorem 2.2 is the following.

Corollary 2.3. Let $\Gamma$ and $B \subset \Omega$ be as in Theorem 2.2. Then, given $c > 0$, there exists a subsequence $\Lambda \subset N$ such that

$$\|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(B)} \geq \frac{c}{n^{1/2+\epsilon}} \|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(\Omega)}, \quad n \in \Lambda, \quad (2.2)$$

where $c$ is a positive constant.

The following two results are also relatively simple consequences of Theorem 2.2 and its proof.

Theorem 2.4. Suppose that $\Gamma \in C(p + 1, \alpha)$ with $p + \alpha > \frac{1}{2}$ and let $B \subset \Omega$ be as in Theorem 2.2. Then, given $\epsilon > 0$, there exists a subsequence $\Lambda \subset N$ such that

$$\|f'_\xi - \pi'_n\|_{L^2(B)} \geq \frac{c}{n^{1/2+\epsilon}} \|f'_\xi - \pi'_n\|_{L^2(\Omega)}, \quad n \in \Lambda, \quad (2.3)$$

where $c$ is a positive constant.

Theorem 2.5. Suppose that $\Gamma$ is an analytic Jordan curve and let $B \subset \Omega$ be as in Theorem 2.2. Then there exists a subsequence $\Lambda \subset N$ and a positive constant $c$ such that

$$\|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(B)} \geq c \|K(\cdot, \xi) - K_n(\cdot, \xi)\|_{L^2(\Omega)}, \quad n \in \Lambda, \quad (2.4)$$

and

$$\|f'_\xi - \pi'_n\|_{L^2(B)} \geq c \|f'_\xi - \pi'_n\|_{L^2(\Omega)}, \quad n \in \Lambda. \quad (2.5)$$

We expect that the corresponding errors for the mapping function $f_{\xi}$ satisfy similar results but, so far, we have not been able to prove this.

3. Examples

Example 3.1. Consider the case where $\Omega = \{z : |z| < 1\}$ and $\xi \in \Omega$ is different than zero. Then

$$Q_n(z) = \sqrt{\frac{n+1}{\pi}} z^n, \quad n = 0, 1, \ldots,$$
\[ K(z, \zeta) = \frac{1}{\pi} \sum_{j=0}^{\infty} (j+1)(\bar{\zeta} z)^j = \frac{1}{\pi} \frac{1}{(1 - \bar{\zeta} z)^2}, \quad \zeta, z \in \Omega, \] (3.1)

\[ K_{n-1}(z, \zeta) = \frac{1}{\pi} \sum_{j=0}^{n-1} (j+1)(\bar{\zeta} z)^j = \frac{1}{\pi} \frac{n(\bar{\zeta} z)^{n+1} - (n+1)(\bar{\zeta} z)^n + 1}{(1 - \bar{\zeta} z)^2}. \] (3.2)

Also, \( f_\zeta(z) = \left(1 - |z|^2\right) \left(\frac{z - \zeta}{1 - \bar{\zeta} z}\right) \),

so that the mapping function \( f_\zeta \) has a simple pole at the point \( z = 1/\bar{\zeta} \) but is otherwise analytic in the extended plane.

Equations (3.1) and (3.2) imply that

\[ K(z, \zeta) - K_{n-1}(z, \zeta) = \frac{1}{\pi} \frac{(\bar{\zeta} z)^n}{(1 - \bar{\zeta} z)^2} \left\{ -n \bar{\zeta} z + n + 1 \right\}, \]

and from this it follows that

\[ \limsup_{n \to \infty} \| K(\cdot, \zeta) - K_{n-1}(\cdot, \zeta) \|_{L^2(\Omega)}^{1/n} = |\zeta|. \]

It also follows that if \( B := \{z: |z| < r < 1\} \), then

\[ \limsup_{n \to \infty} \| K(\cdot, \zeta) - K_{n-1}(\cdot, \zeta) \|_{L^2(B)}^{1/n} = r |\zeta|. \]

This illustrates the fact that if \( B \subset \Omega \), then the local error (1.10) can tend to zero geometrically faster than the global error with respect to \( L^2(\Omega) \).

Let \( z_1, z_2 \) denote, respectively, the two boundary points nearest and furthest away from the singularity of \( f_\zeta \) at \( z = 1/\bar{\zeta} \), i.e., \( \zeta_1 := e^{i\alpha} \) and \( \zeta_2 := -e^{i\alpha} \), where \( \alpha := \arg \zeta \). Then,

\[ K(z_1, \zeta) - K_{n-1}(z_1, \zeta) = \frac{1}{\pi} \frac{|\zeta|^n}{(1 - |\zeta|)^2} \{ -n |\zeta| + n + 1 \} =: e_n(z_1), \]

\[ K(z_2, \zeta) - K_{n-1}(z_2, \zeta) = \frac{1}{\pi} \frac{(-1)^n |\zeta|^n}{(1 + |\zeta|)^2} \{ n |\zeta| + n + 1 \} =: e_n(z_2), \]

and hence

\[ \lim_{n \to \infty} \frac{|e_n(z_1)|}{|e_n(z_2)|} = \frac{1 + |\zeta|}{1 - |\zeta|}. \]

This supports (in a pointwise sense) the remark made at the end of Section 1 concerning the BKM errors in small subregions close to and far away from the singularities of \( f_\zeta \).
Example 3.2. Let $\Omega$ be bounded by $\Gamma = \Gamma_1 \cup \Gamma_2$, where $\Gamma_1$ and $\Gamma_2$ are respectively the half circle

$$\Gamma_1 := \{z = x + iy : |z| = 1, x \leq 0\}$$

and the half ellipse

$$\Gamma_2 := \{z = x + iy : \frac{1}{2}x^2 + y^2 = 1, x > 0\},$$

and set $\zeta = 0$.

In this case $\Gamma \in C(1, 1)$ and the mapping function $f_0$ has a branch point singularity at each of the points $z_1 = i$ and $z_2 = -i$ where the two curves $\Gamma_1$ and $\Gamma_2$ meet, in the sense that

$$f_0(z) - f_0(z_j) \sim (z - z_j)^2 \log(z - z_j), \quad \text{as } z \to z_j, \ j = 1, 2,$$

(cf. [7, p.651]).

Let $B_1$ and $B_2$ denote the two subdomains of $\Omega$ whose boundaries $\partial B_1$ and $\partial B_2$ are as follows: (i) $\partial B_1$ consists of the subarc

$$z = e^{i\theta}, \quad \frac{1}{2}\pi < \theta \leq \frac{7}{12}\pi,$$

of $\Gamma_1$ and the two straight lines that join the point 0.5i respectively to the boundary points $i$ and $e^{i(\pi/12)}$, (ii) $\partial B_2$ consists of the subarc

$$z = e^{i\theta}, \quad \pi < \theta \leq \frac{13}{12}\pi,$$

of $\Gamma_1$ and the two straight lines that join the point $-0.5$ respectively to the boundary points $-1$ and $e^{i(13\pi/12)}$. (Observe that $\partial B_1$ contains the point $z_1 = i$, where $f_0$ has a branch point singularity, while $\partial B_2$ does not involve any singular points of $f_0$.)

In Table 1 we have listed (for various values of $n$) estimates of the errors

$$\epsilon_n(f_0', \Omega) := \|f_0' - \pi_n'\|_{L^2(\Omega)}, \quad \epsilon_n(f_0', B_j) := \|f_0' - \pi_n'\|_{L^2(B_j)}, \quad j = 1, 2,$$

and also of the ratios

$$r_n^{(1)} := \frac{\epsilon_n(f_0', B_1)}{\epsilon_n(f_0', \Omega)}, \quad r_n^{(1,2)} := \frac{\epsilon_n(f_0', B_2)}{\epsilon_n(f_0', B_1)}.$$
Table 2 contains the corresponding estimates for the mapping function \( f_0 \), i.e.,

\[
\epsilon_n(f_0, \Omega) := \| f_0 - \pi_n \|_{L^2(\Omega)}, \quad \epsilon_n(f_0, B_j) := \| f_0 - \pi_n \|_{L^2(B_j)}, \quad j = 1, 2,
\]

\[
r_n^{(j)} := \frac{\epsilon_n(f_0, B_j)}{\epsilon_n(f_0, \Omega)}, \quad j = 1, 2, \quad r_n^{(1,2)} := \frac{\epsilon_n(f_0, B_1)}{\epsilon_n(f_0, B_2)}.
\]

All these estimates were computed by using the FORTRAN conformal mapping package BKMPACK [11].

As might be expected, the results of the two tables show that the local errors \( \epsilon_n(f_0', B_2) \) and \( \epsilon_n(f_0, B_2) \), for the subregion \( B_2 \), are smaller than the errors \( \epsilon_n(f_0', B_1) \) and \( \epsilon_n(f_0, B_1) \) for the subregion \( B_1 \) whose boundary contains the singular point \( z_1 = i \). However, the numerical results also show that the rates of decrease of \( \epsilon_n(f_0', B_2) \) and \( \epsilon_n(f_0, B_2) \) are not substantially different than those of \( \epsilon_n(f_0', B_1) \) and \( \epsilon_n(f_0, B_1) \). The numerics for \( \epsilon_n(f_0', B_2) \) are therefore consistent with the result of Theorem 2.4, while those for \( \epsilon_n(f_0, B_2) \) support our statement at the end of Section 2.

4. Proofs

To establish Theorems 2.2, 2.4 and 2.5 we shall make use of several lemmas. The first two of these are due to Suetin [10].

**Lemma 4.1** (Suetin [10, p.20]). Suppose \( \Gamma \in C(p + 1, \alpha) \), \( p \geq 0 \), \( 0 < \alpha < 1 \). Then the orthonormal polynomials \( Q_n \) of Section 1 satisfy

\[
Q_n(z) = \sqrt{\frac{n + 1}{\pi}} \phi'(z)\left[ \phi(z) \right]^n \left[ 1 + O\left( \frac{\log n}{n^{1+\alpha}} \right) \right], \quad z \in \Gamma,
\]

where \( w = \phi(z) \) is the conformal mapping of \( \overline{C/\Omega} \) onto \{ \( w : |w| > 1 \} \) normalized by \( \phi(\infty) = \infty \) and \( \phi'(\infty) > 0 \).
Lemma 4.2 (Suetin [10, p. 38]). Let $A$ be a simply-connected domain bounded by a Jordan curve $\gamma \subset C(1, \alpha)$, $0 < \alpha \leq 1$. Then for every polynomial $P_n \in \Pi_n$ we have
\[
\int_\gamma |P_n(z)|^2 |dz| \leq c(n + 1) \int_A |P_n(z)|^2 \, dm,
\] where the constant $c$ depends only on $\gamma$.

Lemma 4.3. Suppose $\Gamma \subset C(p + 1, \alpha)$, $p \geq 0$, $0 < \alpha \leq 1$, and let $B \subset \Omega$ be as in Theorem 2.2. Then there exists a positive constant $\tau = \tau(B)$ such that
\[
\|Q_n\|_{L^2(B)} \geq \tau > 0, \quad n = 0, 1, \ldots,
\]
where the $Q_n$ are the orthonormal polynomials of Section 1.

Proof. Since $\partial B$ contains a subarc of $\Gamma$, it is always possible to choose a subarc $\gamma_0 \subset \Gamma \cap \partial B$ and construct a Jordan domain $A \subset B$ such that $\gamma := \partial A \subset C(1, \alpha)$ and $\gamma_0 \subset \gamma$. Then from (4.1) it follows that
\[
\int_\gamma |Q_n(z)|^2 |dz| \geq \int_{\gamma_0} |Q_n(z)|^2 |dz| \geq c_0(n + 1), \quad n = 0, 1, \ldots,
\] (recall that $|\phi(z)| = 1$ on $\gamma_0 \subset \Gamma$). On the other hand, from (4.2) we get
\[
\int_\gamma |Q_n(z)|^2 |dz| \leq c(n + 1) \int_A |Q_n(z)|^2 \, dm \leq c(n + 1) \int_B |Q_n(z)|^2 \, dm.
\]
Thus combining (4.4) and (4.5), we obtain
\[
0 < \frac{c_0}{c} \leq \int_B |Q_n(z)|^2 \, dm,
\]
and this gives the desired inequality (4.3). \(\square\)

Lemma 4.4. With the notations and assumptions of Section 1, there exist positive constants $c_1$ and $c_2$ such that
\[
c_1 \|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)} \leq \|f_\zeta' - \pi_n\|_{L^2(\Omega)} \leq c_2 \|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)},
\]
for $n = 0, 1, \ldots$.

Thus the $L^2(\Omega)$ norms of $f_\zeta' - \pi_n$ and $K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)$ are equivalent.

Proof. Recall that $K(\zeta, \xi)f_\zeta'(z) = K(z, \xi)$ and that $K_{n-1}(\zeta, \xi)\pi_n(z) = K_{n-1}(z, \xi)$. Thus
\[
\|f_\zeta' - \pi_n\|_{L^2(\Omega)}
\]
\[
= \left\| \frac{K(\cdot, \zeta) - K_{n-1}(\cdot, \zeta)}{K(\zeta, \xi) - K_{n-1}(\zeta, \xi)} \right\|_{L^2(\Omega)}
\]
\[
= \|K(\cdot, \zeta)[K_{n-1}(\zeta, \xi) - K(\zeta, \xi)] + K(\zeta, \xi)[K(\cdot, \zeta) - K_{n-1}(\cdot, \xi)]\|_{L^2(\Omega)}.
\]
Since $K(\zeta, \zeta)$ is finite and positive and $K_{n-1}(\zeta, \zeta) \to K(\zeta, \zeta)$ as $n \to \infty$, the estimates (4.6) will follow from (4.7) and the triangle inequality, provided we show that

$$|K_{n-1}(\zeta, \zeta) - K(\zeta, \zeta)| = o\left(\|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)}\right), \quad \text{as } n \to \infty. \quad (4.8)$$

But

$$|K_{n-1}(\zeta, \zeta) - K(\zeta, \zeta)| = \sum_{k=n}^{\infty} |Q_k(\zeta)|^2$$

and

$$\|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)} = \left(\sum_{k=n}^{\infty} |Q_k(\zeta)|^2\right)^{1/2}.$$

Thus

$$\frac{|K_{n-1}(\zeta, \zeta) - K(\zeta, \zeta)|}{\|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)}} = \left(\sum_{k=n}^{\infty} |Q_k(\zeta)|^2\right)^{1/2}, \quad (4.9)$$

and this yields (4.8), since the right-hand side of (4.9) clearly tends to zero as $n \to \infty$. \qed

**Proof of Theorem 2.2.** We shall follow closely the argument of [5]. Let

$$E_n := \|K(\cdot, \zeta) - K_n(\cdot, \zeta)\|_{L^2(\Omega)} = \left(\sum_{k=n+1}^{\infty} |Q_k(\zeta)|^2\right)^{1/2}$$

and

$$r_n := \frac{\|K(\cdot, \zeta) - K_n(\cdot, \zeta)\|_{L^2(\Omega)}}{E_n} \leq \|K_n(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)} + \|K_{n-1}(\cdot, \zeta) - K(\cdot, \zeta)\|_{L^2(\Omega)}$$

that is,

$$\|Q_n(\zeta)Q_n(\cdot)\|_{L^2(\Omega)} \leq (E_n + E_{n-1}) \max(r_n, r_{n-1}), \quad n = 1, 2, \ldots. \quad (4.10)$$

On the other hand, by Lemma 4.3, we have that

$$\|Q_n(\zeta)Q_n(\cdot)\|_{L^2(\Omega)} \geq |Q_n(\zeta)| \tau = (E_{n-1}^2 - E_n^2)^{1/2} \tau, \quad n = 1, 2, \ldots, \quad (4.11)$$

for some $\tau > 0$. Thus, from (4.10) and (4.11), we get

$$\left(\frac{E_{n-1}^2 - E_n^2}{r_n^2} \right)^{1/2} \leq (E_{n-1} + E_n) \max(r_n, r_{n-1}),$$

and this implies that

$$\tau^2 \left(\frac{E_{n-1}^2 - E_n^2}{E_{n-1} + E_n}\right) \leq \max(r_n^2, r_{n-1}^2), \quad n = 1, 2, \ldots. \quad (4.12)$$

Next we note that $E_n$ decreases to zero as $n \to \infty$ ($E_n \downarrow 0$, as $n \to \infty$). Hence it follows from elementary properties of series that

$$\sum_{n=1}^{\infty} \left(\frac{E_{n-1}^2 - E_n^2}{E_{n-1} + E_n}\right) = \infty.$$
(This divergence can be seen from the comparison
\[ \frac{E_{n-1} - E_n}{E_{n-1} + E_n} \geq \frac{1}{2} \left( 1 - \frac{E_n}{E_{n-1}} \right) \]
and the observation that \( \prod_{n=1}^\infty \frac{E_n}{E_{n-1}} \) diverges to zero.) Therefore, from (4.12), we get that
\[ \sum_{n=1}^\infty \max(r_n^2, r_{n-1}^2) = \infty \]
and this implies the desired result \( \sum_{n=0}^\infty r_n^2 = \infty \). \( \square \)

**Proof of Theorem 2.4.** From (4.7) (with \( \Omega \) replaced by \( B \)) and (4.9) we get
\[ \| f'_{\xi} - \pi'_{\xi} \|_{L^2(B)} \geq \frac{1}{K_{n-1}(\xi, \xi)} \| K(\cdot, \xi) - K_{n-1}(\cdot, \xi) \|_{L^2(B)} \]
\[ \geq c_1 \| K(\cdot, \xi) - K_{n-1}(\cdot, \xi) \|_{L^2(B)} \]
\[ \geq c_2 \left( \sum_{k=n}^{\infty} |Q_k(\xi)|^2 \right)^{1/2} \| K(\cdot, \xi) - K_{n-1}(\cdot, \xi) \|_{L^2(\Omega)}, \]
doing (4.14) gives a subsequence \( A \subset \mathbb{N} \) such that
\[ \| f'_{\xi} - \pi'_{\xi} \|_{L^2(B)} \geq \frac{c_3}{n^{1/2+\epsilon}} \left( \sum_{k=n}^{\infty} |Q_k(\xi)|^2 \right)^{1/2} \| K(\cdot, \xi) - K_{n-1}(\cdot, \xi) \|_{L^2(\Omega)}, \quad n \in A. \]

Also, from [10, p.35], we have
\[ \left( \sum_{k=n}^{\infty} |Q_k(\xi)|^2 \right)^{1/2} \leq \frac{c_4}{n^{p+\alpha}}, \quad n = 1, 2, \ldots. \]  
(4.14)

We now assume, without loss of generality, that \( 0 < \epsilon < p + \alpha - \frac{1}{2} \). Then, from (4.13) and (4.14), we have that
\[ \| f'_{\xi} - \pi'_{\xi} \|_{L^2(B)} \geq \frac{c_5}{n^{1/2+\epsilon}} \| K(\cdot, \xi) - K_{n-1}(\cdot, \xi) \|_{L^2(\Omega)}, \quad n \in A. \]
(4.15)

Finally, by using Lemma 4.4, we get from this last inequality that (2.3) holds for all \( n \in A \). \( \square \)

**Proof of Theorem 2.5.** Let \( E_n \) and \( r_n \) have the same meanings as in the proof of Theorem 2.2. Since \( \Gamma \) is an analytic curve, it is well known that
\[ \limsup_{n \to \infty} E_n^{1/n} = \frac{1}{\rho}, \]
for some \( \rho > 1 \) (cf. [3, p.35]). Furthermore, since
\[ \liminf_{n \to \infty} \frac{E_n}{E_{n-1}} \leq \limsup_{n \to \infty} E_n^{1/n}, \]
there exists a subsequence \( A_0 \subset \mathbb{N} \) such that

\[
\lim_{n \to \infty} \frac{E_n}{E_{n-1}} = \frac{1}{\rho_0} < 1.
\]

For this subsequence we have

\[
\lim_{n \to \infty} \frac{E_{n-1} - E_n}{E_{n-1} + E_n} = \frac{1 - \rho_0^{-1}}{1 + \rho_0^{-1}},
\]

and so from (4.12) we get

\[
0 < \tau^2 \left( \frac{\rho_0 - 1}{\rho_0 + 1} \right) \leq \lim \inf_{n \to \infty} \max_{\sigma \in A_0} \left( r_n^2, r_{n-1}^2 \right).
\]

It follows that there exists a subsequence \( A \subset \mathbb{N} \) such that

\[
r_n \geq c > 0, \quad n \in A,
\]

and this yields the desired result (2.4). The second result (2.5) follows by modifying in an obvious manner the proof of Theorem 2.4. \( \square \)

References


