Recovery of Boundaries and Types for Multiple Obstacles from the Far-field Pattern

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Abstract

We consider an inverse scattering problem for multiple obstacles \( D = \bigcup_{j=1}^{N} D_j \subset \mathbb{R}^3 \) with different types of boundary of \( D_j \). By constructing an indicator function from the far-field pattern of scattered wave, we can firstly determine the boundary location for all obstacles, then identify the boundary type for each obstacle, as well as the boundary impedance in case of Robin-type obstacles. The reconstruction procedures for these identifications are also given. Comparing with the existing probing method which is applied to identify one obstacle in generally, we should analyze the behavior of both the imaginary part and the real part of the indicator function so that we can identify the type of multiple obstacles.

Keywords: Inverse scattering, probe method, uniqueness, indicator

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1 Introduction

Let \( D \) be a bounded domain in \( \mathbb{R}^3 \) such that \( D = \bigcup_{j=1}^{N} D_j \), \( \overline{D_i} \cap \overline{D_j} = \emptyset \) (\( i \neq j \)). Each \( D_j \) is a simply connected domain with \( C^2 \) boundary \( \partial D_j \). The scattering of time-harmonic acoustic plane waves by the obstacle \( D \) with some boundary is modelled as an exterior boundary value problem for the Helmholtz equation. That is, for a given incident plane wave \( u^i(x) = e^{ikx \cdot d} \), \( d \in S^2 = \{ \xi \in \mathbb{R}^3 : |\xi| = 1 \} \), the total
wave field $u = u^i + u^s \in H^1_{\text{loc}}(R^3 \setminus \overline{D})$ satisfies
\[
\begin{align*}
\Delta u + k^2 u &= 0, & \text{in } R^3 \setminus \overline{D} \\
Bu(x, t) &= 0, & \text{on } \partial D \\
\frac{\partial u^s}{\partial r} - iku^s &= O \left( \frac{1}{r} \right), & r = |x| \to \infty
\end{align*}
\]
(1.1)
where $B$ is a boundary operator corresponding to different types of the obstacle $D$, that is,
\[
Bu = \begin{cases} 
   u & \text{if } \partial D_j \text{ is sound-soft}, \\
   \frac{\partial u}{\partial \nu} & \text{if } \partial D_j \text{ is sound-hard}, \\
   \frac{\partial u}{\partial \nu} + i\sigma(x)u & \text{if } \partial D_j \text{ is Robin-type},
\end{cases}
\]
(1.2)
where $\nu$ is the unit normal on $\partial D$ directed into the exterior of $D$, $\sigma(x) > 0$ is the boundary impedance coefficient. By the results in [5], we know that there exists a unique solution for the forward scattering problem (1.1).

For the incident field $u^i(x) = e^{ikx \cdot d}$, the far-field pattern $u^\infty(\theta, d)$ can be defined by
\[
u^s = e^{ik|x|} \left\{ u^\infty(\theta, d) + O \left( \frac{1}{|x|} \right) \right\}, \quad |x| \to \infty,
\]
where $\theta, d \in S^2$.

Generally, the inverse scattering problem corresponding to (1.1) is to identify the boundary $\partial D$ and also $\sigma(x)$ in case of Robin-type boundary, from a knowledge of far-field pattern. If $D$ is just one obstacle, then identifying $\partial D$ for each kind of boundary conditions has been discussed thoroughly. For example, if $D$ is sound-soft (Dirichlet boundary condition on $\partial D$) or sound-hard (Neumann boundary condition on $\partial D$), the problems have been studied by many researchers, see [3], [6], [8], [9], [11], [14], [18]. In the case of obstacle with Robin-type boundary, the problem of reconstructing $\sigma(x)$, when $\partial D$ is given, has also been studied, see [4], [6], [16], [17]. For the inverse scattering problem of determining both $\partial D$ and boundary impedance, an approximate determination (or reconstruction) of the shape of $D$ and boundary impedance was discussed in [20] by using the asymptotic behavior of the low frequency scattered waves associated with three different incident waves (or frequencies). In [13], one numerical method is proposed to determine both $\partial D$ and impedance $\sigma(x)$. In [1] and [2], the authors proved the uniqueness result of recovering $\partial D$ for a Robin-type obstacle with unknown boundary impedance from the far-field pattern, by applying the probe method introduced by M. Ikehata (see [8], [9], [10], [11] and [12] for example). Moreover, it has also been noticed that the probe method, as well as the point-source method proposed in [19], can be applied to determine the boundaries of multiple obstacles, if their boundary types are the same (sound-soft or sound-hard). Now, we propose a new problem: if there are many obstacles with different types of boundary such as sound-soft, sound-hard, as well as Robin-type, can we still identify their locations as well as the type of boundary for each obstacle?
This is the main topic of this paper. Our answer to this problem is "yes". More precisely, our result can be stated as follows.

**Theorem 1.1** Let \( D \) be a bounded domain consisting of finite obstacles \( D_j \) \((j = 1, 2, \cdots, N)\), namely, \( D = \bigcup_{j=1}^{N} D_j \). We assume that each obstacle \( D_j \) is simply connected bounded domain with \( C^2 \) boundary \( \partial D_j \) and \( \mathcal{D}_i \cap \mathcal{D}_j = \emptyset \) for \( i \neq j \). For given incident plane waves \( u^i(x, d) = e^{ikx \cdot d} \), consider the following scattering problem for total wave field \( u(x, d) = u^i(x, d) + u^s(x, d) \):

\[
\begin{align*}
\Delta u + k^2 u &= 0, & \text{in } \mathbb{R}^3 \setminus \mathcal{D}, \\
B_j u(x, t) &= 0, & \text{on } \partial D_j, j = 1, 2, \cdots, N \\
\frac{\partial u^s}{\partial r} -iku^s &= O\left(\frac{1}{r}\right), & r = |x| \to \infty,
\end{align*}
\]

where \( B_j \) is one of the boundary operator in (1.2) for \( j = 1, 2, \cdots, N \). Assume that \( \mathcal{D} \subset \Omega \) for some known sphere \( \Omega \) and \( 0 < \sigma_j(x) \in C(\partial D_j) \) for Robin-type obstacles \( D_j \). If there exists at least one Robin-type obstacle, then from the far-field pattern \( u^\infty(\theta, d) \) for all \( \theta, d \in S^2 \), we can

1. determine the number of obstacles \( N \),
2. locate \( \partial D_j \) for \( j = 1, 2, \cdots, N \),
3. identify the type of each obstacle \( D_j \),
4. determine \( \sigma_j(x) \) for the Robin-typed obstacles \( D_j \).

Our main tool to deal this problem is still the probe method. This method locates the shape of an obstacle by constructing the indicator function and analyzing its behavior. However, there are some new ingredients in this paper. In the case of multiple obstacles, we not only have to determine the location of each obstacle, but also we have to determine the number of obstacles and identify the type of each obstacle. This is the major and important difference between the multiple-obstacle inversion and single-obstacle one. Especially, we should catch some characteristics of the indicator function such that we can distinguish the sound-hard obstacle and obstacle with Robin-type boundary, since in most cases, we can consider the Neumann boundary as the special case of Robin boundary with \( \sigma(x) = 0 \). Then the most important ingredient of this paper is that we succeeded in providing a method distinguishing sound-hard boundary and Robin-type boundary. More precisely, we can determine the positions of obstacles and identify sound-soft boundary from the real part of the indicator function, while distinguishing the sound-hard boundary from Robin-type boundary is done by considering the imaginary part of the indicator function. In order to carry out this, the most important and difficult thing is to rewrite the indicator function in an appropriate form and analyze its behavior. The number of obstacles can be obtained immediately when we get the whole image of all obstacles.

We will give a mathematically rigorous reconstruction procedure for recovering \( \partial D_j \) for \( j = 1, 2, \cdots, N \). Then the uniqueness of identifying \( \partial D_j \) and the determination of number of obstacles from \( u^\infty(d, \theta) \) for all \( d, \theta \in S^2 \) becomes obvious from
the reconstruction. Since our reconstruction procedure is point wise, it is enough
to consider the case that \( D \) consists of 3 obstacles with sound-soft, sound-hard and
Robin-type boundary respectively, and to illustrate the reconstruction procedure
for identifying the location and type for each obstacle. This does not loose any
generality. More precisely, we assume that \( D_1, D_2, D_3 \) are sound soft, sound hard
and Robin-type, respectively. Once we have identified the location and type of each
obstacle, we determine \( \sigma_3(x) \) on \( \partial D_3 \) by the moment method. So, henceforth we
assume \( N = 3 \).

**Remark 1.1** For our problem, if \( \sigma(x) \in C(\partial D_3) \), the well-posedness for this direct
problem can be established from the standard scattering theory. That is, we can
apply the radiation condition to get the uniqueness (Theorem 3.12, [5]) and use the
combined single-layer and double-layer theory to get the existence of the solution.

**Remark 1.2** We can also identify \( D_1 \) and \( D_2 \) in case of \( D_3 = \emptyset \) if we assume the
unique solvability of the boundary value problem (2.2) given later.

**Remark 1.3** Our reconstruction method considers the inverse scattering problem
with multiple obstacles with different boundary types by firstly transform the far-field
pattern of scattered wave to a Dirichlet-to-Neumann map defined on the surface of
a ball, and then apply this D-to-N map as inversion data to recover the obstacles by
probe method. From the numerical point of view, we should consider the influence
of noisy in far-field pattern and error in computation on our final inversion results.
The main difficulty is that we should solve an integral equation of second kind with
hyper-singularity (see (2.4) in the sequel) from noisy far-field to construct the D-to-N
map. This problem can be solved by the technique proposed in [15]. The numerical
test of this problem as well as its influence on our inversion algorithm is being
consideration.

Our paper is organized as follows:

- Section 2: Preliminary results
- Section 3: Probe method
- Section 4: Moment method for determining \( \sigma(x) \)
- Section 5: Some estimates
- Section 6: Singularity Analysis
2 Preliminary results

In this section, we give some known results for the probe method, which are necessary for our paper.

Without loss of generality, we assume that $D \subset B(0, \frac{R}{2})$ for some constant $R > 0$. We also assume that 0 is not a Dirichlet eigenvalue of $\Delta + k^2$ in $\Omega := B(0, R)$ for given $k > 0$.

**Proposition 2.1** The scattered solution $u^c(x, d)$ for $|x| > \frac{R}{2}$ can be determined uniquely from $u^\infty(d, \theta)$.

The physical background for this proposition is obvious, that is, the far-field pattern of scattered wave determines the near-field outside the obstacle completely. This procedure has nothing to do with the boundary conditions of scatterers. For the proof, see Theorem 3.6 and Corollary 3.8 in [5], or [1], [2].

Let $G(x, y) = \frac{\epsilon^{-i|x-y|}}{4\pi|x-y|}$ be the fundamental solution of the Helmholtz equation. For each $y \in \mathbb{R}^3 \setminus D$, we define $E(\cdot, y) \in H^1_{\text{loc}}(\mathbb{R}^3 \setminus D)$ as the solution to

\[
\begin{cases}
\Delta E + k^2 E = 0, & \text{in } \mathbb{R}^3 \setminus D \\
B_i E(x, y) = -B_i G(x, y) & \text{on } \partial D, \quad i = 1, 2, 3 \\
\frac{\partial E}{\partial r} - i k E = O \left( \frac{1}{r} \right), & r = |x| \to \infty.
\end{cases}
\]

**Proposition 2.2** For $x, y \in \partial \Omega$, $E(x, y)$, $\frac{\partial}{\partial \nu(x)} E(x, y)$ and $\frac{\partial}{\partial \nu(y)} E(x, y)$ can be determined from $u^\infty(d, \theta)$ for all $d, \theta \in S^2$.

The proof for $D = D_1 \cup D_2 \cup D_3$ given here is an analogy to that given in [1] for $D = D_3$.

**Proof:** In fact, since we can choose $R$, so we assume that 0 is not the Dirichlet eigenvalue of $\Delta + k^2$. Therefore $\{e^{ikx \cdot d} | d \in S^2\}$ is dense in $L^2(\partial \Omega)$ ([6], Theorem 5.5). For any fixed $y \in \partial B(0, R_1)(R_1 > R)$, there exists a sequence $\{\alpha_j^n(y), d_j^n(y)\}$ such that

\[
\sum_{1 \leq j \leq m_n(y)} \alpha_j^n(y)e^{ikx \cdot d_j^n(y)} \to G(x - y) \quad \text{in } L^2(\partial \Omega).
\]

as $n \to \infty$. On the other hand, since both $\sum_{1 \leq j \leq m_n(y)} \alpha_j^n(y)e^{ikx \cdot d_j^n(y)}$ and $G(x - y)$ satisfy Helmholtz equation in $\Omega$, by the result in [6]( Theorem 5.4), we know that $\sum_{1 \leq j \leq m_n(y)} \alpha_j^n(y)e^{ikx \cdot d_j^n(y)} \to G(x - y)$ uniformly on any compact subset of $\Omega$ (together with all their derivatives). Therefore it follows that

\[
B_i \sum_{1 \leq j \leq m_n(y)} \alpha_j^n(y)e^{ikx \cdot d_j^n(y)} \to B_i G(x - y)
\]
in $L^2(\partial D_i), i = 1, 2, 3$ as $n \to \infty$. Since $u^s(x, d) \in H^1(R^3 \setminus \overline{D})$ satisfies
\[
\begin{cases}
\Delta u^s + k^2 u^s = 0, & \text{in } R^3 \setminus \overline{D} \\
B_i u^s = -B_i e^{ikx-d}, & \text{on } \partial D_i, \quad i = 1, 2, 3 \\
\frac{\partial u^s}{\partial r} - ik u^s = O\left(\frac{1}{r}\right), & r = |x| \to \infty,
\end{cases}
\]
by the continuous dependence of direct scattering problem, we have
\[
\sum_{1 \leq j \leq m_n(y)} \alpha_{ij}^n(y) u^s(x, d^n_j(y)) \to E(x, y) \text{ uniformly on } R/2 < |x| < 2R
\]
for $y \in \partial B(0, R_1)$. Now we get from Proposition 1 that, for $y \in \partial B(0, R_1)$ and $R/2 < |x| < 2R$, $E(x, y)$ can be determined by \(\{u^\infty(d, \theta) : \theta, d \in S^2\}\). Since $R_1$ is arbitrary, we complete the proof by letting $R_1 \to R$. \hfill \Box

Consider a solution $u(x) \in H^1(\Omega \setminus \overline{D})$ to the following boundary value problem
\[
\begin{cases}
\Delta u + k^2 u = 0, & \text{in } \Omega \setminus \overline{D} \\
B_j u(x, t) = 0, & \text{on } \partial D_j, j = 1, 2, 3 \\
u(x) = f, & \text{on } \partial \Omega
\end{cases}
\tag{2.2}
\]
for given $f \in H^{1/2}(\partial \Omega)$. Since we have used $\overline{D}$ to indicate the closure of domain $D$, we will use $\overline{z}$ to indicate the complex conjugate of complex number $z$ in the sequel.

**Lemma 2.1** If $D_3 \neq \emptyset$, then there exists a unique solution to (2.2) for any $f \in H^{1/2}(\partial \Omega)$.

**Proof** Firstly, we prove the uniqueness. It is enough to prove that $f = 0$ implies $u = 0$ in $\Omega \setminus \overline{D}$. For $f = 0$, it is easy to see from (2.2) that
\[
0 = \int_{\Omega \setminus \overline{D}} (\Delta u + k^2 u) \overline{u} dx = \int_{\partial D} \overline{u} \frac{\partial u}{\partial \nu} ds - \int_{\Omega \setminus \overline{D}} (\nabla u \cdot \nabla \overline{u} - k^2 u \overline{u}) dx,
\]
\[
0 = \int_{\Omega \setminus \overline{D}} (\Delta \overline{u} + k^2 \overline{u}) u dx = \int_{\partial D} u \frac{\partial \overline{u}}{\partial \nu} ds - \int_{\Omega \setminus \overline{D}} (\nabla \overline{u} \cdot \nabla u - k^2 \overline{u} u) dx
\]
due to $u = 0$ on $\partial \Omega$. Subtracting these two equalities and noticing the boundary conditions of $u$ on $\partial D_1$ and $\partial D_2$ lead to
\[
\int_{\partial D_3} \left( \frac{\partial u}{\partial \nu} - \frac{\partial u}{\partial \nu} \right) ds = 0.
\]
Now the boundary condition in $\partial D_3$ leads to
\[
\int_{\partial D_3} \sigma(x)|u(x)|^2 ds = 0
\]
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from which we get \( u = 0 \) on \( \partial D_3 \) and \( \frac{\partial u}{\partial \nu} = 0 \) on \( \partial D_3 \) from the boundary condition. Now the uniqueness of the Cauchy problem for the Helmholtz equations outside \( D_3 \) implies \( u = 0 \) in \( \Omega \setminus \overline{D} \). On the other hand, by the integral equation method for the scattering problem ([5], [6]), we know that the direct problem (2.2) can be transformed into a Fredholm integral equation of the second kind, therefore the uniqueness implies the existence due to the Fredholm alternative theorem.

**Remark 2.1** The existence of \( D_3 \) is important to the proof of our uniqueness. If we do not have an obstacle with Robin-type boundary, i.e., \( D = D_1 \cup D_2 \), then we have to assume the uniqueness of

\[
\begin{cases}
\Delta u + k^2 u = 0 & \text{in } \Omega \setminus (D_1 \cup D_2) \\
B_i u = 0 & \text{on } \partial D_i, i = 1, 2 \\
u(x) = f & \text{on } \partial \Omega.
\end{cases}
\] (2.3)

Define the Dirichlet-to-Neumann map \( \Lambda_{\partial D, \sigma} \) formally by

\[
\Lambda_{\partial D, \sigma} : f \rightarrow \frac{\partial u}{\partial \nu} |_{\partial \Omega} \in H^{-1/2}(\partial \Omega),
\]

where \( u \in H^1(\Omega \setminus \overline{D}) \) is the solution of (2.2) for \( f \in H^{1/2}(\partial \Omega) \). In the next Lemma, we show the relations between the far-field patterns and the Dirichlet-to-Neumann map.

**Lemma 2.2** Let \( u \) be the solution to (2.2) for \( f \in H^{1/2}(\partial \Omega) \). Then, \( \frac{\partial u}{\partial \nu} |_{\partial \Omega} \) can be obtained from \( f(x) \) and \( u^\infty(d, \theta) \) for \( \theta, d \in S^2 \).

**Proof** Let \( x_0 \in \partial B(0, R_0) \) for \( R/2 < R_0 < R \). By the Green’s formula, we have that, for \( G_D = G_D(x, x_0) = G(x, x_0) + E(x, x_0) \),

\[
u(x_0) = \int_{\partial \Omega} \left( G_D \frac{\partial u}{\partial \nu} - u \frac{\partial G_D}{\partial \nu} \right) ds + \sum_{j=1}^3 \int_{\partial D_j} \left( G_D \frac{\partial u}{\partial \nu} - u \frac{\partial G_D}{\partial \nu} \right) ds
\]

because \( B_j G_D = B_j u = 0 \) on \( \partial D_j \), where \( \nu_1 \) is the outward normal to the boundary of domain \( \Omega \setminus \overline{D} \).

Taking the normal derivatives of \( u \) on \( \partial B(0, R_0) \) in above expression and letting \( R_0 \to R \), by the properties of the single layer potential and double layer potential ([5]), we have

\[
\frac{1}{2} \frac{\partial u(x_0)}{\partial \nu_1(x_0)} = \int_{\partial \Omega} \frac{\partial G_D(x, x_0)}{\partial \nu_1(x_0)} \frac{\partial u(x)}{\partial \nu_1(x)} ds - \frac{\partial}{\partial \nu_1(x_0)} \int_{\partial \Omega} f(x) \frac{\partial G_D(x, x_0)}{\partial \nu_1(x)} ds
\] (2.4)
for $x_0 \in \partial B(0, R) = \partial \Omega$. The equation (2.4) is a Fredholm integral equation of the second kind with respect to $\left.\frac{\partial u(x)}{\partial \nu(x)}\right|_{\partial \Omega}$. There exists a unique solution due to the unique solvability of (2.2).

By Proposition 2.2, we know that, for $x, y \in \partial \Omega$, $\frac{\partial E(x,y)}{\partial \nu(x)}$ and $\frac{\partial E(x,y)}{\partial \nu(y)}$ can be obtained from $u^\infty(d, \theta)$, $\theta, d \in S^2$. Therefore $\left.\frac{\partial u}{\partial \nu}\right|_{\partial \Omega}$ can be obtained from $u^\infty(d, \theta)$, $\theta, d \in S^2$ and $f(x)$.

The proof is complete. □

From this lemma, we see that the original inverse problem can be restated as the problem of reconstructing the shapes of the 3 obstacles and the boundary impedance of $D_3$ from the Dirichlet-to-Neumann map $\Lambda_{\partial D, \sigma}$.

**Remark 2.2** The Dirichlet-to-Neumann map $\Lambda_{\partial D, \sigma}$ can be defined by the following weak form.

For any $g \in H^{1/2}(\partial \Omega)$, take any $v \in H^1(\Omega)$ with $v|_{\partial \Omega} = g$. Then it follows

$$\langle \Lambda_{\partial D, \sigma} f, g \rangle = \int_{\Omega \setminus D} (\nabla u \cdot \nabla v - k^2uv) \, dx + \int_{\partial D} v \frac{\partial u}{\partial \nu} \, ds(x)$$

$$= \int_{\Omega \setminus D} (\nabla u \cdot \nabla v - k^2uv) \, dx + \int_{\partial D_1} v \frac{\partial u}{\partial \nu} \, ds(x) - \int_{\partial D_3} i\sigma(x)uv \, ds(x)$$

(2.5)

for any $f \in H^{1/2}(\partial \Omega)$, where $u$ is the solution to (2.2) for $f \in H^{1/2}(\partial \Omega)$.

Corresponding to the case $D = \emptyset$, we can formally define the Dirichlet-to-Neumann map $\Lambda_{0,0} : H^{1/2}(\partial \Omega) \rightarrow H^{-1/2}(\partial \Omega)$ by

$$\Lambda_{0,0} : f \rightarrow \left.\frac{\partial u_1}{\partial \nu}\right|_{\partial \Omega}$$

where $u_1(x) \in H^1(\Omega)$ is the solution to

$$\begin{cases} 
\Delta u_1 + k^2 u_1 = 0, & \text{in } \Omega \\
u_1(x) = f \in H^{1/2}(\partial \Omega), & \text{on } \partial \Omega. 
\end{cases}$$

(2.6)

Here note that by the assumption 0 is not the Dirichlet eigenvalue of the operator $\Delta + k^2$ in $\Omega$, (2.6) is uniquely solvable.

The weak formula of $\Lambda_{0,0}$ is given by

$$\langle \Lambda_{0,0} f, g \rangle = \int_{\Omega} (\nabla u_1 \cdot \nabla v - k^2 u_1 v) \, dx,$$

(2.7)

where $u_1$ is the solution of (2.6) for $f \in H^{1/2}(\partial \Omega)$ and $v \in H^1(\Omega)$ satisfies $v|_{\partial \Omega} = g$ for $g \in H^1(\partial \Omega)$. For the solution $u$ of (2.2) and the solution $u_1$ of (2.6), we have
Lemma 2.3 Let \( u \in H^1(\Omega \setminus \overline{D}) \) and \( u_1 \in H^1(\Omega) \) be the solutions to (2.2) and (2.6), respectively. There exists a constant \( C = C(k, R, \sigma_0) \) such that, for all \( f \in H^{1/2}(\partial \Omega) \),
\[
\|u - u_1\|_{H^1(\Omega \setminus \overline{D})} \leq C \|u_1\|_{H^1(D)}
\]
where \( \sigma_0 > 0 \) is a constant satisfying \( 0 < \sigma(x) \leq \sigma_0, x \in \partial D_3 \).

The proof of Lemma 2.3 is almost the same as that given in [10]. But for the readers convenience we give the proof in Section 5.

3 Probe Method

Definition 1 For any continuous curve \( c = \{c(t) \mid 0 \leq t \leq 1\} \), if it satisfies \( c(0), c(1) \in \partial \Omega \) and \( c(t) \in \Omega \ (0 < t < 1) \), then we call \( c \) a needle in \( \Omega \).

Definition 2 For any needle \( c \) in \( \Omega \), we call
\[
t(c, D) = \sup \{0 < t < 1 | c(s) \in \Omega \setminus \overline{D} \text{ for all } 0 < s < t\}
\]
geometric impact parameter (GIP). It is obvious that \( t(c, D) = 1 \) if \( c \) does not touch any point on \( \partial D \).

From this definition, we know if a needle \( c \) touches \( \overline{D} \), then \( t(c, D) < 1 \) and \( t(c, D) \) is the first hitting time, i.e., \( c(t(c, D)) \in \partial D \) and \( c(t) \in \Omega \setminus \overline{D} \) for \( 0 < t < t(c, D) \).

Since \( \Omega \setminus \overline{D} \) is connected, we have a reconstruction algorithm for \( \partial D \) in terms of the geometric impact parameter and the needle, i.e.,
\[
\partial D = \{c(t) \mid t = t(c, D), c \text{ is a needle and } t(c, D) < 1\}. \tag{3.1}
\]

In order to reconstruct \( \partial D \), it suffices to consider the problem of calculating the GIP for each needle from the Dirichlet-to-Neumann map.

Lemma 3.1 Suppose that \( \Gamma \) is an arbitrary open set of \( \partial \Omega \). For each \( 0 < t < 1 \), there exists a sequence \( \{v_n\}_{n=1}^{\infty} \) in \( H^1(\Omega) \), which satisfies
\[
\Delta v_n + k^2 v_n = 0
\]
such that \( \text{supp}(v_n|_{\partial \Omega}) \subset \Gamma \) and
\[
v_n \rightharpoonup G(\cdot - c(t)) \text{ in } H^1_{\text{loc}}(\Omega \setminus \{c(t') \mid 0 < t' \leq t\}).
\]

This result comes from the Runge approximation theorem, see [8], [9].
Remark 3.1 Usually the Runge approximation is not constructive, because its proof is done by using the unique continuation and Hahn-Banach theorem. However, for the Helmholtz equation, it is possible to make the Runge approximation constructive by using the translation theory (see [7]).

It is obvious that \(v_n|_{\partial \Omega}\) depends on \(c(t)\). We denote it by \(v_n|_{\partial \Omega} = f_n(\cdot, c(t))\), where \(f_n(\cdot, c(t)) \in H^{1/2}(\partial \Omega)\) and \(\text{supp}(f_n(\cdot, c(t))) \subset \Gamma\).

**Definition 3** For a given needle \(c\) in \(\Omega\) and \(0 < t < 1\), we define the indicator function

\[
I(t, c) = \lim_{n \to -\infty} \langle (\Lambda_{\partial D, \sigma} - \Lambda_{0, 0}) f_n(\cdot, c(t)), f_n(\cdot, c(t)) \rangle, \tag{3.2}
\]

where \(\langle \cdot, \cdot \rangle\) is the pairing between \(H^{-1/2}(\partial \Omega)\) and \(H^{1/2}(\partial \Omega)\), \((\Lambda_{\partial D, \sigma} - \Lambda_{0, 0}) f_n(\cdot, c(t))\) is the complex conjugate of \((\Lambda_{\partial D, \sigma} - \Lambda_{0, 0}) f_n(\cdot, c(t))\).

Next we show that \(\Re(I(t, c))\) and \(\Im(I(t, c))\) (\(\Re, \Im\) denote the real part and imaginary part respectively) can be used to calculate GIP from which the locations of 3 obstacles can be determined, and we can also identify the type of each obstacle.

**Theorem 3.1** For a given needle \(c(t)\) in \(\Omega\), it follows that

(A) \(c(t, c(D)) \in \partial D\) if and only if

(1) \(I(t, c)\) exists for all \(0 \leq t < t(c, D)\) and

\[\Re(I(t, c)) < +\infty, \quad \text{for} \quad 0 \leq t < t(c, D),\]

(2) \(\lim_{t \to t(c, D)-} \Re(I(t, c)) = +\infty\).

(B) when \(c(t(c, D)) \in \partial D = \partial D_1 \cup \partial D_2 \cup \partial D_3\), we can identify \(\partial D_i\) for \(i = 1, 2, 3\) by

\[
\lim_{t \to t(c, D)-} \Re(I(t, c)) = +\infty \iff c(t(c, D)) \in \partial D_1,
\]

\[
\lim_{t \to t(c, D)-} \Im(I(t, c)) = -\infty \quad \text{and} \quad \lim_{t \to t(c, D)-} \Re(I(t, c)) = +\infty \iff c(t(c, D)) \in \partial D_2,
\]

\[
\lim_{t \to t(c, D)-} \Re(I(t, c)) = -\infty \quad \text{and} \quad \lim_{t \to t(c, D)-} \Im(I(t, c)) = +\infty \iff c(t(c, D)) \in \partial D_3.
\]

**Remark 3.2** The result (A) gives a criterion for the geometric impact parameter \(t(c, D)\) for a fixed needle \(c(t)\). Furthermore, since \(\partial D = \partial D_1 \cup \partial D_2 \cup \partial D_3\), we can identify \(\partial D_i\) according to (B).

**Proof** For a given needle \(c(t)\), by Lemma 3.1, we know that there exists a sequences \(\{v_n(x)\} \in H^1(\Omega)\) which satisfies

\[
\begin{aligned}
\Delta v_n + k^2 v_n &= 0, &\text{in} \quad \Omega \\
v_n &= f_n(\cdot, c(t)), &\text{on} \quad \partial \Omega; \quad \text{supp}(f_n(\cdot, c(t))) \subset \Gamma,
\end{aligned}
\]
and
\[ v_n \rightarrow G(\cdot - c(t)) \quad \text{in} \quad H^1_{loc}(\Omega \setminus \{c(t')|0 < t' \leq t\}) \quad (n \rightarrow \infty). \]

Let \( u_n(x) \in H^1(\Omega \setminus D) \) satisfy
\[
\begin{cases}
\Delta u_n + k^2 u_n = 0, & \text{in } \Omega \setminus D \\
B_i u_n = 0, & \text{on } \partial D_i, \quad i = 1, 2, 3 \\
u_n = f_n, & \text{on } \partial \Omega,
\end{cases}
\]
(3.3)
then \( w_n = u_n - v_n|_{\Omega \setminus D} \in H^1(\Omega \setminus D) \) satisfies
\[
\begin{cases}
\Delta w_n + k^2 w_n = 0, & \text{in } \Omega \setminus D \\
B_j w_n = -B_j v_n, & \text{on } \partial D_j, \quad j = 1, 2, 3 \\
w_n = 0, & \text{on } \partial \Omega.
\end{cases}
\]

By Lemma 2.3 and Lemma 3.1, we know that, for \( c(t) \notin D \), it holds that
\[ w_n \rightarrow w \quad \text{in} \quad H^1(\Omega \setminus D), \quad n \rightarrow \infty, \]
(3.4)
where \( w = w(x, c(t)) \) satisfies
\[
\begin{cases}
\Delta w + k^2 w = 0, & \text{in } \Omega \setminus D \\
B_j w = -B_j G(\cdot - c(t)), & \text{on } \partial D_j, \quad j = 1, 2, 3 \\
w = 0, & \text{on } \partial \Omega.
\end{cases}
\]
(3.5)
On the other hand, by the calculation in Section 6, we have two kinds of expressions for \( \langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n, f_n \rangle \), i.e.,
\[
\langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n(\cdot, \cdot; c(t)), f_n(\cdot, \cdot; c(t)) \rangle
= - \int_{\Omega \setminus D} (|\nabla w_n|^2 - k^2 |w_n|^2) dx - \int_D (|\nabla v_n|^2 - k^2 |v_n|^2) dx + \int_{\partial D_3} (2i\sigma v_n \bar{w}_n + i\sigma |v_n|^2 + i\sigma |w_n|^2) \, ds + \int_{\partial D_1} \left[ \left( \frac{\partial w_n}{\partial \nu} - \bar{w}_n \frac{\partial v_n}{\partial \nu} \right) + \left( \frac{\partial \bar{w}_n}{\partial \nu} - \bar{w}_n \frac{\partial v_n}{\partial \nu} \right) \right] \, ds.
\]
(3.6)
\[
\langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n(\cdot, \cdot; c(t)), f_n(\cdot, \cdot; c(t)) \rangle
= \int_{\Omega \setminus D} (|\nabla w_n|^2 - k^2 |w_n|^2) dx + \int_D (|\nabla v_n|^2 - k^2 |v_n|^2) dx - \int_{\partial D_2} \left[ \bar{u}_n \frac{\partial v_n}{\partial \nu} + u_n \frac{\partial \bar{v}_n}{\partial \nu} \right] \, ds - \int_{\partial D_3} \left[ \bar{u}_n \frac{\partial v_n}{\partial \nu} + u_n \frac{\partial \bar{v}_n}{\partial \nu} - i\sigma |u_n|^2 \right] \, ds.
\]
(3.7)
Let $n$ tend to infinity in (3.6). Then, by (3.4), we have

\[
-I(t, c) = \int_D \{\|\nabla G(-c(t))\|^2 - k^2|G(-c(t))|^2\} \, dx \\
+ \int_{\Omega \backslash \bar{D}} \{\|\nabla w\|^2 - k^2|w|^2\} \, dx \\
- i \int_{\partial D_3} \sigma(x) \{\|G(-c(t))\|^2 + |w|^2\} \, ds - 2i \int_{\partial D_3} \sigma(x) \tilde{w}G \, ds - \\
\int_{\partial D_1} \left[ \left( \frac{\partial \tilde{w}}{\partial \nu} - \frac{\partial G}{\partial \nu} \right) \tilde{w} - \left( \frac{\partial \tilde{G}}{\partial \nu} - \frac{\partial w}{\partial \nu} \right) \right] \, ds.
\]

(3.8)

If $t(c, D) = 1$, then, by the definition of $t(c, D)$, we know that $c(t)$ does not touch $\partial D$, i.e. $c(t) \in \Omega \backslash \bar{D}$ for $0 < t < 1$. Since $c(t) \in \Omega \backslash \bar{D}$ for $0 < t < 1$ and $c(1) \in \partial \Omega$, it is easy to verify that

\[
\lim_{t \to 1} \Re I(t, c) \neq -\infty, \quad |\Re I(t, c)| < +\infty, \quad \text{for } 0 \leq t < 1.
\]

If $t(c, D) < 1$, then we know that $c(t) \in \Omega \backslash \bar{D}$ for $0 < t < t(c, D)$ and $x_0 = c(t(c, D)) \in \partial D$.

Likewise before, since $c(t) \in \Omega \backslash \bar{D}$ for $0 \leq t < t(c, D)$, we have $|\Re I(t, c)| < +\infty$ for $0 \leq t < t(c, D)$. On the other hand,

\[
- \Re I(t, c) = \int_D \{\|\nabla G(-c(t))\|^2 - k^2|G(-c(t))|^2\} \, dx \\
+ \int_{\Omega \backslash \bar{D}} \{\|\nabla w\|^2 - k^2|w|^2\} \, dx + 2 \int_{\partial D_3} \sigma(x) \Im \tilde{w}G(-c(t)) \, ds - \\
\Re \left[ \int_{\partial D_1} \left( \frac{\partial \tilde{w}}{\partial \nu} - \frac{\partial G}{\partial \nu} \right) \tilde{w} - \left( \frac{\partial \tilde{G}}{\partial \nu} - \frac{\partial w}{\partial \nu} \right) \tilde{w} \right] \, ds \\
\geq \int_D |\nabla G(-c(t))|^2 \, dx - k^2 \int_D |G(-c(t))|^2 \, dx - k^2 \int_{\Omega \backslash \bar{D}} |w|^2 \, dx \\
+ 2 \int_{\partial D_3} \sigma(x) \Im \tilde{w}G(-c(t)) \, ds - \\
\Re \left[ \int_{\partial D_1} \left( \frac{\partial \tilde{w}}{\partial \nu} - \frac{\partial G}{\partial \nu} \right) \tilde{w} - \left( \frac{\partial \tilde{G}}{\partial \nu} - \frac{\partial w}{\partial \nu} \right) \tilde{w} \right] \, ds
\]

(3.9)

We can identify $\partial D$ from the real part of indicator function $I(t, c)$. In fact, according to the result of singularity analysis about $w(x, x_0)$ and $G(x - x_0)$ for $x_0 \in \partial D$ given in Theorem 5.1 and Theorem 5.2 below, we have from (3.9),

\[
\lim_{t \to t(c, D)_j} \Re I(t, c)) = -\infty.
\]
if \( j = 2, 3 \). On the other hand, consider the real part of the limit of the real part of (3.7) as \( n \to \infty \). It is easy to find that the real part will tend to \(+\infty\) when \( c(t) \to \partial D_1 \), since \( \int_D |\nabla G(\cdot - c(t))|^2 \, dx \) will blow up, while the integrals on the boundary are bounded. These facts imply that we can distinguish the sound-soft boundary \( D_1 \) from the other two kinds of boundaries (sound-hard and Robin-type).

Now we want to distinguish \( \partial D_2 \) and \( \partial D_3 \) further. For this purpose, we need to consider the imaginary part of (3.7). In fact, it yields from (3.6) that

\[
\Im(\langle \tilde{G}_\sigma \cdot f_n, f_n \rangle) = \int_{\partial D_3} \sigma(x)|u_n|^2 \, ds.
\] (3.10)

Now we estimate the behavior of the imaginary part of indicator function. Remind our previous notations, we get

\[
\lim_{n \to \infty} \Im(\langle \tilde{G}_\sigma \cdot f_n, f_n \rangle) = \lim_{n \to \infty} \int_{\partial D_3} \sigma(x)|v_n + w_n|^2 \, ds
\]
\[
= \int_{\partial D_3} \sigma(x)|(G(x - c(t))) + w(x, c(t))|^2 \, ds,
\] (3.11)

where \( w \) is the function defined by (3.5). According to the singularity analysis in section 5 and section 6, we know that \(|G(x - c(t)) + w(x, c(t))|\) is estimated by \(|G(x - c(t))|\). Hence, from (3.11) and the estimate for \( G \) in section 5, we have

\[
\lim_{t \to t(c,D_3)} \Im I(t,c) = \lim_{t \to t(c,D_2)} \int_{\partial D_3} \sigma(x)|(G(x - c(t))) + w(x, c(t))|^2 \, ds = +\infty,
\]
\[
\lim_{t \to t(c,D_2)} \Im I(t,c) = \lim_{t \to t(c,D_2)} \int_{\partial D_3} \sigma(x)|(G(x - c(t))) + w(x, c(t))|^2 \, ds < \infty.
\]

Since \( D_2 \) and \( D_3 \) are separated, these behavior of \( \Im I(t,c) \) enable us to distinguish \( \partial D_3 \) and \( \partial D_2 \).

The proof is complete. \( \square \)

Now we give the reconstruction procedure for the shape and type of each obstacle. It can be realized by the following steps:

- Calculate the Dirichlet-to-Neumann map \( \Lambda_{\sigma,D} \) from the far field patterns \( u^\infty(d,\theta) \), \( d, \theta \in S^2 \).
- For any given needle \( c(t) \), calculate the sequences \( v_n \) and \( f_n(\cdot,c) \).
- Calculate \( \langle (\tilde{G}_{\sigma,D} - \Lambda_{0,0})f_n(\cdot,c(t)), f_n(\cdot,c(t)) \rangle \).
• Calculate \( I(c,t) \) and

\[
\partial D_1 = \{ c(t_0) : |\Re I(c,t)| < +\infty \text{ for } 0 \leq t < t_0; \lim_{t \to t_0^-} \Re I(c,t) = +\infty \};
\]

\[
\partial D_2 = \{ c(t_0) : |\Re I(c,t)|, |\Im I(c,t)| < +\infty \text{ for } 0 \leq t < t_0; \lim_{t \to t_0^-} \Re I(t,c) = -\infty \text{ and } \lim_{t \to t_0^-} \Im I(t,c) = +\infty \};
\]

\[
\partial D_3 = \{ c(t_0) : |\Re I(c,t)|, |\Im I(c,t)| < +\infty \text{ for } 0 \leq t < t_0; \lim_{t \to t_0^-} \Re I(t,c) = -\infty \text{ and } \lim_{t \to t_0^-} \Im I(t,c) = +\infty \}.
\]

The rest of the part of the proof of Theorem 1.1 is to reconstruct boundary impedance on \( D_3 \). This will be given in the next section.

4 Moment method for determining \( \sigma(x) \)

In this section, we reconstruct the boundary impedance \( \sigma(x) \). Since in the previous section, we have reconstructed \( \partial D \) from the far field patterns \( u_\infty(d,\theta) \), \( d,\theta \in S^2 \), therefore in this section we assume that \( \partial D = \partial D_1 \cup \partial D_2 \cup \partial D_3 \) is known.

Consider the boundary value problem

\[
\left\{ \begin{array}{ll}
\Delta u + k^2 u = 0, & \text{in } \Omega \setminus D \\
B_j u(x) = 0, & \text{on } \partial D_j, \quad j = 1,2 \\
\frac{\partial u}{\partial n} + i\sigma(x) u = 0, & \text{on } \partial D \\
u(x) = f, & \text{on } \partial \Omega 
\end{array} \right.
\]

(4.1)

for a given \( f(x) \in H^{1/2}(\partial \Omega) \).

**Lemma 4.1** Suppose that \( u_j(x) \in H^1(\Omega \setminus D) \), \( j = 1,2, \cdots \) satisfy (4.1) with \( f = f_j \). Put \( \phi_j(x) = u_j(x)|_{\partial D_3} \). If

\[
\text{span}\{f_j(x)\} = H^{1/2}(\partial \Omega),
\]

(4.2)

then we have

\[
\text{span}\{\phi_j(x)\} = H^{1/2}(\partial D_3).
\]

**Proof** Assume that \( f(x) \in H^{-1/2}(\partial D_3) \) which satisfies

\[
\int_{\partial D_3} \phi_j f ds = 0, \quad j = 1,2, \cdots,
\]

(4.3)

we want to prove that \( f(x) = 0 \). Here \( \int_{\partial D_3} \phi_j f ds \) denotes the pairing \( \langle f, \phi_j \rangle \) between \( H^{-1/2}(\partial D_3) \) and \( H^{1/2}(\partial D_3) \).
Consider the following boundary value problem

\[
\begin{cases}
\Delta v + k^2 v = 0, & \text{in } \Omega \setminus \overline{D} \\
B_j v(x) = 0, & \text{on } \partial D_j, \quad j = 1, 2 \\
\frac{\partial v}{\partial \nu} + i\sigma(x)v = \tilde{f}, & \text{on } \partial D_3 \\
v = 0, & \text{on } \partial \Omega.
\end{cases}
\] (4.4)

Since \( \sigma(x) > 0 \), likewise the proof of Lemma 2.1, we know there exists a unique solution \( v \in H^1(\Omega \setminus D) \) for (4.4).

By the Green’s formula, we know that

\[
0 = \int_{\Omega \setminus D} (v \Delta u_j - u_j \Delta v) \, dx
= \int_{\partial \Omega} \left( \frac{\partial u_j}{\partial \nu_1} v - \frac{\partial v}{\partial \nu_1} u_j \right) + \int_{\partial D} \left( \frac{\partial u_j}{\partial \nu_1} v - \frac{\partial v}{\partial \nu_1} u_j \right),
\] (4.5)

where \( \nu_1 \) is the outward normal of domain \( \Omega \setminus D \).

Noticing \( \nu = -\nu \) on \( \partial D \) and \( v|_{\partial \Omega} = 0 \), we have

\[
\int_{\partial \Omega} \frac{\partial v}{\partial \nu} u_j \, ds = \int_{\partial D_3} \left( i\sigma v u_j + \frac{\partial v}{\partial \nu} u_j \right) \, ds
\]
due to the boundary conditions on \( \partial D_1 \) and \( \partial D_2 \). Therefore, it holds that

\[
\int_{\partial \Omega} f_j \frac{\partial v}{\partial \nu} \, ds = \int_{\partial D_3} \phi_j \tilde{f} \, ds = 0, \quad j = 1, 2, \ldots
\]

Since \( \text{span}\{f_j(x)\} = H^{1/2}(\partial \Omega) \), we obtain

\[
\frac{\partial v}{\partial \nu}|_{\partial \Omega} = 0.
\]

By the uniqueness of the Cauchy problem for the Helmholtz equations in domain \( \Omega \setminus D \), we have \( v(x) = 0 \) in \( \Omega \setminus D \). Then by (4.4), we know \( f(x) = 0 \). The proof is complete. \( \Box \)

On the other hand, we can obtain \( u_j|_{\partial D} \) and \( \frac{\partial u_j}{\partial \nu}|_{\partial D} \) by solving the following Cauchy problem

\[
\begin{cases}
\Delta u_j + k^2 u_j = 0, & \text{in } \Omega \setminus D \\
u_j = f_j, \quad \frac{\partial u_j}{\partial \nu} = \Lambda_{\partial D, \sigma} f_j, & \text{on } \partial \Omega
\end{cases}
\] (4.6)

for a given \( f_j(x) \), hence both \( u_j|_{\partial D_3} \) and \( \frac{\partial u_j}{\partial \nu}|_{\partial D_3} \) are obtained.

Now, by integrating the Robin-type boundary condition over \( \partial D_3 \), we have that the impedance \( \sigma(x) \) satisfies

\[
\int_{\partial D_3} i\sigma(x) u_j \, ds = -\int_{\partial D_3} \frac{\partial u_j}{\partial \nu} \, ds, \quad j = 1, 2, \ldots
\] (4.7)
Here note that $\text{span}\{u_j|_{\partial D_3}\}$ is dense in $H^{1/2}(\partial D_3)$ by Lemma 4.1, hence $\sigma(x)$ can be determined uniquely from this moment problem.

Now the recovery of the impedance $\sigma(x)$ can be realized by the following steps:

- Choose $f_j, \ j = 1, 2, \cdots$ such that $\text{span}\{f_j\}_{j=1}^\infty = H^{1/2}(\partial \Omega)$.
- For every $f_j$, solve the Cauchy problem (4.6) and obtain $u_j|_{\partial D_3}$ and $\frac{\partial u_j}{\partial \nu}|_{\partial D_3}$.
- Solve the moment problem (4.7) to get $\sigma(x)$.

5 Some Estimates

In this section we give the proof of Lemma 2.3 and estimate of $\|w\|_{L^2(\Omega \setminus D)}$.

**Proof of Lemma 2.3**

Let $p(x) = u(x) - u_1(x)|_{\Omega \setminus D}$. It is easy to verify that $p(x)$ satisfies

\[
\begin{cases}
\Delta p + k^2 p = 0, & \text{in } \Omega \setminus D \\
B_j p = -B_j u_1, & \text{on } \partial D_j, \ j = 1, 2, 3 \\
p(x) = 0, & \text{on } \partial \Omega.
\end{cases}
\] (5.1)

By the well-posedness of the boundary value problem (5.1), we know that the solution $p(x) \in H^1(\Omega \setminus D)$ depends continuously on the boundary data on $\partial D = \partial D_1 \cup \partial D_2 \cup \partial D_3$. Therefore, there exists a constant $C > 0$ such that

\[
\|p\|_{H^1(\Omega \setminus D)} \leq C\{\|B_1 u_1\|_{H^{1/2}(\partial D_1)} + \|B_2 u_1\|_{H^{1/2}(\partial D_2)} + \|B_3 u_1\|_{H^{1/2}(\partial D_3)}\} \quad (5.2)
\]

On the other hand, the trace theorem for $u_1(x)$ on the domain $D$ yields

\[
\|B_1 u_1\|_{H^{1/2}(\partial D_1)} + \|B_2 u_1\|_{H^{1/2}(\partial D_2)} + \|B_3 u_1\|_{H^{1/2}(\partial D_3)} \leq C\|u_1\|_{H^1(D)}
\]

due to $0 < \sigma(x) < \sigma_0$, and the proof is complete. \hfill \Box

**Theorem 5.1** There exists a constant $C$ independent of $D$ such that

\[
\|w\|_{L^2(\Omega \setminus D)} \leq C.
\]

**Proof** We adapt the proof of [10] to our case. First we define a function $v(x)$ by

\[
\begin{cases}
\Delta v + k^2 v = w, & \text{in } \Omega \setminus D \\
B_j v = 0, & \text{on } \partial D_j, \ j = 1, 2 \\
\frac{\partial v}{\partial \nu} + i\sigma v = 0, & \text{on } \partial D_3 \\
v(x) = 0, & \text{on } \partial \Omega.
\end{cases}
\] (5.3)
Then, from the well-posedness of this boundary problem, we have
\[ \|v\|_{H^2(\Omega \setminus \overline{D})} \leq C \|w\|_{L^2(\Omega \setminus \overline{D})}. \] (5.4)

Since \( \Omega \setminus \overline{D} \) is a domain in \( \mathbb{R}^3 \) with \( C^2 \) boundary, by the Sobolev embedding theorems, we know that \( H^2(\Omega \setminus \overline{D}) \) can be embedded into \( B^{1/2}_{1/2}(\Omega \setminus \overline{D}) \) (Hölder space with exponent \( 1/2 \)) and \( \|v\|_{B^{1/2}_{1/2}} \leq C \|v\|_{H^2} \). So we have
\[ \|v\|_{B^{1/2}_{1/2}} \leq C \|w\|_{L^2}. \]

From this inequality, we know that
\[ \left\{ \begin{array}{l}
|v(x) - v(y)| \leq C|x - y|^{1/2} \|w\|_{L^2(\Omega \setminus \overline{D})}, \quad x, y \in \Omega \setminus \overline{D} \\
\|v\|_{L^\infty(\Omega \setminus \overline{D})} \leq C \|w\|_{L^2(\Omega \setminus \overline{D})}.
\end{array} \right. \] (5.5)

Remind the definition of weak solutions \( w \) and \( v \) to (3.5) and (5.3) respectively, by the Green formula and the boundary conditions for \( v, w \), we have
\[
0 = \int_{\Omega \setminus \overline{D}} (\Delta + k^2) \tilde{w}(x)v(x)dx = -\int_{\partial D} v \frac{\partial \tilde{w}}{\partial \nu} ds - \int_{\partial D} (\nabla \tilde{w}(x) \nabla v(x) - k^2 \tilde{w}(x)v(x)) dx \\
= \int_{\partial D_2} v \frac{\partial \tilde{G}(x - c(t))}{\partial \nu} ds + \int_{\partial D_3} v [\tilde{w}i\sigma + \left( \frac{\partial}{\partial \nu} + i\sigma \right) \tilde{G}] ds - \\
\int_{\partial D} (\nabla \tilde{w}(x) \nabla v(x) - k^2 \tilde{w}(x)v(x)) dx,
\]
which yields
\[
\int_{\Omega \setminus \overline{D}} |w(x)|^2 dx = \int_{\Omega \setminus \overline{D}} (\Delta + k^2)v\tilde{w}dx \\
= \int_{\partial D_1} \tilde{G} \frac{\partial v}{\partial \nu} ds + \int_{\partial D_3} v \tilde{w} \tilde{\sigma} ds - \int_{\Omega \setminus \overline{D}} (\nabla \tilde{w}(x) \cdot \nabla v(x) - k^2 \tilde{w}(x)v(x)) dx \\
= \int_{\partial D_1} \tilde{G} \frac{\partial v}{\partial \nu} ds - \int_{\partial D_2} v \frac{\partial \tilde{G}}{\partial \nu} ds - \int_{\partial D_3} v \left( \frac{\partial}{\partial \nu} + i\sigma \right) \tilde{G} ds \\
= \int_{\partial D_1} \tilde{G} \frac{\partial v}{\partial \nu} ds - \int_{\partial D_2} v \tilde{w} \tilde{\sigma} ds - v(c(t)) \left[ \int_{\partial D_2} + \int_{\partial D_3} \right] \frac{\partial \tilde{G}}{\partial \nu} ds - \\
\int_{\partial D_2} \tilde{G}(x - c(t)) \frac{\partial \tilde{G}(x - c(t))}{\partial \nu} ds. \tag{5.6}
\]

On the other hand, if \( y \notin \overline{D}_j \), we have
\[
\int_{\partial D_j} \frac{\partial}{\partial \nu} \tilde{G}(x - y)ds + k^2 \int_{D_j} \tilde{G}(x - y)dx = \int_{D_j} (\Delta + k^2) \tilde{G}(x - y)dx = 0.
\]
Therefore (5.6) leads to
\[
\|w\|^2_{L^2(\Omega, \mathcal{D})} = \int_{\partial D_1} \tilde{G} \frac{\partial v}{\partial \nu} \ ds - \int_{\partial D_3} v \tilde{G} ds + k^2 v(c(t)) \left( \int_{\partial D_2} + \int_{\partial D_3} \right) \frac{\partial \tilde{G}(x - c(t))}{\partial \nu} \ ds
\]
(5.7)

On one hand, (5.5) tells us
\[
\frac{|v(x) - v(y)|}{|x - y|} \leq C \frac{1}{|x - y|^{1/2}} \|w\|_{L^2(\Omega, \mathcal{D})},
\]
which implies
\[
\left| \int_{\partial D_1} \tilde{G} \frac{\partial v}{\partial \nu} \ ds \right| \leq C \|w\|_{L^2(\Omega, \mathcal{D})} \int_{\partial D_1} |\tilde{G}(x - c(t))| \frac{1}{|x - c(t)|^{1/2}} \ ds \leq C \|w\|_{L^2(\Omega, \mathcal{D})}
\]

as \(c(t) \to \partial D_1\). On the other hand, the integrals \(\int_{\partial D} |\tilde{G}(x - c(t))| ds\), \(\int_{\partial D} |x - c(t)|^{1/2} \frac{\partial \tilde{G}(x - c(t))}{\partial \nu} ds\) and \(\int_D |\tilde{G}(x - c(t))| dx\) are bounded as \(c(t) \to \partial D\). Therefore by (5.5) and (5.7), we have
\[
\|w\|^2_{L^2(\Omega, \mathcal{D})} \leq C \|w\|_{L^2(\Omega, \mathcal{D})}.
\]
The proof is complete.

\[\square\]

**Theorem 5.2** Assume \(x_0 \in \partial D\) and \(c(t) \in (\Omega \setminus \overline{D}) \cap \partial B(x_0, \delta)\) for some \(\delta > 0\), where \(B(x_0, \delta)\) is an open ball centered at \(x_0\) with radius \(\delta\), then there exists some constant \(C > 0\) such that for \(\delta\) small enough the following estimates hold:
\[
\int_D |\nabla G(x - c(t))|^2 dx \geq \frac{C}{\delta}, \quad \int_D |G(x - c(t))|^2 dx \leq C,
\]
\[
\int_{\partial D} |G(x - c(t))|^2 ds \leq C |\ln \delta|, \quad \int_{\partial D} |w(x, c(t))|^2 ds \leq C \int_{\partial D} |G(x - c(t))|^2 ds,
\]
where \(D\) should be \(D_j\) for \(j = 1, 2, 3\) in the former three estimates and for \(j = 2, 3\) in the forth estimate, the constants \(C > 0\) may be different.

**Proof:** Except the fourth estimate, the proofs of the estimates are given in [2].

For the readers convenience we repeat them. Denote the tangent plane of \(\partial D\) at point \(x_0\) by \(T(x_0, \partial D)\). From the expressions of Green’s function, we have
\[
|\nabla G(x - c(t))|^2 = O \left( \frac{1}{|x - c(t)|^4} \right), \quad |G(x - c(t))|^2 = O \left( \frac{1}{|x - c(t)|^2} \right)\]
(5.8)
We have that, for $\delta$ small enough,
\[
\int_D \frac{1}{|x - c(t)|^4} \, dx \geq \int_{D \cap B(x_0, \delta)} \frac{1}{|x - c(t)|^4} \, dx \geq \frac{1}{(2\delta)^4} \int_{B(x_0, \delta)} \, dx = \frac{C}{\delta}.
\] (5.9)

Hence we have obtained the first estimate. The second estimate is obvious.

On the other hand, let $c'(t) \in \Omega \setminus \overline{D}$ satisfy
\[
c'(t) \in \partial B(x_0, \delta), \quad c'(t) - x_0 \text{ is perpendicular to } T(x_0, \partial D).
\]

Then,
\[
\int_{\partial D} |G(x - c(t))|^2 \, ds \leq C \left( \int_{\partial D_1} + \int_{\partial D_2} \right) \frac{1}{|x - c(t)|^2} \, ds,
\]
where
\[
\partial D_1 := \partial D \cap \{ x \in \mathbb{R}^3 \mid |x - c'(t)|^2 \geq \frac{1}{|\ln \delta|} \},
\]
\[
\partial D_2 := \partial D \cap \{ x \in \mathbb{R}^3 \mid |x - c'(t)|^2 \leq \frac{1}{|\ln \delta|} \}.
\]

Since $\frac{1}{2|\log \delta|} - \sqrt{2} \geq 0$ for small enough $\delta$ and
\[
|c(t) - c'(t)| \leq \sqrt{2}\delta, \quad |x - c(t)| \geq \frac{1}{2|\log \delta|},
\]
we have
\[
\int_{\partial D_1} \frac{1}{|x - c'(t)|^2} \, ds \leq |\ln \delta| \int_{\partial D_1} \, ds \leq C|\ln \delta|. \tag{5.10}
\]

For the second integral, since
\[
\partial D_2' = \{ x \in \mathbb{R}^3 \mid x \in T(x_0, \partial D), |x - x_0|^2 \leq \frac{1}{|\ln \delta|^2 - \delta^2} \}
\]
approximates $\partial D_2$ for small $\delta > 0$, we know that
\[
\int_{\partial D_2} \frac{1}{|x - c(t)|^2} \, ds \leq 2 \int_{\partial D_2'} \frac{1}{|x - c(t)|^2} \, ds = \int_{\partial D_2'} \frac{1}{|x - x_0| + \sqrt{|\ln \delta|^2 - \delta^2}} \, ds = 4\pi(|\ln \delta| - |\ln(\ln \delta)|) \leq C|\ln \delta|. \tag{5.11}
\]

for $\delta > 0$ small enough. Then the third estimate follows from (5.10)-(5.11).

The fourth estimate will be given in the next section. The proof is complete. □
6 Singularity Analysis

6.1 Expression of $\Lambda_{\partial D, \sigma} - \Lambda_{0,0}$

Here we prove (3.6). Let $v(x) \in H^1(\Omega \setminus \overline{D})$. From the definition of the weak solution of $u_n$ to (3.3), we have

$$0 = \int_{\partial D} v \frac{\partial u_n}{\partial \nu_1} ds + \int_{\partial D} v \frac{\partial u_n}{\partial \nu} ds - \int_{\Omega \setminus D} (\nabla u_n \nabla v - k^2 v u_n) dx.$$

Hence, reminding the boundary condition of $u_n$, we get

$$\int_{\partial D} v \frac{\partial u_n}{\partial \nu_1} ds = \int_{\Omega \setminus D} (\nabla u_n \nabla v - k^2 v u_n) dx + \int_{\partial D_1} \frac{\partial u_n}{\partial \nu} \partial v \nu ds - \int_{\partial D_3} i\sigma u_n \partial v \nu ds. \quad (6.1)$$

Firstly, we take $v = \tilde{w}_n$ in this expression, we get that

$$0 = \int_{\Omega \setminus D} (\nabla u_n \nabla \tilde{w}_n - k^2 \tilde{w}_n u_n) dx + \int_{\partial D_1} \frac{\partial u_n}{\partial \nu} \tilde{w}_n ds - \int_{\partial D_3} i\sigma u_n \tilde{w}_n ds. \quad (6.2)$$

due to $w_n|_{\Omega} = 0$. On the other hand, by taking $v = \tilde{v}_n$ also in the above expression, we have

$$\langle \Lambda_{\partial D, \sigma} f_n, \tilde{f}_n \rangle = \int_{\Omega \setminus D} (\nabla u_n \nabla \tilde{v}_n - k^2 \tilde{v}_n u_n) dx + \int_{\partial D_1} \frac{\partial u_n}{\partial \nu} \tilde{v}_n ds - \int_{\partial D_3} i\sigma u_n \tilde{v}_n ds. \quad (6.3)$$

Analogously, we have

$$\langle \Lambda_{0,0} f_n, \tilde{f}_n \rangle = \int_{\partial \Omega} \frac{\partial v_n}{\partial \nu} \tilde{v}_n ds = \int_{\Omega} (\nabla v_n \nabla \tilde{v}_n - k^2 v_n \tilde{v}_n) dx. \quad (6.4)$$

From the above expression, we get that

$$\langle \Lambda_{\partial D, \sigma} - \Lambda_{0,0} f_n, \tilde{f}_n \rangle = \int_{\Omega \setminus D} (\nabla \tilde{w}_n \nabla v_n - k^2 \tilde{w}_n v_n) dx + \int_{\partial D_1} \frac{\partial u_n}{\partial \nu} \nu ds - \int_{\partial D_3} i\sigma \tilde{w}_n v_n ds. \quad (6.5)$$

Remind $w_n = u_n - v_n$ and consider

$$J_n := \int_{\Omega \setminus D} (\nabla w_n \nabla \tilde{w}_n - k^2 w_n \tilde{w}_n) dx - \int_{\partial D_3} i\sigma w_n \tilde{w}_n ds + \int_{\partial D_1} \tilde{w}_n \frac{\partial w_n}{\partial \nu} ds$$

$$= -\int_{\Omega \setminus D} (\nabla v_n \nabla \tilde{w}_n - k^2 v_n \tilde{w}_n) dx + \int_{\partial D_3} i\sigma v_n \tilde{w}_n ds - \int_{\partial D_1} \tilde{w}_n \frac{\partial v_n}{\partial \nu} ds.$$

Then, we get

$$\int_{\Omega \setminus D} (\nabla v_n \nabla \tilde{w}_n - k^2 v_n \tilde{w}_n) dx = -J_n + \int_{\partial D_3} i\sigma v_n \tilde{w}_n ds - \int_{\partial D_1} \tilde{w}_n \frac{\partial v_n}{\partial \nu} ds. \quad (6.6)$$
Inserting this expression into (6.5), and reminding (6.2), (6.3) leads to

\[
\langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n, f_n \rangle \\
= - J_n + \int_{\partial D_3} i \sigma v_n \tilde{w}_n ds - \int_{\partial D_1} \tilde{w}_n \frac{\partial v_n}{\partial \nu} ds - \int_D (|\nabla v_n|^2 - k^2 |v_n|^2) dx + \\
\int_{\partial D_1} \frac{\partial \tilde{u}_n}{\partial \nu} v_n ds - \int_{\partial D_3} i \sigma \tilde{u}_n v_n ds
\]

\[
= - \int_{\Omega \backslash D} (|\nabla w_n|^2 - k^2 |w_n|^2) dx - \int_D (|\nabla v_n|^2 - k^2 |v_n|^2) dx + \\
\int_{\partial D_3} (2 i \sigma v_n \tilde{w}_n + i \sigma |v_n|^2 + i \sigma |w_n|^2) ds + \\
\int_{\partial D_1} \left[ \left( v_n \frac{\partial \tilde{w}_n}{\partial \nu} - \tilde{w}_n \frac{\partial v_n}{\partial \nu} \right) + \left( v_n \frac{\partial \tilde{v}_n}{\partial \nu} - \tilde{v}_n \frac{\partial v_n}{\partial \nu} \right) \right] ds. \tag{6.7}
\]

This expression will be used to identify \( \partial D_1 \) from \( \partial D \). Now we prove the other expression (3.7) for \( \langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n, f_n \rangle \), which applies the value of \( v_n \) and \( w_n \) on \( \partial D_2 \) and \( \partial D_3 \). This expression will be applied to distinguish \( \partial D_2 \) and \( \partial D_3 \) from \( \partial D \) furthermore.

By a straightforward calculation, we get

\[
\int_{\Omega \backslash D} |\nabla (u_n - v_n)|^2 dx = \int_{\partial \Omega} u_n \frac{\partial (\tilde{u}_n - \tilde{v}_n)}{\partial \nu} ds - \int_{\partial D} u_n \frac{\partial (\tilde{u}_n - \tilde{v}_n)}{\partial \nu} ds + \\
\int_{\Omega \backslash D} k^2 u_n (\tilde{u}_n - \tilde{v}_n) dx - \int_{\Omega \backslash D} \nabla v_n \cdot \nabla (\tilde{u}_n - \tilde{v}_n) dx.
\]

From the definition of the Dirichlet-to-Neumann map, this generates

\[
\int_{\Omega \backslash D} |\nabla w_n|^2 dx = \langle (\Lambda_{\partial D, \sigma} - \Lambda_{0,0}) f_n, f_n \rangle - \int_{\partial D} u_n \frac{\partial (\tilde{u}_n - \tilde{v}_n)}{\partial \nu} ds + \\
\int_{\Omega \backslash D} k^2 u_n (\tilde{u}_n - \tilde{v}_n) dx - \int_{\Omega \backslash D} \nabla v_n \cdot \nabla \tilde{u}_n dx + \int_{\Omega \backslash D} |\nabla v_n|^2 dx. \tag{6.8}
\]
Applying $\nabla v_n \cdot \nabla \tilde{u}_n = \nabla \cdot (\tilde{u}_n \nabla v_n) - \tilde{u}_n \Delta v_n$ in this expression, we get

$$- \int_{\Omega \setminus \overline{D}} \nabla v_n \cdot \nabla \tilde{u}_n dx + \int_{\Omega \setminus \overline{D}} |\nabla v_n|^2 dx = - \int_{\partial \Omega} \tilde{u}_n \frac{\partial v_n}{\partial \nu} ds + \int_{\partial D} \tilde{u}_n \frac{\partial v_n}{\partial \nu} ds$$

$$- k^2 \int_{\Omega \setminus \overline{D}} \tilde{u}_n v_n dx + \int_{\Omega \setminus \overline{D}} |\nabla v_n|^2 dx - \int_{\partial D} |\nabla v_n|^2 dx. \quad (6.9)$$

Also by applying $|\nabla v_n|^2 = \nabla \cdot (\tilde{v}_n \nabla v_n) - \tilde{v}_n \Delta v_n$ and noticing $w_n = u_n - v_n = 0$ on $\partial \Omega$ in (6.9), we get

$$- \int_{\Omega \setminus \overline{D}} \nabla v_n \cdot \nabla \tilde{u}_n dx + \int_{\Omega \setminus \overline{D}} |\nabla v_n|^2 dx = \int_{\partial D} \tilde{u}_n \frac{\partial v_n}{\partial \nu} ds - k^2 \int_{\Omega \setminus \overline{D}} \tilde{u}_n v_n dx -$$

$$\int_{\partial D} \tilde{v}_n \Delta v_n dx - \int_{\partial D} |\nabla v_n|^2 dx. \quad (6.10)$$

Now inserting (6.10) into (6.8) says

$$\int_{\Omega \setminus \overline{D}} |\nabla w_n|^2 dx$$

$$= (\Lambda_{\overline{D}, \sigma} - \Lambda_{0,0}) f_n, f_n + \int_{\partial D} \left( \tilde{u}_n \frac{\partial v_n}{\partial \nu} - u_n \frac{\partial (\tilde{u}_n - \tilde{v}_n)}{\partial \nu} \right) ds + k^2 \int_{\partial D} |v_n|^2 dx +$$

$$k^2 \int_{\partial D} (u_n (\tilde{u}_n - \tilde{v}_n) - \tilde{u}_n v_n + v_n \tilde{v}_n) dx - \int_{\partial D} |\nabla v_n|^2 dx, \quad (6.11)$$

that is,

$$\langle \Lambda_{\overline{D}, \sigma} - \Lambda_{0,0} \rangle f_n, f_n$$

$$= \int_{\Omega \setminus \overline{D}} (|\nabla w_n|^2 - k^2 |w_n|^2) dx + \int_{\partial D} (|\nabla v_n|^2 - k^2 |v_n|^2) dx -$$

$$\int_{\partial D} \left( \tilde{u}_n \frac{\partial v_n}{\partial \nu} - u_n \frac{\partial (\tilde{u}_n - \tilde{v}_n)}{\partial \nu} \right) ds$$

$$= \int_{\Omega \setminus \overline{D}} (|\nabla w_n|^2 - k^2 |w_n|^2) dx + \int_{\partial D} (|\nabla v_n|^2 - k^2 |v_n|^2) dx -$$

$$\int_{\partial D_2} \left( \tilde{u}_n \frac{\partial v_n}{\partial \nu} + u_n \frac{\partial \tilde{v}_n}{\partial \nu} \right) ds - \int_{\partial D_3} \left( \tilde{u}_n \frac{\partial v_n}{\partial \nu} + u_n \frac{\partial \tilde{v}_n}{\partial \nu} - i \sigma |u_n|^2 \right) ds. \quad (6.12)$$

### 6.2 Estimate for $w$

Here we prove the fourth estimate in Theorem 5.2.

For given needle $c \in \Omega \setminus \overline{D}$, put $x_0 = c(t) \in \Omega \setminus \overline{D}$ and let $a \in \partial D$ be the point at which the needle $c$ first hits $\partial D$. Suppose $x_0$ is very near to $a$. Consider two
families of functions \( \{w(\cdot, x_0)\}, \{z(\cdot, x_0)\} \) depending on \( x_0 \) in some function space \( X \). We denote by \( w(\cdot, x_0) \sim z(\cdot, x_0) \) in \( X \) if \( \{w(\cdot, x_0) - z(\cdot, x_0)\} \) is a bounded set in \( X \) for \( x_0 \) very near to \( a \).

Let \( G_0(x - x_0) = \frac{1}{4\pi |x - x_0|} \). Then it is easy to see that
\[
(\partial_\nu + i\sigma)G(x - x_0) \sim (\partial_\nu + i\sigma)G_0(x - x_0)
\]
in \( L^2(\partial D) \), hence
\[
w(\cdot, x_0) \sim w_0(\cdot, x_0) \quad \text{in} \quad H^1(\Omega \setminus \overline{D}),
\]
where \( w = w(\cdot, x_0) \in H^1(\Omega \setminus \overline{D}) \) is the solution to (3.5) and \( w_0 = w_0(\cdot, x_0) \in H^1(\Omega \setminus \overline{D}) \) is the solution to
\[
\begin{cases}
\Delta w_0 + k^2 w_0 = 0, \\
\left( \frac{\partial}{\partial \nu} + i\sigma \right) w_0 = -\left( \frac{\partial}{\partial \nu} + i\sigma \right) G_0(\cdot - x_0), & \text{on} \partial D, \\
w_0 = 0, & \text{on} \partial \Omega.
\end{cases}
\]
By the Sobolev embedding \( H^{1/2}(\partial D) \hookrightarrow L^r(\partial D) \) with \( 2 \leq r \leq 4 \) and the Hölder inequality, for any \( q(\frac{4}{3} \leq q \leq 2) \), there exists a constant \( C > 0 \) such that
\[
\left| \int_{\partial D} ib\sigma(x)G_0(x - x_0)\phi ds \right| \leq \|i\sigma G_0(\cdot - x_0)\|_{L^r(\partial D)} \|\phi\|_{L^r(\partial D)} \leq C \|i\sigma G_0(\cdot - x_0)\|_{L^q(\partial D)} \|\phi\|_{H^{1/2}(\partial D)}
\]
for \( \phi \in H^{1/2}(\partial D) \), where \( \frac{1}{r} = 1 - \frac{1}{q} \) with \( \frac{4}{3} \leq q < 2 \).

Hence \( i\sigma G_0(\cdot - x_0) \sim 0 \) in \( H^{-1/2}(\partial D) \), and by the well-posedness of our boundary value problem, this implies
\[
w_0(\cdot, x_0) \sim w_1(\cdot, x_0) \quad \text{in} \quad H^1(\Omega \setminus \overline{D}),
\]
where \( w_1 = w_1(\cdot, x_0) \in H^1(\Omega \setminus \overline{D}) \) is the solution to
\[
\begin{cases}
\Delta w_1 + k^2 w_1 = 0, \\
\left( \frac{\partial}{\partial \nu} + i\sigma(x) \right) w_1 = -\frac{\partial}{\partial \nu} G_0(\cdot - x_0), & \text{on} \partial D, \\
w_1 = 0, & \text{on} \partial \Omega.
\end{cases}
\]
Now consider the solution \( w_2 = w_2(\cdot, x_0) \in H^1(\Omega \setminus \overline{D}) \) to
\[
\begin{cases}
\Delta w_2 = 0, \\
\left( \frac{\partial}{\partial \nu} + i\sigma(x) \right) w_2 = -\frac{\partial}{\partial \nu} G_0(\cdot - x_0), & \text{on} \partial D, \\
w_2 = 0, & \text{on} \partial \Omega.
\end{cases}
\]
For this problem, we have
\textbf{Claim 1:} \( i\sigma(x)w_2(\cdot, x_0) \sim 0 \) in \( H^{-1/2}(\partial D) \), \( w_2(x, x_0) \sim 0 \) in \( H^1(\Omega \setminus \overline{D}) \).
The proof given here also gives a more precise estimate for $w_2$, which will be used in the sequel.

Let $y = (y_1, y_2, y_3) = (y_1(x, x_0), y_2(x, x_0), y_3(x, x_0))$ be a boundary normal coordinates near point $a$ such that

$$y(a) = 0, \quad J(x) : = \frac{\partial(y(x, x_0))}{\partial x} = I \text{(identity matrix)}$$

at $x = x_0$ and $D_0 = \{y_1 < 0\}$ locally near point $a$. Also, let

$$A(x) : = |J(x)|^{-1}J(x)(J(x))^T, \quad x(x(x, x_0)) = x, \quad A(y) : = A(x(y; x_0)), \quad u(y) : = u(x(y; x_0)).$$

Then it is easy to see

(1) $A(y) \in C^1$ near $y = 0$;

(2) $\Delta u = 0$ near point $a \iff \nabla \cdot A \nabla u = 0$ near 0;

(3) $\delta(x(y; x_0) - x_0) = \delta(y - y_0)$;

(4) $\partial_\nu = \partial_{y_1}$.

In order to simplify the description of our argument, from now on we extend $x(x; y_0)$ and $A(y)$ to an open ball $V \subset \mathbb{R}^3$ centered at $y = 0$ without destroying their regularities and positivity of $A(y)$. By a direct estimate, we can easily see

$$G_0(y; y_0) \sim G_0(y - y_0) \quad \text{in } H^1(V),$$

where we have adopted the convention $y_0 = y(x_0; x_0)$.

Now consider the solution $w_2^0 \in H^1(R^3_+)$ to

$$\begin{cases}
\Delta w_2^0 = 0, & \text{in } y_1 > 0 \\
\partial_{y_1} w_2^0 = -\partial_{y_1} G_0(y - y_0) & \text{on } y_1 = 0
\end{cases} \quad (6.19)$$

and put $w_2(y) := w_2(x(y, x_0))$. If we can prove

**Claim 2:** $\nabla \cdot (A(y) - A(y_0)) \nabla w_2^0 \sim 0 \text{ in } (H^1_0(V \cap R^3_+))^*$.

Then we have

$$w_2 \sim w_2^0 \quad \text{in } H^1(V \cap R^3_+) \quad (6.20)$$

by observing

$$\begin{cases}
\nabla \cdot \nabla A \nabla (w_2 - w_2^0) = -\nabla \cdot \nabla (A(y) - A(y_0)) \nabla w_2^0, & \text{in } V \cap R^3_+ \\
\partial_{y_1} (w_2 - w_2^0) = -\partial_{y_1} G_0(y, y_0) + \partial_{y_1} G_0(y - y_0), & \text{on } y_1 = 0.
\end{cases} \quad (6.21)$$

Proof for Claim 2 will be given in Section 6.3. Therein we also give a precise expression for $w_2^0(y)$. Then, this expression and (6.20) imply Claim 1. The proof is complete.
Now we can see that
\[ w_1(\cdot, x_0) \sim w_2(\cdot, x_0) \quad \text{in } H^1(\Omega \setminus D) \]  \hspace{1cm} (6.22)
from Claim 1 and the well-posedness of our boundary value problem.

Now summing up (6.13), (6.16), (6.20) and (6.22), as well as the expression of \( \tilde{w}_2^0(y) \) given in the next subsection, we have
\[
\int_{\partial D} |w(x, x_0)|^2 ds \leq C \left( \int_{\partial D} |G(x - c(t))|^2 ds + 1 \right),
\]
which completes the proof of the fourth estimate in Theorem 5.2.

### 6.3 Proof for Claim 2

**Proof:** Let \( y_0 = (y_{01}, y_{02}, y_{03}) = (y_{01}, y'_0) \). Then it is well known that \( H(y) = H(y; y_0) = G_0(y - y_0) \) can be given by
\[
H(y) = \begin{cases} 
H_+(y) = H_+(y; y_0), & \text{in } y_1 > y_{01} \\
H_-(y) = H_-(y; y_0), & \text{in } y_1 < y_{01}
\end{cases}
\]  \hspace{1cm} (6.23)
with the solution \( H_\pm(y) \) to
\[
\begin{align*}
\Delta H_\pm(y) &= 0, \quad \text{in } \pm (y_1 - y_{01}) > 0 \\
H_+(y)|_{y_1 = y_{01} + 0} &= H_-(y)|_{y_1 = y_{01} - 0} \\
\partial_{y_1} H_+(y)|_{y_1 = y_{01} + 0} - \partial_{y_1} H_-(y)|_{y_1 = y_{01} - 0} &= -\delta(y' - y'_0).
\end{align*}
\]  \hspace{1cm} (6.24)
Denote by \( \Gamma_\pm(y_1, \eta') \) and \( w(y_1, \eta') \) the Fourier transforms of \( H_\pm(y) \) and \( \tilde{w}_2^0(y) \) with respect to \( y' \), respectively. Then, \( \Gamma_\pm := e^{i\eta\cdot\eta'} \Gamma_\pm \) and \( w' := e^{i\eta\cdot\eta'} w \) satisfy
\[
\begin{align*}
(\partial_{y_1}^2 - |\eta'|^2) \Gamma_\pm' &= 0, \quad \text{in } \pm (y_1 - y_{01}) > 0 \\
\Gamma_\pm'|_{y_1 = y_{01} + 0} &= \Gamma_\pm'|_{y_1 = y_{01} - 0} \\
\partial_{y_1} \Gamma_\pm'|_{y_1 = y_{01} + 0} - \partial_{y_1} \Gamma_\pm'|_{y_1 = y_{01} - 0} &= -1
\end{align*}
\]  \hspace{1cm} (6.25)
and
\[
\begin{align*}
(\partial_{y_1}^2 - |\eta'|^2) w' &= 0, \quad \text{in } y_1 > 0 \\
\partial_{y_1} w' &= -\partial_{y_1} \Gamma_-, \quad \text{on } y_1 = 0
\end{align*}
\]  \hspace{1cm} (6.26)
respectively. \( \Gamma_\pm' := \Gamma_\pm'(y_1) \) is given by
\[
\Gamma_\pm'(y_1) = 2^{-1}|\eta'|^{-1}e^{\mp(y_1 - y_{01})|\eta'|}.
\]
Hence \( w' = w'(y_1) = 2^{-1}|\eta'|^{-1}e^{-(y_1 + y_{01})|\eta'|} \). Comparing these two formula, we have
\[
\tilde{w}_2^0(y) = H_+(y_1, y'_1 - y_{01}, y'_0) = \frac{1}{4\pi \sqrt{(y_1 + y_{01})^2 + |y' - y'_0|^2}}.
\]
This completes the proof of Claim 2. □

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References


