Title

New approach to the Hadamard variational formula for the Green function of the Stokes equations (Mathematical Analysis in Fluid and Gas Dynamics)

Author(s)

Ushikoshi, Erika

Citation

数理解析研究所講究録 2014, 1883: 49-59

Issue Date

2014-04

URL

http://hdl.handle.net/2433/195678

Type

Departmental Bulletin Paper

Textversion

publisher
New approach to the Hadamard variational formula for the Green function of the Stokes equations.

Faculty of Engineering, Tamagawa University

Introduction.

Let $\Omega \subset \mathbb{R}^d (d \geq 2)$ be a bounded domain with a smooth boundary $\partial \Omega$. We consider the stationary Stokes equations with the homogeneous boundary condition, which describes the motion of the incompressible viscous fluid moving infinitesimally in $\Omega$.

\[
\begin{aligned}
&\Delta v - \nabla q = f \quad \text{in } \Omega, \\
&\text{div } v = 0 \quad \text{in } \Omega, \\
&v = 0 \quad \text{on } \partial \Omega,
\end{aligned}
\]

(0.1)

where $v = v(x) = (v^1(x), \cdots, v^d(x))$ and $q = q(x)$ denote the unknown velocity and the pressure at $x = (x^1, \cdots, x^d) \in \Omega$ respectively, while $f = f(x) = (f^1(x), \cdots, f^d(x))$ is the given external force.

Our motivation is to lay the foundation of the analysis of the Hadamard variational formula for the Green functions of the Stokes equations, which may lead us to the generalization to the higher variation $\delta^n G$ and $\delta^n R$. Here $G$ is the Green matrix for the velocity and $R$ is the Green function for the pressure. More precisely, let $\{\Omega_\epsilon\}_{\epsilon \geq 0}$ be a family of the domain with a smooth boundary. For a small parameter $\epsilon \geq 0$, we regard $\Omega_\epsilon$ as a perturbed domain $\Omega$ with a volume preserving diffeomorphism $\Phi_\epsilon : \overline{\Omega} \to \overline{\Omega}_\epsilon$. We consider the Green function associated with (0.1) in $\Omega_\epsilon$

\[
\begin{aligned}
&\Delta_x G_{\epsilon,n}(x, y) - \nabla_x R_{\epsilon,n}(x, y) = \epsilon_n \delta(x - y), \quad (x, y) \in \Omega_\epsilon \times \Omega_\epsilon, \\
&\text{div } G_{\epsilon,n}(x, y) = 0, \quad (x, y) \in \Omega_\epsilon \times \Omega_\epsilon, \\
&G_{\epsilon,n}(x, y) = 0, \quad x \in \partial \Omega_\epsilon, y \in \Omega_\epsilon,
\end{aligned}
\]

(0.2)

for $n = 1, \cdots, d$, where $G_{\epsilon,n}(x, y) = \{G_{\epsilon,n}^i(x, y)\}_{i=1,\cdots,d}$ is the Green matrix for the velocity, $R_{\epsilon,n}(x, y) = \{R_{\epsilon,n}^i(x, y)\}_{i=1,\cdots,d}$ is the Green function for the pressure and $\{\epsilon_n\}_{n=1,\cdots,d}$ denotes a canonical basis in $\mathbb{R}^d$. In this paper, we construct a new and systematic method and establish the formula for the first variation $\{\delta G, \delta R\}$ defined by $\delta G(x, y) :=$
\[
\lim_{\epsilon \to 0} \epsilon^{-1}(G_\epsilon(x, y) - G(x, y)) \quad \text{and} \quad \delta R(x, y) := \lim_{\epsilon \to 0} \epsilon^{-1}(R_\epsilon(x, y) - R(x, y)),
\]
Moreover, we inductively derive the second variation \( \{\delta^2 G, \delta^2 R\} \) defined by
\[
\delta^2 G(x, y) := \lim_{\epsilon \to 0} \frac{G_\epsilon(x, y) - G(x, y) - \epsilon \delta G(x, y)}{\epsilon^2}
\]
and
\[
\delta^2 R(x, y) := \lim_{\epsilon \to 0} \frac{R_\epsilon(x, y) - R(x, y) - \epsilon \delta R(x, y)}{\epsilon^2}.
\]
For the smooth function \( \rho \) defined on \( \partial \Omega \), we denote \( \Omega_\epsilon \) by the interior domain with the boundary \( \partial \Omega_\epsilon := \{x + \epsilon \rho(x) \nu_x \mathbin{;} x \in \partial \Omega\} \), where \( \nu_x \) denotes the unit outer normal to \( \partial \Omega \).
The variational formula for the usual Laplace operator was first introduced by Hadamard [7] when \( \rho \) is a non-negative or a non-positive function on \( \partial \Omega \). Later, Garabedian [5], Garabedian-Schiffer [6] and Aomoto [1] refined the proof of [7], and they gave the formula as
\[
(0.3) \quad \delta G(y, z) = \int_{\partial \Omega} \frac{\partial G}{\partial \nu_x}(x, y) \frac{\partial G}{\partial \nu_x}(x, z) \rho(x) \, d\sigma_x
\]
for all \( y, z \in \Omega \). Furthermore, Garabedian-Schiffer [6] also gave rigorous proof of the second variation formula under the monotone perturbation. The formula was extended to some normal elliptic boundary value problem by Peetre [15] and Fujiwara-Ozawa [4]. In this paper, we consider the generalization of their results to the elliptic system of equations, and establish the formula for the higher variation. Recently, the author and Kozono [9] established the formula for the Green function of the Stokes equations corresponding to the velocity, and later on, its formula for the pressure was also proved by [17]. More precisely, they transformed (0.2) to the system in \( \Omega \) by making use of the volume preserving diffeomorphism \( \Phi_\epsilon : \Omega \to \Omega_\epsilon \) as in Inoue-Wakimoto [8], and gave the representation formula of \( \delta G(y, z) \) and \( \delta R(y, z) \) as
\[
(0.4) \quad \delta G_m^n(y, z) = \int_{\partial \Omega} \sum_{i=1}^{d} \frac{\partial G^n_i}{\partial \nu_x}(x, y) \frac{\partial G^m_i}{\partial \nu_x}(x, z) \rho(x) \, d\sigma_x,
\]
\[
(0.5) \quad \delta R_m^n(y, z) = \int_{\partial \Omega} \sum_{i=1}^{d} \frac{\partial R_i}{\partial \nu_x}(y, x) \frac{\partial G^m_i}{\partial \nu_x}(x, z) \rho(x) \, d\sigma_x
\]
for \( m, n = 1, \cdots, d \) and for all \( y, z \in \Omega \), respectively.

The analysis of the \( \epsilon \)-dependence of the Green function \( G_\epsilon \) is one of the most important problem to derive the Hadamard variational formula. The author [17] investigated that by making use of the method developed by Fujiwara-Ozawa [4] and Ozawa [12]. Indeed, she applied the Schauder estimate of the Stokes equations due to Solonnikov [16], and proved that there exist \( \delta G_n'(x, y) := \frac{d}{d \epsilon} \Phi^{-1}_\epsilon \cdot G_{\epsilon,n}(x, y) \big|_{\epsilon=0} \) and \( \delta R_n'(x, y) := \frac{d}{d \epsilon} \Phi^{-1}_\epsilon \cdot R_{\epsilon,n}(x, y) \big|_{\epsilon=0} \). Then, she derived that \( \{\delta G', \delta R'\} \) is a solution of the inhomogeneous Stokes equations in \( \Omega \) with the homogeneous Dirichlet boundary condition on
\[ \partial \Omega. \] Since \( \{\delta G', \delta R'\} \) is slightly different from the usual variation \( \{\delta G, \delta R\} \), we construct the variational formula for \( \{\delta G, \delta R\} \) by integration by parts of the volume integral for \( \{\delta G', \delta R'\} \). In such a procedure, we need to restrict ourselves to choose a special diffeomorphism \( \Phi_\varepsilon(x) \) for each fixed \( y \in \Omega \) in such a way that \( \Phi_\varepsilon \) vanishes identically in the neighborhood of \( y \). Indeed, since the order of the singularity of \( R(x, y) \) at \( x = y \) is by one degree higher than that of \( G(x, y) \), it is necessary to control behavior of \( R(x, y) \) near \( x = y \) in transforming the volume integral in \( \Omega \) that of the surface integral on \( \partial \Omega \).

In the present paper, we handled the general volume preserving perturbation as in [9]. By making use of the error estimates between \( \delta G - \delta G' \) and \( \delta R - \delta R' \), we directly prove that \( \{\delta G, \delta R\} \) satisfies the homogeneous Stokes equations in \( \Omega \) with some inhomogeneous boundary condition on \( \partial \Omega \). As a result, by the usual integral representation formula we succeed to obtain a satisfactory Hadamard variational formula for both \( \delta G \) and \( \delta R \) like (0.4) and (0.5) without any restriction on choice of the diffeomorphism \( \Phi_\varepsilon \). Furthermore, we can inductively investigate the second variation of the Green function \( \{\delta^2 G, \delta^2 R\} \).

Namely, we establish a certain algorithm to get the second variation of the Hadamard variational formula for the velocity and the pressure.

## 1 Results.

To state our result, we first introduce an assumption on the perturbation \( \{\Omega_\varepsilon\}_{\varepsilon \geq 0} \) of domains from \( \Omega \).

**Assumption.** For every \( \varepsilon \geq 0 \), there is a diffeomorphism \( \Phi_\varepsilon : \overline{\Omega} \rightarrow \overline{\Omega}_\varepsilon \) satisfying the following condition.

(A.1) \( \Phi_\varepsilon = (\phi_1^\varepsilon, \phi_2^\varepsilon, \cdots, \phi_d^\varepsilon) \in C^\infty(\overline{\Omega})^d \);

(A.2) \( \Phi_0(x) = x \) for all \( x \in \overline{\Omega} \);

(A.3) There exists \( S = (S^1, S^2, \cdots, S^d) \in C^\infty(\overline{\Omega})^d \) such that \( K(x; \varepsilon) := \Phi_\varepsilon(x) - x - S(x)\varepsilon \) satisfies

\[
\sup_{x \in \overline{\Omega}} |K_j(x; \varepsilon)| + \sup_{x \in \overline{\Omega}} |\nabla K_j(x; \varepsilon)| = O(\varepsilon^3), \quad \text{as} \ \varepsilon \rightarrow 0, \quad j = 1, \cdots, d;
\]

(A.4) It holds that

\[
\det \left( \frac{\partial \phi_i^\varepsilon}{\partial x_j^\varepsilon}(x) \right)_{i,j=1,\cdots,d} = 1 \quad \text{for all} \ x \in \overline{\Omega} \text{and all} \ \varepsilon \geq 0.
\]

It should be noticed that by (A.4), \( \Phi_\varepsilon \) defines a volume preserving diffeomorphism from \( \overline{\Omega} \) onto \( \overline{\Omega}_\varepsilon \) i.e., \( \text{vol}(\Omega_\varepsilon) = \text{vol}(\Omega) \) for all \( \varepsilon \geq 0 \). Moreover, the vector function \( S \in C^\infty(\overline{\Omega})^d \) defined by (A.3) satisfies the divergence free property. Namely, it holds that

\[
\text{div} \ S(x) = 0
\]
for all \( x \in \overline{\Omega} \). For the proof, see Inoue-Wakimoto[8, Proposition 2.3].

Now we can state our result.

Let \( \{ G_{\epsilon,m}, R_{\epsilon,m} \}_{m=1,\ldots,d} \) be the Green function of the Dirichlet boundary value problem for the Stokes equations, i.e.,

\[
\begin{cases}
\Delta G_{\epsilon,m}(\tilde{x}, \tilde{z}) - \nabla R_{\epsilon,m}(\tilde{x}, \tilde{z}) = \delta(\tilde{x} - \tilde{z}) & \tilde{x}, \tilde{z} \in \Omega_{\epsilon} \times \Omega_{\epsilon}, \\
\text{div} G_{\epsilon,m}(\tilde{x}, \tilde{z}) = 0 & \tilde{x} \in \partial \Omega_{\epsilon}, \ \tilde{z} \in \Omega_{\epsilon},
\end{cases}
\]

(1.2)

for \( m = 1, \ldots, d \), where \( \{ e_m \}_{m=1,\ldots,d} \) denotes a canonical basis in \( \mathbb{R}^d \). Clearly, the Green function \( \{ G_{0,m}, R_{0,m} \}_{m=1,\ldots,d} = \{ G_m, R_m \}_{m=1,\ldots,d} \), respectively. Furthermore, we introduce the fundamental solution \( \{ p_m \}_{m=1,\ldots,d} \) for the pressure of (1.2) as follows;

\[
p_m(x, z) := -\frac{1}{\omega_d} \frac{(x^m - z^m)}{|x - z|^d}, \quad m = 1, \ldots, d,
\]

(1.3)

where \( \omega_d \) denotes the volume of unit sphere in \( \mathbb{R}^d \), i.e., \( \omega_d := \frac{2\pi^{d/2}}{\Gamma(d/2)} \).

**Theorem 1.1.** Let \( \{ G_{\epsilon,m}, R_{\epsilon,m} \}_{m=1,\ldots,d} \) be the Green matrix of the Dirichlet boundary value problem for (1.2) with \( \int_{\Omega_{\epsilon}}(R_{\epsilon,m}(\tilde{x}, \tilde{z}) - p_m(\tilde{x}, \tilde{z}))d\tilde{x} = 0 \) for all \( \tilde{z} \in \Omega_{\epsilon} \). Then there exist

\[
\delta G_m^n(y, z) := \lim_{\epsilon \to 0} \frac{G_{\epsilon,m}^n(y, z) - G_m^n(y, z)}{\epsilon}, \quad \delta R_m(y, z) := \lim_{\epsilon \to 0} \frac{R_{\epsilon,m}(y, z) - R_m(y, z)}{\epsilon}
\]

(1.4)

for all \( y, z \in \Omega \) with \( y \neq z \), which have the explicit representation as

\[
\delta G_m^n(y, z) = \int_{\partial \Omega} \sum_{i=1}^d \frac{\partial G_1^n(x, y)}{\partial \nu_x} \frac{\partial G_m^n(x, z)}{\partial \nu_x} S(x) \cdot \nu_x \, d\sigma_x,
\]

\[
\delta R_m(y, z) = \int_{\partial \Omega} \sum_{i=1}^d \frac{\partial R_1(y, x)}{\partial \nu_x} \frac{\partial G_m^n(x, z)}{\partial \nu_x} S(x) \cdot \nu_x \, d\sigma_x
\]

for \( m, n = 1, \ldots, d \), where \( \nu_x = (\nu_x^1, \ldots, \nu_x^d) \) is the unit outer normal to \( \partial \Omega \) at \( x \in \partial \Omega \) and \( \sigma_x \) denotes the surface element of \( \partial \Omega \).

We next mention the Hadamard variational formula for the second variation.

**Theorem 1.2.** Let \( \{ G_{\epsilon,m}, R_{\epsilon,m} \}_{m=1,\ldots,d} \) be the Green function of the Dirichlet boundary value problem for (1.2) with \( \int_{\Omega_{\epsilon}}(R_{\epsilon,m}(\tilde{x}, \tilde{z}) - p_m(\tilde{x}, \tilde{z}))d\tilde{x} = 0 \) for all \( \tilde{z} \in \Omega_{\epsilon} \). Then there exist

\[
\delta^2 G_m^n(y, z) := \lim_{\epsilon \to 0} \frac{G_{\epsilon,m}^n(y, z) - G_m^n(y, z) - \epsilon \delta G_m^n(y, z)}{\epsilon^2},
\]

(1.5)

\[
\delta^2 R_m(y, z) := \lim_{\epsilon \to 0} \frac{R_{\epsilon,m}(y, z) - R_m(y, z) - \epsilon \delta R_m(y, z)}{\epsilon^2}
\]

(1.6)
for all \(y, z \in \Omega\) with \(y \neq z\), which have the explicit representation as

\[
\delta^2 G_m^n(y, z) = \int_{\partial \Omega} \sum_{i=1}^{d} \frac{\partial G_m^n(x, z)}{\partial v_z} (\nabla_x \delta G_m^i(x, z) \cdot S(x) + 2 \frac{\partial^2 G_m^n(x, z)}{\partial v_z^2} (S(x) \cdot v_z)^2) \, d\sigma_x,
\]

\[
\delta^2 R_m(y, z) = \int_{\partial \Omega} \sum_{i=1}^{d} \frac{\partial R_i(y, x)}{\partial v_x} (\nabla_x \delta G_m^i(x, z) \cdot S(x) + 2 \frac{\partial^2 G_m^n(x, z)}{\partial v_z^2} (S(x) \cdot v_z)^2) \, d\sigma_x
\]

for \(m, n = 1, \cdots, d\), where \(\nu_x = (\nu_x^1, \cdots, \nu_x^d)\) is the unit outer normal to \(\partial \Omega\) at \(x \in \partial \Omega\) and \(\sigma_x\) denotes the surface element of \(\partial \Omega\).

**Remark 1.1.** (1) Theorem 1.1 are the same formulas given by [17]. However, we establish a new approach to prove them, which is different from the previous one. This method enables us to remove a restriction about the diffeomorphism \(\Phi_\epsilon\) and to simplify the computation in [17].

(2) We establish the method to construct the second variation of the Green function \(\{G_\epsilon, R_\epsilon\}\) in Theorem 1.2. This approach seems to be also applicable to the case of the Laplace equation under the general perturbation of domains.

## 2 Preliminaries.

Although our main result Theorem 1.1 and 1.2 hold for all \(d \geq 2\), for the sake of simplicity, we restrict ourselves to the case \(d \geq 3\). Indeed, it is easy to see that our argument in the subsequent sections works even in the case \(d = 2\).

Firstly, we introduce the Green matrix of the Stokes equations derived by Odqvist [11]. The Green matrix \(\{G_n^i\}_{n=1,\cdots,d}\) for the velocity and the Green function \(\{R_n\}_{n=1,\cdots,d}\) for the pressure can be represented by the fundamental tensor \(\{u_n, p_n\}_{n=1,\cdots,d}\) of the Stokes equations (1.2) with the compensation term \(\{q_n, q_n\}_{n=1,\cdots,d}\) as follows.

\[
\begin{cases}
G_n^i(x, y) = u_n^i(x, y) - q_n^i(x, y), \\
R_n(x, y) = p_n(x, y) - q_n(x, y),
\end{cases}
\]

where

\[
u_n(x, y) := -\frac{1}{2\omega_d(d - 2)} \left[ \frac{\delta^{in}}{|x-y|^{d-2}} + (d-2) \frac{(x^i-y^i)(x^n-y^n)}{|x-y|^{d}} \right], \quad (2.2)
\]

\(\{p_n\}_{n=1,\cdots,d}\) is as in (1.3) for \(i, n = 1, \cdots, d\). The compensation term \(\{q_n, q_n\}_{n=1,\cdots,d}\) is chosen so that (1.2) is satisfied, that is,

\[
\begin{cases}
\Delta_x q_n^i(x, y) - \nabla_x q_n(x, y) = 0, & x \in \Omega, \\
\sum_{i=1}^{d} \nabla_x q_n^i(x, y) = 0, & x \in \Omega, \\
q_n^i(x, y) = u_n^i(x, y), & x \in \partial \Omega, & i, n = 1, \cdots, d
\end{cases}
\]

(2.3)
where $\nabla_{x^{i}} := \frac{\partial}{\partial x^{i}}$ for $i = 1, \cdots, d$. For any fixed $y \in \Omega$, $q^{i}_{n}(\cdot, y)$ and $q_{n}(\cdot, y)$ are analytic functions in $\Omega$ and continuous in $\overline{\Omega}$.

Finally, we recall the Green integral formula for the Stokes operator $\mathcal{L}$ as in [11], [10],

$$
\int_{\Omega} \sum_{i=1}^{d} \{ \mathcal{L}^{i}(v, \pi)(x)w^{i}(x) - \mathcal{L}^{i}(w, -\tilde{\pi})(x)v^{i}(x) \} \, dx
$$

$$
= \int_{\partial\Omega} \sum_{i,j=1}^{d} \{ T^{ij}(v, \pi)(x)w^{i}(x) - T^{ij}(w, -\tilde{\pi})(x)v^{i}(x) \} \nu_{x}^{j} \, d\sigma_{x},
$$

where $\{ T^{ij} \}_{i,j=1,\cdots,d}$ is the stress tensor for the velocity $v$ and the pressure $\pi$ defined by

$$
T^{ij}(v, \pi)(x) := -\delta^{ij}\pi(x) + \left( \frac{\partial v^{i}}{\partial x^{j}}(x) + \frac{\partial v^{j}}{\partial x^{i}}(x) \right), \quad i,j = 1, \cdots, d
$$

for the vector functions $v, w \in C^{2}(\overline{\Omega})^{d}$ with $\text{div} \, v = \text{div} \, w = 0$ in $\Omega$ and scalar functions $\pi, \tilde{\pi} \in C^{1}(\overline{\Omega})$, $\nu_{x} = (\nu_{x}^{1}, \cdots, \nu_{x}^{d})$ is the unit outer normal to $\partial\Omega$ at $x \in \partial\Omega$ and $\sigma_{x}$ denotes the surface element of $\partial\Omega$.

**Lemma 2.1.** Let $\{ G_{n}, R_{n} \}_{n=1,\cdots,d}$ be the Green function for the Stokes equations as in (2.1). Then it holds that

$$
\lim_{\rho \to 0} \int_{\partial B_{\rho}(y)} \sum_{i,j=1}^{d} T^{ij}(G_{n}, R_{m})(x, y)v^{i}(x)v_{x}^{j} \, d\sigma_{x} = -v^{n}(y), \quad n = 1, \cdots, d
$$

for all $y \in \Omega$ and all smooth vector functions $v = (v^{1}, \cdots, v^{d})$ near $y$, where $\{ T^{ij} \}_{i,j=1,\cdots,d}$ is the stress tensor defined by (2.5), $\partial B_{\rho}(y)$ denotes the surface centered at $y$ with the radius $\rho$, $\nu_{x}$ is the unit inner normal vector to $\partial B_{\rho}(y)$ at $x$ and $\sigma_{x}$ denotes the surface element of $\partial B_{\rho}(y)$.

### 3 Analysis of the $\varepsilon$-dependence of the Green function.

In this section, we consider the $\varepsilon$-dependence of the Green function $\{ G_{\varepsilon,m}, R_{\varepsilon,m} \}_{m=1,\cdots,d}$. Namely, we investigate the differentiability of the Green function with respect to $\varepsilon$. Indeed, it holds that;

**Lemma 3.1.** For any fixed $z$ in $\Omega$, there exist $\{ \delta G_{m}(\cdot, z) \}_{m=1,\cdots,d} \in C^{2+\theta}(\overline{\Omega} \setminus \{ z \})$ and $\{ \delta R_{m}(\cdot, z) \}_{m=1,\cdots,d} \in C^{1+\theta}(\overline{\Omega} \setminus \{ z \})$ with $0 < \theta < 1$, defined by

$$
\delta G_{m}(x, z) := \lim_{\varepsilon \to 0} \frac{g_{\varepsilon,m}(x,z) - G_{m}(x,z)}{\varepsilon},
$$

$$
\delta R_{m}(x, z) := \lim_{\varepsilon \to 0} \frac{r_{\varepsilon,m}(x,z) - R_{m}(x,z)}{\varepsilon}, \quad m = 1, \cdots, d
$$
for all $x \in \overline{\Omega}$ with $x \neq z$, where $\{g_{\epsilon,m}, r_{\epsilon,m}\}_{m=1, \cdots, d}$ is respectively defined by

\begin{align}
(3.3) & \quad g_{\epsilon,m}^{i}(x, z) := \sum_{j=1}^{d} \frac{\partial x^{i}}{\partial \tilde{x}^{j}} G_{\epsilon m}^{j}(\tilde{x}, \tilde{z}), \\
(3.4) & \quad r_{\epsilon,m}(x, z) := R_{\epsilon,m}(\tilde{x}, \tilde{z}), \quad i, m = 1, \cdots, d.
\end{align}

Similarly to Lemma 3.1, we can also assure the existence of the second variation $\{\delta^{2}G_{m}', \delta^{2}R_{m}'\}_{m=1, \cdots, d}$ defined by

\begin{align}
(3.5) & \quad \delta^{2}G_{m}'(x, z) := \lim_{\epsilon \rightarrow 0} \frac{g_{\epsilon,m}(x, z) - G_{m}(x, z) - \epsilon \delta G_{m}'(x, z)}{\epsilon^{2}}, \\
(3.6) & \quad \delta^{2}R_{m}'(x, z) := \lim_{\epsilon \rightarrow 0} \frac{r_{\epsilon,m}(x, z) - R_{m}(x, z) - \epsilon \delta R_{m}'(x, z)}{\epsilon^{2}}, \quad m = 1, \cdots, d,
\end{align}

where $\{g_{\epsilon,m}, r_{\epsilon,m}\}_{m=1, \cdots, d}$ and $\{\delta G_{m}', \delta R_{m}'\}_{m=1, \cdots, d}$ are as in (3.3), (3.4), (3.1) and (3.2), respectively.

**Corollary 3.1.** For any fixed $z$ in $\Omega$, there exist $\{\delta^{2}G_{m}'(\cdot, z)\}_{m=1, \cdots, d} \in C^{2+\theta}(\overline{\Omega} \setminus \{z\})$ and $\{\delta^{2}R_{m}'(\cdot, z)\}_{m=1, \cdots, d} \in C^{2+\theta}(\overline{\Omega} \setminus \{z\})$ with $0 < \theta < 1$.

**Remark 3.1.** The existence of $\delta G$ defined by (1.4) is assured by the following identity, which is derived by Lemma 3.1. Indeed, it holds that

\begin{align}
(3.7) & \quad \delta G_{m}^{n}(x, z) = \delta G_{m}^{\prime n}(x, z) - \nabla_{x}G_{m}^{n}(x, z) \cdot S(x) - \nabla_{z}G_{m}^{n}(x, z) \cdot S(z) + \sum_{i=1}^{d} \frac{\partial S^{n}}{\partial x^{i}}(x) G_{m}^{i}(x, z)
\end{align}

for $m, n = 1, \cdots, d$ and for all $x \in \overline{\Omega} \setminus \{z\}$, where $\{\delta G_{m}', \delta R_{m}'\}_{m=1, \cdots, d}$ are as in (3.1) and (3.2), respectively, and $\{S^{i}\}_{i=1, \cdots, d}$ is the vector function introduced by (A.3). Furthermore, we also have by Corollary 3.1 that

\begin{align}
(3.8) & \quad \delta^{2}G_{m}^{n}(x, z) \\
& = \delta^{2}G_{m}^{\prime n}(x, z) - \nabla_{x}\delta G_{m}^{n}(x, z) \cdot S(x) - \nabla_{z}\delta G_{m}^{n}(x, z) \cdot S(z) + \delta G_{m}(x, z) \cdot \nabla_{x}S^{n}(x) \\
& \quad + \sum_{i=1}^{d} \left( \nabla_{x}G_{m}^{i}(x, z) \cdot S(z) \frac{\partial S^{n}}{\partial x^{i}}(x) - G_{m}(x, z) \cdot \nabla_{x}S^{i}(x) \frac{\partial S^{n}}{\partial x^{i}}(x) + \nabla_{x}G_{m}^{i}(x, z) \cdot S(x) \frac{\partial S^{n}}{\partial x^{i}}(x) \right) \\
& \quad - \nabla_{x}\nabla_{z}G_{m}^{n}(x, z) S(x) \cdot S(z) - \frac{1}{2} \nabla_{z}^{2}G_{m}^{n}(x, z) S(z) \cdot S(z) - \frac{1}{2} \nabla_{x}^{2}G_{m}^{n}(x, z) S(x) \cdot S(x)
\end{align}

for $m, n = 1, \cdots, d$ and for all $x \in \overline{\Omega} \setminus \{z\}$, where $\{\delta^{2}G_{m}', \delta^{2}R_{m}'\}_{m=1, \cdots, d}$ are as in (3.5) and (3.6), respectively.
4 Construction of the Hadamard variational formula.

In this section, we shall introduce the key lemmas to establish the representation formula for both of them. The following lemma is essential to construct the Hadamard variational formula for the first variation $\{\delta G_{m}, \delta R_{m}\}_{m=1,\cdots,d}$.

Lemma 4.1. For any fixed $z \in \Omega$, there exist $\{\delta G_{m}(\cdot, z)\}_{m=1,\cdots,d} \in C^{2+\theta}(\overline{\Omega} \setminus \{z\})$ and $\{\delta R_{m}(\cdot, z)\}_{m=1,\cdots,d} \in C^{2+\theta}(\overline{\Omega} \setminus \{z\})$ with $0 < \theta < 1$, defined by (1.4) respectively, and they satisfy the Stokes equations with the inhomogeneous Dirichlet boundary condition, i.e.,

$$
\begin{align*}
\Delta_x \delta G_m(x, z) - \nabla_x \delta R_m(x, z) &= 0, \quad x \in \Omega, \\
\text{div} \delta G_m(x, z) &= 0, \quad x \in \Omega, \\
\delta G_m^n(x, z) &= -\nabla_x G_m^n(x, z) \cdot S(x), \quad x \in \partial \Omega
\end{align*}
$$

for $m, n = 1, \cdots, d$, where $\{S^i\}_{i=1,\cdots,d}$ is the vector function introduced by (A.3).

We have similarly to Lemma 4.1 that $\{\delta^2 G_m, \delta^2 R_m\}_{m=1,\cdots,d}$ as in (1.5) and (1.6) also satisfies the homogeneous Stokes equations with the inhomogeneous Dirichlet boundary condition. Indeed, it holds;

Corollary 4.1. For any fixed $z \in \Omega$, there exist $\{\delta^2 G_{m}(\cdot, z)\}_{m=1,\cdots,d} \in C^{2+\theta}(\overline{\Omega} \setminus \{z\})$ and $\{\delta^2 R_{m}(\cdot, z)\}_{m=1,\cdots,d} \in C^{1+\theta}(\overline{\Omega} \setminus \{z\})$ defined by (1.5) and (1.6) with $0 < \theta < 1$, and they satisfy the Stokes equations with the inhomogeneous Dirichlet boundary condition, i.e.,

$$
\begin{align*}
\Delta_x \delta^2 G_m(x, z) - \nabla_x \delta^2 R_m(x, z) &= 0, \quad x \in \Omega, \\
\text{div} \delta^2 G_m(x, z) &= 0, \quad x \in \Omega, \\
\delta^2 G_m^n(x, z) &= -2\nabla_x G_m^n(x, z) \cdot S(x) - \nabla_x^2 G_m^n(x, z) S(x) \cdot S(x), \quad x \in \partial \Omega
\end{align*}
$$

for $m, n = 1, \cdots, d$, where $\{S^i\}_{i=1,\cdots,d}$ is the vector function introduced by (A.3).

5 Proof of the main theorems.

In this section, we complete the proofs of Theorem 1.1 and 1.2.

5.1 Proof of Theorem 1.1.

We apply the Green integral formula for the Stokes operator $L$ introduced by (2.4) in $\Omega \setminus B_{\rho}(y)$ to the functions

$$
\begin{align*}
\nu &= \delta G_m(x, z), \quad \pi = \delta R_m(x, z), \\
\omega &= G_n(x, y), \quad \bar{\pi} = -R_m(x, y)
\end{align*}
$$
for $m, n = 1, \cdots, d$. Then since $\mathcal{L}(G_n, R_n)(x, y) = 0$ in $\Omega \setminus B_\rho(y)$, we have by Lemma 4.1 that

\[(5.1)\]

$$\int_{\partial(\Omega \setminus B_\rho(y))} \sum_{i,j=1}^{d} \{ T^{ij}(\delta G_m, \delta R_m)(x, z)G_n^i(x, y) - T^{ij}(G_n, R_n)(x, y)\delta G_m^i(x, z) \} \, d\sigma_x = 0$$

for $m, n = 1, \cdots, d$. We next consider the limit $\rho \to 0$ at the point of $y$. It follows from Lemma 2.1 that

\[(5.2)\]

$$\lim_{\rho \to 0} \int_{\partial B_\rho(y)} \sum_{i,j=1}^{d} \left( T^{ij}(\delta G_m, \delta R_m)(x, z)G_n^i(x, y) - T^{ij}(G_n, R_n)(x, y)\delta G_m^i(x, z) \right) \nu_x^j \, d\sigma_x$$

$$= \delta G_m^n(y, z), \quad m, n = 1, \cdots, d.$$  

Since $G_n(x, y) = 0$ for $x \in \partial \Omega$, and by (3.7) we have that

$$\delta G_m^n(x, z) = -\nabla_x G_m^n(x, z) \cdot S(x), \quad m, n = 1, \cdots, d$$

for $x \in \partial \Omega$, it follows from (5.1) and (5.2) that

\[(5.3)\]

$$\delta G_m^n(y, z) = \int_{\partial \Omega} \sum_{i,j,k=1}^{d} T^{ij}(G_n, R_n)(x, y) \frac{\partial G_m^i}{\partial x^k}(x, z) S^k(x) \nu_x^j \, d\sigma_x$$

for $m, n = 1, \cdots, d$ and for $y, z \in \Omega$. Furthermore, since $G_m(x, z) = 0$ for $x \in \partial \Omega$, we have that

\[(5.4)\]

$$\frac{\partial G_m^i}{\partial x^k}(x, z) = \frac{\partial G_m^i}{\partial \nu_z}(x, z) \nu_z^k, \quad i, k, m = 1, \cdots, d$$

for $x \in \partial \Omega$. Applying (5.4) to the right hand side of (5.3), it holds that

\[(5.5)\]

$$\delta G_m^n(y, z)$$

$$= \int_{\partial \Omega} \sum_{i,j=1}^{d} \left( \frac{\partial G_n^i}{\partial \nu_z}(x, y) \frac{\partial G_m^i}{\partial \nu_x}(x, z) \right) S(x) \cdot \nu_z \, d\sigma_x$$

$$+ \text{div} \ G_n(x, y) \text{div} \ G_m(x, z) - R_n(x, y) \text{div} \ G_m(x, z) \right) S(x) \cdot \nu_z \, d\sigma_x$$

$$= \int_{\partial \Omega} \sum_{i=1}^{d} \frac{\partial G_n^i}{\partial \nu_z}(x, y) \frac{\partial G_m^i}{\partial \nu_x}(x, z) S(x) \cdot \nu_z \, d\sigma_x, \quad m, n = 1, \cdots, d$$
for $y, z \in \Omega$.

Furthermore, it follows from (4.1) at the point $x = y$ and (5.5) that

$$\nabla_{y^{n}}\delta R_{m}(y, z) = \Delta_{y} \int_{\partial\Omega} \sum_{i=1}^{d} \frac{\partial G_{n}^{i}}{\partial v_{x}}(x, y) \frac{\partial G_{m}^{i}}{\partial \nu_{x}}(x, z) S(x) \cdot \nu_{x} d\sigma_{x}$$

for $m, n = 1, \cdots, d$. Since $\partial\Omega$ is sufficiently smooth, we have that for each $x \in \partial\Omega$,

$$\Delta_{y} G_{m}^{n}(y, x) = \nabla_{y^{n}} R_{m}(y, x), \quad m, n = 1, \cdots, d$$

for $y \in \Omega$. Since $G_{n}^{i}(x, y) = G_{i}^{n}(y, x), i, n = 1, \cdots, d$ for $(x, y) \in \overline{\Omega} \times \Omega$, we apply (5.7) to the right hand side of (5.6), which yields Theorem 1.1.

### 5.2 Proof of Theorem 1.2.

In the same manner as Theorem 1.1, it follows from the Green integral formula (2.4) and (3.8) that

$$\delta^{2}G_{m}^{n}(y, z)$$

$$= -\int_{\partial\Omega} \sum_{i,j=1}^{d} T^{ij}(G_{n}, R_{m})(x, y) \left(2\nabla_{x}\delta G_{m}^{i}(x, z) \cdot S(x) + \sum_{k,l=1}^{d} \frac{\partial^{2}G_{m}^{i}}{\partial x^{l}\partial x^{k}}(x, z) S^{k}(x) S^{\iota}(x) \nu_{x}^{j}d\sigma_{x}\right)$$

for $m, n = 1, \cdots, d$. Then by (5.4), we thus have that

$$\delta^{2}G_{m}^{n}(y, z)$$

$$= \int_{\partial\Omega} \sum_{i=1}^{d} \frac{\partial G_{n}^{i}}{\partial \nu_{x}}(x, y) \left(2\nabla_{x}\delta G_{m}^{i}(x, z) \cdot S(x) + \frac{\partial^{2}G_{m}^{i}}{\partial \nu_{x}^{2}}(x, z) (S(x) \cdot \nu_{x})^{2}\right) d\sigma_{x}$$

for $m, n = 1, \cdots, d$. Furthermore, similarly to the proof of Lemma 1.2, by (4.2) and (5.8) we thus complete Theorem 1.2.

## References


