THE CALDERÓN PROBLEM WITH PARTIAL DATA
IN TWO DIMENSIONS

OLEG YU. IMANUVILOV, GUNTHER UHLMANN, AND MASAHIRO YAMAMOTO

1. Introduction

We consider the problem of determining a complex-valued potential $q$ in a bounded two-dimensional domain from the Cauchy data measured on an arbitrary open subset of the boundary for the associated Schrödinger equation $\Delta + q$. A motivation comes from the classical inverse problem of electrical impedance tomography. In this inverse problem one attempts to determine the electrical conductivity of a body by measurements of voltage and current on the boundary of the body. This problem was proposed by Calderón [9] and is also known as Calderón’s problem. In dimensions $n \geq 3$, the first global uniqueness result for $C^2$-conductivities was proven in [28]. In [25], [5] the global uniqueness result was extended to less regular conductivities. Also see [14] for the determination of more singular conormal conductivities. In dimension $n \geq 3$ global uniqueness was shown for the Schrödinger equation with bounded potentials in [28]. The case of more singular conormal potentials was studied in [14].

In two dimensions the first global uniqueness result for Calderón’s problem was obtained in [24] for $C^2$-conductivities. Later the regularity assumptions were relaxed in [6] and [2]. In particular, the paper [2] proves uniqueness for $L^\infty$-conductivities. In two dimensions a recent breakthrough result of Bukhgeim [7] gives unique identifiability of the potential from Cauchy data measured on the whole boundary for the associated Schrödinger equation. As for the uniqueness in determining two coefficients, see [10], [18].

In all the above-mentioned articles, the measurements are made on the whole boundary. The purpose of this paper is to show global uniqueness in two dimensions, both for the Schrödinger and conductivity equations, by measuring all the Neumann data on an arbitrary open subset $\tilde{\Gamma}$ of the boundary produced by inputs of Dirichlet data supported on $\tilde{\Gamma}$. We formulate this inverse problem more precisely below.

Let $\Omega \subset \mathbb{R}^2$ be a bounded domain with smooth boundary which consists of $N$ smooth closed curves $\gamma_j$, $\partial \Omega = \bigcup_{j=1}^N \gamma_j$, and let $\nu$ be the unit outward normal vector to $\partial \Omega$. We denote $\frac{\partial u}{\partial \nu} = \nabla u \cdot \nu$. A bounded and positive function $\tilde{\gamma}(x)$...
models the electrical conductivity of \( \Omega \). Then a potential \( u \in H^1(\Omega) \) satisfies the Dirichlet problem

\[
\begin{align*}
\text{div}(\tilde{\gamma} \nabla u) &= 0 \quad \text{in } \Omega, \\
u |_{\partial \Omega} &= f,
\end{align*}
\]

where \( f \in H^{\frac{1}{2}}(\partial \Omega) \) is a given boundary voltage potential. The Dirichlet-to-Neumann (DN) map is defined by

\[
\Lambda_{\tilde{\gamma}}(f) = \tilde{\gamma} \frac{\partial u}{\partial \nu} |_{\partial \Omega}.
\]

The inverse problem is to recover \( \tilde{\gamma} \) from \( \Lambda_{\tilde{\gamma}} \). This problem can be reduced to studying the set of Cauchy data for the Schrödinger equation with the potential \( q \) given by

\[
q = -\frac{\Delta \sqrt{\gamma}}{\sqrt{\gamma}}.
\]

More generally we define the set of Cauchy data for a bounded potential \( q \) by

\[
\hat{C}_q = \left\{ (u |_{\tilde{\Gamma}}, \frac{\partial u}{\partial \nu} |_{\tilde{\Gamma}}) \mid (\Delta + q)u = 0 \text{ on } \Omega, \ u |_{\Gamma_0} = 0, \ u \in H^1(\Omega) \right\}.
\]

We have \( \hat{C}_q \subset H^{\frac{1}{2}}(\partial \Omega) \times H^{-\frac{1}{2}}(\partial \Omega) \).

Let \( \tilde{\Gamma} \subset \partial \Omega \) be a nonempty open subset of the boundary. Denote \( \Gamma_0 = \partial \Omega \setminus \tilde{\Gamma} \).

Our main result gives global uniqueness by measuring the Cauchy data on \( \tilde{\Gamma} \).

Consider the following sets of Cauchy data on \( \tilde{\Gamma} \):

\[
C_q = \left\{ (u |_{\tilde{\Gamma}}, \frac{\partial u}{\partial \nu} |_{\tilde{\Gamma}}) \mid (\Delta + q_j)u = 0 \text{ in } \Omega, \ u |_{\Gamma_0} = 0, \ u \in H^1(\Omega) \right\}, \quad j = 1, 2.
\]

**Theorem 1.1.** Assume \( C_{q_1} = C_{q_2} \). Then \( q_1 = q_2 \).

**Remark.** As far as a regularity of the potentials \( q_j \) is concerned, we can relax the assumptions: \( q_j \) are of \( C^{2+\alpha} \) in a neighborhood of the boundary \( \partial \Omega \) and \( q_j \in C^{1+\alpha}(\tilde{\Omega}) \).

Using Theorem 1.1 one concludes immediately as a corollary the following global identifiability result for the conductivity equation (1.1). This result uses the fact that knowledge of the Dirichlet-to-Neumann map on an open subset of the boundary determines \( \gamma \) and its first derivatives on \( \tilde{\Gamma} \) (see [22], [29]).

**Corollary 1.1.** With some \( \alpha > 0 \), let \( \tilde{\gamma}_j \in C^{4+\alpha}(\tilde{\Omega}) \), \( j = 1, 2 \), be nonvanishing real-valued functions. Assume that

\[
\Lambda_{\tilde{\gamma}_1}(f) = \Lambda_{\tilde{\gamma}_2}(f) \text{ on } \tilde{\Gamma} \text{ for all } f \in H^{\frac{1}{2}}(\Gamma), \ \text{supp} \ f \subset \tilde{\Gamma}.
\]

Then \( \tilde{\gamma}_1 = \tilde{\gamma}_2 \).

It is easy to see that Theorem 1.1 implies the analogous result to [19] in the two-dimensional case.

Notice that Theorem 1.1 does not assume that \( \Omega \) is simply connected. An interesting inverse problem is whether one can determine the potential or conductivity in a region of the plane with holes by measuring the Cauchy data only on the accessible boundary. This is also called the obstacle problem.
Let $\Omega, D$ be domains in $\mathbb{R}^2$ with smooth boundaries such that $\overline{D} \subset \Omega$. Let $V \subset \partial \Omega$ be an open set. Let $q_j \in C^{2+\alpha}(\Omega \setminus \overline{D})$, for some $\alpha > 0$ and $j = 1, 2$. Let us consider the following set of partial Cauchy data:

$$\tilde{C}_{q_j} = \left\{ \left( u|_V, \frac{\partial u}{\partial \nu}|_V \right) \mid (\Delta + q_j)u = 0 \text{ in } \Omega \setminus \overline{D}, u|_{\partial D \cup \partial \Omega \setminus V} = 0, u \in H^1(\Omega \setminus \overline{D}) \right\}.$$ 

**Corollary 1.2.** Assume $\tilde{C}_{q_1} = \tilde{C}_{q_2}$. Then $q_1 = q_2$.

A similar result holds for the conductivity equation.

**Corollary 1.3.** Let $\tilde{\gamma}_j \in C^{4+\alpha}(\Omega \setminus \overline{D})$, $j = 1, 2$, be nonvanishing real-valued functions. Assume

$$\Lambda_{\tilde{\gamma}_1}(f) = \Lambda_{\tilde{\gamma}_2}(f) \text{ on } V \quad \forall f \in H^2(\partial(\overline{\Omega} \setminus D)), \text{ supp } f \subset V.$$ 

Then $\tilde{\gamma}_1 = \tilde{\gamma}_2$.

In a forthcoming article we will give other applications of Theorem 1.1 to inverse boundary-value problems in two dimensions. We discuss briefly one important example, the anisotropic conductivity problem. In this case the conductivity depends on direction and is represented by a positive definite symmetric matrix

$$\sigma = \{\sigma^{ij}\} \text{ in } \Omega.$$ 

The conductivity equation with voltage potential $g$ on $\partial \Omega$ is given by

$$\sum_{i,j=1}^{2} \frac{\partial}{\partial x_i} (\sigma^{ij} \frac{\partial u}{\partial x_j}) = 0 \text{ in } \Omega, u|_{\partial \Omega} = g.$$ 

The Dirichlet-to-Neumann map is defined by

$$\Lambda_\sigma(g) = \sum_{i,j=1}^{2} \sigma^{ij} \nu_i \frac{\partial u}{\partial x_j}|_{\partial \Omega}.$$ 

It has been known for a long time that $\Lambda_\sigma$ does not determine $\sigma$ uniquely in the anisotropic case [23]. Let $F : \Omega \to \overline{\Omega}$ be a diffeomorphism such that $F(x) = x$ for $x$ on $\tilde{\Gamma}$. Then

$$\Lambda_{F_* \sigma} = \Lambda_\sigma,$$

where

$$(1.6) \quad F_* \sigma = \left( \frac{(DF) \circ \sigma \circ (DF)^T}{\det DF} \right) \circ F^{-1}.$$ 

Here $DF$ denotes the differential of $F$, $(DF)^T$ its transpose, and the composition inside parentheses in (1.6) is matrix composition. The question of whether one can determine the conductivity up to the obstruction (1.6) in the case of full Cauchy data has been solved in two dimensions for $C^2$ conductivities in [24], Lipschitz conductivities in [26], and merely $L^\infty$ conductivities in [3]. The method of proof in all these papers is the reduction to the isotropic case performed using isothermal coordinates [27]. Using the same method and Corollary 1.1 we have

**Theorem 1.2.** Let $\sigma_k = \{\sigma^{ij}_k\} \in C^{7+\alpha}(\overline{\Omega})$ for $k = 1, 2$ and some positive $\alpha$. Suppose that $\sigma_k$ are positive definite symmetric matrices on $\Omega$. Let $\tilde{\Gamma} \subset \partial \Omega$ be some open set. Assume

$$\Lambda_{\sigma_1}(g)|_{\tilde{\Gamma}} = \Lambda_{\sigma_2}(g)|_{\tilde{\Gamma}} \quad \forall g \in H^2(\partial \Omega), \text{ supp } g \subset \tilde{\Gamma}.$$
Then there exists a diffeomorphism
\[ F : \overline{\Omega} \to \overline{\Omega}, \quad F|_{\tilde{\Gamma}} = \text{Identity}, \quad F \in C^{6+\alpha}({\overline{\Omega}}), \alpha > 0 \]
such that
\[ F_* \sigma_1 = \sigma_2. \]

We mention that in [3] K. Astala, M. Lassas, and L. Päivärinta have shown a partial data result in the anisotropic problem in two dimensions for bounded measurable conductivities, similar to Theorem 1.2, assuming that one knows both the Dirichlet-to-Neumann and Neumann-to-Dirichlet map on \( \tilde{\Gamma} \). On the other hand, to the authors’ knowledge, there are no uniqueness results similar to Theorem 1.1 with Dirichlet data supported and Neumann data measured on the same arbitrary open subset of the boundary, even for smooth potentials or conductivities. In dimension \( n \geq 3 \) Isakov [17] proved global uniqueness assuming that \( \Gamma_0 \) is a subset of a plane or a sphere. In dimensions \( n \geq 3 \), [8] proves global uniqueness in determining a bounded potential for the Schrödinger equation with Dirichlet data supported on the whole boundary and Neumann data measured in roughly half the boundary. The proof relies on a Carleman estimate with a linear weight function. This implies a similar result for the conductivity equation with \( C^2 \) conductivities. In [20] the regularity assumption on the conductivity was relaxed to \( C^{3/2+\alpha} \) with some \( \alpha > 0 \). The corresponding stability estimates are proved in [13]. In [19], the result in [8] was generalized to show that by measuring all possible pairs of Dirichlet data on a possibly very small subset of the boundary \( \Gamma_+ \) and Neumann data on a slightly larger open domain than \( \partial \Omega \setminus \Gamma_+ \), one can uniquely determine the potential. The method of the proof uses Carleman estimates with nonlinear weights. The case of the magnetic Schrödinger equation was considered in [11] and an improvement on the regularity of the coefficients is done in [21]. Stability estimates for the magnetic Schrödinger equation with partial data were proven in [30].

The two-dimensional case has special features since one can construct a much larger set of complex geometrical optics solutions than in higher dimensions. On the other hand, the problem is formally determined in two dimensions and is therefore more difficult. The proof of our main result is based on the construction of appropriate complex geometrical optics solutions by Carleman estimates with degenerate weight functions.

This paper is composed of four sections and an appendix. In Section 2, we establish our key Carleman estimates, and in Section 3, we construct appropriate complex geometrical optics solutions. In Section 4, we complete the proof of Theorem 1.1. In the appendix we consider the solvability of the Cauchy-Riemann equations with Cauchy data on a subset of the boundary. We also establish a Carleman estimate for Laplace’s equation with degenerate harmonic weights that we use in the earlier sections.

2. CARLEMAN ESTIMATES WITH DEGENERATE WEIGHTS

Throughout the paper we use the following notations.

**Notation.** \( i = \sqrt{-1}; x_1, x_2, \xi_1, \xi_2 \in \mathbb{R}^1; z = x_1 + ix_2; \xi = \xi_1 + i\xi_2; \overline{\xi} \) denotes the complex conjugate of \( \xi \in \mathbb{C} \); we identify \( x = (x_1, x_2) \in \mathbb{R}^2 \) with \( z = x_1 + i x_2 \in \mathbb{C} \).

\( \partial_z = \frac{1}{2}(\partial_{x_1} - i \partial_{x_2}); \partial_{\overline{z}} = \frac{1}{2}(\partial_{x_1} + i \partial_{x_2}); D = (\frac{\partial}{\partial_{x_1}}, \frac{\partial}{\partial_{x_2}}); \beta = (\beta_1, \beta_2); |\beta| = \beta_1 + \beta_2; D^\beta = (\frac{\partial}{\partial_{x_1}})^{\beta_1} (\frac{\partial}{\partial_{x_2}})^{\beta_2}. \)

The tangential derivative on the boundary
is given by \( \partial_x = \nu_2 \frac{\partial}{\partial x_2} - \nu_1 \frac{\partial}{\partial x_1} \), with \( \nu = (\nu_1, \nu_2) \) the unit outer normal to \( \partial\Omega \); \( B(\mathbf{r}, \delta) = \{ x \in \mathbb{R}^2 | |x - \mathbf{r}| < \delta \} \); \( f : \mathbb{R}^2 \to \mathbb{R}^1; f'' \) is the Hessian matrix with entries \( \frac{\partial^2 f}{\partial x_i \partial x_j} \). \( \mathcal{L}(X, Y) \) denotes the Banach space of all bounded linear operators from a Banach space \( X \) to another Banach space \( Y \).

Let \( \Phi(z) = \varphi(x_1, x_2) + i\psi(x_1, x_2) \in C^2(\overline{\Omega}) \) be a holomorphic function in \( \Omega \) with real-valued \( \varphi \) and \( \psi \):

\[
(2.1) \quad \partial_x \Phi(z) = 0 \quad \text{in} \quad \Omega.
\]

Denote by \( \mathcal{H} \) the set of critical points of the function \( \Phi \)

\[
\mathcal{H} = \{ z \in \overline{\Omega} | \partial_z \Phi(z) = 0 \}.
\]

Assume that \( \Phi \) has no critical points on \( \overline{T} \) and that all the critical points are nondegenerate:

\[
(2.2) \quad \mathcal{H} \cap \partial\Omega \setminus \overline{T}_0 = \{ \emptyset \}, \quad \partial_z^2 \Phi(z) \neq 0, \quad \forall z \in \mathcal{H}.
\]

Then we know that \( \Phi \) has only a finite number of critical points and we can set

\[
(2.3) \quad \mathcal{H} = \{ \mathbf{x}_1, ..., \mathbf{x}_l \}.
\]

Consider the problem

\[
(2.4) \quad \Delta u + q_0 u = f \quad \text{in} \quad \Omega, \quad u|\Gamma_0 = g,
\]

where \( \nu \) is the unit outward normal vector to \( \partial\Omega \).

Assume that \( \Phi \) satisfies

\[
(2.5) \quad \Gamma_0 \subset \{ x \in \partial\Omega | (\nu, \nabla \varphi) = 0 \}.
\]

We have

**Proposition 2.1.** Let \( q_0 \in L^\infty(\Omega) \). Assume \( (2.1), (2.2), (2.5) \). There exists \( \tau_0 > 0 \) such that for all \( |\tau| > \tau_0 \) there exists a solution to problem \( (2.4) \) such that

\[
(2.6) \quad \|ue^{-\tau \varphi}\|_{L^2(\Omega)} \leq C(\|fe^{-\tau \varphi}\|_{L^2(\Omega)} \sqrt{\tau}) + \|ge^{-\tau \varphi}\|_{L^2(\Gamma_0)}).
\]

The proof of this proposition given in the appendix.

Let us introduce the operators:

\[
\partial_z^{-1} g = \frac{1}{2\pi i} \int_{\Omega} \frac{g(\zeta, \overline{\zeta})}{\zeta - z} d\zeta \wedge d\overline{\zeta} = -\frac{1}{\pi} \int_{\Omega} \frac{g(\zeta, \overline{\zeta})}{\zeta - z} d\xi d\overline{\xi},
\]

\[
\partial_z^{-1} g = -\frac{1}{2\pi i} \int_{\Omega} \frac{\overline{g(\zeta, \overline{\zeta})}}{\zeta - z} d\zeta \wedge d\overline{\zeta} = -\frac{1}{\pi} \int_{\Omega} \frac{\overline{g(\zeta, \overline{\zeta})}}{\zeta - \overline{z}} d\xi d\overline{\xi} = \partial_{\overline{z}}^{-1} g.
\]

See, e.g., pp. 28–31 in [32] where \( \partial_z^{-1} \) and \( \partial_{\overline{z}}^{-1} \) are denoted by \( T \) and \( \overline{T} \), respectively. Then we have (e.g., p. 47 and p. 56 in [32]).

**Proposition 2.2. (A)** Let \( m \geq 0 \) be an integer number and let \( \alpha \in (0, 1) \). Then \( \partial_z^{-1}, \partial_{\overline{z}}^{-1} \in \mathcal{L}(C^{m+\alpha}(\overline{\Omega}), C^{m+\alpha+1}(\overline{\Omega})) \).

**Proposition 2.2. (B)** Let \( 1 \leq p \leq 2 \) and \( 1 < \tilde{p} < \frac{2p}{2-p} \). Then \( \partial_z^{-1}, \partial_{\overline{z}}^{-1} \in \mathcal{L}(L^p(\Omega), L^{\tilde{p}}(\Omega)) \).

We define two other operators:

\[
(2.7) \quad R_{\Phi, \tau} g = e^{(\overline{\Phi} - \Phi)} \partial_z^{-1} (ge^{(\Phi - \overline{\Phi})}), \quad \overline{R}_{\Phi, \tau} g = e^{(\overline{\Phi} - \Phi)} \partial_{\overline{z}}^{-1} (ge^{(\Phi - \overline{\Phi})}).
\]
We have

**Proposition 2.3.** Let \( g \in C^\alpha(\bar{\Omega}) \) for some positive \( \alpha \). The function \( R_{\Phi, \tau} g \) is a solution to
\[
\partial_z R_{\Phi, \tau} g - \tau(\partial_z \Phi) R_{\Phi, \tau} g = g \quad \text{in } \Omega.
\]

The function \( \tilde{R}_{\Phi, \tau} g \) solves
\[
\partial_z \tilde{R}_{\Phi, \tau} g + \tau(\partial_z \Phi) \tilde{R}_{\Phi, \tau} g = g \quad \text{in } \Omega.
\]

**Proof.** The proof is by direct computations:
\[
\partial_z \tilde{R}_{\Phi, \tau} g + \tau \frac{\partial \Phi}{\partial z} \tilde{R}_{\Phi, \tau} g = \partial_z(e^{\tau(\Phi - \Phi)}e^{-1}(ge^{\tau(\Phi - \Phi)}))
\]
\[
+ \tau \frac{\partial \Phi}{\partial z} (e^{\tau(\Phi - \Phi)}e^{-1}(ge^{\tau(\Phi - \Phi)}))
\]
\[
= - \tau \frac{\partial \Phi}{\partial z} (e^{\tau(\Phi - \Phi)}e^{-1}(ge^{\tau(\Phi - \Phi)})) + (e^{\tau(\Phi - \Phi)})(ge^{\tau(\Phi - \Phi)})
\]
\[
+ \tau \frac{\partial \Phi}{\partial z} (e^{\tau(\Phi - \Phi)}e^{-1}(ge^{\tau(\Phi - \Phi)})) = g.
\]
\[\square\]

Using the stationary phase argument, we show

**Proposition 2.4.** Let \( g \in L^1(\Omega) \) and let the function \( \Phi \) satisfy (2.1), (2.2). Then
\[
\lim_{|\tau| \to +\infty} \int_\Omega ge^{\tau(\Phi(z) - \Phi(\bar{\Omega}))} dx = 0.
\]

**Proof.** Let \( \{g_k\}_{k=1}^\infty \subset C_0^\infty(\Omega) \) be a sequence of functions such that \( g_k \to g \) in \( L^1(\Omega) \). Let \( \epsilon > 0 \) be an arbitrary number. Suppose that \( \hat{j} \) is large enough such that \( \|g - g_j\|_{L^1(\Omega)} \leq \frac{\epsilon}{2} \). Then
\[
|\int_\Omega ge^{\tau(\Phi(z) - \Phi(\bar{\Omega}))} dx| \leq |\int_\Omega (g - g_j)e^{\tau(\Phi(z) - \Phi(\bar{\Omega}))} dx| + |\int_\Omega g_j e^{\tau(\Phi(z) - \Phi(\bar{\Omega}))} dx|.
\]
The first term on the right hand side of this inequality is less then \( \epsilon/2 \) and the second goes to zero as \( |\tau| \) approaches infinity by the stationary phase argument. \[\square\]

Denote
\[
\mathcal{O}_\epsilon = \{ x \in \Omega | \text{dist}(x, \partial \Omega) \leq \epsilon \}.
\]

We have

**Proposition 2.5.** Let \( \alpha > 0 \), \( g \in C^{1+\alpha}(\Omega) \), and \( g|_{\mathcal{O}_\epsilon} = 0 \). Then
\[
|R_{\Phi, \tau} g(x)| + |\tilde{R}_{\Phi, \tau} g(x)| \leq C\|g\|_{C^{1+\alpha}(\bar{\Omega})} / |\tau| \quad \forall x \in \mathcal{O}_{\epsilon/2}.
\]

If \( g \in C^{2+\alpha}(\bar{\Omega}) \), \( g|_{\mathcal{O}_\epsilon} = 0 \), and \( g|_{\bar{\Omega}} = 0 \), then
\[
\|R_{\Phi, \tau} g\|_{C^0(\bar{\mathcal{O}}_\epsilon)} + \|\tilde{R}_{\Phi, \tau} g\|_{C^0(\bar{\mathcal{O}}_\epsilon)} = o\left(\frac{1}{|\tau|}\right)
\]
\[\text{as } |\tau| \to \infty.\]
Proof. Denote \( \tilde{g}(x, \xi_1, \xi_2) = -\frac{1}{\pi} \frac{g(x, \xi_1, \xi_2)}{\xi - z} \). Let \( x = (x_1, x_2) \) be an arbitrary point in \( \mathbb{C}_+^2 \). We set \( z = x_1 + ix_2 \). We prove \( \text{(2.10)} \) and \( \text{(2.11)} \) for the function \( R_{\Phi, \tau} g \). Proof of the estimates for the function \( \tilde{R}_{\Phi, \tau} g \) is exactly the same. Let us prove \( \text{(2.10)} \) first. Let \( \delta > 0 \) be sufficiently small and let \( e_k \in C_0^\infty (B(x_k, \delta)) \) such that \( e_k|_{B(x_k, \delta/2)} = 1 \).

We decompose

\[
I(\tau) = \int_{\Omega} \tilde{g} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 
\]

(2.12)

\[
= \sum_{k=1}^\ell \int_{B(x_k, \delta)} e_k \tilde{g} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 + \int_{\Omega} (1 - \sum_{k=1}^\ell e_k) \tilde{g} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2.
\]

By the stationary phase argument we can estimate the second integral on the right hand side of (2.12) as

\[
\| \int_{\Omega} (1 - \sum_{k=1}^\ell e_k) \tilde{g} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 \|_{C^0(\mathbb{C}_+^2)} \leq C \frac{\| g \|_{C^1+\alpha(\Omega)}}{\| \tau \|}.
\]

In order to estimate the first term on the right hand side of (2.12), we use that

\[
\sum_{k=1}^\ell \int_{B(x_k, \delta)} e_k \tilde{g} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 = \sum_{k=1}^\ell \left\{ \int_{B(x_k, \delta)} e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 \right\}
\]

(2.13)

Applying the stationary phase argument to the second term in (2.14) again, we get

\[
\| \int_{B(x_k, \delta)} e_k \frac{1}{\pi} \frac{g(x_k)}{\xi - z} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2 \|_{C^1(\mathbb{C}_+^2)} \leq C \frac{\| g \|_{C^0(\Omega)}}{\| \tau \|}.
\]

In order to estimate the first term on the right hand side of (2.14), we observe

\[
\sum_{k=1}^\ell \int_{B(x_k, \delta)} e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2
\]

(2.15)

\[
= \sum_{k=1}^\ell \lim_{\delta' \to 0} \int_{B(x_k, \delta') \setminus B(x_k, \delta')} e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2
\]

\[
= \sum_{k=1}^\ell \lim_{\delta' \to 0} \int_{B(x_k, \delta') \setminus B(x_k, \delta')} e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) \frac{1}{\tau \partial_{\xi_1} \Phi} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2
\]

\[
= -\sum_{k=1}^\ell \lim_{\delta' \to 0} \int_{B(x_k, \delta') \setminus B(x_k, \delta')} \partial_{\xi_1} \left( e_k \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) \frac{1}{\tau \partial_{\xi_1} \Phi} e^{\tau(\Phi - \Phi)} d\xi_1 d\xi_2
\]

\[
- \sum_{k=1}^\ell \lim_{\delta' \to 0} \int_{B(x_k, \delta') \setminus B(x_k, \delta')} \frac{1}{\xi - z} (\xi_1 - i\xi_2 - ((\tilde{x}_k)_1 - i(\tilde{x}_k)_2))
\]

\[
\times e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(x_k)}{\xi - z} \right) \frac{1}{\tau \partial_{\xi_1} \Phi} e^{\tau(\Phi - \Phi)} d\sigma.
\]
Here and henceforth we set $S(\tilde{x}_k, \delta') = \partial B(\tilde{x}_k, \delta')$.

Note that for each fixed $x$ from $O_2$ function $e_k(\xi_1, \xi_2)(\tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z}) \in C^{1+\alpha}(\overline{\Omega})$ and $(\tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z})(x, \tilde{x}_k) = 0$. Thus

$$
\lim_{\delta' \to +0} \int_{S(\tilde{x}_k, \delta')} \frac{1}{2\delta'}(\xi_1 - i\xi_2 - ((\tilde{x}_k)_1 - i(\tilde{x}_k)_2))e_k(\tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z}) \frac{1}{\partial z} e^{\tau(\Phi - \overline{\Phi})} d\sigma = 0.
$$

By [2.2] there exists a constant $C$ such that

$$
|\partial_z \left( \frac{e_k}{\tau} \Phi (\tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z}) \right) | \leq C \sum_{k=1}^{\ell} \|g\|_{C^{1+\alpha}}(\overline{\Omega}).
$$

Using these inequalities, we pass to the limit in (2.16) and we obtain

$$
\sum_{k=1}^{\ell} \int_{\Omega} e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z} \right) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2 = - \frac{1}{\tau} \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( e_k \left( \tilde{g} + \frac{1}{\pi} \frac{g(\tilde{x}_k)}{\zeta - z} \right) \frac{1}{\partial z} \Phi \right) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2.
$$

This inequality and (2.13), (2.15) imply (2.10).

Now we prove (2.11). Thanks to the improved regularity of the function $g$, similarly to (2.10) we have

$$
\| \int_{\Omega} (1 - \sum_{k=1}^{\ell} e_k) \tilde{g} e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2 \|_{C^0(\overline{\Omega})} \leq \frac{C}{|\tau|^2}.
$$

By (2.17) and the assumption that $g|_{\mathcal{H}} = 0$ we get

$$
I(\tau) = - \frac{1}{\tau} \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( \frac{e_k \tilde{g}}{\tau \partial_z \Phi} \right) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2 + o\left( \frac{1}{\tau} \right).
$$

Consider the radial cut-off function $\chi \in C_0^\infty(B(0, 1))$ such that

$$
\chi \geq 0, \quad \chi|_{B(0, \frac{1}{2})} = 1.
$$

Then by (2.18)

$$
I(\tau) = - \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( \frac{e_k \tilde{g}}{\tau \partial_z \Phi} \right) \chi(|\xi - \tilde{x}_k| \ln |\tau|) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2
$$

$$
- \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( \frac{e_k \tilde{g}}{\tau \partial_z \Phi} \right) (1 - \chi(|\xi - \tilde{x}_k| \ln |\tau|)) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2 + o\left( \frac{1}{\tau} \right)
$$

$$
= \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( \frac{1}{\tau \partial_z \Phi} \partial_z \left( \frac{e_k \tilde{g}}{\tau \partial_z \Phi} \right) (1 - \chi(|\xi - \tilde{x}_k| \ln |\tau|)) \right) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2
$$

$$
- \sum_{k=1}^{\ell} \int_{B(\tilde{x}_k, \delta)} \partial_z \left( \frac{e_k \tilde{g}}{\tau \partial_z \Phi} \right) \chi(|\xi - \tilde{x}_k| \ln |\tau|) e^{\tau(\Phi - \overline{\Phi})} d\xi_1 d\xi_2 + o\left( \frac{1}{\tau} \right).
$$
Using the inequalities
\[ \sum_{k=1}^{\ell} \int_{B(\tilde{x}, \delta)} \partial_z \left( \frac{1}{\tau \partial_\xi \chi} \partial_\xi (\frac{e_k g}{\partial_\xi \Phi}) (1 - \chi(|\xi - \tilde{x}| \ln |\tau|)) \right) e^{r(\Phi - \bar{\Phi})} \partial_\xi_1 \partial_\xi_2 \leq \frac{C}{\tau^2} \]
and
\[ \sum_{k=1}^{\ell} \int_{B(\tilde{x}, \delta)} \partial_\xi (\frac{e_k g}{\partial_\xi \Phi}) \chi(|\xi - \tilde{x}| \ln |\tau|) e^{r(\Phi - \bar{\Phi})} \partial_\xi_1 \partial_\xi_2 \]
\[ \leq \frac{C}{\tau^2} \sum_{k=1}^{\ell} \int_{B(\tilde{x}, \delta)} \frac{1}{|\xi - \tilde{x}|^{2-\alpha}} \chi(|\xi - \tilde{x}| \ln |\tau|) \partial_\xi_1 \partial_\xi_2 = o(\frac{1}{\tau}), \]
we obtain (2.21).

Denote
\[ r(z) = \Pi_{k=1}^\ell (z - \tilde{x}_k) \text{ where } \tilde{x}_k = \tilde{x}_{1,k} + i\tilde{x}_{2,k}, \quad \mathcal{H} = \{\tilde{x}_1, \ldots, \tilde{x}_\ell\}. \]

We have

**Proposition 2.6.** Let \( \alpha \) be some positive number, \( g \in C^{1+\alpha}(\Omega) \), and \( g|_{\partial \Omega} = 0 \). Then for each \( \delta \in (0, 1) \), there exists a constant \( C(\delta) > 0 \) such that

\[ \|R_{\Phi, \tau}(\bar{\tau}g)\|_{L^2(\Omega)} \leq C(\delta) \|g\|_{C^{1+\alpha}(\Omega)} / |\tau|^{1-\delta}, \]

\[ \|R_{\Phi, \tau}(\tau g)\|_{L^2(\Omega)} \leq C(\delta) \|g\|_{C^{1+\alpha}(\Omega)} / |\tau|^{1-\delta}. \]

**Proof.** Denote \( v = \bar{R}_{\Phi, \tau}(\bar{\tau}g) \). By Proposition 2.5

\[ \|v\|_{L^2(\Omega)} \leq C \|g\|_{C^{1+\alpha}(\Omega)}/|\tau|. \]

Then by Proposition 2.3 we have

\[ \frac{\partial v}{\partial z} + \tau \frac{\partial \Phi}{\partial z} v = \bar{\tau}g \quad \text{in } \Omega. \]

There exists a function \( p \) such that

\[ -\frac{\partial p}{\partial z} + \tau \frac{\partial \Phi}{\partial z} p = v \quad \text{in } \Omega, \]

and there exists a constant \( C > 0 \) independent of \( \tau \) such that

\[ \|p\|_{L^2(\Omega)} \leq C \|v\|_{L^2(\Omega)} \]

Let \( \chi \) be a nonnegative function such that \( \chi \equiv 0 \) on \( \Omega_{\frac{1}{\tau}} \) and \( \chi \equiv 1 \) on \( \Omega \setminus \Omega_{\frac{1}{\tau}} \). Setting \( \bar{p} = \chi p \) and using \( g|_{\partial \Omega} = 0 \), we have that

\[ \int_{\Omega} r(z)\bar{p}dx = \int_{\Omega_{\frac{1}{\tau}}} r(z)\bar{p}dx = \int_{\Omega} r(z)\bar{\tau}dx \]

and

\[ \frac{\partial \bar{p}}{\partial z} + \tau \frac{\partial \bar{\Phi}}{\partial z} \bar{p} = \chi v - \frac{\partial \chi}{\partial z} \quad \text{in } \Omega. \]

Then

\[ \|\chi^\frac{1}{\tau} v\|_{L^2(\Omega)} = \int_{\Omega} r(z)\bar{p}dx + \int_{\Omega} \frac{\partial \chi}{\partial z} \bar{\tau}dx. \]
Applying to equation (2.23) the operator $\frac{\partial}{\partial z}$, we have

$$- \frac{\partial}{\partial z} \frac{\partial \bar{p}}{\partial z} = \frac{\partial}{\partial z} ( - \tau \frac{\partial \Phi}{\partial z} \bar{p} + \chi v - p \frac{\partial \chi}{\partial z} )$$

in $\Omega$, $\bar{p}|_{\partial \Omega} = 0$.

The classical a priori estimate for the Laplace operator yields

$$\| \bar{p} \|_{H^1(\Omega)} \leq C \| \frac{\partial \Phi}{\partial z} \bar{p} - \chi v + p \frac{\partial \chi}{\partial z} \|_{L^2(\Omega)}.$$  

Then by (2.22)

$$\| \bar{p} \|_{H^1(\Omega)} \leq C (|\tau| \| p \|_{L^2(\Omega)} + \| v \|_{L^2(\Omega)}) \leq C |\tau| \| v \|_{L^2(\Omega)}.$$  

Taking the scalar product of (2.23) and $\frac{r(z)}{\partial \Phi(z)} \bar{g}$, we get

$$\int_{\Omega} \frac{r(z)}{\partial \Phi(z)} \bar{g} \left( - \frac{\partial \bar{p}}{\partial z} + \tau \frac{\partial \Phi}{\partial z} \bar{p} \right) dx = \int_{\Omega} \frac{r(z)}{\partial \Phi(z)} \bar{g} \left( \chi v - p \frac{\partial \chi}{\partial z} \right) dx.$$  

Then

$$\tau \int_{\Omega} \bar{g} r(z) \bar{p} dx = \int_{\Omega} \frac{r(z)}{\partial \Phi(z)} \bar{g} \left( \chi v - p \frac{\partial \chi}{\partial z} \right) dx - \int_{\Omega} \frac{\partial}{\partial z} \left( \frac{r(z)}{\partial \Phi(z)} \bar{g} \right) \bar{p} dx.$$  

By (2.25) and the Sobolev embedding theorem, for each $\varepsilon \in (0, \frac{1}{2})$, we have

$$(2.26) \quad \left| \int_{\Omega} \frac{\partial}{\partial z} \left( \frac{r(z)}{\partial \Phi(z)} \bar{g} \right) \bar{p} dx \right| \leq C \| g \|_{C^{1+\varepsilon}(\Omega)} \left( \frac{1}{\partial \Phi(z)} \right)_{L^{2-\varepsilon}(\Omega)} \| \bar{p} \|_{L^{2+\varepsilon}(\Omega)}$$

$$\leq C \| g \|_{C^{1+\varepsilon}(\Omega)} \| \bar{p} \|_{H^{\delta_3(\varepsilon)}(\Omega)}$$

$$\leq C \| g \|_{C^{1+\varepsilon}(\Omega)} \| \tau \|_{\delta_3(\varepsilon)} \| v \|_{L^2(\Omega)}.$$  

Here we choose $\delta_3(\varepsilon) > 0$ such that $\delta_3(\varepsilon) \to +0$ as $\varepsilon \to +0$ and $H^{\delta_3(\varepsilon)}(\Omega) \subset L^{\frac{2+\varepsilon}{\varepsilon}}(\Omega)$. Therefore

$$(2.27) \quad \left| \int_{\Omega} \bar{g} r(z) \bar{p} dx \right| \leq C \| g \|_{C^{1+\varepsilon}(\Omega)} \| \tau \|^{-1+\delta_3(\varepsilon)} \| v \|_{L^2(\Omega)}$$

as $\delta_3(\varepsilon) \to +0$.

By (2.21)

$$(2.28) \quad \left| \int_{\Omega} p \frac{\partial \chi}{\partial z} \sigma dx \right| \leq C \| p \|_{L^2(\Omega)} \| v \|_{L^2(\sigma)} \leq C \| g \|_{C^{1+\varepsilon}(\Omega)} \| p \|_{L^2(\Omega)} / |\tau|.$$  

By (2.22), (2.27), and (2.28) we obtain from (2.24)

$$\| v \|_{L^2(\sigma)} \leq C \| g \|_{C^{1+\varepsilon}(\Omega)} (|\tau|^{-1+\delta_3(\varepsilon)} \| v \|_{L^2(\Omega)} + \| p \|_{L^2(\Omega)} / |\tau|)$$

$$\leq C |\tau|^{-1+\delta_3(\varepsilon)} \| g \|_{C^{1+\varepsilon}(\Omega)} \| v \|_{L^2(\Omega)}.$$  

The proof of the proposition is complete. \square

We have

**Proposition 2.7.** Let $\alpha > 0$, $g \in C^{2+\alpha}(\Omega)$, $g|_{\sigma} = 0$, and $g|_{\mathcal{H}} = 0$. Then

$$(2.29) \quad \left\| R_{\Phi, \tau} g + \frac{g}{\tau \partial \Phi} \right\|_{L^2(\Omega)} + \left\| \bar{R}_{\Phi, \tau} g - \frac{g}{\tau \partial \Phi} \right\|_{L^2(\Omega)} = o \left( \frac{1}{|\tau|} \right)$$

as $|\tau| \to +\infty$. 
Proof. By (2.2) and Proposition 2.5,

\[ \| \tilde{R}_{\Phi,\tau} g \|_{C^0(\overline{\Omega_\tau}^+)} + \| R_{\Phi,\tau} g \|_{C^0(\overline{\Omega_\tau}^-)} = o\left(\frac{1}{\tau}\right). \]

Therefore instead of (2.29) it suffices to prove

\[ \left\| \chi_1 R_{\Phi,\tau} g + \frac{g}{\tau \partial_z \Phi} \right\|_{L^2(\Omega)} + \left\| \chi_1 \tilde{R}_{\Phi,\tau} g - \frac{g}{\tau \partial_z \Phi} \right\|_{L^2(\Omega)} = o\left(\frac{1}{\tau}\right) \text{ as } |\tau| \to +\infty, \]

where \( \chi_1 \in C_0^\infty(\Omega) \) and \( \chi_1 |_{\Omega \setminus \mathcal{O}_{\tau/2}} = 1 \). Denote \( w = \chi_1 \tilde{R}_{\Phi,\tau} g - \frac{g}{\tau \partial_z \Phi} \). Here we note that \( \frac{g}{\partial_z \Phi} \in L^\infty(\Omega) \). This follows from (2.2), \( g \in C^{1+\alpha}(\Omega) \), and \( g|_{\partial \Omega} = 0 \). Then (2.29) and \( g|_{\partial \Omega} = 0 \) yield

\[ \partial_z w + \tau (\partial_z \Phi) w = -\partial_z \left( \frac{g}{\tau \partial_z \Phi} \right) + (\partial_z \chi_1) \tilde{R}_{\Phi,\tau} g \quad \text{in } \Omega, \quad w|_{\partial \Omega} = 0. \]

Note that by (2.2) and the fact that \( g|_{\partial \Omega} = 0 \), we obtain

\[ |\partial_z \left( \frac{g}{\partial_z \Phi} \right)| = \left| \frac{\partial_z g}{\partial_z \Phi} - \frac{g}{\partial_z \Phi} \frac{\partial^2 \Phi}{\partial_z \Phi \partial_x \Phi} \right| \leq \frac{C}{\Pi_{k=1}^p |x - \tilde{x}_k|}. \]

Consider the radial cut-off function \( \chi \in C_0^\infty(B(0,1)) \) such that

\[ \chi \geq 0, \quad \chi|_{B(0,\frac{1}{2})} = 1. \]

By (2.33) and Proposition 2.2(B),

\[ \tilde{\tilde{R}}_{\Phi,\tau} \left( \sum_{k=1}^\ell \chi(|x - \tilde{x}_k| \ln |\tau|) \partial_z \left( \frac{g}{\partial_z \Phi} \right) \right) \to 0 \quad \text{in } L^2(\Omega) \quad \text{as } |\tau| \to +\infty. \]

In fact, fixing large \( |\tau| \), small \( \delta > 0 \), and \( p > 1 \) such that \( p - 1 \) is sufficiently small, we apply Proposition 2.2(B) and (2.33) to conclude

\[
\| \tilde{R}_{\Phi,\tau} \left( \sum_{k=1}^\ell \chi(|x - \tilde{x}_k| \ln |\tau|) \partial_z \left( \frac{g}{\partial_z \Phi} \right) \right) \|_{L^2(\Omega)} \\
\leq C \sum_{k=1}^\ell \left( \int_{B(\tilde{x}_k,\delta)} |\chi(|x - \tilde{x}_k| \ln |\tau|)|^p \left| \partial_z \left( \frac{g}{\partial_z \Phi} \right) \right| \, dx \right)^{\frac{1}{p}} \\
\leq C'' \| g \|_{C^{1+\alpha}(\overline{\Pi})} \sum_{k=1}^\ell \left( \int_{B(\tilde{x}_k,\delta)} |\chi(|x - \tilde{x}_k| \ln |\tau|)|^p \frac{1}{|x - \tilde{x}_k|^p} \, dx \right)^{\frac{1}{p}} \\
\leq C''' \| g \|_{C^{1+\alpha}(\overline{\Pi})} (\int_0^\delta |\chi(\rho \ln |\tau|)|^p \rho^{1-\rho} \, d\rho)^{\frac{1}{2}}.
\]

Thus we obtain (2.34) by the Riemann-Lebesgue lemma.

By Proposition 2.6 we obtain

\[ \tilde{R}_{\Phi,\tau} \left( \sum_{k=1}^\ell \chi(|x - \tilde{x}_k| \ln |\tau|) \partial_z \left( \frac{g}{\partial_z \Phi} \right) \right) \to 0 \quad \text{in } L^2(\Omega) \quad \text{as } |\tau| \to +\infty. \]
In fact the function \( \left(1 - \sum_{k=1}^{\ell} \chi(|x - \tilde{x}_k| \ln |\tau|) \right) \frac{1}{r(z)} \) for any nonzero \( \tau \). Short calculations give the estimate
\[
\| \left(1 - \sum_{k=1}^{\ell} \chi(|x - \tilde{x}_k| \ln |\tau|) \right) \frac{1}{r(z)} \|_{C^{1+\alpha}(\bar{\Omega})} \leq C |\tau|^{-\frac{1}{2}}.
\]
So by Proposition 2.6
\[
\| \tilde{R}_{\Phi, \tau} \left( \left(1 - \sum_{k=1}^{\ell} \chi(|x - \tilde{x}_k| \ln |\tau|) \right) \frac{1}{r(z)} \right) \|_{L^2(\Omega)} \leq \frac{C}{|\tau|^{\frac{1}{2} - \delta'}}.
\]
Therefore (2.34) and (2.35) yield
\[
\| \tilde{R}_{\Phi, \tau} \left( \left(1 - \sum_{k=1}^{\ell} \chi(|x - \tilde{x}_k| \ln |\tau|) \right) \frac{1}{r(z)} \right) \|_{L^2(\Omega)} = o(1) \text{ as } |\tau| \to +\infty.
\]

Denote \( \tilde{w} = w + \frac{1}{\tau} \chi_1 \tilde{R}_{\Phi, \tau} (\frac{g}{\partial_{\zeta}\Phi}) \).

By (2.36), it suffices to prove
\[
\| \tilde{w} \|_{L^2(\Omega)} = o \left( \frac{1}{|\tau|} \right) \text{ as } |\tau| \to +\infty.
\]

In terms of (2.32) and (2.9), observe that
\[
\partial_z \tilde{w} + \tau (\partial_z \Phi) \tilde{w} = f \text{ in } \Omega, \quad \tilde{w}|_{\partial\Omega} = 0,
\]
where \( f = \frac{1}{\tau} (\partial_z \chi_1) \tilde{R}_{\Phi, \tau} (\frac{g}{\partial_{\zeta}\Phi}) + (\partial_z \chi_1) \tilde{R}_{\Phi, \tau} g \). By (2.36) and (2.38) we have
\[
\| f \|_{L^2(\Omega)} = o \left( \frac{1}{|\tau|} \right) \text{ as } |\tau| \to +\infty.
\]

Applying Proposition 5.2 to equation (2.38), we get
\[
\| \partial_{x_1}(e^{i\tau\psi} \tilde{w}) \|_{L^2(\Omega)}^2 + \tau \int_{\partial\Omega} (\nabla \varphi, \nu)|\tilde{w}|^2 d\sigma \\
+ \operatorname{Re} \int_{\partial\Omega} i \left( \left( \nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2} \right) \tilde{w} \right) \bar{\tilde{w}} d\sigma + \| \partial_{x_2}(e^{i\tau\psi} \tilde{w}) \|_{L^2(\Omega)}^2
= \| f \|_{L^2(\Omega)}^2.
\]
Thanks to the zero Dirichlet boundary conditions for the function \( \hat{w} \) we obtain
\[
\| \partial_z (e^{i r \psi} \hat{w}) \|_{L^2(\Omega)}^2 + \| \partial_{zz} (e^{i r \psi} \hat{w}) \|_{L^2(\Omega)}^2 = \| f \|_{L^2(\Omega)}^2.
\]
Poincaré’s inequality implies
\[
\| \hat{w} \|_{H^1(\Omega)} \leq C \| f \|_{L^2(\Omega)}.
\]
From this and using (2.39), we obtain (2.37). As for the first term in (2.29), we can argue similarly. The proof of the proposition is completed. \( \square \)

3. Complex geometrical optics solutions

In this section, we construct complex geometrical optics solutions for the Schrödinger equation \( \Delta + q_1 \) with \( q_1 \) satisfying the conditions of Theorem 1.1. Consider

\[
L_1 u = \Delta u + q_1 u = 0 \quad \text{in} \quad \Omega.
\]

We will construct solutions to (3.1) of the form

\[
u_1(x) = e^{r \Phi(z)} (a(z) + a_0(z)/\tau) + e^{r \Phi(\bar{z})} (a(\bar{z}) + a_1(\bar{z})/\tau) + e^{r \psi} u_{11} + e^{r \psi} u_{12}, \quad u_1|_{\Gamma_0} = 0.
\]

The function \( \Phi \) satisfies (2.1), (2.2), and
\[
(3.3) \quad \text{Im} \Phi|_{\Gamma_0} = 0.
\]

The amplitude function \( a(z) \) is not identically zero on \( \overline{\Omega} \) and has the following properties:

\[
(3.4) \quad a \in C^2(\overline{\Omega}), \quad \partial_z a \equiv 0, \quad \text{Re} a|_{\Gamma_0} = 0, \quad a(z)|_{\mathcal{H} \cap \partial \Omega} = \partial_z a(z)|_{\mathcal{H} \cap \partial \Omega} = 0.
\]

The function \( u_{11} \) is given by

\[
u_{11} = - \frac{1}{4} e^{r \psi} \frac{\bar{R}_{\phi, r}}{r} (e_1 (\partial_z^{-1} (aq_1) - M_1(z)) \nonumber \\
- e^{-i r \psi} \frac{\bar{R}_{\phi, -r}}{r} (e_1 (\partial_z^{-1} (a\bar{q}_1) - M_3(\bar{z}))) \nonumber \\
- \frac{e^{i r \psi} e_2 (\partial_z^{-1} (aq_1) - M_1(z))}{4 \partial_z \Phi} - \frac{e^{-i r \psi} e_2 (\partial_z^{-1} (a\bar{q}_1) - M_3(\bar{z}))}{4 \partial_z \Phi} \nonumber \\
= w_1 e^{-r \phi} + w_2 e^{-r \psi},
\]

where the polynomials \( M_1(z) \) and \( M_3(\bar{z}) \) satisfy

\[
(3.6) \quad \partial_z^j (\partial_z^{-1} (aq_1) - M_1(z)) = 0, \quad x \in \mathcal{H}, \ j = 0, 1, 2,
\]
\[
(3.7) \quad \partial_z^j (\partial_z^{-1} (a\bar{q}_1) - M_3(\bar{z})) = 0, \quad x \in \mathcal{H}, \ j = 0, 1, 2.
\]

Note that by (3.4)

\[
(3.8) \quad \partial_z^j \partial_z^k (\partial_z^{-1} (aq_1) - M_1(z)) = 0, \quad x \in \mathcal{H} \cap \partial \Omega, \ j, k \in \{0, 1, 2\}, \ j + k \leq 2,
\]
\[
(3.9) \quad \partial_z^j \partial_z^k (\partial_z^{-1} (a\bar{q}_1) - M_3(\bar{z})) = 0, \quad x \in \mathcal{H} \cap \partial \Omega, \ j, k \in \{0, 1, 2\}, \ j + k \leq 2.
\]

The functions \( e_1, e_2 \in C^\infty(\Omega) \) are constructed so that

\[
(3.10) \quad e_1 + e_2 \equiv 1 \text{ on } \overline{\Omega}, \quad e_2 \text{ vanishes in some neighborhood of } \mathcal{H} \setminus \partial \Omega, \quad \text{and } e_1 \text{ vanishes in a neighborhood of } \partial \Omega.
\]
and we set
\[ w_1 = -\frac{1}{4} e^{-\Phi} \tilde{R}_{\Phi, \tau}(e_1(\partial^{-1}_z(aq_1) - M_1(z))) - \frac{1}{4} e^{-\Phi} \tilde{R}_{\Phi, -\tau}(e_1(\partial^{-1}_z(\bar{a}q_1) - M_3(\bar{z}))) \]

and
\[ w_2 = -\frac{e^{-\Phi}}{\tau} e_2(\partial^{-1}_z(aq_1) - M_1(z)) - \frac{e^{-\Phi}}{\tau} e_2(\partial^{-1}_z(\bar{a}q_1) - M_3(\bar{z})). \]

Finally, \( a_0, a_1 \) are holomorphic functions such that
\[ (a_0(z) + a_1(z))|_{\Gamma_0} = \frac{(\partial^{-1}_z(aq_1) - M_1(z))}{4\partial_z\Phi} + \frac{(\partial^{-1}_z(\bar{a}q_1) - M_3(\bar{z}))}{4\partial_z\Phi}. \]

Then, noting that \( \partial_z \Phi = \partial_z \tilde{\Phi}, \quad (3.8) \) and \( (2.29) \), we have
\[ \Delta w_1 = 4\partial_z \partial_{\tilde{z}} w_1 \]
\[ = -\partial_{\tilde{z}}(e^{-\Phi} \partial_z \tilde{R}_{\Phi, \tau}(e_1(\partial^{-1}_z(aq_1) - M_1(z)))) + (\tau \partial_\Phi)e^{-\Phi} \tilde{R}_{\Phi, \tau}(e_1(\partial^{-1}_z(aq_1) - M_1(z))) - \partial_z(e^{-\Phi} \partial_{\tilde{z}} \tilde{R}_{\Phi, -\tau}(e_1(\partial^{-1}_z(\bar{a}q_1) - M_3(z)))) + (\tau \partial_\Phi)e^{-\Phi} \tilde{R}_{\Phi, -\tau}(e_1(\partial^{-1}_z(\bar{a}q_1) - M_3(z))) \]
\[ = -\partial_{\tilde{z}}(e^{-\Phi} e_1(\partial^{-1}_z(aq_1) - M_1(z))) - \partial_z(e^{-\Phi} e_1(\partial^{-1}_z(\bar{a}q_1) - M_3(z))). \]

Moreover
\[ \Delta w_2 = 4\partial_z \partial_{\tilde{z}} w_2 \]
\[ = -\partial_{\tilde{z}}(e^{-\Phi} (e_2(\partial^{-1}_z(aq_1) - M_1(z)))) - \partial_z(e^{-\Phi} e_2(\partial^{-1}_z(\bar{a}q_1) - M_3(z))) - e^{-\Phi} \Delta \left( \frac{e_2(\partial^{-1}_z(aq_1) - M_1(z))}{4\tau \partial_\Phi} \right) - e^{-\Phi} \Delta \left( \frac{e_2(\partial^{-1}_z(\bar{a}q_1) - M_3(\bar{z})))}{4\tau \partial_\Phi} \right). \]

Therefore
\[ \Delta(u_{11}e^{\tau \varphi}) = \Delta(w_1 + w_2) \]
\[ = -aq_1 e^{-\Phi} - \bar{a}q_1 e^{-\Phi} - e^{-\Phi} \Delta \left( \frac{e_2(\partial^{-1}_z(aq_1) - M_1(z))}{4\tau \partial_\Phi} \right) - e^{-\Phi} \Delta \left( \frac{e_2(\partial^{-1}_z(\bar{a}q_1) - M_3(\bar{z}))}{4\tau \partial_\Phi} \right). \]

By \( (3.4) \) and \( (3.3) \) observe that
\[ (e^{-\Phi(z)} a(z) + e^{-\Phi(z)} \bar{a}(z))|_{\Gamma_0} = 0. \]

Let \( u_{12} \) be a solution to the inhomogeneous problem
\[ \Delta(u_{12}e^{\tau \varphi}) + q_1 u_{12} e^{\tau \varphi} = -q_1 u_{11} e^{\tau \varphi} + h_1 e^{\tau \varphi} \quad \text{in } \Omega, \]
\[ u_{12} = \frac{1}{4} \tilde{R}_{\Phi, \tau}(e_1(\partial^{-1}_z(aq_1) - M_1(z))) + \frac{1}{4} \tilde{R}_{\Phi, -\tau}(e_1(\partial^{-1}_z(\bar{a}q_1) - M_3(z))) \quad \text{on } \Gamma_0, \]
where

\[ h_1 = e^{\tau \psi} \Delta \left( \frac{e_2(\partial_z^{-1}(aq_1) - M_1(z))}{4\tau \partial_z \Phi} \right) + e^{-\tau \psi} \Delta \left( \frac{e_2(\partial_z^{-1}(\bar{q} q_1) - M_3(z))}{4\tau \partial_z \Phi} \right) - a_0 q_1 e^{\tau \psi} / \tau - a_1 q_1 e^{-\tau \psi} / \tau. \]  

By (3.24) and (3.31)–(3.35), we conclude that (3.1) is satisfied.

By Proposition 2.1 there exists a positive \( \tau_0 \) such that for all \( |\tau| > \tau_0 \) there exists a solution to (3.13), (3.14) satisfying (3.21), (3.34) satisfying

\[ \|u_{12}\|_{L^2(\Omega)} = o(\frac{1}{\tau}) \]  

as \( \tau \to +\infty. \]

This can be done because

\[ \|q_1 u_{11} + b_1\|_{L^2(\Omega)} \leq C(\delta)/|\tau|^{1-\delta} \quad \forall \delta \in (0, 1); \|u_{11}\|_{L^2(\partial \Omega)} = o(\frac{1}{\tau}) \]

and \( (\nabla \varphi, \nu) = 0 \) on \( \Gamma_0 \). The latter fact can be seen as follows: On \( \partial \Omega \), the Cauchy-Riemann equations imply

\[ (\nabla \varphi, \nu) = \nu_1 \partial_z \varphi + \nu_2 \partial_{\bar{z}} \varphi = \nu_1 \partial_z \psi - \nu_2 \partial_{\bar{z}} \psi = -\frac{\partial \psi}{\partial \bar{r}}, \]

which is the tangential derivative of \( \psi = \Im \Phi \) on \( \partial \Omega \). By (3.3) the tangential derivative of \( \psi \) vanishes on \( \Gamma_0 \).

Consider now the Schrödinger equation

\[ L_2 \psi = \Delta \psi + q_2 \psi = 0 \quad \text{in} \quad \Omega. \]  

(3.17)

We will construct solutions to (3.17) of the form

\[ v(x) = e^{-\tau \Phi(z)}(a(z) + b_0(z)/\tau) \]

\[ + e^{-\tau \Phi(z)}(a(z) + \bar{b}_1(z)/\tau) + e^{-\tau \psi} v_{11} + e^{-\tau \psi} v_{12}, \quad v|_{\Gamma_0} = 0. \]

The construction of \( v \) repeats the corresponding steps of the construction of \( u_1 \). The only difference is that instead of \( q_1 \) and \( \tau \), we use \( q_2 \) and \( -\tau \), respectively. We provide the details for the sake of completeness. The function \( v_{11} \) is given by

\[ v_{11} = -\frac{1}{4} e^{-i\tau \psi} \bar{R}_{\Phi,-\tau}(e_1(\partial_z^{-1}(aq_2(z)) - M_2(z))) \]

\[ - \frac{1}{4} e^{i\tau \psi} \bar{R}_{\Phi,\tau}(e_1(\partial_z^{-1}(\bar{a}q_2(z)) - M_4(z))) \]

\[ + \frac{e^{-i\tau \psi} e_2(\partial_z^{-1}(aq_2) - M_2(z))}{4\partial_z \Phi} + \frac{e^{i\tau \psi} e_2(\partial_z^{-1}(\bar{a}q_2) - M_4(z))}{4\partial_z \Phi}, \]

where

\[ (3.20) \quad \partial_z(\partial_z^{-1}(aq_2) - M_2(z)) = 0, \quad x \in \mathcal{H}, \quad j = 0, 1, 2, \]

\[ (3.21) \quad \partial_z \partial_{\bar{z}}^k(\partial_z^{-1}(aq_2) - M_2(z)) = 0, \quad x \in \mathcal{H} \cap \partial \Omega, \quad j, k \in \{0, 1, 2\}, \quad k + j \leq 2, \]

\[ (3.22) \quad \partial_{\bar{z}}^k(\partial_z^{-1}(aq_2) - M_4(z)) = 0, \quad x \in \mathcal{H}, \quad j = 0, 1, 2, \]

\[ (3.23) \quad \partial_z \partial_{\bar{z}}^k(\partial_z^{-1}(\bar{a}q_2) - M_4(z)) = 0, \quad x \in \mathcal{H} \cap \partial \Omega, \quad j, k \in \{0, 1, 2\}, \quad k + j \leq 2. \]

Finally \( b_0, b_1 \) are holomorphic functions such that

\[ (b_0 + \bar{b}_1)|_{\Gamma_0} = -\frac{(\partial_z^{-1}(aq_2) - M_2(z))}{4\partial_z \Phi} - \frac{(\partial_z^{-1}(\bar{a}q_2) - M_4(z))}{4\partial_z \Phi}. \]
Denote
\[ h_2 = e^{-\tau \psi} \Delta \left( \frac{e_2(\partial_x^{-1}(aq_2) - M_2(z))}{4\tau \partial_x \Phi} \right) + e^{\tau \psi} \Delta \left( \frac{e_2(\partial_x^{-1}(\pi q_2) - M_4(\pi))}{4\tau \partial_x \Phi} \right) - \frac{b_0}{\tau} q_2 e^{\tau \psi} - \frac{b_1}{\tau} q_2 e^{\tau \psi}. \]

The function \( v_{12} \) is a solution to the problem:
\begin{align*}
\Delta (v_{12} e^{-\tau \phi}) + q_2 v_{12} e^{-\tau \phi} &= -q_2 v_{11} e^{-\tau \phi} - h_2 e^{-\tau \phi} \quad \text{in } \Omega, \\
v_{12}|_{\Gamma_0} &= \frac{1}{4} \tilde{R}_{\phi,-\tau} (e_1(\partial_x^{-1}(q_2 a) - M_2(z))) \\
&\quad + \frac{1}{4} R_{\phi,\tau} (e_1(\partial_x^{-1}(q_2 \pi) - M_4(\pi))) \quad (3.25)
\end{align*}

such that
\[ \|v_{12}\|_{L^2(\Omega)} = o\left(\frac{1}{\tau}\right) \quad \text{as } \tau \to +\infty. \quad (3.26) \]

4. PROOF OF THEOREM 1.1

We first apply the stationary phase with a general phase function \( \Phi \) and then we construct an appropriate weight function.

**Proposition 4.1.** Suppose that \( \Phi \) satisfies (2.1), (2.2), and (3.3). Let \( \{ \tilde{x}_1, \ldots, \tilde{x}_\ell \} \) be the set of critical points of the function \( \text{Im} \Phi \). Then for any potentials \( q_1, q_2 \in C^{2+\alpha}(\Omega) \), \( \alpha > 0 \), with the same Cauchy data on \( \Gamma \) and for any holomorphic function \( \phi \) satisfying (3.4) and \( M_1(z), M_2(z), M_3(\pi), M_4(\pi) \) as in Section 3, we have
\begin{align*}
\left| \int_{\Omega} \frac{\pi |q| a^2(\tilde{x}_k) \text{Re} e^{2i\tau \text{Im} \Phi(\tilde{x}_k)}}{|(\text{det Im} \Phi')(\tilde{x}_k)|^2} + \int_{\Omega} q(a(a_0 + b_0) + \overline{a}(a_1 + b_1))dx \\
+ \frac{1}{4} \int_{\Omega} \left( qa \frac{\partial_x^{-1}(aq_2) - M_2(z)}{\partial_x \Phi} + qa \frac{\partial_x^{-1}(q_2 \pi) - M_4(\pi)}{\partial_x \Phi} \right) dx \\
- \frac{1}{4} \int_{\Omega} \left( qa \frac{\partial_x^{-1}(aq_1) - M_1(z)}{\partial_x \Phi} + qa \frac{\partial_x^{-1}(\pi q_1) - M_3(\pi)}{\partial_x \Phi} \right) dx \right) &= 0, \quad \tau > 0,
\end{align*}

where
\[ q = q_1 - q_2. \]

**Proof.** Let \( u_1 \) be a solution to (3.1) satisfying (3.2), and let \( u_2 \) be a solution to the equation
\[ \Delta u_2 + q_2 u_2 = 0 \quad \text{in } \Omega, \quad u_2|_{\partial \Omega} = u_1|_{\partial \Omega}. \]

Since the Dirichlet-to-Neumann maps are equal, we have
\[ \nabla u_2 = \nabla u_1 \quad \text{on } \Gamma. \]
Denoting $u = u_1 - u_2$, we obtain

\begin{equation}
\Delta u + q_2 u = -q u_1 \quad \text{in } \Omega, \quad u|_{\partial \Omega} = \frac{\partial u}{\partial \nu}|_{\tilde{\Gamma}} = 0.
\end{equation}

Let $v$ satisfy (3.17) and (3.18). We multiply (4.2) by $v$ and integrate over $\Omega$, and we use $v|_{\Gamma_0} = 0$ and $\frac{\partial u}{\partial \nu} = 0$ on $\tilde{\Gamma}$ to obtain $\int_{\Omega} q u_1 v dx = 0$. By (3.2), (3.16), (3.18), and (3.26), we have

\begin{equation}
0 = \int_{\Omega} q u_1 v dx = \int_{\Omega} q(a^2 + \overline{a}^2 + |a|^2 e^{\tau(\Phi - \overline{\Phi})} + |a|^2 e^{\tau(\overline{\Phi} - \Phi)})
\end{equation}

\begin{align*}
&+ \frac{1}{\tau}(a(a_0 + b_0) + \overline{a}(\overline{a}_1 + \overline{b}_1)) + u_{11} e^{\tau(\Phi - \overline{\Phi} + \overline{\Phi} - \Phi)} \\
&+ (ae^{\tau\Phi} + \overline{a}e^{\tau\overline{\Phi}})v_{11} e^{-\tau\psi} dx + o\left(\frac{1}{\tau}\right), \quad \tau > 0.
\end{align*}

The first and second terms in the asymptotic expansion of (4.3) are independent of $\tau$, so that

\begin{equation}
\int_{\Omega} q(a^2 + \overline{a}^2) dx = 0.
\end{equation}

Using the stationary phase argument (see p. 215 in [13]; cf. [16]) and functions $e_1, e_2$ defined in (3.10), we obtain

\begin{equation}
\int_{\Omega} q(|a|^2 e^{\tau(\Phi - \overline{\Phi})} + |a|^2 e^{\tau(\overline{\Phi} - \Phi)}) dx = \int_{\Omega} e_1 q(|a|^2 e^{\tau(\Phi - \overline{\Phi})} + |a|^2 e^{\tau(\overline{\Phi} - \Phi)}) dx \\
+ \int_{\Omega} e_2 q(|a|^2 e^{\tau(\Phi - \overline{\Phi})} + |a|^2 e^{\tau(\overline{\Phi} - \Phi)}) dx.
\end{equation}

By the Cauchy-Riemann equations, we see that $\text{sgn}(\text{Im} \Phi''(\tilde{x}_k)) = 0$, where $\text{sgn} A$ denotes the signature of the matrix $A$, that is, the number of positive eigenvalues of $A$ minus the number of negative eigenvalues (e.g., [13], p. 210). Moreover we note that

\[ \text{det Im } \Phi''(z) = -(\partial_{x_1} \partial_{x_2} \varphi)^2 - (\partial^2_{x_1} \varphi)^2 \neq 0. \]

To see this, suppose that $\text{det Im } \Phi''(z) = 0$. Then

\[ \partial_{x_1} \partial_{x_2} \varphi(\text{Re } z, \text{Im } z) = \partial^2_{x_1} \varphi(\text{Re } z, \text{Im } z) = 0 \]

and the Cauchy-Riemann equations imply that all second-order partial derivatives of functions $\varphi, \psi$ at the point $z$ are zero. This fact contradicts the assumption that critical points of the function $\Phi$ are nondegenerate.

Using the stationary phase argument (see p. 215 in [13]; cf. [16]), we obtain

\begin{equation}
\int_{\Omega} e_1 q(|a|^2 e^{\tau(\Phi - \overline{\Phi})} + |a|^2 e^{\tau(\overline{\Phi} - \Phi)}) dx = 2 \sum_{k=1}^{\ell} \frac{\pi q|a|^2 e^{2\tau\text{Re } z_k} \text{Im } \Phi(\tilde{x}_k)}{\tau |(\text{det Im } \Phi''(\tilde{x}_k))|^2} + o\left(\frac{1}{\tau}\right).
\end{equation}
Let \( \tilde{x}_1, \ldots, \tilde{x}_k \) be the set of critical points of the function \( \Phi \) on \( \Gamma_0 \). Integrating by parts, we have

\[
\int_{\Omega} e^2 q(|a|^2 e^{\tau(\Phi - \Phi)}) + |a|^2 e^{\tau(\Phi - \Phi)}) dx
\]

\[
= \int_{\Omega} e^2 q|a|^2 \left( \frac{\nabla \psi, \nabla e^{\tau(\Phi - \Phi)}}{2i\tau|\nabla \psi|^2} - \frac{\nabla \psi, \nabla e^{\tau(\Phi - \Phi)}}{2i\tau|\nabla \psi|^2} \right) dx
\]

\[
= \lim_{\delta \to +0} \int_{\Omega \setminus \bigcup_{k=1}^{k'} B(\tilde{x}_k, \delta)} e^2 q|a|^2 \left( \frac{\nabla \psi, \nabla e^{\tau(\Phi - \Phi)}}{2i\tau|\nabla \psi|^2} - \frac{\nabla \psi, \nabla e^{\tau(\Phi - \Phi)}}{2i\tau|\nabla \psi|^2} \right) dx
\]

\[
+ \int_{\partial \Omega \setminus \bigcup_{k=1}^{k'} B(\tilde{x}_k, \delta)} e^2 q|a|^2 \left( \frac{\nabla \psi, \nu}{2i\tau|\nabla \psi|^2} - \frac{\nabla \psi, \nu}{2i\tau|\nabla \psi|^2} \right) e^{\tau(\Phi - \Phi)} d\sigma
\]

\[
= - \int_{\Omega} \text{div} \left( e^2 q|a|^2 \nabla \psi \right) \left( e^{\tau(\Phi - \Phi)} - e^{\tau(\Phi - \Phi)} \right) dx
\]

\[
+ \int_{\partial \Omega} q|a|^2 \frac{\partial \psi}{2i\tau|\nabla \psi|^2} \left( e^{\tau(\Phi - \Phi)} - e^{\tau(\Phi - \Phi)} \right) d\sigma
\]

\[
= - \int_{\text{supp} e^2} \text{div} \left( e^2 q|a|^2 \nabla \psi \right) \left( e^{\tau(\Phi - \Phi)} - e^{\tau(\Phi - \Phi)} \right) dx.
\]

In the last equality, we used the fact that \( e^{\tau(\Phi - \Phi)} - e^{\tau(\Phi - \Phi)} = 0 \) on \( \Gamma_0 \), which follows since \( \text{Im} \Phi = 0 \) on \( \Gamma_0 \), and \( q = 0 \) on \( \Gamma \) and \( \text{supp} e^2 \) in order to show that

\[
\text{div} \left( e^2 q|a|^2 \nabla \psi \right) \quad \text{and} \quad \frac{q|a|^2}{2i\tau|\nabla \psi|^2}
\]

are bounded functions. The latter fact follows from the unique boundary determination of potentials from the Dirichlet-to-Neumann map (see for instance \cite{[12]}, \cite{[29]}). Applying Proposition \ref{2.4} we obtain

\[
\int_{\Omega} e^2 q(|a|^2 e^{\tau(\Phi - \Phi)} + |a|^2 e^{\tau(\Phi - \Phi)}) dx = o \left( \frac{1}{\tau} \right) \quad \text{as} \quad |\tau| \to +\infty.
\]

Therefore

\[
(4.6) \int_{\Omega} q(|a|^2 e^{\tau(\Phi - \Phi)} + |a|^2 e^{\tau(\Phi - \Phi)}) dx = o \left( \frac{1}{\tau} \right).
\]
We calculate the two remaining terms in (4.3). We have
\[
\int_{\Omega} qu_{11}e^{-\tau\phi}(ae^{-\tau\Phi} + \overline{ae^{-\tau\Phi}})dx
\]
\[
= -\frac{1}{4} \int_{\Omega} q \left\{ e^{-\tau\Phi} \overline{R}_{\phi,-r}(e_1(\partial_{\tau}^{-1}(aq_1) - M_1(z))) \\
+ e^{r\Phi} R_{\phi,-r}(e_1(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z}))) \right\} (ae^{-\tau\Phi} + \overline{ae^{-\tau\Phi}})dx
\]
\[
- \int_{\Omega} \left( \frac{e^{\tau\Phi}}{\tau} e_2(\partial_{\tau}^{-1}(aq_1) - M_1(z)) + \frac{e^{\tau\Phi}}{\tau} e_2(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})) \right) dx
\times q(ae^{-\tau\Phi} + \overline{ae^{-\tau\Phi}})dx
\]
\[
= -\frac{1}{4} \int_{\Omega} (qa \overline{R}_{\phi,-r}(e_1(\partial_{\tau}^{-1}(aq_1) - M_1(z))) \\
+ a \tau R_{\phi,-r}(e_1(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})))e^{r(\Phi - \overline{\Phi})} \\
+ qa R_{\phi,-r}(e_1(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})))e^{-r(\Phi - \overline{\Phi})}dx
\]
\[
- \int_{\Omega} \left( \frac{e^{r(\Phi - \overline{\Phi})}}{\tau} \overline{ae}_2(\partial_{\tau}^{-1}(aq_1) - M_3(\overline{z})) + \frac{e^{-r(\Phi - \overline{\Phi})}}{\tau} ae_2(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})) \right) dx
\]
\[
= I_1 + I_2 + I_3 + I_4.
\]
We estimate \(I_1\) and \(I_2\) separately. Using Proposition 2.7, 3.4, and Proposition 2.4 we get
\[
I_2 = -\frac{1}{4} \int_{\Omega} (qa \overline{R}_{\phi,-r}(e_1(\partial_{\tau}^{-1}(aq_1) - M_1(z)))e^{r(\Phi - \overline{\Phi})} \\
+ qa R_{\phi,-r}(e_1(\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})))e^{-r(\Phi - \overline{\Phi})})dx
\]
\[
= -\frac{1}{4} \int_{\Omega} \left( \frac{e_1 qa}{\tau \partial_{\tau} \phi} (\partial_{\tau}^{-1}(aq_1) - M_1(z))e^{2i\tau \text{Im}\Phi} \\
+ \frac{e_1 qa}{\tau \partial_{\tau} \phi} (\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z}))e^{-2i\tau \text{Im}\Phi} \right) dx + o \left( \frac{1}{\tau} \right)
\]
\[
= o \left( \frac{1}{\tau} \right) \quad \text{as} \quad |\tau| \to +\infty.
\]
By Proposition 2.7 we obtain
\[
I_1 = -\frac{1}{4\tau} \int_{\Omega} e_1 \left( \frac{qa (\partial_{\tau}^{-1}(aq_1) - M_1(z))}{\partial_{\tau} \phi} + q \overline{a} (\partial_{\tau}^{-1}(\overline{aq}_1) - M_3(\overline{z})) \right) dx + o \left( \frac{1}{\tau} \right) \quad \text{as} \quad |\tau| \to +\infty.
\]
By Proposition 2.4 we conclude that

\[ (4.9) \quad J_3 = o \left( \frac{1}{\tau} \right) \quad \text{as } |\tau| \to +\infty. \]

Similarly

\[
\int_{\Omega} qv_1 e^{-\tau \varphi} (a e^{-\Phi} + \bar{a} e^{-\overline{\Phi}}) dx
\]

\[ = -\frac{1}{4} \int_{\Omega} q \left\{ e^{-\tau \Phi} \bar{R}_{\Phi,-\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z)))
\right.
\]

\[ + e^{-\tau \Phi} R_{\Phi,\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z}))) \right\} (a e^{-\Phi} + \bar{a} e^{-\overline{\Phi}}) dx
\]

\[ + \int_{\Omega} q \left( \frac{e^{-\tau \Phi}}{\tau} e_2 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z))
\]

\[ + \frac{e^{-\tau \Phi}}{\tau} e_2 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z})) \right) (a e^{-\Phi} + \bar{a} e^{-\overline{\Phi}}) dx
\]

\[ = -\frac{1}{4} \int_{\Omega} (q a \bar{R}_{\Phi,-\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z)))
\]

\[ + q a \bar{R}_{\Phi,\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z}))) dx
\]

\[ - \frac{1}{4} \int_{\Omega} [q a e^{-\tau \Phi} \bar{R}_{\Phi,-\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z)))
\]

\[ + q a e^{-\tau \Phi} R_{\Phi,\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z}))) dx
\]

\[ + \int_{\Omega} q \left( \frac{a e^{-\tau \Phi}}{\tau} e_2 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z))
\]

\[ + \frac{a e^{-\tau \Phi}}{\tau} e_2 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z})) \right) dx
\]

\[ = J_1 + J_2 + J_3 + J_4. \]

By Proposition 3.20 and Proposition 2.7 we have

\[ (4.10) \quad J_1 = \frac{1}{4\tau} \int_{\Omega} e_1 \left( q a \partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z) \right)
\]

\[ + q a \partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z}) \right) dx + o \left( \frac{1}{\tau} \right) \]

as \(|\tau| \to +\infty\). Proposition 2.2, Proposition 3.20, and Proposition 2.4 yield

\[ (4.11) \quad J_2 = -\frac{1}{4} \int_{\Omega} [q a e^{-\tau \Phi} \bar{R}_{\Phi,-\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (aq_2) - M_2(z)))
\]

\[ + q a e^{-\tau \Phi} R_{\Phi,\tau} (e_1 (\partial_{\overline{\Phi}}^{-1} (\overline{a} q_2) - M_4(\overline{z}))) dx = o \left( \frac{1}{\tau} \right). \]

By Proposition 2.4 we see that

\[ (4.12) \quad J_3 = o \left( \frac{1}{\tau} \right) \quad \text{as } |\tau| \to +\infty. \]
Therefore, applying (4.5), (4.7), (4.10), (4.11), (4.9), and (4.12) in (4.3), we conclude that

\[
2 \sum_{k=1}^{\ell} \frac{\pi|q(a^2)(x_k)| e^{2i\tau \Im \Phi(x_k)}}{|(\det \Im \Phi')(x_k)|^2} + \int_{\Omega} q(a(a_0 + b_0) + \bar{a}(\bar{a}_1 + \bar{b}_1)) dx + \frac{1}{4} \int_{\Omega} \left( qa \frac{\partial^{-1}(aq_2) - M_2(z)}{\partial \Phi} + q \frac{\partial^{-1}(q_2 \pi) - M_1(\pi)}{\partial \Phi} \right) dx \]

(4.13)

as \( \tau \to +\infty \). Passing to the limit in this equality and applying Bohr’s theorem (e.g., [H], p. 393), we finish the proof of the proposition.

We need the following proposition in the construction of the phase function \( \Phi \).

Let \( \tilde{y}_0, \tilde{y}_1, \ldots, \tilde{y}_m \in \Omega \) and \( \tilde{y}_{m+1}, \ldots, \tilde{y}_{m+n} \in \Gamma_0 \).

Denote by \( \mathcal{R} = (\mathcal{R}(\tilde{y}_1), \ldots, \mathcal{R}(\tilde{y}_m), \mathcal{R}_1(\tilde{y}_{m+1}), \ldots, \mathcal{R}_1(\tilde{y}_{m+n})) \) the following operator:

\[
\mathcal{R}(\tilde{y}_k)g = (u(\tilde{y}_k), \partial_z u(\tilde{y}_k), \partial_z^2 u(\tilde{y}_k)), \quad \mathcal{R}_1(\tilde{y}_k)g = (\Re u(\tilde{y}_k), \partial_z u(\tilde{y}_k)/(\nu_2 + \nu_1)),
\]

where

\[
(4.14) \quad \partial_z u = 0 \text{ in } \Omega, \quad \Re u(\tilde{y}_0) = 0, \quad \Im u|_{\Gamma_0} = 0, \quad \Im u|_{\Gamma} = g.
\]

For any \( g \in C_0^\infty(\bar{\Omega}) \) problem (4.14) has at most one solution. We have

**Proposition 4.2.** The operator \( \mathcal{R} : D(\mathcal{R}) \subset C_0^\infty(\bar{\Omega}) \to C^{3m} \times \mathbb{R}^{2n} \) satisfies \( \Im \mathcal{R} = C^{3m} \times \mathbb{R}^{2n} \).

**Proof.** We note that \( \Im \mathcal{R} = C^{3m} \times \mathbb{R}^{2n} \) if and only if the closure of \( \Im \mathcal{R} \) is equal to \( C^{3m} \times \mathbb{R}^{2n} \). This follows immediately from Corollary 5.1. Let \( \bar{H} \) be an arbitrary element of the space \( C^{3m} \times \mathbb{R}^{2n} \). Consider the problem (5.1) where

\[
\begin{align*}
\hat{x}_1 &= \hat{y}_1, & j \in \{1, \ldots, m\}, \\
\hat{x}_{m+1} &= \tilde{y}_0, \\
c_{0,1} &= h_1, & c_{1,1} = h_2, & c_{2,1} = h_3, & \ldots, & c_{0,m} = h_{3m-2}, \\
c_{1,m} &= h_{3m-1}, & c_{2,m} = h_{3m}, & c_{0,m+1} = 0.
\end{align*}
\]

Taking into account that \( \partial_z u|_{\Gamma_0} = (\nu_2 + i\nu_1) \partial_\tau \Re u \), we take a function \( b \) such that

\[
\begin{align*}
b(\tilde{y}_{m+1}) &= h_{m+1}, & \partial_\tau b(\tilde{y}_{m+1}) &= h_{m+2}, & \ldots, \\
b(\tilde{y}_{m+n}) &= h_{m+2n-1}, & \partial_\tau b(\tilde{y}_{m+n}) &= h_{m+2n}.
\end{align*}
\]

According to Corollary 5.1 (5.1) with such initial data can be solved approximately. If necessary we can add to these solutions a real constant such that \( u(\tilde{y}_0) = 0 \). The proof of the proposition is complete.

**End of proof of Theorem 1.1**

**Proof.** We will construct a complex geometrical optics solution of the form (3.2) where \( \Phi \) and \( a \) satisfy (2.1), (2.2), (3.3), and (3.4).
Let $\hat{\Omega}$ be a bounded domain in $\mathbb{R}^2$ such that $\overline{\Omega} \subset \hat{\Omega}$, $\Gamma_0 \subset \partial \hat{\Omega}$, $\partial \hat{\Omega} \cap \hat{\Gamma} = \emptyset$. Let $\hat{x}$ be an arbitrary point in $\hat{\Omega}$. By Proposition 4.2 and Corollary 5.1 there exists a sequence of holomorphic functions $u \in C^2(\hat{\Omega})$ such that

\begin{align}
\text{(4.15)} & \quad \text{Im} u|_{\Gamma_0} = 0, \quad \text{Im} u(\hat{x}) \neq 0, \quad \partial_z u(\hat{x}) = 0, \quad \text{and} \quad \partial^2_z u(\hat{x}) \neq 0. \\
\text{(4.16)} & \quad \frac{\partial \text{Im} u}{\partial \nu}|_{\Gamma_0} < \alpha' < 0, \quad \text{if } \text{Int}((\partial \Omega \setminus \Gamma_0) \cap \gamma_j) \neq \emptyset.
\end{align}

In the case $\text{Int}((\partial \Omega \setminus \Gamma_0) \cap \gamma_j) = \emptyset$, then $\{x \in \gamma_j | \partial_z u(\hat{x}) = 0\} = \{y_{1,j}, y_{2,j}\}$, and

\begin{align}
\text{(4.17)} & \quad \partial_{x}^2 u(y_{1,j}) \neq 0, \quad \partial_{x}^2 u(y_{2,j}) \neq 0.
\end{align}

Here $y_{1,j}, y_{2,j}$ are the maximum and minimum points of the function $\text{Re} u$ on the boundary contour $\gamma_j$. In fact, the existence of such $u$ is proved as follows. By Corollary 5.1 and the Cauchy-Riemann equations, there exists a sequence of holomorphic functions $u_\varepsilon$ in $\Omega$ such that

\begin{align}
\text{u_\varepsilon} & \in C^2(\hat{\Omega}), \quad \text{Im} u_\varepsilon|_{\Gamma_0} = 0, \\
\text{(4.18)} & \quad \frac{\partial \text{Im} u_\varepsilon}{\partial \nu}|_{\Gamma_0} < \alpha' < 0, \quad \text{if } \text{Int}((\partial \Omega \setminus \Gamma_0) \cap \gamma_j) \neq \emptyset.
\end{align}

In the case $\text{Int}((\partial \Omega \setminus \Gamma_0) \cap \gamma_j) = \emptyset$, then $\text{Re} u_\varepsilon \to b_j$ in $C^2(\gamma_j)$, where $b_j \in C^2(\gamma_j)$ is a function such that

\begin{align}
\{x \in \gamma_j | \partial_z b_j = 0\} & = \{y_{1,j}, y_{2,j}\} \quad \text{and} \quad \partial_{x}^2 b_j(y_{1,j}) \neq 0, \quad \partial_{x}^2 b_j(y_{2,j}) \neq 0, \\
\text{Im} u_\varepsilon(\hat{x}) & \to 1, \quad \partial_z u_\varepsilon(\hat{x}) := c_\varepsilon \to 0, \quad \partial_{x}^2 u_\varepsilon(\hat{x}) \to 1 \quad \text{as } \varepsilon \to 0.
\end{align}

Let $\mathcal{R}$ be the operator similar to one introduced in Proposition 4.2

\[ \mathcal{R}g = (u(\hat{x}), \partial_z u(\hat{x}), \partial_{x}^2 u(\hat{x})) \]

where

\[ \partial_z u = 0 \quad \text{in} \quad \hat{\Omega}, \quad \text{Re} u(x_0) = 0, \quad \text{Im} u|_{\Gamma_0} = 0, \quad \text{Im} u|_{\partial \hat{\Omega} \setminus \Gamma_0} = g, \]

and $x_0 \in \Omega$, $x_0 \neq \hat{x}$. Obviously we can consider it as operator from the space $D(\mathcal{R}) \subset C^3(\partial \hat{\Omega} \setminus \Gamma_0) \to C^3$. We have (e.g., p. 79 in [1]) that there exists a mapping $M : C^3 \to C^3(\partial \hat{\Omega} \setminus \Gamma_0)$ such that $\mathcal{R}M = I$ and

\[ ||M y||_{C^3(\Gamma)} \leq C |y|, \quad y \in C^3, \]

with some constant $C > 0$. We consider the sequence $y_\varepsilon = (0, -c_\varepsilon, 0) \in C^3$. Let $g_\varepsilon = M(y_\varepsilon) \to 0$ in $C^3(\partial \hat{\Omega} \setminus \Gamma_0)$. Denote by $w_\varepsilon$ the function which satisfies

\[ \partial_z w_\varepsilon = 0 \quad \text{in} \quad \hat{\Omega}, \quad \text{Re} w_\varepsilon(x_0) = 0, \quad \text{Im} w_\varepsilon|_{\Gamma_0} = 0, \quad \text{Im} w_\varepsilon|_{\partial \hat{\Omega} \setminus \Gamma_0} = g_\varepsilon, \]

\[ w_\varepsilon(\hat{x}) = 0, \quad \partial_z w_\varepsilon(\hat{x}) = -c_\varepsilon, \quad \partial_{x}^2 w_\varepsilon(\hat{x}) = 0. \]

Hence $\text{Im} (u_\varepsilon + w_\varepsilon(\hat{x}) \to 1, \quad \partial_z (u_\varepsilon + w_\varepsilon)(\hat{x}) = 0$ and $\partial_{x}^2 (u_\varepsilon + w_\varepsilon)(\hat{x}) \to 1$ and $w_\varepsilon \to 0$ in $C^2(\hat{\Omega})$.

Hence $u_\varepsilon + w_\varepsilon$ is the function which we are looking for provided that $\varepsilon$ is sufficiently small.

In general, the function $u$ may have critical points on the part of the boundary $\partial \hat{\Omega} \setminus \Gamma_0$.

Next we construct a holomorphic function $p \in C^2(\hat{\Omega})$ such that $u + \epsilon p$ does not have critical points on $\partial \hat{\Omega} \setminus \Gamma_0$ for all sufficiently small positive $\epsilon$ and $\text{Im} p|_{\Gamma_0} = 0$. 
transformation, if necessary, we may assume that $\partial \Omega \setminus \Gamma_0$ is a segment on the line $\{x_2 = 0\}$. Let $\{(y_k, 0)\}_{k=1}^N$ be the set of critical points of the function $u$ on the boundary $\partial \Omega \setminus \Gamma_0$.

We divide the set $\{(y_k)\}_{k=1}^N$ into two sets $\mathcal{O}_1$ and $\mathcal{O}_2$ in the following way: Let us fix some point $y_k$. By Taylor’s formula $\frac{\partial \text{Re} u}{\partial x_1}(x_1, 0) = c_1(x_1 - y_k)^{\kappa_1 + 1} + o((x_1 - y_k)^{\kappa_1 + 1})$ and $\frac{\partial \text{Im} u}{\partial x_1}(x_1, 0) = c_2(x_1 - y_k)^{\kappa_2 + 1} + o((x_1 - y_k)^{\kappa_2 + 1})$ with some $(c_1, c_2) \neq 0$. If $c_2 \neq 0$ and $\kappa_2 \leq \kappa_1$, then we say that $y_k \in \mathcal{O}_1$. If $c_1 \neq 0$ and $\kappa_2 > \kappa_1$, then we say that $y_k \in \mathcal{O}_2$.

Now we construct a set of $\mathcal{S}$ open in $C^2(\overline{\Gamma}) \times C^2_0(\overline{\Gamma})$ such that if $(b_1, b_2) \in \mathcal{S}$ and the holomorphic function $p$ satisfies $\text{Re} p|_{\Gamma} = b_1, \text{Im} p|_{\Gamma} = b_2$ (if such a function $p$ exists), then the function $u + \epsilon p$ does not have critical points on $\Gamma$ for all small positive $\epsilon$.

Let us consider the two cases. Assume $y_k \in \mathcal{O}_1$. If $\kappa_2$ is odd, then we take Cauchy data such that the holomorphic function $p$ satisfies the following: $b_1$ is small and $\frac{\partial b_1}{\partial \nu}$ is positive near $y_k$ if $c_2$ is positive, and $\frac{\partial b_1}{\partial \nu}$ is negative near $y_k$ if $c_2$ is negative and small on $\partial \Omega \setminus \Gamma_0$. If $\kappa_2$ is even and $\kappa_1 \neq \kappa_2$, then we take Cauchy data such that $\frac{\partial b_2}{\partial \nu}(y_k) - 1, \frac{\partial b_1}{\partial \nu}(y_k) - 1$ are small and otherwise $\frac{1}{c_2} \frac{\partial b_2}{\partial \nu}(y_k) \neq \frac{1}{c_1} \frac{\partial b_1}{\partial \nu}(y_k)$.

Assume $y_k \in \mathcal{O}_2$. If $\kappa_1$ is odd, then we take the Cauchy data for the holomorphic function $p$ such that $\frac{\partial b_2}{\partial \nu}$ is positive near $y_k$ if $c_1$ is positive, and $\frac{\partial b_1}{\partial \nu}$ is negative near $y_k$ if $c_1$ is negative. If $\kappa_1$ is even, then we take $\frac{\partial b_1}{\partial \nu}(y_k) - 1, \frac{\partial b_2}{\partial \nu}(y_k) - 1$ to be small. Now we have finished the construction of Cauchy data on $\Gamma_0$ and in a neighborhood $\mathcal{U}$ of the set $\{(y_k, 0)\}_{k=1}^N$. On the part of the boundary $\partial \Omega \setminus (\Gamma_0 \cup \mathcal{U})$ we continue functions $b_1, b_2$ as smooth functions in $C^2(\overline{\Gamma}) \times C^2_0(\overline{\Gamma})$. By Proposition 5.1 and general results on solvability of the boundary-value problem for $\partial \nu$ (see, e.g., [2]) there exists a holomorphic function $p$ which satisfies the above choice of the Cauchy data with $\text{Im} p|_{\Gamma_0} = 0$. For all small positive $\epsilon$ the function $u + \epsilon p$ does not have critical points on $\partial \Omega \setminus \Gamma_0$.

Denote by $\mathcal{H}_\epsilon$ the set of critical points of the function $u + \epsilon p$ in $\Omega$. By the implicit function theorem, there exists a neighborhood of $\tilde{x}$ such that for all small $\epsilon$ in this neighborhood the function $u + \epsilon p$ has only one critical point $\tilde{x}(\epsilon)$, this critical point is nondegenerate, and

\[ \tilde{x}(\epsilon) \to \tilde{x} \quad \text{as} \quad \epsilon \to 0. \]

Let us fix a sufficiently small $\epsilon$. Let $\mathcal{H}_\epsilon = \{x_{k, \epsilon}\}_{1 \leq k \leq N(\epsilon)}$. By Proposition 4.2 there exists a function $w$ holomorphic in $\Omega$, such that

\[ \text{Im} w|_{\Gamma_0} = 0, \quad w|_{\mathcal{H}_\epsilon} = \partial_2 w|_{\mathcal{H}_\epsilon} = 0, \quad \partial_2^2 w|_{\mathcal{H}_\epsilon} \neq 0. \]

Denote $\Phi_\delta = u + \epsilon p + \delta w$. For all sufficiently small positive constants $\delta$, we have

\[ \mathcal{H}_\epsilon \subset \mathcal{G}_\delta = \{x \in \Omega|\partial_2 \Phi_\delta(x) = 0\}. \]

We show now that for all small positive $\delta$, the critical points of the function $\Phi_\delta$ are nondegenerate. Let $\tilde{x}$ be a critical point of the function $u + \epsilon p$. If $\tilde{x}$ is a nondegenerate critical point, by the implicit function theorem, there exists a ball $B(\tilde{x}, \delta_1)$ such that the function $\Phi_\delta$ in this ball has only one nondegenerate critical
point for all sufficiently small \( \delta \). Let \( \bar{x} \) be a degenerate critical point of \( u + cp \). Without loss of generality we may assume that \( \bar{x} = 0 \). In some neighborhood of \( 0 \), we have \( \partial_z \Phi_\delta = \sum_{k=1}^{\infty} c_k z^{k+1} - \delta \sum_{k=1}^{\infty} b_k z^k \) for some natural positive number \( \delta \) and some \( c_1 \neq 0 \). Moreover \( (4.20) \) implies \( b_1 \neq 0 \). Let \( (x_{1,\delta}, x_{2,\delta}) \in \mathcal{G}_\delta \) and \( z_\delta = x_{1,\delta} + ix_{2,\delta} \rightarrow 0 \). Then either

\[
(4.21) \quad z_\delta = 0 \text{ or } z_\delta^k = \delta b_1/c_1 + o(\delta).
\]

Therefore \( \partial^2 \Phi(z_\delta) \neq 0 \) for all sufficiently small \( \delta \). Observe that by \( (4.15) \) \( \text{Im} \Phi_\delta(\hat{x}(\epsilon)) \neq 0 \). Moreover, without loss of generality we may assume that

\[
(4.22) \quad \text{Im} \Phi_\delta(\hat{x}(\epsilon)) \neq 0 \text{ for all sufficiently small } \epsilon \text{ such that } \hat{x}(\epsilon) \neq x.
\]

To see this, we argue as follows. If \( (4.22) \) is not valid, then we add to the function \( \Phi_\delta \) a function \( \delta_1 \hat{w} \) where \( \delta_1 \) is a small parameter and \( \hat{w} \) is holomorphic in \( \Omega \),

\[
\text{Im} \hat{w}|_{\Gamma_0} = 0, \quad \text{Im} \hat{w}(\hat{x}(\epsilon)) = 1, \quad \hat{w}|_{\partial \mathcal{G}_\delta \setminus \{\hat{x}(\epsilon)\}} = \partial_z \hat{w}|_{\mathcal{G}_\delta} = 0, \quad \partial^2 \hat{w}|_{\mathcal{G}_\delta} = 0.
\]

Since the function \( \Phi_\delta \) was constructed as the approximation of the function \( u \), by \( (4.16), (4.17) \) we have

\[
(4.23) \quad \frac{\partial \text{Im} \Phi_\delta}{\partial \nu}|_{\Gamma_0} < \alpha'' < 0, \quad \text{if } \text{Int}(\partial \Omega \setminus \Gamma_0) \cap \gamma_j \neq \emptyset.
\]

In the case \( \text{Int}(\partial \Omega \setminus \Gamma_0) \cap \gamma_j = \emptyset \), then \( \{x \in \gamma_j \mid \partial \text{Re} \Phi_\delta = 0\} = \{y_{1,j}(\delta), y_{2,j}(\delta)\} \), and

\[
(4.24) \quad \partial^2 \text{Re} \Phi_\delta(y_{1,j}(\delta)) \neq 0, \quad \partial^2 \text{Re} \Phi_\delta(y_{2,j}(\delta)) \neq 0.
\]

Thanks to \( (4.21) \), we can claim that all critical points of \( \Phi_\delta \) are nondegenerate.

By \( (4.23), (4.24) \), we can apply Proposition \( \text{I.2} \). Hence there exists a function \( a_\delta \in C^2(\Omega) \) such that

\[
\partial_z a_\delta = 0 \quad \text{in } \Omega, \quad \text{Re} a_\delta|_{\Gamma_0} = 0,
\]

and

\[
a_\delta(x)|_{\partial \Omega \cap \partial \Omega} = \partial_z a_\delta(x)|_{\partial \Omega \cap \partial \Omega} = 0, \quad a_\delta(\hat{x}(\epsilon)) \neq 0.
\]

Hence we can apply Proposition \( \text{I.1} \) to conclude

\[
\sum_{x \in \mathcal{G}_\delta} q(x)e(x) = C(q).
\]

By \( \text{I.1} \), \( c(\hat{x}(\epsilon)) \) is not equal to zero.

Since the exponents are linearly independent functions of \( \tau \), thanks to \( (4.22) \), we have \( q(\hat{x}(\epsilon)) = 0 \). Thus \( (4.19) \) implies \( q(\hat{x}) = 0 \). Thus the proof is completed. \( \square \)

5. APPENDIX

Consider the Cauchy problem for the Cauchy-Riemann equations

\[
(5.1) \quad L(\phi, \psi) = \left( \frac{\partial \phi}{\partial x_1} - \frac{\partial \psi}{\partial x_2}, \frac{\partial \phi}{\partial x_2} + \frac{\partial \psi}{\partial x_1} \right) = 0 \quad \text{in } \Omega, \quad (\phi, \psi)|_{\Gamma_0} = (b_1(x), b_2(x)),
\]

\[
(\phi + i\psi)(\hat{x}_j) = c_{0,j}, \quad \partial_z(\phi + i\psi)(\hat{x}_j) = c_{1,j}, \quad \partial^2 z(\phi + i\psi)(\hat{x}_j) = c_{2,j} \quad \forall j \in \{1, \ldots, N\}.
\]

Here \( \hat{x}_1, \ldots, \hat{x}_N \) are arbitrary fixed points in \( \Omega \). We consider the pair \( b_1, b_2 \) and complex numbers \( \hat{C} = (c_{0,1}, c_{1,1}, c_{2,1}, \ldots, c_{0,N}, c_{1,N}, c_{2,N}) \) as initial data for \( (5.1) \). The following proposition establishes the solvability of \( (5.1) \) for a dense set of Cauchy data.
Proposition 5.1. There exists a set $\mathcal{O} \subset C^2(\overline{\Gamma_0})^2 \times \mathbb{C}^3$ such that for each $(\ell_1, \ell_2, \ell_3) \in \mathcal{O}$, (5.1) has at least one solution $(\phi, \psi) \in (C^2(\overline{\Omega}))^2$ and $\overline{\mathcal{O}} = C^2(\overline{\Gamma_0})^2 \times \mathbb{C}^3$.

Proof. Denote by $B = (\ell_1, \ell_2)$ an arbitrary element of the space $C^3(\overline{\Gamma_0}) \times C^3(\overline{\Gamma_0})$. Consider the extremal problem

$$
(5.2) \quad J_\epsilon(\phi, \psi) = |||\phi, \psi|| - B|||^{4}_{B^{1+\frac{1}{2}}(\overline{\Gamma_0})} + \epsilon|||\phi, \psi||^{4}_{B^{1+\frac{1}{2}}(\partial\Omega)} + \epsilon|||\partial(\phi, \psi)||^{4}_{B^{1+\frac{1}{2}}(\partial\Omega)} + \frac{1}{\epsilon} |||\Delta L(\phi, \psi)||^{4}_{L^{1+1}(\Omega)} + \sum_{j=1}^{N} \sum_{k=0}^{2} |\partial_{k}^{2}(\phi + i\psi)(\hat{x})_j|^{2} \to \inf,
$$

(5.3) \quad (\phi, \psi) \in W^{3}_{4}(\Omega).

Here $B^{1+\frac{1}{2}}$ denotes the Besov space of corresponding order.

For each $\epsilon > 0$ there exists a unique solution to (5.2), (5.3) which we denote as $(\hat{\phi}_\epsilon, \hat{\psi}_\epsilon)$. This fact can be proved using standard arguments. We fix $\epsilon > 0$. Denote by $\mathcal{U}_{ad}$ the set of admissible elements of the problem (5.2), (5.3), namely

$$
\mathcal{U}_{ad} = \{(\phi, \psi) \in W^{3}_{4}(\Omega)| J_\epsilon(\phi, \psi) < \infty\}.
$$

Denote $\hat{J}_\epsilon = \inf_{(\phi, \psi) \in \mathcal{U}_{ad}} J_\epsilon(\phi, \psi)$. Clearly, the pair $(0, 0) \in \mathcal{U}_{ad}$. Therefore there exists a minimizing sequence $\{(\phi_k, \psi_k)\}_{k=1}^{\infty} \subset W^{3}_{4}(\Omega)$ such that

$$
\hat{J}_\epsilon = \lim_{k \to +\infty} J_\epsilon(\phi_k, \psi_k).
$$

Observe that the minimizing sequence is bounded in $W^{3}_{4}(\Omega)$. Indeed, since the sequence $\{L(\phi_k, \psi_k), L(\phi_k, \psi_k)\}_{|\partial\Omega|}$ is bounded in $L^4(\Omega) \times B^{\frac{1}{2}}(\partial\Omega)$, the standard elliptic $L^p$-estimate implies that the sequence $\{L(\phi_k, \psi_k)\}$ is bounded in the space $W^{3}_{4}(\Omega)$. Taking into account that the sequence of the traces of the functions $(\phi_k, \psi_k)$ is bounded in the Besov space $B^{1+\frac{1}{2}}(\partial\Omega)$ and applying the estimates for elliptic operators one more time, we obtain that $\{(\phi_k, \psi_k)\}$ is bounded in $W^{3}_{4}(\Omega)$. By the Sobolev imbedding theorem the sequence $\{(\phi_k, \psi_k)\}$ is bounded in $C^2(\overline{\Omega})$. Then taking if necessary a subsequence (which we denote again as $\{(\phi_k, \psi_k)\}$), we obtain

$$
(\phi_k, \psi_k) \to (\hat{\phi}_\epsilon, \hat{\psi}_\epsilon) \quad \text{weakly in} \ W^{3}_{4}(\Omega), \quad (\phi_k, \psi_k) \to (\hat{\phi}_\epsilon, \hat{\psi}_\epsilon) \quad \text{weakly in} \ B^{1+\frac{1}{2}}(\partial\Omega), \quad (\hat{\phi}_\epsilon, \hat{\psi}_\epsilon) \to (\hat{\phi}_\epsilon, \hat{\psi}_\epsilon) \quad \text{weakly in} \ B^{1+\frac{1}{2}}(\partial\Omega),
$$

$$
\partial_{k}^{2}(\phi + i\psi)(\hat{x})_j - c_{k,j} \to C_{k,j,\epsilon},
$$

$$
\Delta L(\phi_k, \psi_k) \to r_\epsilon \text{ weakly in } L^{4}(\Omega), \quad L(\phi_k, \psi_k) \to \bar{r}_\epsilon \text{ weakly in } W^{3}_{4}(\Omega).
$$

Obviously, $r_\epsilon = \Delta L(\hat{\phi}_\epsilon, \hat{\psi}_\epsilon), \bar{r}_\epsilon = L(\hat{\phi}_\epsilon, \hat{\psi}_\epsilon)$. Then, since the norms in the spaces $L^{4}(\Omega)$ and $B^{1+\frac{1}{2}}(\partial\Omega), B^{\frac{3}{2}}(\partial\Omega), B^{\frac{1}{2}}(\Gamma_0)$ are lower semicontinuous with respect to weak convergence, we obtain that

$$
J_\epsilon(\hat{\phi}_\epsilon, \hat{\psi}_\epsilon) \leq \lim_{k \to +\infty} J_\epsilon(\phi_k, \psi_k) = \hat{J}_\epsilon.
$$

Thus the pair $(\hat{\phi}_\epsilon, \hat{\psi}_\epsilon)$ is a solution of the extremal problem (5.2), (5.3). Since the set of admissible elements is convex and the functional $J_\epsilon$ is strictly convex, this solution is unique.
By Fermat’s theorem (see, e.g., [1], p. 155) we have
\[ J'_t(\hat{\phi}_t, \hat{\psi}_t)[\hat{\delta}] = 0, \quad \forall \hat{\delta} \in W^3_4(\Omega). \]

This equality can be written in the form
\[
I_{\gamma, \Omega}^\nu((\hat{\phi}_t, \hat{\psi}_t) - B)[\hat{\delta}]
+ \epsilon I_{\gamma, \Omega}^\nu((\hat{\phi}_t, \hat{\psi}_t))[\hat{\delta}]
+ \epsilon I_{\gamma, \Omega}^\nu(\xi((\hat{\phi}_t, \hat{\psi}_t)))[\hat{\delta}] + (p_t, \Delta L\hat{\delta})_{L^2(\Omega)}
+ \sum_{j=1}^{N} \sum_{k=0}^{2} (\partial^k_\xi(\hat{\phi}_t + i\hat{\psi}_t)(\hat{x}_j) - c_k, j)\rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j)
+ \rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j) = 0,
\]
where \( p_t = \frac{1}{\epsilon}((\Delta(\frac{\partial\phi}{\partial x_1} - \frac{\partial\phi}{\partial x_2}))^2, (\Delta(\frac{\partial\phi}{\partial x_2} + \frac{\partial\phi}{\partial x_1}))^2) \). Here \( I_{\gamma, \Omega}^\nu \) denotes the derivate of the functional \( w \rightarrow \|w\|^4_{B^2_4(\Gamma_0)} \) at \( \hat{\delta} \).

This implies that the sequence \( \{(\hat{\phi}_t, \hat{\psi}_t)\} \) is bounded in \( B^4_4(\Gamma_0) \), the sequences \( \{\rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j)\} \) are bounded in \( C \), the sequence \( \epsilon I_{\gamma, \Omega}^\nu(\xi((\hat{\phi}_t, \hat{\psi}_t)))[\hat{\delta}]
+ \epsilon I_{\gamma, \Omega}^\nu(\xi(\hat{\phi}_t))[\hat{\delta}]) \) converges to zero for any \( \hat{\delta} \) in \( W^3_4(\Omega) \). Then (5.4) implies that the sequence \( \{p_t\} \) is bounded in \( L^4(\Omega) \).

Therefore there exist \( B \in B^4_4(\Gamma_0), C_{0,j}, C_{1,j}, C_{2,j} \in C \), and \( p = (p_1, p_2) \in L^4(\Omega) \) such that
\[
(\hat{\phi}_{t_k}, \hat{\psi}_{t_k}) - B \rightarrow B \quad \text{weakly in } B^4_4(\Gamma_0), \quad p_{t_k} \rightarrow p \quad \text{weakly in } L^4(\Omega),
\]
\[
(\hat{\phi}_{t_k} + i\hat{\psi}_{t_k})(\hat{x}_j) - c_{k, j} \rightharpoonup C_{k, j}, \quad k \in \{0, 1, 2\}, j \in \{1, \ldots, N\}.
\]

Passing to the limit in (5.4), we get
\[
I_{\gamma, \Omega}^\nu(B)[\hat{\beta}] + (p, \Delta L\hat{\delta})_{L^2(\Omega)} + 2\text{Re} \sum_{j=1}^{N} \sum_{k=0}^{2} C_{k, j} \rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j) = 0 \quad \forall \hat{\delta} \in W^3_4(\Omega).
\]

Next we claim that
\[
\Delta p = 0 \quad \text{in } \Omega \setminus \bigcup_{j=1}^{N} \{\hat{x}_j\}
\]
in the sense of distributions. Suppose that (5.8) is already proved. This implies
\[
(p, \Delta L\hat{\delta})_{L^2(\Omega)} + 2\text{Re} \sum_{j=1}^{N} \sum_{k=0}^{2} C_{k, j} \rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j) = 0 \quad \forall \hat{\delta}_1, \hat{\delta}_2 \in C^\infty(\Omega).
\]

If \( p = (p_1, p_2) \), denoting \( P = p_1 - ip_2 \), we have
\[
\text{Re}(\Delta P, \rho \hat{\delta}(\delta_1 + i\delta_2))_{L^2(\Omega)} + \text{Re} \sum_{j=1}^{N} \sum_{k=0}^{2} C_{k, j} \rho \hat{\delta}^k(\delta_1 + i\delta_2)(\hat{x}_j) = 0 \quad \forall \hat{\delta}_1, \hat{\delta}_2 \in C^\infty(\Omega).
\]
Since by \( \text{(5.8)} \) \( \text{supp} \, \Delta \subset \bigcup_{j=1}^{N} \{ \hat{x}_j \} \), there exist some constants \( m_{\beta,j} \) and \( \hat{\ell}_j \) such that \( \Delta P = \sum_{j=1}^{N} \sum_{|\beta|=1}^{\hat{\ell}_j} m_{\beta,j} D^\beta \delta (x - \hat{x}_j) \). The above equality can be written in the form

\[ -2 \sum_{|\beta|=1}^{\hat{\ell}_j} m_{\beta,j} \partial_2 D^\beta \delta (x - \hat{x}_j) = \sum_{k=0}^{2} (-1)^k \overline{C_{k,j}} \partial_x^k \delta (x - \hat{x}_j). \]

From this we obtain
\[ C_{0,j} = C_{1,j} = C_{2,j} = 0, \quad j \in \{1, \ldots, N\} \]
Therefore
\[ \Delta \rho = 0 \quad \text{in} \ \Omega. \]
This implies
\[ (p, \Delta \hat{\delta})_{L^2(\Omega)} = 0 \quad \forall \hat{\delta} \in W^3_4(\Omega), \quad L\hat{\delta}|_{\partial \Omega} = \frac{\partial L\hat{\delta}}{\partial n}|_{\partial \Omega} = 0. \]
This equality and \( \text{(5.7)} \) yield
\[ \text{(5.11)} \quad (\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) - B \to 0 \quad \text{weakly in} \ B^L_{4,4}(\Gamma_0). \]
From \( \text{(5.6)}, \text{(5.9)} \) we obtain
\[ \partial_x^k (\hat{\phi}_{e_k} + i\hat{\psi}_{e_k}) (\hat{x}) \to c_{k,j}, \quad k \in \{0, 1, 2\}, \ j \in \{1, \ldots, N\}. \]
By the Sobolev embedding theorem \( B^4_{4,4}(\Gamma_0) \subset C^2(\Gamma_0) \). Therefore \( \text{(5.12)} \) implies
\[ \text{(5.13)} \quad (\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) - B \to 0 \quad \text{in} \ C^2(\Gamma_0). \]
Let the pair \( (\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) \) be a solution to the boundary-value problem
\[ \text{(5.14)} \quad L(\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) = L(\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) \quad \text{in} \ \Omega, \quad \hat{\psi}_{e_k}|_{\partial \Omega} = \psi^*_{e_k}. \]
Here \( \psi^*_{e_k} \) is a smooth function such that \( \psi^*_{e_k}|_{\Gamma_0} = 0 \) and the pair \( (L(\hat{\phi}_{e_k}, \hat{\psi}_{e_k}), \psi^*_{e_k}) \) is orthogonal to all solutions of the adjoint problem (see \( \text{[32]} \)). Moreover since \( L(\hat{\phi}_{e_k}, \hat{\psi}_{e_k}) \to 0 \) in \( W^2_4(\Omega) \), we may assume \( \psi^*_{e_k} \to 0 \) in \( C^4(\partial \Omega) \).
This fact can be seen in the following way. Let \( \{(e_j, \hat{e}_j)\}_{j=1}^{K} \) be a basis of the kernel of the adjoint problem which is a finite-dimensional space. We choose \( r_k \in C^\infty_0(\Gamma) \) such that
\[ \frac{1}{2} \int_{\Gamma} \chi_j r_k dt = \delta_{jk} \quad \forall j, k \in \{1, \ldots, K\}. \]
Here we note that we can represent \( e_k + i\hat{e}_k = \overline{z(s)} \chi_k (z(s)) \) (Section 2 of Chapter IV of \( \text{[32]} \)) where \( s \) is the length parameter of \( \hat{\Gamma} \) from one fixed point on \( \hat{\Gamma} \), \( z(s) \) is the parametrization of \( \hat{\Gamma} \), and \( \chi_k (z) \) are some real-valued functions. Then observe that the functions \( \chi_j \) are linearly independent. Assume the contrary. Then there exists a function \( e \) such that it is the linear combination of the functions \( e_j + i\hat{e}_j \) and \( \partial_{\hat{t}} e = 0 \) and \( e|_{\Gamma} = 0 \). By uniqueness of solution for the Cauchy problem for the
operator \( \partial_j \) we have that \( e = 0 \) in \( \Omega \). This is impossible since \((e_j, \tilde{e}_j)\) are linearly independent.

Hence we can find functions \( \tilde{r}_k \in L^2(\tilde{\Gamma}) \) such that
\[
\frac{1}{2} \int_{\tilde{\Gamma}} \chi_j \tilde{r}_k dt = \delta_{jk} \quad \forall j, k \in \{1, \ldots, K\}.
\]

Let the sequence \( \{\tilde{r}_{k, \delta}\}_{\delta \in (0, 1)} \subset C_0^\infty(\tilde{\Gamma}) \) approximate the function \( \tilde{r}_k \) in \( L^2(\tilde{\Gamma}) \).

Let us show that the vectors \( \tilde{v}_{k, \delta} \) are linearly independent for small \( \delta \). Suppose that they are linearly dependent; then there exists \( \tilde{C}_\delta = (c_{1, \delta}, \ldots, c_{K, \delta}) \) such that
\[
(5.15) \quad \sum_{j=1}^{K} c_{j, \delta} \tilde{v}_{j, \delta} = 0, \quad |\tilde{C}_\delta| = 1.
\]

Taking if necessary a subsequence, we pass to the limit in (5.15) and we see that there exists a vector \( \tilde{C} \neq 0 \) such that \( \sum_{j=1}^{K} c_j \tilde{\epsilon}_j = 0 \). This is of course impossible.

Let us fix \( \delta = \delta_0 \) sufficiently small and let \( H = \{h_{kl}\} \) be the matrix such that
\[
\sum_{l=1}^{K} h_{kl} \tilde{v}_{l, \delta_0} = \tilde{e}_k, \quad k \in \{1, \ldots, K\}.
\]

Setting \( r_k = \sum_{l=1}^{K} h_{kl} \tilde{r}_{k, \delta_0} \), we obtain the desired set of functions.

Let us show that such functions can be constructed. First of all the traces are linearly independent functions on \( \Gamma \). Finally we take
\[
\psi_{ek} = \sum_{j=1}^{K} \text{Re} \int_{\Omega} (e_j + i\tilde{e}_j)(L(\hat{\phi}_{ek}, \hat{\psi}_{ek})_1 + iL(\hat{\phi}_{ek}, \hat{\psi}_{ek})_2) dx r_j.
\]

Among all possible solutions to problem (5.14) (clearly there is no unique solution to this problem) we choose one such that \( \int_{\Gamma} \hat{\phi}_{ek} dx = 0 \). Thus we obtain
\[
(5.16) \quad (\hat{\phi}_{ek}, \hat{\psi}_{ek}) \to 0 \quad \text{in} \ W^2_4(\Omega).
\]

Therefore the sequence \( \{(\hat{\phi}_{ek} - \hat{\phi}_{ek}, \hat{\psi}_{ek} - \hat{\psi}_{ek})\} \) represents the desired approximation for the solution of the Cauchy problem (5.1).

Now we prove (5.8). Let \( \tilde{x} \) be an arbitrary point in \( \Omega \setminus \bigcup_{j=1}^{N} \{\hat{x}_j\} \) and let \( \tilde{\chi} \) be a smooth function such that it is zero in some neighborhood of \( \Gamma_0 \cup \bigcup_{j=1}^{N} \{\hat{x}_j\} \) and the set \( A = \{x \in \Omega|\tilde{\chi}(x) = 1\} \) contains an open connected subset \( \mathcal{F} \) such that \( \tilde{x} \in \mathcal{F} \) and \( \Gamma \cap \mathcal{F} \) is an open set in \( \partial \Omega \). In addition we assume that \( \text{Int}(\text{supp} \chi) \) is a simply connected domain. By (5.7) we have
\[
(5.17) \quad 0 = (p, \Delta L(\tilde{\chi} \tilde{\delta}))_{L^2(\Omega)} = (\tilde{\chi}p, \Delta L \tilde{\delta})_{L^2(\Omega)} + (p, [\Delta L, \tilde{\chi}] \tilde{\delta})_{L^2(\Omega)} \quad \forall \tilde{\delta} \in W^2_4(\Omega).
\]

The simple computations provide the formula
\[
\Delta L(\tilde{\chi} \tilde{\delta}) = L\tilde{\chi} \Delta \tilde{\delta} + L(2(\nabla \tilde{\chi}, \nabla \tilde{\delta}) + \Delta \tilde{\chi} \tilde{\delta})
\]
\[
= \tilde{\chi} L \Delta \tilde{\delta} + [L, \tilde{\chi}] \Delta \tilde{\delta} + L(2(\nabla \tilde{\chi}, \nabla \tilde{\delta}) + \Delta \tilde{\chi} \tilde{\delta})
\]
\[
= \tilde{\chi} L \Delta \tilde{\delta} + [L, \tilde{\chi}] L \tilde{\delta} + (2(\nabla \tilde{\chi}, \nabla \cdot) + \Delta \tilde{\chi}) L \tilde{\delta} + [L, \Delta, \tilde{\chi}] \tilde{\delta}
\]
\[
= \tilde{\chi} L \Delta \tilde{\delta} + [L, \tilde{\chi}] L \tilde{\delta} + (2(\nabla \tilde{\chi}, \nabla \cdot) + \Delta \tilde{\chi}) L \tilde{\delta} + [L, [\Delta, \tilde{\chi}] \tilde{\delta}].
\]
The commutator \([L, \tilde{\chi}]\) is a matrix with smooth coefficients; \([L, [\Delta, \tilde{\chi}]]\) is a first-order operator. The Laplace operator can be factorized as \(\Delta = \tilde{L}L\) where

\[
\tilde{L} = \begin{pmatrix}
\frac{\partial}{\partial x_1} & \frac{\partial}{\partial x_2} \\
-\frac{\partial}{\partial x_2} & \frac{\partial}{\partial x_1}
\end{pmatrix}
\]

Denote \(L\tilde{\delta} = \tilde{\delta}\). Then we have

\[
(\chi p, \Delta \tilde{\delta})_{L^2(\Omega)} = -(p, [L, \tilde{\chi}]\tilde{\delta} + (2(\nabla \tilde{\chi}, \nabla \cdot) + \Delta \tilde{\chi})\tilde{\delta} + [L, [\Delta, \tilde{\chi}]]\tilde{\delta}).
\]

Consider the functional \(\tilde{\delta} : L^4(\text{supp} \tilde{\chi}) \to (p, [L, [\Delta, \tilde{\chi}]]\tilde{\delta})_{L^2(\text{supp} \tilde{\chi})}\), where

\[
L\tilde{\delta} = \tilde{\delta} \quad \text{in} \quad \Omega, \quad \text{Im} \tilde{\delta}|_S = 0, \quad \int_{\text{supp} \tilde{\chi}} \text{Re} \tilde{\delta} dx = 0,
\]

where \(S\) denotes the boundary of \(\text{supp} \tilde{\chi}\). For each \(\tilde{\delta} \in L^4(\text{supp} \tilde{\chi})\) there exists a unique solution to this problem in \(W^1_4(\text{supp} \tilde{\chi})\). Hence the functional is defined and continuous on \(L^4(\text{supp} \tilde{\chi})\). Therefore there exists \(q \in L^4(\text{supp} \tilde{\chi})\) such that

\[
\int_{\text{supp} \tilde{\chi}} q \tilde{\delta} dx = (p, [L, [\Delta, \tilde{\chi}]]\tilde{\delta})_{L^2(\text{supp} \tilde{\chi})}.
\]

Consider the boundary-value problem

\[
\Delta \tilde{p} = \tilde{f} \quad \text{in} \quad \text{supp} \tilde{\chi}, \quad \tilde{p}|_S = 0.
\]

Here \(\tilde{f} = 2\text{div} (\nabla \tilde{\chi} p) + q - L^*[L, \tilde{\chi}]*p - \Delta \tilde{\chi} p\). A solution to this problem exists and is unique, since \(\tilde{f} \in (W^1_4(\text{supp} \tilde{\chi}))'\). Then \(P \in W^1_4(\text{supp} \tilde{\chi})\). On the other hand, thanks to (5.18), \(P = \tilde{\chi} p\).

Next we take another smooth cut-off function \(\tilde{\chi}_1\) such that \(\text{supp} \tilde{\chi}_1 \subset A\) and \(\text{Int}(\text{supp} \chi_1)\) is a simply connected domain. A neighborhood of \(\tilde{x}\) belongs to \(A_1 = \{x|\tilde{\chi}_1 = 1\}\), the interior of \(A_1\) is connected, and \(\text{Int} \ A_1 \cap \Gamma\) contains an open subset \(\mathcal{O}\) in \(\partial \Omega\). Similarly to (5.17) we have

\[
(\tilde{\chi}_1 p, \Delta \tilde{\delta})_{L^2(\Omega)} = (p, [\Delta L, \tilde{\chi}_1]\tilde{\delta})_{L^2(\Omega)} = 0 \quad \forall \tilde{\delta} \in W^1_4(\Omega).
\]

This equality implies that \(\tilde{\chi}_1 p \in W^2_4(\Omega)\), using a similar argument to the one above. Let \(\omega\) be a domain such that \(\omega \cap \Omega = \emptyset\) and \(\partial \omega \cap \partial \Omega \subset \mathcal{O}\) contains an open set in \(\partial \Omega\).

We extend \(p\) on \(\omega\) by zero. Then

\[
(\Delta(\tilde{\chi}_1 p), L\tilde{\delta})_{L^2(\Omega \cup \omega)} + (p, [\Delta L, \tilde{\chi}_1]\tilde{\delta})_{L^2(\Omega \cup \omega)} = 0.
\]

Hence, since \([\Delta L, \tilde{\chi}_1]|_{A_1} = 0\), we have

\[
L^*\Delta(\tilde{\chi}_1 p) = 0 \quad \text{in} \quad A_1 \cup \omega, \quad p|_{\omega} = 0.
\]

By Holmgren’s theorem \(\Delta(\tilde{\chi}_1 p)|_{\text{Int} A_1} = 0\); that is, \((\Delta p)(\tilde{x}) = 0\). \(\square\)

Consider now the Cauchy problem for the Cauchy-Riemann equations

\[
L(\phi, \psi) = (\frac{\partial \phi}{\partial x_1} - \frac{\partial \psi}{\partial x_2}, \frac{\partial \phi}{\partial x_2} + \frac{\partial \psi}{\partial x_1}) = 0 \quad \text{in} \quad \Omega, \quad (\phi, \psi)|_{\partial_0} = (b(x), 0), (\phi + i\psi)(\hat{x}_j) = c_{0,j},
\]

\[
\partial_2(\phi + i\psi)(\hat{x}_j) = c_{1,j}, \quad \partial_1^2(\phi + i\psi)(\hat{x}_j) = c_{2,j} \quad \forall j \in \{1, \ldots, N\}.
\]

Here \(\hat{x}_1, \ldots, \hat{x}_N\) are arbitrary fixed points in \(\Omega\). We consider the function \(b\) and complex numbers \(\tilde{C} = (c_{0,1}, c_{1,1}, c_{2,1}, \ldots, c_{0,N}, c_{1,N}, c_{2,N})\) as initial data for (5.19).
We get as a corollary of Proposition 5.1 the solvability of (5.19) for a dense set of Cauchy data.

**Corollary 5.1.** There exists a set \( \mathcal{O}_0 \subset C^2(\Omega_0) \times C^3N \) such that for each \((b, \vec{C}) \in \mathcal{O}_0\), (5.19) has at least one solution \((\phi, \psi) \in (C^2(\Omega))^2\) and \( \mathcal{O}_0 = C^2(\Omega_0) \times C^3N \).

The proof of Corollary 5.1 is exactly the same as the proof of Proposition 5.1. The only difference is that instead of the extremal problem (5.2), (5.3) we have to consider the following extremal problem:

\[
\begin{aligned}
J_c& (\phi, \psi) = \|\phi - b\|^4_{B^4\{t \}} + \epsilon\| (\phi, \psi) \|^4_{B^4\{\phi \}} + \epsilon\| \frac{\partial (\phi, \psi)}{\partial \nu} \|^4_{B^4\{\nu \}} \\
&+ \frac{1}{\epsilon}\| \Delta L(\phi, \psi) \|^4_{L^4(\Omega)} + \sum_{j=1}^{N} \sum_{k=0}^2 \| \partial_x^j (\phi + i\psi)(\hat{x}_j) - c_{k,j} \|^2 \rightarrow \inf,
\end{aligned}
\]

(5.21)

\((\phi, \psi) \in W^4_2(\Omega), \quad \psi|_{\Gamma_0} = 0,\)

where \(b\) is an arbitrary element of the space \(C^3(\Gamma_0)\).

We have

**Proposition 5.2.** Let \(\Phi\) satisfy (2.1) and (2.2). Let \(\tilde{f} \in L^2(\Omega)\) and let \(\tilde{v}\) be a solution to

\[
2\partial_x \tilde{v} - \tau (\partial_x \Phi) \tilde{v} = \tilde{f} \quad \text{in } \Omega
\]

(5.22)

or let \(\tilde{v}\) be a solution to

\[
2\partial_x \tilde{v} - \tau (\partial_x \Phi) \tilde{v} = \tilde{f} \quad \text{in } \Omega.
\]

(5.23)

In the case that \(\tilde{v}\) solves (5.22), we have

\[
\begin{aligned}
\|\partial_x(e^{-i\tau\psi}\tilde{v})\|^2_{L^2(\Omega)} - \tau \int_{\partial\Omega} (\nabla \varphi, \nu) |\tilde{v}|^2 d\sigma \\
+ & \Re \int_{\partial\Omega} i \left( \left( \nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2} \right) \tilde{v} \right) \nu d\sigma + \|\partial_x(e^{-i\tau\psi}\tilde{v})\|^2_{L^2(\Omega)} = \|\tilde{f}\|^2_{L^2(\Omega)}.
\end{aligned}
\]

(5.24)

In the case that \(\tilde{v}\) solves (5.23), we have

\[
\begin{aligned}
\|\partial_x(e^{i\tau\psi}\tilde{v})\|^2_{L^2(\Omega)} - \tau \int_{\partial\Omega} (\nabla \varphi, \nu) |\tilde{v}|^2 d\sigma \\
+ & \Re \int_{\partial\Omega} i \left( \left( -\nu_2 \frac{\partial}{\partial x_1} + \nu_1 \frac{\partial}{\partial x_2} \right) \tilde{v} \right) \nu d\sigma + \|\partial_x(e^{i\tau\psi}\tilde{v})\|^2_{L^2(\Omega)} = \|\tilde{f}\|^2_{L^2(\Omega)}.
\end{aligned}
\]

(5.25)

**Proof.** We prove the statement of the proposition first for the equation \(2\frac{\partial \tilde{v}}{\partial x} - \tau \frac{\partial \phi}{\partial x} = \tilde{f}\). Since \(2\frac{\partial \tilde{v}}{\partial x} - \tau \frac{\partial \phi}{\partial x} = (\frac{\partial}{\partial x_1} - i \frac{\partial}{\partial x_2}) \tau + (\frac{\partial}{\partial x_2} - \frac{\partial}{\partial x_1}) \tau\), taking the \(L^2\)-norms of the right and the left hand sides of (5.22), we get

\[
\left\| \left( \frac{\partial}{\partial x_1} - i \frac{\partial}{\partial x_2} \tau \right) \tilde{v} \right\|^2_{L^2(\Omega)} + 2\Re \left( \left( \frac{\partial}{\partial x_1} - i \frac{\partial}{\partial x_2} \tau \right) \tilde{v}, \left( -i \frac{\partial}{\partial x_1} - \frac{\partial}{\partial x_2} \tau \right) \tilde{v} \right)_{L^2(\Omega)}
\]

\[
+ \left\| \left( -i \frac{\partial}{\partial x_2} - \frac{\partial}{\partial x_1} \tau \right) \tilde{v} \right\|^2_{L^2(\Omega)} = \|\tilde{f}\|^2_{L^2(\Omega)}.
\]
Thus estimate (5.25) follows immediately from the above equality and (5.26),

Now we prove a Carleman estimate for the Laplace operator.

Finally by (2.1) we observe that

(5.26)
\[
\frac{\partial \psi}{\partial x_2} = \frac{\partial \varphi}{\partial x_1} \quad \text{and} \quad \frac{\partial \psi}{\partial x_1} = -\frac{\partial \varphi}{\partial x_2}.
\]

Thus (5.24) follows immediately.

Now we prove the statement of the proposition for (5.23). Since \(2\frac{\partial}{\partial x_2} - \tau \frac{\partial \varphi}{\partial x_2} = \left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) + \left(-\frac{\partial}{\partial x_2} + \frac{\partial \varphi}{\partial x_2}\right)\), taking the \(L^2\)-norms of the right and left hand sides of (5.24), we get

\[
\left\| \left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \bar{v} \right\|_{L^2(\Omega)}^2 + 2\text{Re} \left( \left( \frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \bar{v}, \left( i\frac{\partial}{\partial x_2} - \frac{\partial \varphi}{\partial x_2}\right) \bar{v} \right)_{L^2(\Omega)}
\]
\[
+ \left\| \left( i\frac{\partial}{\partial x_2} - \frac{\partial \varphi}{\partial x_2}\right) \bar{v} \right\|_{L^2(\Omega)}^2 = \| \bar{f} \|_{L^2(\Omega)}^2.
\]

Since \(\left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right), \left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \equiv 0\), we obtain

\[
\left\| \left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \bar{v} \right\|_{L^2(\Omega)}^2 + \left( \left( \frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \bar{v}, \left( i\frac{\partial}{\partial x_2} - \frac{\partial \varphi}{\partial x_2}\right) \bar{v} \right)_{L^2(\Omega)}
\]
\[
+ \left\| \left( i\frac{\partial}{\partial x_2} - \frac{\partial \varphi}{\partial x_2}\right) \bar{v} \right\|_{L^2(\Omega)}^2 = \| \bar{f} \|_{L^2(\Omega)}^2.
\]

This equality implies

\[
\left\| \left(\frac{\partial}{\partial x_1} + i\frac{\partial \varphi}{\partial x_1}\right) \bar{v} \right\|_{L^2(\Omega)}^2 - \tau \int_{\partial \Omega} \left( \frac{\partial}{\partial x_2} \nu_1 - \frac{\partial \varphi}{\partial x_2} \nu_2 \right) |\bar{v}|^2 d\sigma
\]
\[
+ \int_{\partial \Omega} i \left( \left( -\nu_2 \frac{\partial}{\partial x_1} + \nu_1 \frac{\partial}{\partial x_2} \right) \bar{v} \right) \bar{v} d\sigma + \left\| \left( i\frac{\partial}{\partial x_2} - \frac{\partial \varphi}{\partial x_2}\right) \bar{v} \right\|_{L^2(\Omega)}^2 = \| \bar{f} \|_{L^2(\Omega)}^2.
\]

Thus estimate (5.25) follows immediately from the above equality and (5.26), finishing the proof of the proposition.

Now we prove a Carleman estimate for the Laplace operator.
Proposition 5.3. Suppose that $\Phi$ satisfies (2.1), (2.2), (2.3). Let $u \in H^1_0(\Omega) \cap H^2(\Omega)$ be a real-valued function. Then there exists $\tau_0$ such that for all $|\tau| \geq \tau_0$ we have

$$\begin{align*}
|\tau||ue^{\tau \varphi}|^2_{L^2(\Omega)} + \|ue^{\tau \varphi}\|^2_{H^1(\Omega)} + \|\frac{\partial u}{\partial \nu}e^{\tau \varphi}\|^2_{L^2(\Omega)} + \tau^2\|\frac{\partial \Phi}{\partial z}|ue^{\tau \varphi}|^2_{L^2(\Omega)} \leq C(||(\Delta u)e^{\tau \varphi}|^2_{L^2(\Omega)} + |\tau|\int_F|\frac{\partial u}{\partial \nu}|^2e^{2\tau \varphi}d\sigma).
\end{align*}$$

(5.27)

Proof. Without loss of generality, we may assume that $\tau > 0$. Denote $\tilde{v} = ue^{\tau \varphi}, \Delta u = f$. Observe that $\Delta = 4\frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial \bar{z}^2}$ and $\varphi(x_1, x_2) = \frac{1}{2}(\Phi(z) + \Phi(\bar{z}))$. Therefore

$$e^{\tau \varphi}\Delta e^{-\tau \varphi}\tilde{v} = (2\frac{\partial}{\partial z} - \tau \frac{\partial \Phi}{\partial z})(2\frac{\partial}{\partial \bar{z}} - \tau \frac{\partial \bar{\Phi}}{\partial \bar{z}})\tilde{v} = (2\frac{\partial}{\partial z} - \tau \frac{\partial \Phi}{\partial z})(2\frac{\partial}{\partial \bar{z}} - \tau \frac{\partial \bar{\Phi}}{\partial \bar{z}})\tilde{v} = fe^{\tau \varphi}.$$

Denote $\tilde{w}_1 = \overline{Q(z)(2\frac{\partial}{\partial z} - \tau \frac{\partial \Phi}{\partial z})}\tilde{v}, \tilde{w}_2 = Q(z)(2\frac{\partial}{\partial \bar{z}} - \tau \frac{\partial \bar{\Phi}}{\partial \bar{z}})\tilde{v}$, where $Q(z) \in C^2(\overline{\Omega})$ is a holomorphic function in $\overline{\Omega}$. Thanks to the zero Dirichlet boundary condition for $u$ we have

$$\begin{align*}
\tilde{w}_1|_{\partial \Omega} &= 2\overline{Q(z)}\partial_z\tilde{v}|_{\partial \Omega} = (\nu_1 + i\nu_2)Q(z)\frac{\partial \tilde{v}}{\partial \nu}|_{\partial \Omega}, \\
\tilde{w}_2|_{\partial \Omega} &= 2Q(z)\partial_{\bar{z}}\tilde{v}|_{\partial \Omega} = (\nu_1 - i\nu_2)Q(z)\frac{\partial \tilde{v}}{\partial \nu}|_{\partial \Omega}.
\end{align*}$$

By Proposition 5.2 we obtain

$$\begin{align*}
&\|(\frac{\partial}{\partial x_1} - i\tau \frac{\partial \psi}{\partial x_1})\tilde{w}_1|^2_{L^2(\Omega)} - \tau \int_{\partial \Omega} (\nabla \varphi, \nu)\overline{Q'}(\frac{\partial \tilde{v}}{\partial \nu})|^2d\sigma \\
+ &\text{Re} \int_{\partial \Omega} i[(\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})\tilde{w}_1]|w_1|^2d\sigma + \|(\frac{\partial}{\partial x_2} - i\tau \frac{\partial \psi}{\partial x_2})\tilde{w}_1|^2_{L^2(\Omega)} = \|f e^{\tau \varphi}\|^2_{L^2(\Omega)}
\end{align*}$$

and

$$\begin{align*}
&\|(\frac{\partial}{\partial x_1} + i\tau \frac{\partial \psi}{\partial x_1})\tilde{w}_2|^2_{L^2(\Omega)} - \tau \int_{\partial \Omega} (\nabla \varphi, \nu)\overline{Q'}(\frac{\partial \tilde{v}}{\partial \nu})|^2d\sigma + \\
&\text{Re} \int_{\partial \Omega} i[(-\nu_2 \frac{\partial}{\partial x_1} + \nu_1 \frac{\partial}{\partial x_2})\tilde{w}_2]|w_2|^2d\sigma + \|(\frac{\partial}{\partial x_2} + i\tau \frac{\partial \psi}{\partial x_2})\tilde{w}_2|^2_{L^2(\Omega)} = \|f e^{\tau \varphi}\|^2_{L^2(\Omega)}.
\end{align*}$$

We simplify the integral $\text{Re} \int_{\partial \Omega} i((\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})\tilde{w}_1)|\tilde{w}_1|^2d\sigma$. We recall that $\tilde{v} = ue^{\tau \varphi}$ and $\tilde{w}_1|_{\partial \Omega} = \overline{Q(z)(\nu_1 + i\nu_2)\frac{\partial}{\partial \nu}e^{\tau \varphi}}$. Denote $A + iB = \overline{Q(z)(\nu_1 + i\nu_2)}$. We get

$$\begin{align*}
\text{Re} \int_{\partial \Omega} i((\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})\tilde{w}_1)|\tilde{w}_1|^2d\sigma &= \text{Re} \int_{\partial \Omega} i(\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})[(A + iB)\frac{\partial}{\partial \nu}e^{\tau \varphi}](A - iB)|\frac{\partial}{\partial \nu}e^{\tau \varphi}d\sigma \\
&= \text{Re} \int_{\partial \Omega} i((\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})((A + iB)||\frac{\partial}{\partial \nu}|^2(A - iB)d\sigma \\
&\quad + \text{Re} \int_{\partial \Omega} i\frac{1}{2}(A^2 + B^2)(\nu_2 \frac{\partial}{\partial x_1} - \nu_1 \frac{\partial}{\partial x_2})|\frac{\partial}{\partial \nu}|^2d\sigma \\
&= \int_{\partial \Omega} (\partial_\tau AB - \partial_\tau BA)|\frac{\partial}{\partial \nu}|^2d\sigma.
\end{align*}$$

Now we simplify the integral \( \text{Re} \int_{\partial \Omega} i((-\nu_2 \frac{\partial}{\partial x_1} + \nu_1 \frac{\partial}{\partial x_2})\tilde{w}_2) \bar{\tilde{w}}_2 d\sigma \). We recall that \( \tilde{v} = u e^{\tau \varphi} \) and \( \bar{\tilde{w}}_2 |_{\partial \Omega} = (\nu_1 - i\nu_2)Q(z)\frac{\partial}{\partial \varphi} = (\nu_1 - i\nu_2)Q(z)\frac{\partial}{\partial \varphi} e^{\tau \varphi} \). A straightforward computation gives

\[
\text{Re} \int_{\partial \Omega} i((-\nu_2 \frac{\partial}{\partial x_1} + \nu_1 \frac{\partial}{\partial x_2})\bar{\tilde{w}}_2) \tilde{w}_2 d\sigma = \int_{\partial \Omega} (\partial_{x} AB - \partial_{x} BA) |\tilde{v}|^2 d\sigma.
\]

Using the above formula, we obtain

\[
\|\frac{\partial}{\partial x_1}(e^{i\psi \tau} \tilde{w}_2)\|_{L^2(\Omega)}^2 + \|\frac{\partial}{\partial x_2}(e^{i\psi \tau} \tilde{w}_2)\|_{L^2(\Omega)}^2
\]

\[
- 2\tau \int_{\partial \Omega} |\nu, \nabla \varphi| Q |\tilde{v}|^2 d\sigma
\]

\[
+ \|\frac{\partial}{\partial x_1}(e^{-i\psi \tau} \tilde{w}_1)\|_{L^2(\Omega)}^2 + \|\frac{\partial}{\partial x_2}(e^{-i\psi \tau} \tilde{w}_1)\|_{L^2(\Omega)}^2
\]

\[
+ 2\int_{\partial \Omega} (\partial_{x} AB - \partial_{x} BA) |\tilde{v}|^2 d\sigma = 2\|Q f e^{\tau \varphi}\|_{L^2(\Omega)}^2.
\]

We can rewrite (5.29) in the form

\[
\|\frac{\partial}{\partial x_1}(e^{i\psi \tau} \tilde{w}_2)\|_{L^2(\Omega)}^2 + \|\frac{\partial}{\partial x_2}(e^{i\psi \tau} \tilde{w}_2)\|_{L^2(\Omega)}^2
\]

\[
- 2\tau \int_{\partial \Omega} |\nu, \nabla \varphi| Q |\tilde{v}|^2 d\sigma
\]

\[
+ \|\frac{\partial}{\partial x_1}(e^{-i\psi \tau} \tilde{w}_1)\|_{L^2(\Omega)}^2 + \|\frac{\partial}{\partial x_2}(e^{-i\psi \tau} \tilde{w}_1)\|_{L^2(\Omega)}^2
\]

\[
+ 2\int_{\partial \Omega} (\partial_{x} AB - \partial_{x} BA) |\tilde{v}|^2 d\sigma = 2\|Q f e^{\tau \varphi}\|_{L^2(\Omega)}^2.
\]

At this point, in order to estimate the integral \( \int_{\partial \Omega} (\partial_{x} AB - \partial_{x} BA) |\tilde{v}|^2 d\sigma \), we have to make a choice of the holomorphic function \( Q \). If \( \Omega \) is simply connected, after an appropriate conformal transformation to the ball, we can take \( Q \equiv 1 \). Then the function \( (\partial_{x} AB - \partial_{x} BA) \) will be positive.

In the general situation, using Proposition 5.1 we choose the holomorphic function \( Q(z) \) such that \( (\partial_{x} AB - \partial_{x} BA) \) is positive on \( \Gamma_0 \). Such a function can be constructed in the following way. Let \( \gamma_j \) be a contour from \( \partial \Omega \). We parameterize it by the smooth curve \( x(s) : [0, \ell_j] \rightarrow \gamma_j \), satisfying \( |x'(s)| = 1 \) and \( \partial_{x} A = \frac{d}{ds} A \circ x(s) \). We take now \( A \circ x(s) = \ell_j \sin(s/\ell_j), B \circ x(s) = \ell_j \cos(s/\ell_j) \). Then

\[
(\partial_{x} AB - \partial_{x} BA) = \ell_j \quad \text{on } \gamma_j.
\]
Taking into account that $A + iB = Q(z)(\nu_1 + i\nu_2)$, we set
\begin{equation}
    b_1 = \text{Re} \left\{ \frac{\ell_j \sin(s/\ell_j) - i\ell_j \cos(s/\ell_j)}{(\nu_1 - i\nu_2) \circ x(s)} \right\}, \quad b_2 = \text{Im} \left\{ \frac{\ell_j \sin(s/\ell_j) - i\ell_j \cos(s/\ell_j)}{(\nu_1 - i\nu_2) \circ x(s)} \right\}.
\end{equation}

We take $Q$ as a solution to problem (5.11) with the initial data close to the one given by (5.31). Then we have the estimate
\begin{equation}
    \int_{\partial \Omega} |\frac{\partial \bar{v}}{\partial \nu}|^2 d\sigma \leq C_1(\|Qfe^\tau\|^2_{L^2(\Omega)} + \|\tau\|_{L^2(\Omega)}),
\end{equation}

The function $Q(z)$, which allowed us to establish the estimate (5.32), might be equal to zero at some points of $\Omega$. Thus, from now on, we take $Q(z) \equiv 1$. The equality (5.30) is valid. Applying this to (5.32), we have
\begin{equation}
    \|\frac{\partial}{\partial x_1}(e^{i\psi_\tau}w_2)\|^2_{L^2(\Omega)} + \|\frac{\partial}{\partial x_2}(e^{i\psi_\tau}w_2)\|^2_{L^2(\Omega)} - 2\tau\int_{\partial \Omega} (\nu, \nabla \varphi) \frac{\partial \bar{v}}{\partial \nu}^2 d\sigma
\end{equation}
\begin{equation}
    + \|\frac{\partial}{\partial x_1}(e^{-i\psi_\tau}w_1)\|^2_{L^2(\Omega)} + \|\frac{\partial}{\partial x_2}(e^{-i\psi_\tau}w_1)\|^2_{L^2(\Omega)}
\end{equation}
\begin{equation}
    \leq C_2(\|fe^{i\psi_\tau}\|^2_{L^2(\Omega)} + \|\tau\|_{L^2(\Omega)}),
\end{equation}

Since $\varphi$ is a harmonic function, we have \[\int_{\partial \Omega} \frac{\partial \varphi}{\partial \nu} d\sigma = 0.\] By (2.1), (2.2) the function $\varphi$ is not constant, so the set $\partial \Omega_\nu = \{x \in \partial \Omega | (\nu, \nabla \varphi) > 0\}$ is not empty.

We now establish a Poincaré-type inequality with boundary terms. Let $\Gamma$ be some open subset of $\partial \Omega$. Observe that the functional $(\|\nabla W\|_{L^2(\Omega)} + \|W\|_{L^2(\Gamma_\nu)})$ is the norm on the Sobolev space $H^1(\Omega)$. In order to prove this, it suffices to establish the existence of constant $C_3$ such that
\begin{equation}
    \|W\|_{L^2(\Omega)} \leq C_3(\|\nabla W\|_{L^2(\Omega)} + \|W\|_{L^2(\Gamma_\nu)}) \quad \forall W \in H^1(\Omega).
\end{equation}

Suppose that (5.34) is false. Then there exists a sequence $\{W_k\} \subset H^1(\Omega)$ such that $\|W_k\|_{L^2(\Omega)} = 1$ and
\begin{equation}
    \|\nabla W_k\|_{L^2(\Omega)} + \|W_k\|_{L^2(\Gamma_\nu)} \rightarrow 0.
\end{equation}

On the other hand the sequence $W_k$ is clearly bounded in $H^1(\Omega)$. So taking a subsequence and using the compactness of the embedding of $H^1(\Omega)$ into $L^2(\Omega)$, we see that there exists $\tilde{W} \in H^1(\Omega)$ such that
\begin{equation}
    W_k \rightarrow \tilde{W} \quad \text{in} \quad L^2(\Omega).
\end{equation}

By (5.35), $\tilde{W} \equiv \text{const}$. On the other hand, by (5.33), $\tilde{W}|_{\Gamma_\nu} = 0$. Therefore $\tilde{W} \equiv 0$ and we have a contradiction with (5.36) and the fact that $\|W_k\|_{L^2(\Omega)} = 1$.

Thus, by (5.34) there exists a positive constant $C_4$, independent of $\tau$, such that
\begin{equation}
    \frac{1}{C_4}(\|\bar{w}_1\|^2_{L^2(\Omega)} + \|\bar{w}_2\|^2_{L^2(\Omega)}) \leq \frac{1}{2} \|\frac{\partial}{\partial x_1}(e^{i\psi_\tau}w_2)\|^2_{L^2(\Omega)}
\end{equation}
\begin{equation}
    + \frac{1}{2} \|\frac{\partial}{\partial x_2}(e^{i\psi_\tau}w_2)\|^2_{L^2(\Omega)} - \tau \int_{\partial \Omega} (\nu, \nabla \varphi) \frac{\partial \bar{v}}{\partial \nu}^2 d\sigma
\end{equation}
\begin{equation}
    + \frac{1}{2} \|\frac{\partial}{\partial x_1}(e^{-i\psi_\tau}w_1)\|^2_{L^2(\Omega)} + \frac{1}{2} \|\frac{\partial}{\partial x_2}(e^{-i\psi_\tau}w_1)\|^2_{L^2(\Omega)}.
\end{equation}

Since $\bar{v}$ is a real-valued function we have
\begin{equation}
    2\|\frac{\partial \bar{v}}{\partial x_1}\|_{L^2(\Omega)}^2 + \|\frac{\partial \bar{v}}{\partial x_2}\|_{L^2(\Omega)}^2 - \tau \frac{\partial \bar{v}}{\partial x_1} \leq C_5(\|\bar{w}_1\|^2_{L^2(\Omega)} + \|\bar{w}_2\|^2_{L^2(\Omega)}).
Therefore
\[ 4\|\frac{\partial \tilde{\psi}}{\partial x_1}\|^2_{L^2(\Omega)} - 2\tau \int_{\Omega} (\frac{\partial}{\partial x_1} \frac{\partial \psi}{\partial x_2} - \frac{\partial}{\partial x_2} \frac{\partial \psi}{\partial x_1}) \tilde{\psi}^2 dx + \tau^2 \|\frac{\partial \psi}{\partial x_2}\|^2_{L^2(\Omega)} \]
\[ + 4\|\frac{\partial \tilde{\psi}}{\partial x_2}\|^2_{L^2(\Omega)} + \tau^2 \|\frac{\partial \psi}{\partial x_1}\|^2_{L^2(\Omega)} \leq C_6(\|\tilde{w_1}\|^2_{L^2(\Omega)} + \|\tilde{w_2}\|^2_{L^2(\Omega)}). \]
(5.38)

Now we claim that there exists a constant $C_7$ independent of $\tau$ such that
\[ |\tau||\tilde{\psi}\|^2_{L^2(\Omega)} \leq C_7(\|\tilde{\psi}\|^2_{H^1(\Omega)} + \tau^2 \|\frac{\partial \psi}{\partial z}\|^2_{L^2(\Omega)}). \]
(5.39)

It suffices to prove inequality (5.39) locally assuming that $\text{supp } v \subseteq B(y, \delta)$ where $y \in \mathcal{H}$ and the radius $\delta$ can be taken sufficiently small. If $y \in \mathcal{H} \cap \partial \Omega$, by (2.2) one can take $\delta$ such that $v|_{\partial \Omega \cap B(y, \delta)} = 0$. Moreover, if $y \in \mathcal{H}$ is an arbitrary point, we may assume, without loss of generality, that $y = 0$. Since all critical points of the function $\Phi$ are assumed to be nondegenerate, there exists a holomorphic function $\Psi(z)$ such that $\partial_z \Phi(z) = z \Psi(z)$ and $\Psi(0) \neq 0$. Thus for some positive $\delta$ there exists a positive constant $C_8$ such that
\[ |z| \leq C_8 |\partial_z \Phi(z)| \quad \forall (\text{Re } z, \text{Im } z) \in B(0, \delta). \]

Then there exists a positive constant $C_9$ such that
\[ \int_{\Omega} |v|^2 dx = \int_{\Omega} (\partial_z z)|v|^2 dx = - \int_{\Omega} z(\partial_z \bar{v} + \bar{v} \partial_z v) dx \leq C_9 \int_{\Omega} (|\nabla v|^2 + |z|^2 |v|^2) dx. \]
(5.38)

By (5.38), (5.39) there exists a positive constant $C_{10}$ such that
\[ |\tau||\tilde{\psi}\|^2_{L^2(\Omega)} + \|\tilde{\psi}\|^2_{H^1(\Omega)} + \tau^2 \|\frac{\partial \psi}{\partial z}\|^2_{L^2(\Omega)} \leq C_{10}(\|\tilde{w_1}\|^2_{L^2(\Omega)} + \|\tilde{w_2}\|^2_{L^2(\Omega)}). \]
(5.40)

By (5.40) we obtain from (5.39), (5.37) that there exists a positive constant $C_{11}$ such that
\[ \frac{1}{C_{11}}(\|\tau||\tilde{\psi}\|^2_{L^2(\Omega)} + \|\tilde{\psi}\|^2_{H^1(\Omega)} + \tau^2 \|\frac{\partial \psi}{\partial z}\|^2_{L^2(\Omega)}) - \tau \int_{\partial \Omega} (\nu, \nabla \varphi) \frac{\partial \tilde{\psi}}{\partial \nu} \tilde{\psi}^2 d\sigma \]
\[ + \int_{\partial \Omega} 2(\partial_{\tau} AB - \partial_{\nu} BA) \frac{\partial \tilde{\psi}}{\partial \nu} \tilde{\psi}^2 d\sigma \leq \|fe^{\tau \varphi}\|^2_{L^2(\Omega)} + |\tau| \int_{\Gamma} (\nu, \nabla \varphi) \frac{\partial \tilde{\psi}}{\partial \nu} \tilde{\psi}^2 d\sigma. \]

The proof of the proposition is finished. \hfill \Box

Now we give the proof of Proposition 2.1

Proof. Let us introduce the space
\[ H = \left\{ v \in H^1_0(\Omega) \left| \Delta v + q_0 v \in L^2(\Omega), \frac{\partial v}{\partial \nu}|_\Gamma = 0 \right. \right\} \]
with the scalar product
\[ (v_1, v_2)_H = \int_{\Omega} e^{2\tau \varphi}(\Delta v_1 + q_0 v_1)(\Delta v_2 + q_0 v_2) dx. \]
By Proposition 5.3 $H$ is a Hilbert space. Consider the linear functional on $H$:
\[ v \rightarrow \int_{\Omega} v \bar{f} dx + \int_{\Gamma_0} g \frac{\partial v}{\partial \nu} d\sigma. \]
By (5.27) this is the continuous linear functional with the norm estimated by $C_{12}(\|fe^{\tau \varphi}\|^2_{L^2(\Omega)})$. Therefore by the Riesz representation theorem there exists an element $\tilde{v} \in H$ so that
\[ \int_{\Omega} v \bar{f} dx + \int_{\Gamma_0} g \frac{\partial v}{\partial \nu} d\sigma = \int_{\Omega} e^{2\tau \varphi}(\Delta \tilde{v} + q_0 \tilde{v})(\Delta v + q_0 v) dx. \]
Then, as a solution to (2.4), we take the function \( u = e^{2\tau \varphi} (\Delta \hat{\nu} + q_0 \hat{\nu}) \).

\[ \square \]

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References

DEPARTMENT OF MATHEMATICS, COLORADO STATE UNIVERSITY, 101 Weber Building, Fort Collins, Colorado 80523
E-mail address: oleg@math.colostate.edu

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF WASHINGTON, SEATTLE, WASHINGTON 98195
E-mail address: gunther@math.washington.edu

DEPARTMENT OF MATHEMATICAL SCIENCES, UNIVERSITY OF TOKYO, KOMABA, MEGURO, TOKYO 153, JAPAN
E-mail address: myama@ms.u-tokyo.ac.jp