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Saito, Hirokazu; Shibata, Yoshihiro

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On some decay properties of solutions for the Stokes equations with surface tension and gravity in the half space

Hirokazu Saito
Department of Pure and Applied Mathematics of Graduate school, Fundamental Science and Engineering, Waseda University

Yoshihiro Shibata
Department of Mathematics and Research Institute of Science and Engineering, Waseda University

Abstract

In the present paper, we consider decay properties of solutions for the Stokes equations with the surface tension and gravity in the half space when $t \to \infty$. The Stokes equations arise in the study of a free boundary problem for the Navier-Stokes equations in unbounded domains. We are interested in the global-time wellposedness of the free boundary problem. When we construct solutions of the free boundary problem, decay properties for the Stokes equations and Banach’s fixed point theorem will be combined. That is the reason why we consider decay properties of solutions for the Stokes equations. This paper shows the $L^q - L^r$ estimates with $1 < r < 2 < q < \infty$ of solutions for the Stokes equations, mainly. Our technique is based on the analysis of some resolvent problem which is obtained by the Laplace transform of the Stokes equations. By examining the spectrum of the resolvent problem in detail, we show the decay properties of solutions of the Stokes equations.

1 Introduction

This article is brief survey of the results related to [9], mainly.

In the present paper, we consider decay properties of solutions for the Stokes equations with the surface tension and gravity in the half space $\mathbb{R}^N_+ = \{x = (x', x_N) \in \mathbb{R}^N \mid x' \in \mathbb{R}^{N-1}, x_N > 0\}$ $(N \geq 2)$:

\[
\begin{aligned}
\partial_t u - \text{Div} S(u, \theta) &= 0, \quad \text{div} u = 0 \quad \text{in} \quad \mathbb{R}^N_+, \quad t > 0, \\
\partial_t h + u_N &= 0 \quad \text{on} \quad \mathbb{R}^N_+, \quad t > 0, \\
S(u, \theta)n + (\gamma_a - \sigma \Delta')hn &= 0 \quad \text{on} \quad \mathbb{R}^N_+, \quad t > 0, \\
u|_{t=0} &= f(x), \quad h|_{t=0} = d(x').
\end{aligned}
\]

(1.1)

Here, $u = u(x, t) = (u_1(x, t), \ldots, u_N(x, t))^T$ and $\theta = \theta(x, t)$ are unknown $N$-component velocity vector and scalar pressure at $(x, t) \in \mathbb{R}^N_+ \times (0, \infty)$, respectively, and $h = h(x', t)$ is also unknown scalar function at $(x', t) \in \mathbb{R}^{N-1}_+ \times (0, \infty)$ which is explained more precisely below; $f(x)$ and $d(x')$ are given initial data for $u(x, t)$ and $h(x', t)$, respectively; $\mathbb{R}^N_0$ is the boundary of $\mathbb{R}^N_+$ and $n = (0, \ldots, 0, -1)^T$ is the unit outer normal vector on $\mathbb{R}^N_0$; the derivatives $\text{div} u$ and $\Delta' h$ denote

\[
\text{div} u = \sum_{j=1}^N D_j u_j \quad \text{and} \quad D_j = \frac{\partial}{\partial x_j}.
\]

\[
S(u, \theta) = -\theta I + D(u) \quad \text{is the stress tensor for the newtonian fluids, where} \quad I \quad \text{is the} \quad N \times N \quad \text{identity matrix and} \quad D(u) \quad \text{is also} \quad N \times N \quad \text{matrix whose} \quad (i, j) \quad \text{component} \quad D_{ij}(u) \quad \text{is give by} \quad D_{ij}(u) = D_i u_j + D_j u_i; \quad \gamma_a \quad \text{is}
\]

\[\text{div} u = \sum_{j=1}^N D_j u_j \quad (D_j = \frac{\partial}{\partial x_j}) \quad \text{and} \quad \Delta' h = \sum_{j=1}^{N-1} D_j^2 h; \quad S(u, \theta) = -\theta I + D(u) \quad \text{is the stress tensor for the newtonian fluids, where} \quad I \quad \text{is the} \quad N \times N \quad \text{identity matrix and} \quad D(u) \quad \text{is also} \quad N \times N \quad \text{matrix whose} \quad (i, j) \quad \text{component} \quad D_{ij}(u) \quad \text{is give by} \quad D_{ij}(u) = D_i u_j + D_j u_i; \quad \gamma_a \quad \text{is}
\]

\[\text{div} u = \sum_{j=1}^N D_j u_j \quad \text{and} \quad \Delta' h = \sum_{j=1}^{N-1} D_j^2 h; \quad S(u, \theta) = -\theta I + D(u) \quad \text{is the stress tensor for the newtonian fluids, where} \quad I \quad \text{is the} \quad N \times N \quad \text{identity matrix and} \quad D(u) \quad \text{is also} \quad N \times N \quad \text{matrix whose} \quad (i, j) \quad \text{component} \quad D_{ij}(u) \quad \text{is give by} \quad D_{ij}(u) = D_i u_j + D_j u_i; \quad \gamma_a \quad \text{is}
\]
the gravitational acceleration and $\sigma > 0$ is the surface tension coefficient. For the matrix $M = M(x) = (M_{ij}(x))$, $\text{Div } M$ denotes that

\[
\text{ith component of } \text{Div } M = \sum_{j=1}^{N} D_{j} M_{ij}(x),
\]

and therefore $\text{Div } S(u, \theta)$ is given by

\[
\text{ith component of } \text{Div } S(u, \theta) = -D_{i} \theta + \Delta u_{i} + D_{i} \text{div } u.
\]

Now, we introduce the following two nonlinear problems:

\[
\begin{cases}
\partial_{t} u + (v \cdot \nabla) u = \text{Div } S(v, \pi) - \gamma_{a} \nabla x_{N}, & \text{div } v = 0 \text{ in } \Omega(t), \quad t > 0, \\
V = v \cdot n_{t} & \text{on } \Gamma(t), \quad t > 0, \\
S(v, \pi) n_{t} = \sigma \kappa n_{t} & \text{on } \Gamma(t), \quad t > 0, \\
v = 0 & \text{on } \Gamma_{b}, \quad t > 0, \\
v|_{t=0} = v_{0} & \text{in } \Omega(0),
\end{cases}
\]

(1.2)

\[
\begin{cases}
\partial_{t} u + (v \cdot \nabla) u = \text{Div } S(v, \pi) - \gamma_{a} \nabla x_{N}, & \text{div } v = 0 \text{ in } \Omega(t), \quad t > 0, \\
V = v \cdot n_{t} & \text{on } \Gamma(t), \quad t > 0, \\
S(v, \pi) n_{t} = \sigma \kappa n_{t} & \text{on } \Gamma(t), \quad t > 0, \\
v|_{t=0} = v_{0} & \text{in } \Omega(0),
\end{cases}
\]

(1.3)

These two problems are free boundary problems for the Navier-Stokes equations of incompressible flows for the Newtonian fluids. Here, $(v, \pi, \Gamma(t))$ is unknown, where $v = v(x, t) = (v_{1}(x, t), \ldots, v_{N}(x, t))^{T}$ is the $N$-component velocity vector, $\pi = \pi(x, t)$ is the pressure, and for a scalar function $h = h(x', t)$ defined on $\mathbb{R}_{0}^{N} \times (0, \infty)$, $\Gamma(t)$ is given by

\[
\Gamma(t) = \{x = (x', x_{N}) \in \mathbb{R}^{N} | x' \in \mathbb{R}^{N-1}, x_{N} = h(x', t)\};
\]

$\Gamma_{b} = \{x = (x', x_{N}) \in \mathbb{R}^{N} | x' \in \mathbb{R}^{N-1}, x_{N} = -b\} (b > 0)$ is the fixed boundary; $V$ is the velocity of the evolution of $\Gamma(t)$ in the normal direction and $n_{t}$ is the unit outer normal vector on $\Gamma(t)$; $\kappa = \kappa(x, t)$ is the mean curvature of $\Gamma(t)$ which is negative when $\Omega(t)$ is convex in a neighborhood of $x \in \Gamma(t)$. The domain $\Omega(t)$ is given by

\[
\begin{align*}
\Omega(t) &= \{x = (x', x_{N}) \in \mathbb{R}^{N} | x' \in \mathbb{R}^{N-1}, -b < x_{N} < h(x', t)\} \quad \text{for } (1.2), \\
\Omega(t) &= \{x = (x', x_{N}) \in \mathbb{R}^{N} | x' \in \mathbb{R}^{N-1}, x_{N} < h(x', t)\} \quad \text{for } (1.3).
\end{align*}
\]

First, we see the history of the problem (1.2). This problem is first studied by Beale [3] mathematically. Beale [3] shows the local-time unique existence theorem in the case that $\sigma = 0$, and show the fact that global-time solutions depending analytically on the initial data $(v_{0}, h_{0})$ can not exist even if $(v_{0}, h_{0})$ is sufficiently small. After that, Beale [4] proves the unique existence theorem globally in time for small initial data by taking into account the surface tension $\sigma \kappa n_{t}$ with $\sigma > 0$. Beale and Nishida [5] gives large-time behavior of solutions for Beale [4], but the paper has just outline of proof. We can find the detailed proof in Hayata [7]. Tani and Tanaka [12] shows the global-time unique existence theorem for small initial data in the case with or without surface tension under weaker assumptions of the initial data than Beale's. And also, Hayata and Kawashima [6] gives some decay properties of large-time behavior of solutions for small initial data in the case of $\sigma = 0$. In addition to these results, there are Allain [2] and Tani [13] as long as we know. Note that these all results are in the framework of $L_{2}$ in time and $L_{2}$ in space. As another approach to (1.2), Abels [1] uses the $L_{q}$ settings in both time and space, and he obtain the unique existence theorem locally in time in the case of $\sigma = 0$ for $q > N$.

Next, we see the history of the problem (1.3). We have seen a lot of results of (1.2) above, on the other hand results of (1.3) are not so many. Shibata and Shimizu [10, 11] shows the maximal $L_{p} - L_{q}$ regularity theorem for the linearized problem of (1.3) and resolvent estimates for the resolvent problem obtained by the Laplace transform of the linearized problem. And Prüss and Simonett [8] considers the two-phase problem corresponding to (1.3), and shows the unique existence of solutions locally in time.
for sufficiently small initial data and its instability when upper fluid is heavier than lower one. But, we think that these all results Shibata and Shimizu [10, 11], and Prüss and Simonett [8] can not be applied directly to show the global-time wellposedness of the problem (1.3).

Our final goal is to show the global-time wellposedness of (1.3) in the scaling critical spaces $L_q$ in time and $L_q$ in space with $(2/p) + (N/q) = 1$. As the first step, we consider decay properties of (1.1), noting that the equations (1.1) is homogeneous part of the linearized equations of (1.3). Especially, we obtain the $L_q - L_r$ estimates of the solution of (1.1) for $r < 2 < q < \infty$, and also obtain estimates of $L_\infty$ norm of the lower order terms: $u$, $\nabla u$, $D_j h$ and $D_j D_k h$ for $j, k = 1, \ldots, N - 1$. The restriction $r < 2$ arises from a kind of hyperbolic effect of the term $h(x', t)$.

Here, we introduce a interesting fact concerning the difference between the problem (1.2) and (1.3). The remarkable one appears in the analysis of Lopatinski determinant of the linearized problem. Beale and Nishida [5], and Hayata [7] show the following expansion of spectrum $\lambda$:

$$
\lambda = -\frac{\gamma_a b}{3} |\xi'|^2 + O(|\xi'|^3) \quad \text{as} \quad |\xi'| \to 0,
$$

where $\xi' = (\xi_1, \ldots, \xi_{N-1})$ is the tangential variable in the Fourier space. On the other hand, our case has the spectrum $\lambda_{\pm}$:

$$
\lambda_{\pm} = \pm i \gamma_a^{1/2} |\xi'|^{1/2} - 2 |\xi'|^2 + O(|\xi'|^{5/2}) \quad \text{as} \quad |\xi'| \to 0 +.
$$

From this viewpoint, our case is more complex than the case of Beale and Nishida [5], and Hayata [7], because we have not only $-|\xi'|^2$ but also $\pm i \gamma_a^{1/2} |\xi'|^{1/2}$ which yields oscillations in time.

This paper is organized as follows. In Section 2, we will state the main results of [9]. In Section 3, the strategy of their approach is explained.

## 2 Main results

First, we introduce some symbols and functional spaces in order to state our main results precisely. Let $\Omega$ be any domain and $\Gamma$ be its boundary. $L_q(\Omega)$ and $W^{m}_q(\Omega)$ are usual Lebesgue and Sobolev spaces, respectively, for $1 \leq q \leq \infty$ and $m \in \mathbb{N}$, where $\mathbb{N}$ denotes the set of all natural numbers. And, we use the convention $W^{m}_q(\Omega) = L_q(\Omega)$. For $1 \leq q < \infty$ and $s > 0$ that $s$ is not integer, the Slobodeckij space is defined by

$$
W^s_q(\Omega) = \{ u \in W^{\alpha}_{q}(\Omega) \mid \| u \|_{W^s_q(\Omega)} < \infty \},
$$

$$
\| u \|_{W^s_q(\Omega)} = \| u \|_{W^s_q(\Omega)} + \sum_{|\alpha| = |s|} \left( \int \int \Omega \frac{|D^\alpha u(x) - D^\alpha u(y)|^q}{|x-y|^{N+|s|}} dxdy \right)^{1/q},
$$

where $|s| = \max\{n \mid n < s, n \in \mathbb{N} \cup \{0\}\}$ and $D^\alpha = \partial^{\alpha_1}/(\partial x_1)^{\alpha_1} \ldots \partial_{\alpha_N}/(\partial x_N)^{\alpha_N}$ for any multi-index $\alpha \in \mathbb{N}_0^N = (\mathbb{N} \cup \{0\})^N$. We use the following functional space for the pressure:

$$
\tilde{W}^1_q(\Omega) = \{ \theta \in L_{q, loc}(\Omega) \mid \nabla \theta \in L_{q}(\Omega)^N \} \quad (1 < q < \infty).
$$

Moreover, for $1 < q < \infty$ we set $W^1_q, r(\Omega) = \{ \theta \in W^1_q(\Omega) \mid \theta|_r = 0 \}$, and

$$
\tilde{W}^1_q, r(\Omega) = \{ \theta \in L_{q, loc}(\Omega) \mid \nabla \theta \in L_{q}(\Omega)^N, \; \theta|_r = 0, \}
$$

there exists $\{ \theta_j \}_{j=1}^\infty \subset W^1_q, r(\Omega)$ such that $\lim_{j \to \infty} \| \nabla (\theta_j - \theta) \|_{L_q(\Omega)} = 0$.

For the simplicity, we use the abbreviations: $W^1_q, d(\mathbb{R}^N)$ and $\tilde{W}^1_q, d(\mathbb{R}^N)$ when $\Omega = \mathbb{R}^N$ and $\Gamma = \mathbb{R}^N_0$ in the above definitions. The second solenoidal space is defined as follows:

$$
J_q(\Omega) = \{ u \in L_{q}(\Omega)^N \mid (u, \nabla \varphi)_\Omega = 0 \quad \text{for all} \; \varphi \in \tilde{W}^1_q, r(\Omega) \} \quad (1 < q < \infty),
$$

where $(1/q) + (1/q') = 1$ and $(f, g)_\Omega = \int_\Omega f(x) \cdot g(x) \; dx = \sum_{j=1}^N \int_\Omega f_j(x)g_j(x) \; dx$ for any $N$-component vector functions $f(x)$ and $g(x)$. Let $C^m(I, X)$ be the set of all $X$-valued $C^m$ functions defined on the interval $I$ for any Banach space $X$ and any $m \in \mathbb{N}_0$. The letter $C$ denotes a generic constant, and the constant $C$ may change from line to line. Then, we have the following unique existence theorem for (1.1).
Theorem 2.1. Let $1 < q < \infty$, and let $f \in J_q(R^N_+)$ and $d \in W^{2-\frac{1}{q}}(R^{N-1})$. Then, (1.1) admits a unique solution $(u, \theta, h)$ in the spaces:

\[
\begin{align*}
  u & \in C^1((0, \infty), J_q(R^N_+)) \cap C^0([0, \infty), J_q(R^N_+)) \cap C^0((0, \infty), W^{2_q}(R^N)), \\
  \theta & \in C^0((0, \infty), \tilde{W}^{2_q}(R^N_+)), \\
  h & \in C^1((0, \infty), W^{2-\frac{1}{q}}(R^{N-1})) \cap C^0((0, \infty), W^{2-\frac{1}{q}}(R^{N-1})) \cap C^0((0, \infty), W^{3-\frac{1}{q}}(R^{N-1})).
\end{align*}
\]

Next, we introduce large-time behaviors of the solutions obtained in Theorem 2.1. For the purpose, we extend $h(x', t)$ to a function $H(x, t)$ defined in $R^N_+ \times (0, \infty)$ through the equations:

\[
\begin{align*}
  \Delta H &= 0 \quad \text{in} \quad R^N_+, \quad t > 0, \\
  H &= h \quad \text{on} \quad R^N_0, \quad t > 0.
\end{align*}
\]

and we set

\[
X_{q,r} = (L_q(R^N_+) \cap L_r(R^N_+))^N \times (W^{2-\frac{1}{q}}(R^{N-1}) \cap L_r(R^{N-1})),
\]

\[
\ell(q, r) = \min \left\{ \frac{1}{2} \left( \frac{1}{r} - \frac{1}{q} \right), \frac{1}{8} \left( 2 - \frac{1}{q} \right) \right\}.
\]

Then, there holds the following theorem.

Theorem 2.2. Let $1 < r < 2 < q < \infty$ and $F = (f(x), d(x'))$ for

\[
f \in J_q(R^N_+) \cap L_r(R^N_+)^N, \quad d \in W^{2-\frac{1}{q}}(R^{N-1}) \cap L_r(R^{N-1}).
\]

Let $(u, \theta, h)$ be the solution in Theorem 2.1 and $H$ be the extension in (2.1). Then, there exists a positive constant $C$ such that for any $t \geq 1$ there hold

\[
\begin{align*}
  \|\partial_t u(t)\|_{L_q(R^N_+)} + \|\nabla \theta(t)\|_{L_q(R^N_+)} & \leq C \max \left\{ t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \ell(q, r) - \frac{1}{4}}, t^{-1} \right\} \|F\|_{X_{q,r}}, \\
  \|\nabla^2 u(t)\|_{L_q(R^N_+)} & \leq C \max \left\{ t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \theta(q, r) - \frac{1}{4}}, t^{-1} \right\} \|F\|_{X_{q,r}}, \\
  \|u(t)\|_{L_q(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \frac{1}{4}} \|F\|_{X_{q,r}}, \\
  \|\nabla u(t)\|_{L_q(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \frac{1}{4}} \|F\|_{X_{q,r}}, \\
  \|D^\alpha \partial_t H(t)\|_{L_q(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \frac{1}{4}} \|\alpha\| \|F\|_{X_{q,r}}, \quad (|\alpha| \leq 2), \\
  \|D^\alpha \nabla H(t)\|_{L_q(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} - \frac{1}{q} \right) - \frac{1}{4}} \|\alpha\| \|F\|_{X_{q,r}}, \quad (|\alpha| \leq 2).
\end{align*}
\]

Moreover, if we assume that $q > N$, then there exists a positive constant $C$ such that for any $t \geq 1$ there hold

\[
\begin{align*}
  \|u(t)\|_{L_\infty(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} + \frac{1}{2} \right) + \frac{1}{4} \|F\|_{X_{q,r}}}, \\
  \|\nabla u(t)\|_{L_\infty(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} + \frac{1}{2} \right) + \frac{1}{4} \|F\|_{X_{q,r}}}, \\
  \|\nabla H(t)\|_{L_\infty(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} + \frac{1}{2} \right) + \frac{1}{4} \|F\|_{X_{q,r}}}, \\
  \|\nabla^2 H(t)\|_{L_\infty(R^N_+)} & \leq C t^{-\frac{N-1}{2} \left( \frac{1}{r} + \frac{1}{2} \right) + \frac{1}{4} \|F\|_{X_{q,r}}}.
\end{align*}
\]

3 Outline of the proof

We show the outline of the proof of Theorem 2.2. By applying the Laplace transform to (1.1), we obtain the resolvent problem independent of time variable $t$:

\[
\begin{align*}
  \lambda v - \Delta v + \nabla \pi = f(x), \quad \text{div} \, v = 0 \quad \text{in} \quad R^N_+, \\
  \lambda \eta + u v = d(x') \quad \text{on} \quad R^N_0, \\
  S(v, \pi)n + (\gamma_0 - \sigma \Delta')\eta n = 0 \quad \text{on} \quad R^N_0,
\end{align*}
\]

where $(v, \pi, \eta)$ is the Laplace transform of $(u, \theta, h)$ and the resolvent parameter $\lambda$ is in $\Sigma_\epsilon$ given by

\[
\Sigma_\epsilon = \{ \lambda \in C \mid |\arg \lambda| < \pi - \epsilon, \lambda \neq 0 \} \quad (0 < \epsilon < \pi/2).
\]
We also use the symbol $\Sigma_{\epsilon, \lambda_0}$ given by
\[ \Sigma_{\epsilon, \lambda_0} = \{ \lambda \in \mathbb{C} \mid |\arg \lambda| \leq \pi - \epsilon, \ |\lambda| \geq \lambda_0 \} \quad (0 < \epsilon < \pi/2, \ \lambda_0 > 0). \]

In order to progress the argument, we define the partial Fourier transform $F_{x'}$ with respect to tangential variable $x'$ and its inverse formula $F_{x'}^{-1}$ for functions $f(x',x_N)$ and $g(\xi',x_N)$, respectively, as follows:
\[
F_{x'}[f(x',x_N)](\xi') = \hat{f}(\xi',x_N) = \int_{\mathbb{R}^{N-1}} e^{-ix' \cdot \xi'} f(x',x_N) \, dx',
\]
\[
F_{x'}^{-1}[g(\xi',x_N)](x') = \frac{1}{(2\pi)^{N-1}} \int_{\mathbb{R}^{N-1}} e^{ix' \cdot \xi'} g(\xi',x_N) \, d\xi'.
\]

We can give the exact solution formulas of the resolvent problem (3.1) as follows. First, we apply the partial Fourier transform with respect to the tangential variable $x'$ to (3.1), and after that we solve the obtained ordinary differential equations with respect to $x_N$ in the Fourier space by seeing $\xi' \in \mathbb{R}^{N-1}$ as a parameter. Then, we have the exact formulas of $\hat{u}(\xi',x_N) = (\hat{v}_1(\xi',x_N), \ldots, \hat{v}_N(\xi',x_N))^T$, $\hat{\eta}(\xi',x_N)$ and $\hat{\pi}(\xi',x_N)$ in the Fourier space. Finally, the inverse partial Fourier transforms of $\hat{v}(\xi',x_N)$, $\hat{\eta}(\xi',x_N)$ and $\hat{\pi}(\xi',x_N)$ yield the exact solution formulas of (3.1). Here, we concentrate on the term:
\[
F_{x'}^{-1} \left[ \frac{D(A,B)}{(B + A)L(A,B)} \hat{d}(\xi') \right] (x'),
\]
which is a part of the solution $\eta = \eta(x',\lambda)$. The symbols in (3.2) are given by
\[
A = |\xi'|, \quad B = \sqrt{\lambda + |\xi'|^2} (\text{Re } B \geq 0), \quad D(A,B) = B^3 + AB^2 + 3A^2B - A^3,
\]
\[
L(A,B) = (B - A)D(A,B) + A(\gamma_a + \sigma A^2).
\]

The following lemma is proved in [11, Lemma 7.2].

**Lemma 3.1.** Let $0 < \epsilon < \pi/2$ and $\alpha' \in \mathbb{N}_0^{N-1}$. There exist a positive number $\lambda_0 = \lambda_0(\epsilon, \gamma_a, \sigma) \geq 2$, depending only on $\epsilon$, $\gamma_a$, and $\sigma$, and a positive constant $C$, depending only on $\alpha'$, $\epsilon$, and $\lambda_0$, such that for any $(\xi', \lambda) \in (\mathbb{R}^{N-1} \setminus \{0\}) \times \Sigma_{\epsilon, \lambda_0}$ there holds
\[
|D_{\xi'}^{2N}L(A,B)^{-1}| \leq C \left\{ |\lambda|(|\lambda|^{\frac{1}{2}} + A)^2 + A(\gamma_a + \sigma A^2) \right\}^{-1} A^{-|\alpha'|}.
\]

We set
\[
I(x,t) = \frac{1}{2\pi i} F_{x'}^{-1} \left[ \int_{\Gamma} e^{\lambda t} \frac{D(A,B)}{(B + A)L(A,B)} \, d\lambda e^{-Ax_N} \hat{d}(\xi') \right] (x'),
\]
where $\Gamma = \Gamma_+ \cup \Gamma_-$ is given by
\[
\Gamma_+ = \{ \lambda \in \mathbb{C} \mid \lambda = 2\lambda_0 + se^{i(3/4)\pi}, \ s : 0 \to \infty \},
\]
\[
\Gamma_- = \{ \lambda \in \mathbb{C} \mid \lambda = 2\lambda_0 + se^{-i(3/4)\pi}, \ s : \infty \to 0 \}
\]
for $\lambda_0 = \lambda_0(\pi/4, \gamma_a, \sigma)$ in Lemma 3.1. Note that $I(x,t)$ is a part of the solution of (2.1). In the present proof, we only show decay properties of $I(x,t)$, but the other terms in $u(x,t)$, $\theta(x,t)$ and $H(x,t)$ are calculated by techniques similar to the present case. In order to derive decay properties from $I(x,t)$, we divide $I(x,t)$ into
\[
I(x,t) = I_0(x,t) + I_{\infty}(x,t),
\]
\[
I_0(x,t) = \frac{1}{2\pi i} F_{x'}^{-1} \left[ \int_{\Gamma} e^{\lambda t} \varphi_0(\xi') D(A,B) \frac{e^{-Ax_N} \hat{d}(\xi')}{(B + A)L(A,B)} \, d\lambda \right] (x') \quad (a \in \{0, \infty\}),
\]
where $\varphi_0(\xi')$ and $\varphi_{\infty}(\xi')$ are cut-off functions such that $\varphi_0(\xi') = \varphi(\xi'/A_0)$, $\varphi_{\infty}(\xi') = 1 - \varphi_0(\xi')$ and $\varphi(\xi') \in C_c^{\infty}(\mathbb{R}^{N-1})$ satisfies
\[
\varphi(\xi') = \begin{cases} 1 & (|\xi'| \leq \frac{1}{3}), \\
0 & (|\xi'| \leq \frac{2}{3}).
\end{cases}
\]
Note that the positive number $0 < A_0 \leq 1$ in $\varphi_0(\xi')$ can be chosen sufficiently small when we need to do so.


3.1 Analysis of $I_0(x, t)$

$L(A, B)$ has the following four roots $B^\pm_j$ ($j = 1, 2$) as a function of $B$

$$B^\pm_j = e^{\pm i\gamma_0 A^{1/4}/4} - \frac{A^{7/4}}{e^{\pm i\gamma_0 A^{1/4}/4}} - \sigma A^{9/4} + O(A^{10/4}) \quad (A \to 0+).$$

Moreover, setting $\lambda_\pm = (B^\pm_j)^2 - A^2$, we obtain

$$\lambda_\pm = \pm i\gamma_0 A^{1/2} - 2A^2 \pm 2\sigma \gamma_0^{-1} A^{5/2} + O(A^{11/4}) \quad (A \to 0+).$$

Note that $\lambda_\pm$ appear only in our brunch since we use the brunch such that $\text{Re } B \geq 0$ in (3.3). Then, by using Cauchy’s integral theorem, we change the integral path $\Gamma$ to the paths:

$$\Gamma_0^\pm = \{ \lambda \in \mathbb{C} | \lambda = \lambda_\pm + (\gamma_0^{1/2}/4)A^{1/2}e^{\pm i\epsilon_0}, \ u : 0 \to 2\pi \},$$

$$\Gamma_1^\pm = \{ \lambda \in \mathbb{C} | \lambda = -(A^2(1-u) + \gamma_0 u) \pm i((A^2/4)(1-u) + \gamma_0 u), \ u : 0 \to 1 \},$$

$$\Gamma_2^\pm = \{ \lambda \in \mathbb{C} | \lambda = -(\gamma_0 \pm i\epsilon_0) + we^{\pm i(\pi-\epsilon_0)}, \ u : 0 \to \infty \},$$

where $\epsilon_0 = \tan^{-1}((A^2/8)/A^2) = \tan^{-1}(1/8)$.

We have the following theorem for $I_0(x, t)$.

**Theorem 3.2.** Let $1 < r < 2 < q < \infty$ and $\alpha \in \mathbb{N}^n$, and let $d \in L_r(\mathbb{R}^{N-1})$. Then, there exists a positive constant $C$ such that for any $t \geq 1$ there hold

$$\|D^\alpha_x \nabla I_0(t)\|_{L_r(\mathbb{R}^N)} \leq C t^{-\frac{N-1}{2} (\frac{1}{r} - \frac{1}{q}) - \frac{1}{2} (\frac{1}{2} - \frac{1}{q}) \| \alpha \|_{L_q(\mathbb{R}^{N-1})},$$

$$\|D^\alpha_x I_0(t)\|_{L_q(\mathbb{R}^N)} \leq C t^{-\frac{N-1}{2} (\frac{1}{r} - \frac{1}{q}) - \frac{1}{2} (\frac{1}{2} - \frac{1}{q}) \| \alpha \|_{L_r(\mathbb{R}^{N-1})}}.$$
for $J = 1, \ldots, N$. Similarly, we obtain
\[ \|\partial_{t}I_{0}^{\pm,0}(\cdot, x_{N}, t)\|_{L_{q}(\mathbb{R}^{N-1})} \leq Ct^{-\frac{N-1}{2}\left(\frac{1}{r}-\frac{1}{q}\right)} \|d\|_{L_{r}(\mathbb{R}^{N-1})} \leq t^{1/4}+x_{N}^{1/2}. \]

Finally, taking $\| \cdot \|_{L_{q}(0,\infty)}$ in the above inequalities yields the required inequalities with $\alpha = 0$. For the case of $\alpha \neq 0$, we can prove analogously. \[ \square \]

3.2 Analysis of $I_{\infty}(x, t)$

$L(A, B)$ has the following four roots $B_j (j = 1, \ldots, 4)$ as a function of $B$:
\[ B_j = a_{j}A + \frac{\sigma}{4(1-a_{j}-a_{j}^{3})} + \frac{(1+3a_{j}^{2})\sigma^{2}}{32(1-a_{j}-a_{j}^{3})^{3}}A^{-1} + O(A^{-2}) \quad (A \to \infty), \]
where $a_{j} (j = 1, \ldots, 4)$ are numbers, satisfying the equation: $x^{4} + 2x^{2} - 4x + 1 = 0$, such that
\[ a_{1} = 1, \quad 0 < a_{2} < \frac{1}{2}, \quad \text{Re} a_{j} < 0 \quad (j = 3, 4). \]

Setting $\lambda_{j} = (B_{j})^{2} - A^{2}$ for $j = 1, 2$ implies that
\[ \lambda_{1} = -\frac{1}{2}A - (3/16)\sigma^{2} + O(A^{-1}) \quad (A \to \infty), \]
\[ \lambda_{2} = -(1-a_{2}^{2})A^{2} + \frac{a_{2}\sigma}{2(1-a_{2}-a_{2}^{3})}A + O(1) \quad (A \to \infty). \] (3.4)

The following lemma is the key when we consider $I_{\infty}(x, t)$.

**Lemma 3.3.** Let $\xi' \in \mathbb{R}^{N-1} \setminus \{0\}$. Then, $L(A, B) \neq 0$ provided that $\lambda \in \{z \in \mathbb{C} | \text{Re} z \geq 0\}$.

We set
\[ L_{0} = \{\lambda \in \mathbb{C} | L(A, B) = 0, \text{Re} B \geq 0, A \in \text{supp} \varphi_{\infty}\}, \]
and then we obtain the following lemma by (3.4) and Lemma 3.3.

**Lemma 3.4.** There exist positive numbers $0 < \epsilon_{\infty} < \pi/2$ and $\lambda_{\infty} > 0$ such that
\[ L_{0} \subset \Sigma_{\epsilon_{\infty}} \cap \{z \in \mathbb{C} | \text{Re} z < -\lambda_{\infty}\}. \]

By using $\lambda_{\infty}$ in Lemma 3.3, we put $\gamma_{\infty} = \min\{\lambda_{\infty}, \frac{4}{3} \times (A_{0}/2)\}^{2}$, and we change $\Gamma$ to the paths:
\[ \Gamma_{4}^{\pm} = \{\lambda \in \mathbb{C} | \lambda = -\gamma_{\infty} \pm iu, u : 0 \to \tau_{0}\}, \]
\[ \Gamma_{5}^{\pm} = \{\lambda \in \mathbb{C} | \lambda = -\gamma_{\infty} \pm iu e^{\pm i(\pi-\epsilon_{\infty})}, u : 0 \to \infty\}, \]
where $\tau_{0} > 0$ is the same number as $\lambda_{0} = \lambda_{0}(\epsilon_{\infty}, \gamma_{\infty}, \sigma)$ in Lemma 3.1. Then, $I_{\infty}(x, t)$ can be written by
\[ I_{\infty}(x, t) = \sum_{n=4}^{5} I_{\infty}^{\pm, n}(x, t), \quad I_{\infty}^{\pm, n}(x, t) = \frac{1}{2\pi i} \int_{\Gamma_{n}^{\pm}} e^{\lambda t} \mathcal{F}_{\xi}^{-1} \left[ \frac{\varphi_{\infty}(\xi')}{(B+A)L(A,B)} \frac{D(A,B)}{(B+A)L(A,B)} e^{-Ax_{N}} \hat{d}(\xi') \right] (x') d\lambda. \]

We have the following theorem for $I_{\infty}(x, t)$.

**Theorem 3.5.** Let $1 < q < \infty$ and $d \in W_{q}^{2-(1/q)}(\mathbb{R}^{N-1})$. Then, there exist a positive number $\delta > 0$ and a positive constant $C$ such that for any $t \geq 1$ there holds
\[ \|\partial_{t}I_{\infty}(t)\|_{W_{q}^{2}(\mathbb{R}^{N})} + \|\nabla I_{\infty}(t)\|_{W_{q}^{2}(\mathbb{R}^{N})} \leq Ce^{-\delta t}\|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1})}. \]
Proof. Set

$$H_{\infty}(x, \lambda) = \mathcal{F}_{\xi'}^{-1} \left[ \frac{\varphi_{\infty}(\xi')D(A,B)}{(B+A)L(A,B)} e^{-A|x_{N}|} \hat{d}(\xi') \right] (x') \quad (\lambda \in \Gamma_{4}^{\pm} \cup \Gamma_{5}^{\pm}). \quad (3.5)$$

First, we write (3.5) by integral. For the purpose, we extend $d \in W_{q}^{2-(1/q)}(\mathbb{R}^{N-1})$ to $d^{*}$ defined in $\mathbb{R}_{+}^{N}$ satisfying $d^{*} = d$ on $\mathbb{R}_{0}^{N}$ and

$$\|d^{*}\|_{W_{q}^{2}(\mathbb{R}_{+}^{N})} \leq C \|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1})}. \quad (3.6)$$

By using the relation:

$$\hat{d^{*}}(\xi,0) = -\int_{0}^{\infty} \frac{d}{dy_{N}}(e^{-Ay_{N}}\hat{d^{*}}(\xi,y_{N})) \, dy_{N} = \int_{0}^{\infty} Ae^{-Ay_{N}}\hat{d^{*}}(\xi, y_{N}) \, dy_{N} - \int_{0}^{\infty} e^{-Ay_{N}} \overline{D_{N}d^{*}}(\xi, y_{N}) \, dy_{N}$$

and $A^{2} = -\sum_{j=1}^{N-1} (i\xi_{j})^{2}$ in (3.5), we have

$$H_{\infty}(x, \lambda) = -\int_{0}^{\infty} \mathcal{F}_{\xi'}^{-1} \left[ \frac{\varphi_{\infty}(\xi')D(A,B)}{A^{2}(B+A)L(A,B)} Ae^{-A(x_{N}+y_{N})} \overline{\nabla d^{*}}(\xi', y_{N}) \right] (x') \, dy_{N} + \sum_{j=1}^{N-1} \int_{0}^{\infty} \mathcal{F}_{\xi'}^{-1} \left[ (i\xi_{j}A^{-1}) \frac{\varphi_{\infty}(\xi')D(A,B)}{A^{2}(B+A)L(A,B)} Ae^{-A(x_{N}+y_{N})} D_{N} \overline{D_{j}d^{*}}(\xi', y_{N}) \right] (x') \, dy_{N}. \quad (3.7)$$

Now, there holds the following lemma.

**Lemma 3.6.** Let $\alpha' \in \mathbb{N}_{0}^{N-1}$. Then, there exists a positive constant $C$ such that for any $\xi' \in (\mathbb{R}^{N-1} \setminus \{0\})$ there hold

$$|D_{\xi}^{\alpha'} \left( \frac{\varphi_{\infty}(\xi')D(A,B)}{A^{2}(B+A)L(A,B)} \right)| \leq CA^{-3-|\alpha'|} \quad (\lambda \in \Gamma_{4}^{\pm}),$$

$$|D_{\xi}^{\alpha} \left( \frac{\varphi_{\infty}(\xi')D(A,B)}{A^{2}(B+A)L(A,B)} \right)| \leq C \frac{(|\lambda|^{1/2}+A)^{2}}{A^{2}\{(|\lambda|^{1/2}+A)^{2}+A(\gamma_{a}+\sigma A^{2})\}} A^{-|\alpha'|} \quad (\lambda \in \Gamma_{5}^{\pm}),$$

where $C$ is independent of $\lambda$.

**Proof.** See [9].

By Lemma 3.6, (3.6), (3.7) and [11, Lemma 5.4], we have the resolvent estimates:

$$\|\lambda H_{\infty}\|_{W_{q}^{2}(\mathbb{R}_{+}^{N})} + \|\nabla H_{\infty}\|_{W_{q}^{2}(\mathbb{R}_{+}^{N})} \leq C \|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1}) \cap L_{r}(\mathbb{R}^{N-1})}$$

for any $\lambda \in \Gamma_{4}^{\pm} \cup \Gamma_{5}^{\pm}$ with some positive constant $C$ independent of $\lambda$. We can easily show the required estimate for $I_{\infty}(x,t)$ by combining the above resolvent estimates with the exact formula of $I_{\infty}(x,t)$. This completes the proof.

By Theorem 3.2 and Theorem 3.5, we have

$$\|D^{\alpha}_{x} \nabla I(t)\|_{L_{q}(\mathbb{R}_{+}^{N})} \leq \|D^{\alpha}_{x} \nabla I_{0}(t)\|_{L_{q}(\mathbb{R}_{+}^{N})} + \|D^{\alpha}_{x} \nabla I_{\infty}(t)\|_{L_{q}(\mathbb{R}_{+}^{N})}$$

$$\leq C t^{-\frac{N-1}{2}(\frac{1}{r}-\frac{1}{q})-\frac{1}{2}(\frac{11}{2q})_{\|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1}) \cap L_{r}(\mathbb{R}^{N-1})}}^{\alpha}} \bigcup_{2}$$

for any multi-index $\alpha \in \mathbb{N}_{0}^{N}$ with $|\alpha| \leq 2$ and $1 < r < 2 < q < \infty$. Similarly, we obtain

$$\|D^{\alpha}_{x} \partial_{t} I(t)\|_{L_{q}(\mathbb{R}_{+}^{N})} \leq C t^{-\frac{N-1}{2}(\frac{1}{r}-\frac{1}{q})-\frac{1}{2}(\frac{11}{2q})_{\|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1}) \cap L_{r}(\mathbb{R}^{N-1})}}^{\alpha}} \bigcup_{2}$$

Finally, we consider the $L_{\infty}$ norms. Let $q > N$. Then, by Theorem 3.5 and Sobolev’s inequality there holds

$$\|\nabla I_{\infty}(t)\|_{W_{q}^{2}(\mathbb{R}_{+}^{N})} \leq C e^{-\delta t} \|d\|_{W_{q}^{2-(1/q)}(\mathbb{R}^{N-1})}. $$
Combining the above inequality and Theorem 3.2 yield that
\[
\|\nabla I(t)\|_{L_{\infty}(\mathbb{R}^{N})} \leq Ct^{-\left(\frac{N-1}{2r}+\frac{1}{2}\right)}\|d\|_{W^{2-\frac{1}{q}}_{q}(\mathbb{R}^{N-1})\cap L_{r}(\mathbb{R}^{N-1})},
\]
\[
\|\nabla^{2} I(t)\|_{L_{\infty}(\mathbb{R}^{N})} \leq Ct^{-\left(\frac{N-1}{2r}+\frac{1}{2}\right)}\|d\|_{W^{2-\frac{1}{q}}_{q}(\mathbb{R}^{N-1})\cap L_{r}(\mathbb{R}^{N-1})},
\]

Note that these estimates of $I(x,t)$ are corresponding to the estimates of $H(x,t)$ in Theorem 2.2 since $I(x,t)$ is a part of the solution $H(x,t)$.

References


