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<tr>
<td><strong>Citation</strong></td>
<td>Osaka Journal of Mathematics. 1970, 7(2), p. 495-525</td>
</tr>
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<td><strong>Version Type</strong></td>
<td>VoR</td>
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<tr>
<td><strong>URL</strong></td>
<td><a href="https://doi.org/10.18910/7709">https://doi.org/10.18910/7709</a></td>
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MIXED PROBLEM FOR THE WAVE EQUATION WITH AN OBLIQUE DERIVATIVE BOUNDARY CONDITION

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(Received April 14, 1970)
(Revised December 9, 1970)

1. Introduction

Consider a mixed problem

\[
\begin{aligned}
\square u &= \left( \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} \right) u(x, y, t) = f(x, y, t) \\
B u &= \left( b_1(x, y) \frac{\partial}{\partial x} + b_2(x, y) \frac{\partial}{\partial y} \right) u(x, y, t) = g(x, y, t) \\
u(x, y, 0) &= u_0(x, y) \\
\frac{\partial u}{\partial t}(x, y, 0) &= u_1(x, y)
\end{aligned}
\]

(1.1)

where \( S = \partial \Omega \) is a \( C^\infty \) simple and compact curve in \( \mathbb{R}^2 \) and \( b_i(x, y) \) \((i=1, 2)\) are real-valued \( C^\infty \)-functions defined on \( S \). We assume that \((b_1(x, y), b_2(x, y))\) is not tangential to \( S \), i.e. \( b_1 n_1 + b_2 n_2 \neq 0 \) on \( S \), where \( n(x, y) = (n_1(x, y), n_2(x, y)) \) is the unit outer normal of \( S \) at \((x, y) \in S\). The boundary operator \( B \) is called an oblique derivative when

\[
b_1(x, y)n_1(x, y) - b_2(x, y)n_2(x, y) \neq 0 \quad \text{on} \quad S.
\]

In this paper we consider the mixed problem (1.1) under the condition (1.2).

In recent years mixed problems for hyperbolic equations have been studied by many authors and the general theory developed (for example S. Agmon [1], T. Balaban [2], H.O. Kreiss [9], R. Sakamoto [10]). Concerning second order equations, the problems with the Dirichlet boundary condition and with the Neumann boundary condition are studied satisfactorily. The author showed the well-posedness in \( L^2 \)-sense of the problems with a fairly general first order derivative boundary condition in [5]. But the problem (1.1) is not contained, under the condition (1.2), in the results of [1], [2], [5], [7], [9] or [10]. Concerning the problem (1.1), we showed its ill-posedness in \( L^2 \)-sense when a domain is
It seems that the ill-posedness is caused mainly by the following two facts: (i) $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ with the boundary condition $Bu=0$ on $S$ has no self-adjoint realization in $L^2(\Omega)$. (ii) $\Pi$ with the boundary operator $B$ does not satisfy the complementary condition posed by S. Agmon [1], which is called the uniform Lopatinski condition.

Therefore to consider the problem (1.1) it is necessary to treat it in a weaker topology than the ordinary $L^2$-sense. J. Chazarain [3] proved the well-posedness of (1.1) in the space of vector-valued ultra-distributions of $t$. On the other hand A. Inoue [8] showed a precise estimate for the solution of (1.1) in the case where the domain is a half-space and $b_i$ is constant, but it seems to me that his method is not applicable to non half-space.

In this paper we will show the following:

**Theorem 1.** For data $\{u_0(x, y), u_1(x, y), f(x, y, t), g(x, y, t)\}$ satisfying the compatibility condition of order $m=N$, the mixed problem (1.1) has a solution $u(x, y, t)$ in $\mathcal{E}^m(\Omega) \cap \mathcal{E}_t^m(\Omega) \cap \cdots \cap \mathcal{E}_t^{m+2}(L^2(\Omega))$ ($m=0, 1, 2, \ldots$) where $N$ is an integer determined by $B$ and $S$. Furthermore (1.1) represents a propagation phenomenon with a finite velocity, which is majorated by

$$\sup_{(x, y) \in \Omega} \sqrt{1+(b_n^2+b_p^2)^2}.$$

Now we give the definition of the compatibility condition of order $m$.

**Definition 1.1.** Data $\{u_0, u_1, f, g\}$ are said to satisfy the compatibility condition of order $m$ when $u_0(x, y) \in H^{m+2}(\Omega), u_1(x, y) \in H^{m+1}(\Omega), f(x, y, t) \in H^{m+1}(\Omega \times (0, T)), g(x, y, t) \in H^{m+1}(S \times (0, T))$ and $Bu_0(x, y) = \frac{\partial^2 u}{\partial t^2}(x, y, 0)$ on $S$

for $p=0, 1, 2, \ldots, m$, where $u_p(x, y)$ ($p=2, 3, \ldots, m$) are defined successively by the formula

$$u_p(x, y) = \Delta u_{p-1}(x, y) + f(x, y, 0).$$

We should like to remark that under the condition (1.2) the mixed problem (1.1) has a velocity larger than that of the Cauchy problem for $\Box$; this fact is shown in the appendix. The mixed problems treated in [5] and [7] have the same velocity as the Cauchy problem, therefore we can say that the above fact is one of the characteristics of the $L^2$ ill-posed problems.

1) The Neumann condition does not satisfy the uniform Lopatinski condition, but the mixed problem with the Neumann boundary condition is well posed in $L^2$-sense since $\partial$ has a self-adjoint realization in $L^2(\Omega)$. 
To prove Theorem 1 we consider at first the mixed problem for an equation with variable coefficients in a domain of a half-space. We reduce this problem, by a Laplace transformation in $t$, to a boundary value problem with a parameter $s \in \mathbb{C}_+ = \{\eta + i\xi : \eta > 0, \xi \in \mathbb{R}\}$. In the treatment we make use of pseudo-differential operators with a parameter $s \in \mathbb{C}_+$.

The author wishes to express his sincere gratitude to Professor H. Tanabe and Professor H. Kumano-go for their many invaluable suggestions.

2. The case where the domain is a half-space

Let $\mathbb{R}^2_+ = \{(x, y) ; x > 0, y \in \mathbb{R}\}$ be a half-space. Consider a hyperbolic operator $L$ and a boundary operator $B$ such that

\begin{equation}
L_y \phi(x, y, t) = \frac{\partial}{\partial x} \left( a_{11} \frac{\partial \phi}{\partial x} + 2a_{12} \frac{\partial \phi}{\partial y} + a_{22} \frac{\partial^2 \phi}{\partial y^2} \right) + \text{(first order)}
\end{equation}

where all the coefficients are real-valued $C^{\infty}$-functions of $x$ and $y$.

Let $u(x, y, t)$ be a solution to the following mixed problem

\begin{equation}
\begin{cases}
L_y u(x, y, t) = f(x, y, t) & \text{in } \mathbb{R}^2_+ \times (0, T) \\
B_y u(x, y, t)|_{x=0} = g(y, t) \\
u(x, y, 0) = u_0(x, y) \\
\frac{\partial u}{\partial t}(x, y, 0) = u_t(x, y)
\end{cases}
\end{equation}

When we derive energy estimates of the solution or show the existence of solution, an essential role is played by an apriori estimate of the boundary value problem with a parameter $s = \eta + i\xi \in \mathbb{C}_+$. 

We denote \( \frac{\partial}{\partial y} \) by \( \partial_y \) and \( \frac{1}{i} \frac{\partial}{\partial y} \) by \( D_y \).

Let \( \mathcal{P}(y, \omega, \varsigma) \) be a matrix-valued \( C^\infty(R \times R \times C^+) \) function. \( \mathcal{P} \in S^m_{C^+} \) means that

\[
|\frac{\partial^a \partial_y^b \mathcal{P}(y, \omega, \varsigma)}{|a|!|b|!}| \leq C_{a,b}(\omega^2 + |\varsigma|^{(m-|\varsigma|)/2})
\]

holds for all \((y, \omega, \varsigma) \in R \times R \times C^+\). For \( \mathcal{P}(y, \omega, \varsigma) \in S^m_{C^+} \) we define a pseudo-differential operator \( \mathcal{P}(y, D_y, \varsigma) \) by

\[
\mathcal{P}(y, D_y, \varsigma)V(y) = \frac{1}{2\pi} \int e^{i\omega \varsigma} \mathcal{P}(y, \omega, \varsigma) \hat{V}(\omega) d\omega
\]

for \( V(y) \in S(R^2) \), where

\[
\hat{V}(\omega) = \int e^{-i\omega \varsigma} V(y) dy.
\]

**Lemma 2.1.**

(i) Let \( \mathcal{P}(y, \omega, \varsigma) \in S^m_{C^+} \) and \( \mathcal{Q}(y, \omega, \varsigma) \in S^{m'}_{C^+} \) then

\[
\mathcal{P}(y, D_y, \varsigma) \mathcal{Q}(y, D_y, \varsigma) = \sum_{|\alpha| < N} \frac{1}{\alpha!} (\partial^\alpha \mathcal{P} \circ D_y^\alpha \mathcal{Q})(y, D_y, \varsigma) + \mathcal{R}_N(y, D_y, \varsigma)
\]

where \( \mathcal{R}_N(y, \omega, \varsigma) \in S^{m'+m'-N}_{C^+} \).

(ii) For \( \mathcal{P}(y, \omega, \varsigma) \in S^m_{C^+} \) there exists \( \mathcal{P}^a(y, \omega, \varsigma) \in S^{m}_{C^+} \) such that

\[
(\mathcal{P}(y, D_y, \varsigma)V, W) = (V, \mathcal{P}^a(y, D_y, \varsigma)W)
\]

holds for all \( V, W \in S(R) \), and the following expansion

\[
\mathcal{P}^a(y, \omega, \varsigma) = \sum_{|\alpha| < N} \frac{1}{\alpha!} \partial^\alpha D^\alpha_y \mathcal{P}^a(y, \omega, \varsigma) + \mathcal{R}_N(y, \omega, \varsigma)
\]

holds where \( \mathcal{P}^a(y, \omega, \varsigma) \) denotes the adjoint matrix of \( \mathcal{P}(y, \omega, \varsigma) \) and \( \mathcal{R}_N(y, \omega, \varsigma) \) \( \in S^{m'-N}_{C^+} \).

(iii) When \( \mathcal{P}(y, \omega, \varsigma) \in S^m_{C^+} \), there exists a constant \( C > 0 \) such that

\[
||\mathcal{P}(y, D_y, \varsigma)V|| \leq C ||V|| \quad \text{for all } V \in S.
\]

---

2) \( S(R) \) is the set of all rapidly decreasing functions defined in \( R \).
(iv) When \( \mathcal{P}(y, \omega, s) \in S_{C_+}^{-1} \), there exists a constant \( C > 0 \) such that

\[
\| \mathcal{P}(y, D_y, s)V \| \leq \frac{C}{|s|} \| V \|
\]

holds for all \( V \in \mathcal{S}(\mathbb{R}) \) and \( s \in C_+ \).

(v) Let \( \mathcal{P}(y, \omega, s) \in S_{C_+}^1 \) and \( \inf \Re \mathcal{P}(y, \omega, s) \geq c(s) \) then there exists a constant \( C > 0 \) and it holds that for all \( s \in C_+ \)

\[
\Re \mathcal{P}(y, D_y, s)V, V \geq c(s) \| V \|^2 - C \| V \|^2.
\]

The proof of this lemma is not given here, because it can be proved without much difficulties only by using the method of H. Kumano-go, "An algebra of pseudo-differential operators", J. Fac. Sci. Univ. Tokyo 17 (1970), 31–50.

### 2.2. Apriori estimate of a solution of (2.5)

In this paragraph, the subscript \( \varphi \) of \( L_\varphi \) and \( B_\varphi \) is dropped for the simplicity, and we denote by \( \| \cdot \| \) the norm of the space \( H^i(\mathbb{R}^3) \) and by \( \langle \cdot, \cdot \rangle \), that of \( H^i(\mathbb{R}) \). Hereafter we assume that all the coefficients depend on \( y \) in \( |y| \leq d \) and that

\[
(2.6) \quad a_{ij}(0) = \delta_{ij} \quad (i, j = 1, 2).
\]

We should like to treat the boundary value problem (2.5) in an equivalent system by putting

\[
(V(x, y, s) = \begin{bmatrix} v_1(x, y, s) \\ v_2(x, y, s) \end{bmatrix} = \begin{bmatrix} i(D_y^2 + \xi^2)^{1/2}v(x, y) \\ \partial y (x, y) \end{bmatrix} \quad (s = \eta + i\xi)
\]

\[
\begin{align*}
(i) \quad & \frac{\partial}{\partial x} V(x, y, s) = \mathcal{M}(y, D_y, s)V(x, y, s) + P(x, y) \\
(ii) \quad & \mathcal{B}(y, D_y, s)V(x, y, s) |_{x=0} = q(y)
\end{align*}
\]

where

\[
P(x, y) = \begin{bmatrix} 0 \\ \rho(x, y) \end{bmatrix}
\]

\[
\mathcal{M}(y, \omega, s) = \mathcal{M}_0(y, \omega, s) + \mathcal{M}_1(y, \omega, s)
\]

\[
\mathcal{M}_0(y, \omega, s) = \begin{bmatrix} 0 \\ \frac{(1 - a_{12} \omega^2)s^2 + a_{12} \omega^2 - 2ia_{12} \omega^2 s}{i(\omega^2 + \xi^2)^{1/2}a_{11}} \end{bmatrix}
\]

\[
\mathcal{M}_1(y, \omega, s) \in S_{C_+}^0
\]

and

\[
\mathcal{B}(y, \omega, s) = \begin{bmatrix} (a_{12} + b)(\omega s + i\omega) + c \\ i(\omega^2 + \xi^2)^{1/2}a_{11} \end{bmatrix}
\]
\[ = B_\omega(y, \omega, s) + \left[ \frac{c}{i(\omega^2 + \xi)^{n/2}} \right]. \]

Remark that the eigenvalues of \( \mathcal{M}(y, \omega, s) \) coincide with the roots of the equation \( L(y, \kappa, i\omega, s) = 0 \) \( (L_0(y, \kappa, i\omega, s) = 0) \) in \( \kappa \).

**Lemma 2.2.** There exists a constant \( \eta_1 \) such that if \( \Re s \geq \eta_1 \), the equation in \( \kappa \)

\[ L(y, \kappa, i\omega, s) = 0 \]

has a root \( \kappa_+ \) with a positive real part and a root \( \kappa_- \) with a negative real part.

**Proof.** Remark that for purely imaginary \( \kappa \), \( L(y, \kappa, i\omega, s) \) is never equal to zero if \( \Re s \geq \eta' \) for some constant \( \eta' > 0 \). Indeed, there exists a constant \( c \) such that \( |\Re s(y, \kappa, i\omega)| \leq c \) for any root \( s(y, \kappa, i\omega) \) of \( L(y, \kappa, i\omega, s) = 0 \) for all \( (y, \frac{1}{i} - \kappa, \omega) \in \mathbb{R}^3 \), therefore the root \( \kappa \) is never purely imaginary. On the other hand

\[ \frac{1}{\lambda^2} L(0, 0, \lambda \kappa, \lambda s) = 0 \]

has a root with positive real part and a root with negative real part when \( \lambda \) is sufficiently large. These two facts prove Lemma. Q.E.D.

Let us denote by \( k_+(y, \omega, s) \) (\( k_-(y, \omega, s) \)) the root with positive real part (negative real part) of \( L_0(y, \kappa, i\omega, s) = 0 \) for \( \Re s > 0 \), and we have

\[ k_{\pm}(y, \omega, s) = \lim \frac{1}{\lambda^{\pm}} k_{\pm}(y, \lambda \omega, \lambda s) \]

for \( \lambda > 0 \).

We have the following lemma from the hyperbolicity of \( L \).

**Lemma 2.3.** There exists a constant \( c > 0 \) such that

\[ \Re k_+(y, \omega, s) \geq c \Re s \]
\[ \Re k_-(y, \omega, s) \leq -c \Re s \]

for all \( \Re s \geq \eta_1 \).

Define \( k_\pm(y, \omega, i\xi) \) by \( \lim_{\eta \to 0^+} k_\pm(y, \omega, \eta + i\xi) \) and set

\[ \Gamma(y, \omega, s) = B_\omega(y, k_-(y, \omega, s), i\omega, s) \]

3) \( L_0 = 0 \) has a root with positive real part and a root with negative real part if \( \Re s \neq 0 \).

4) \( \Gamma(y, \omega, s) \) is called Lopatinski determinant and the uniform Lopatinski condition means that \( \Gamma(y, \omega, s) \neq 0 \) for all \( \Re s \geq 0 \).
for Re $s \geq 0$. Evidently

$$
\Gamma(y, \lambda \omega, \lambda s) = \lambda \Gamma(y, \omega, s) \quad \text{for } \lambda > 0.
$$

Let us assume

**Assumption I.** \[a_{11}a_{22} - a_{12}^2 > 0 \quad \text{for all } y
\]

and

$$
\sup_{y \in R} |\varphi(y)| < \inf_{y \in R} \sqrt{a_{11}(y)(a_{11}(y)a_{22}(y) - a_{12}(y)^2 + b(y)^2)}.
$$

**Lemma 2.4.** Under Assumption I, $\Gamma(y, \omega, s)$ vanishes only for purely imaginary $s$.

Since $\Gamma(y, \omega, s)$ can be written explicitly, Lemma is proved by an elementary calculus.

Hereafter we assume that $b(y) > 0$ for all $y \in R$.

**Lemma 2.5.** There exist two points $(\omega_0, \xi_0)$ on the sphere $\{ (\omega, \xi); \omega^2 + \xi^2 = 1 \}$ such that $\Gamma(0, \omega_0, i\xi_0) = 0$. And we have

$k_+(0, \omega_0, i\xi_0) = k_-(0, \omega_0, i\xi_0) \neq 0$.

\[\text{Im } \frac{\partial k_-(0, \omega_0, i\xi_0)}{\partial \omega} = 0.\]

Proof. Set $k(y) = a_{11}(y)a_{22}(y) - a_{12}(y)^2 + b(y)^2$. $\Gamma(0, \omega_0, i\xi_0) = 0$ means that

$$
\sqrt{\omega_0^2 - \xi_0^2} = ib(0)\tilde{\omega}_0
$$

where $\tilde{\omega}_0 = \omega_0 + \varphi(0)\xi_0$. From this it follows that

$$
\tilde{\omega}_0 = \pm \sqrt{\frac{1}{k(0)}} \xi_0,
$$

and by taking account of the definition of $\kappa_-(y, \omega_0, i\xi_0)$ and $b(0) > 0$ we get

$$
\tilde{\omega}_0 = \sqrt{\frac{1}{k(0)}} \xi_0.
$$

From the explicit form we have

$$
k_+(0, \omega_0, i\xi_0) - k_-(0, \omega_0, i\xi_0) = i2b\tilde{\omega}_0 \neq 0
$$

and

$$
\text{Im } \frac{\partial k_-(0, \omega_0, i\xi_0)}{\partial \omega} = -\frac{\tilde{\omega}_0}{\sqrt{\tilde{\omega}_0^2 - \xi_0^2}} = \frac{i}{b(0)} \neq 0.
$$

Q.E.D.
Since $\Gamma(0, \omega, s)$ equals zero at only two points in $\{(\omega, s); \omega^2 + |s|^2 = 1, \Re s \geq 0\}$ we have that for some positive constant $0 < d_z < d_1$ and $\gamma_i \ (i=1, 2)$

$$|\Gamma(0, \omega, i\xi)| \geq 2\gamma_i$$
on $\{(\omega, \xi); \omega^2 + \xi^2 = 1 \text{ and } d_z \leq |\omega - \omega_0| + |\xi - \xi_0| \leq d_1\}$ and

$$\left|\text{Im} \frac{\partial \kappa}{\partial \omega}(0, \omega, i\xi)\right| \geq 2\gamma_2$$
on $\{(\omega, \xi); \omega^2 + \xi^2 = 1 \text{ and } |\omega - \omega_0| + |\xi - \xi_0| \leq d_1\}$.

Let us suppose

**ASSUMPTION II.** It holds that

(2.8) $$|\kappa_+(y, \omega, s) - \kappa_-(y, \omega, s)| \geq \gamma_0$$

(2.9) $$\left|\text{Im} \frac{\partial \kappa}{\partial \omega}(y, \omega, s)\right| \geq \gamma_2$$

for all $y \in \mathbb{R}, s = \eta + i\xi$ and $\omega$ such that $0 \leq \eta \leq \eta_2$ and $(\omega, \xi) \in \{(\omega, \xi); |\omega - \omega_0| + |\xi - \xi_0| \leq d_1 \text{ and } \omega^2 + \xi^2 = 1\}$ and that

(2.10) $$|\Gamma(y, \omega, s)| \geq \gamma_1$$

for all $y \in \mathbb{R}, s = \eta + i\xi$ and $\omega$ such that $0 \leq \eta \leq \eta_2$ and $(\omega, \xi) \in \{(\omega, \xi); d_z \leq |\omega - \omega_0| + |\xi - \xi_0| \leq d_1 \text{ and } \omega^2 + \xi^2 = 1\}$, where $\eta_2$ and $\gamma_0$ are positive constants.

Take $d_z$ as $d_z < d_3 < d_1$ and set

$$\Delta^i = \{\omega'; |\omega' - \omega_0| + |\xi' - \xi_0| \leq d_1\} \quad (i=1, 2, 3)$$

where $(\omega', \xi')=(\omega, \xi)/(\omega^2 + \xi^2)^{1/2}$, and take a real-valued $C^\infty$-function $\chi_0(\omega, \xi)$ such that

$$\chi_0(\omega, \xi) = \begin{cases} 1 & \omega \in \Delta^{(3)}_i \\ 0 & \omega \in \Delta^{(1)}_i. \end{cases}$$

Operate $\chi_0(D_y, \xi)$ to (i) of (2.7) and we have

(2.11) $$\frac{\partial}{\partial x} \chi_0 V = \mathcal{M} \chi_0 V + [\chi_0, \mathcal{M}] V + \chi_0 P$$

$$= \mathcal{M} \chi_0 V + P_0.$$ 

Put

$$\tilde{\kappa}_\pm(y, \omega, s) = (\xi^2 + \omega^2)^{-1/2} \kappa_\pm(y, \omega, s),$$

then by changing the value of $\mathcal{M}(y, \omega, s)$ in the outside of $\Delta^{(1)}_i$ we may assume that
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\[ \begin{align*}
(2.12) & \quad |\kappa_+(y, \omega, s) - \kappa_-(y, \omega, s)| \geq \gamma_1 > 0 \\
\end{align*} \]

for all \((y, \omega) \in \mathbb{R}^2\) when \(\xi\) is sufficiently large since for \(\omega \in \Delta_{1}^{(1)}\) \((2.12)\) follows from \((2.8)\).

Remark that \(\mathcal{M}(y, \omega, s)\) can be written as

\[
\begin{pmatrix}
0 & i(\omega^2 + \xi^2)^{1/2} \\
-\frac{\kappa_+(y, \omega, s)\kappa_-(y, \omega, s)}{i(\omega^2 + \xi^2)^{1/2}} & \kappa_+(y, \omega, s) + \kappa_-(y, \omega, s)
\end{pmatrix}
\]

Then for a matrix

\[
\mathcal{N}(y, \omega, s) = \begin{pmatrix}
a(y, \omega, s)\kappa_-(y, \omega, s) & -ia(y, \omega, s) \\
\kappa_+(y, \omega, s) & -i
\end{pmatrix}
\]

we get

\[
\mathcal{N}(y, \omega, s) \mathcal{M}(y, \omega, s) = \begin{pmatrix}
\kappa_+(y, \omega, s) & 0 \\
0 & \kappa_-(y, \omega, s)
\end{pmatrix} \mathcal{N}(y, \omega, s)
\]

where \(a(y, \omega, s)\) is an arbitrary function and when \(a(y, \omega, s)\) is not zero \(\mathcal{M}(y, \omega, s)\) is a non-singular matrix for large \(\xi\) from \((2.12)\). Denote the above diagonal matrix by \(\mathcal{J}(y, \omega, s)\). (i) of Lemma 2.1 shows

\[ \begin{align*}
(2.13) & \quad \mathcal{N}(y, D_y, s) \mathcal{M}(y, D_y, s) \\
& = \{\mathcal{K}(y, D_y, s) + (\partial_\omega \mathcal{N} \circ D_y \mathcal{M} - \partial_\omega \mathcal{K} \circ D_y \mathcal{M}) \circ \mathcal{N}^{-1}(y, D_y, s)\}\mathcal{N}(y, D_y, s) \\
& + \mathcal{R}_{-1}(y, D_y, s) \\
& = \{\mathcal{K}(y, D_y, s) + \mathcal{I}(y, D_y, s)\}\mathcal{N}(y, D_y, s) + \mathcal{R}_{-1}(y, D_y, s)
\end{align*} \]

where \(\mathcal{I}(y, \omega, s) \in S_{\mathcal{C}^+}^{\mathcal{S}^+}\) and \(\mathcal{R}_{-1}(y, \omega, s) \in S_{\mathcal{C}^+}^{-1}\). Set \(\mathcal{I}(y, \omega, s) = [t_{ij}(y, \omega, s)]_{i,j=1,2}\) and choose \(a(y, \omega, s) \in S_{\mathcal{C}^+}^{\mathcal{S}^+}\) as \(t_{12}(y, \omega, s)\) is zero in \(\Delta_{1}^{(1)}\). The \((1, 2)\) entry of \((\partial_\omega \mathcal{N} \circ D_y \mathcal{M} - \partial_\omega \mathcal{K} \circ D_y \mathcal{M}) \circ \mathcal{N}^{-1}(y, \omega, s)\) equals

\[
\frac{\partial_\xi \kappa_+}{i(\kappa_+ - \kappa_-)} \{\kappa_+ - \kappa_-\} \partial_\omega a - a \cdot \partial_\omega \kappa_+ \}
\]

then we define \(a(y, \omega, s)\) by

\[
a(y, \omega, s) = \exp \left( \int_\omega^\omega \left( \frac{\partial_\omega \kappa_+}{\kappa_+ - \kappa_-} \right) (y, \xi, s) d\xi \right)
\]

for \(\omega \in \Delta_{1}^{(1)}\) where \(\omega_0 = \omega_0 \xi / \xi_0\), and we define suitably in the outside of \(\Delta_{1}^{(1)}\) as \(a(y, \omega, s) \in S_{\mathcal{C}^+}^{0}\) and \(|a(y, \omega, s)| \geq c_0\). Then we have

\[
\mathcal{I}(y, \omega, s) \in S_{\mathcal{C}^+}^{0}
\]

and

\[ (2.14) \quad t_{12}(y, \omega, s) = 0 \quad \text{for } \omega \in \Delta_{1}^{(1)}. \]
Put $\kappa_r(y, \omega, s) = \kappa_r(y, \omega, s) + i\kappa_l(y, \omega, s)$.

Let us assume

**Assumption III.** There exists a real-valued $C^\infty$-function $\psi(y, \omega, s) \equiv S_{E^+}^1$ satisfying

\begin{align}
\frac{\partial \kappa_2}{\partial y} \frac{\partial \psi}{\partial \omega} - \frac{\partial \kappa_2}{\partial \omega} \frac{\partial \psi}{\partial y} &= 0 \\
\psi(y, \omega, s) &= |\xi| \quad \text{for } \omega \in \Delta^{(2)}_1, \\
\psi(y, \omega, s) &= 0 \quad \text{for } \omega \in \Delta^{(2)}_2.
\end{align}

Set

$$
\mathcal{D}(y, D_y, s) = \begin{bmatrix}
\beta |\xi|^2 & 0 \\
0 & -\psi(y, D_y, s) + \alpha\end{bmatrix}
$$

where $\alpha$ is a positive constant such that $||(\psi + \alpha)w|| \geq ||w||$ for all $w \in L^2(R^2)$ and $\beta$ is a positive constant which will be determined later.

Operate \( \mathcal{H}(y, D_y, s) \) to the both sides of (2.11) and we have from (2.13)

$$
\frac{\partial}{\partial x} \mathcal{H}_x V = \mathcal{K} \mathcal{H}_x V + \mathcal{I} \mathcal{H}_x V + R_{-1} \mathcal{H}_x V + \mathcal{P}_0.
$$

Set $W(x, y, s) = \mathcal{H}(y, D_y, s) \chi_0(D_y, x) \psi(x, y, s)$.

\begin{align*}
2 \Re \left( \mathcal{D}(y, D_y, s) W(x, y, s), -\left( R_{-1} \mathcal{H}_x V + \mathcal{P}_0 \right) \right) \\
&= 2 \Re \left( \mathcal{D} W, -\frac{\partial}{\partial x} W \right) + 2 \Re \left( \mathcal{D} W, \mathcal{K} W \right) + 2 \Re \left( \mathcal{D} W, \mathcal{I} W \right) \\
&= I + II + III.
\end{align*}

\begin{align*}
I &= 2 \Re \beta |\xi|^2 \left( w_1(x, y, s), -\frac{\partial}{\partial x} w_1(x, y, s) \right) \\
&- 2 \Re \left( (\psi + \alpha)^* (\psi + \alpha) w_2(x, y, s), -\frac{\partial}{\partial x} w_2(x, y, s) \right) \\
&= \beta |\xi|^2 \langle w_1(0, y, s) \rangle - \langle (\psi(y, D_y, s) + \alpha) w_2(0, y, s) \rangle^2
\end{align*}

\begin{align*}
II &= \beta |\xi|^2 2 \Re \left( w_1(x, y, s), \kappa_1(y, D_y, s) w_1(x, y, s) \right) \\
&+ 2 \Re \left( (\psi + \alpha)^* (\psi + \alpha) w_2(x, y, s), (\kappa_1)(y, D_y, s) w_2(x, y, s) \right) \\
&= \beta |\xi|^2 2 \Re \left( w_1(x, y, s), \kappa_1(y, D_y, s) w_1(x, y, s) \right) \\
&+ 2 \Re \left( (\psi + \alpha) w_2(x, y, s), (\kappa_1)(y, D_y, s)(\psi + \alpha) w_2(x, y, s) \right) \\
&+ 2 \Re \left( (\psi + \alpha) w_2(x, y, s), [\kappa_1, \psi] w_2(x, y, s) \right)
\end{align*}

by using (v) of Lemma 2.1 and Lemma 2.3

\begin{align*}
\geq &\left( c \eta - C \right) \beta |\xi|^2 \langle w_1(x, y, s) \rangle^2 + \langle (\psi + \alpha) w_2(x, y, s) \rangle^2 \\
&+ 2 \Re \left( (\psi + \alpha) w_2(x, y, s), [\kappa_1, \psi] w_2(x, y, s) \right).
\end{align*}
\[
|III| = \beta |\xi|^2 |(w_1, t_1 w_1 + t_2 w_2)| + |((\psi + \alpha)(\psi + \alpha) w_2, t_1 w_1 + t_2 w_2)| \\
\leq C(|\xi|^2 ||w_1||^2 + ||(\psi + \alpha)w_2||^2 + \beta |\xi|^2 ||w_1, t_{12}(y, D_y, s)w_2||).
\]

From (2.14), we have for any integer \(N\)
\[
||t_{12}(y, D_y, s)w_2|| \leq \frac{C_N}{|s|} ||\chi_y V||.
\]

Therefore we get
\[
|III| \leq C\left(|\xi|^2 ||w_1||^2 + ||(\psi(y, D_y, s) + \alpha)w_2||^2 + ||\chi_y V||^2\right).
\]

Now let us estimate \(2 \text{Re} \left((\psi + \alpha)w_2, [\kappa_-, \psi]w_2\right)\). Put
\[
\kappa_-(y, \omega, s) = \kappa(y, \omega, s) + i\kappa_0(y, \omega, s) + (\kappa_--\kappa_0)(y, \omega, s),
\]
evidently \(\kappa_--\kappa_0 \in S_{C+}^0\) and by an elementary calculus \(\kappa(y, \omega, s)\) can be represented as
\[
\kappa(y, \omega, s) = \eta \kappa_3(y, \omega, s), \quad \kappa_3(y, \omega, s) \in S_{C+}^0
\]
in \(\Delta_3^{11}\).

Thus we have
\[
||[\kappa(y, D_y, s) + (\kappa_--\kappa_0)(y, D_y, s), \psi(y, D_y, s)]w_2|| \leq C\eta ||w_2||.
\]

And
\[
i[\kappa_3(y, D_y, s), \psi(y, D_y, s)] = \left(\frac{\partial \kappa_3}{\partial \omega} \frac{\partial \psi}{\partial y} - \frac{\partial \kappa_3}{\partial y} \frac{\partial \psi}{\partial \omega}\right)(y, D_y, s) + \mathcal{R}_6(y, D_y, s)
\]
by taking account of (2.15)
\[
= \mathcal{R}_6(y, D_y, s)
\]
where \(\mathcal{R}_6(y, \omega, s) \in S_{C+}^0\). Thus we get
\[
|2 \text{Re} \left((\psi + \alpha)w_2, [\psi, i\kappa_3]w_2\right)| \leq C\eta ||(\psi + \alpha)w_2|| ||w_2||.
\]

On the other hand
\[
|2 \text{Re} \left(\mathcal{D} \mathcal{W}_0 - \mathcal{R}_6 \chi_y V + \mathcal{P}_0\right)|| \leq C\left(|\xi|||w_1|| + ||(\psi + \alpha)w_2||||\chi_y V|| + |\xi||P_0||\right).
\]

We get
\[
(c_7 - C)|\beta |\xi|^2||w_1||^2 + ||(\psi + \alpha)w_2||^2 - C\eta ||(\psi + \alpha)w_2|| ||w_2||
\]
\[
- C||\chi_y V||^2 + \beta |\xi|^2<w_1(0, y, s)>^2 - <(\psi + \alpha)w_2(0, y, s)>^2
\]
\[
\leq C |\xi|^2 ||P_0||^2.
\]
Remark that
\[ \frac{1}{C} ||W|| \leq ||\chi V|| \leq C ||W|| \quad \text{if } |s| \geq |s_0| \]
since
\[ ||\chi V|| = ||(\mathcal{T}^{-1} \circ \mathcal{T}) \chi V|| \]
\[ = ||\mathcal{T}^{-1}(y, D_y, s) \mathcal{I}(y, D_y, s) \chi V + (\text{order } -1) \chi V|| \]
\[ \leq C ||W|| + C \frac{1}{|s|} ||\chi V||, \]
and the left-hand side is evident.

Thus it holds that, if we take \( \alpha \) sufficiently large,

\begin{align*}
\text{(2.18)} & \quad c\eta \{ \beta |\xi|^8 ||w_2||^2 + ||(\psi + \alpha)w_2||^2 \} \\
& \quad + \beta |\xi|^8 \langle \psi w_2(0, y, s) \rangle^2 - \langle (\psi + \alpha)w_2(0, y, s) \rangle^2 \\
& \quad \leq C |\xi|^8 ||P_0||^2
\end{align*}

for \( \eta \geq \eta_2 \).

Next we estimate the boundary term. Operate \( \chi(y, D_y, \xi) \) to (ii) of (2.7) and we have

\[ \mathcal{B}(y, D_y, s) \chi(y, D_y, \xi) V(0, y, s) = [\mathcal{B}, \chi_y] V(0, y, s) + \chi g. \]

\[ \mathcal{B}(y, D_y, s) = (\mathcal{B} \circ \mathcal{T}^{-1})(y, D_y, s) \cdot \mathcal{I}(y, D_y, s) + \mathcal{B}_-(y, D_y, s) \]
where \( \mathcal{B}_-(y, \omega, s) \in S_{C^{-1}} \). Then

\begin{align*}
\text{(2.19)} & \quad b_1(y, D_y, s)w_2(0, y, s) + b_2(y, D_y, s)w_2(0, y, s) \\
& \quad = \mathcal{B}_- \chi V(0, y, s) + [\mathcal{B}, \chi_0] V(0, y, s) + \chi_0(D_y, s) g(y)
\end{align*}

where \( b_i(y, \omega, s) \in S_{C^{-1}}^0 \) \((i=1, 2)\) and

\[ b_2(y, \omega, s) = -i(\omega^2 + \xi^2)^{-1/2} \Gamma(y, \omega, s). \]

We have \( |\Gamma(y, \omega, s)| \geq c\eta \) from Lemma 2.3, and from (2.10) \( |b_2(y, \omega, s)| \geq \gamma \) when \( \omega \in \Delta_\ell^{(2)}. \)

\[ \langle \xi b_1(y, D_y, s)w_2(0, y, s) \rangle \]
\[ \geq c\eta \langle w_2(0, y, s) \rangle - C \langle w_2(0, y, s) \rangle \]
\[ \langle \psi(y, D_y, s)b_1(y, D_y, s)w_2(0, y, s) \rangle \]
\[ \geq \langle b_2(y, D_y, s) \psi w_2(0, y, s) \rangle - C \langle w_2(0, y, s) \rangle \]
\[ \geq \gamma \langle \psi(y, D_y, s)w_2(0, y, s) \rangle - C \langle \xi \psi(y, D_y, s)w_2(0, y, s) \rangle \]
\[ + \langle w_2(0, y, s) \rangle \].

Then we get
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\[ c\eta \langle w_2(0, y, s) \rangle + \gamma_1 \langle \psi w_2(0, y, s) \rangle - C \langle \psi w_2(0, y, s) \rangle \]
\[ \leq C \left| \xi \right| \langle b(y, D_y, s) w_2(0, y, s) \rangle \]
\[ \leq C \left| \xi \right| \langle b_2(y, D_y, s) w_2(0, y, s) \rangle + C \left| \xi \right| \left\{ \langle \chi_0 \rangle + \left\langle [\mathcal{B}, \chi_0] V \right\rangle + \left\langle [\mathcal{B}, \chi_0] V \right\rangle \right\} \]
\[ \leq C \left| \xi \right| \langle w_3(0, y, s) \rangle + C \left| \xi \right| \left\{ \langle \chi_0 \rangle + \left\langle [\mathcal{B}, \chi_0] V \right\rangle + \left\langle [\mathcal{B}, \chi_0] V \right\rangle \right\} . \]

By choosing \( \beta \) sufficiently large, it holds that

\[ (2.20) \quad \beta \left| \xi \right|^2 \langle w_3(0, y, s) \rangle - \langle (\psi + \alpha) w_2(0, y, s) \rangle \]
\[ \geq \left| \xi \right|^2 \langle w_2(0, y, s) \rangle + \langle (\psi + \alpha) w_2(0, y, s) \rangle \]
\[ - C \left| \xi \right|^2 \langle \chi_0 \rangle + \left\langle [\mathcal{B}, \chi_0] V \right\rangle , \]

here we used the estimate \( \left\langle \mathcal{B} \chi_0 V \right\rangle \leq C \left| \xi \right| \langle \chi_0 V \rangle \) and \( \langle \chi_0 V \rangle \leq C \langle W \rangle \) holds when \( \left| s \right| \geq \left| s_o \right| \).

Therefore by combining the estimates (2.18) and (2.20), we have

**Proposition 2.6.** Under Assumptions I, II and III, the estimate

\[ (2.21) \quad \eta |\psi(y, D_y, s) + \alpha \chi_0(D_y, \xi) V(x, y, s)|^2 \]
\[ + \langle (\psi(y, D_y, s) + \alpha \chi_0(D_y, \xi) V(0, y, s) \rangle \]
\[ \leq C \{ \left| \psi(x, y) \right| + \left| \chi_0 \right| \mathcal{M} V(x, y, s) \rangle \}
\[ + \left| \chi_0 \right| \mathcal{M} \left| V(0, y, s) \right| \}

holds for all \( s = \eta + i \xi \) such that \( \eta \leq \eta \leq \eta \xi \).

Next let us consider Assumptions.

**Proposition 2.7.** Assumptions II and III are satisfied when the variation of the coefficients and \( d \) are sufficiently small.

Proof. It is evident that Assumption II is satisfied when the variation of the coefficients is so small. Then let us consider Assumption III.

The equation (2.15) (as \( \psi \) is unknown) in \( y \) and \( \omega \) is hyperbolic, and since \( \frac{\partial \omega}{\partial \omega} = 0 \) there exists a unique global solution when \( \psi(0, \omega, s) \) is given.

Take \( d_4, d_5 \) and \( d_4 < d_3 < d_6 \) and define \( \Delta_\xi^{(4)} \) and \( \Delta_\xi^{(5)} \) as the other \( \Delta_\xi^{(4)} \). Let \( \psi_\alpha(\omega, \xi) \) be a real-valued \( C^\infty \)-function such that

\[ \psi_\alpha(\omega, \xi) = \begin{cases} |\xi| & \omega \in \Delta_\xi^{(5)} \\ 0 & \omega \in \Delta_\xi^{(4)} \end{cases} \]
\[ \psi_\alpha(\omega, \xi) = \lambda \psi_\alpha(\omega, \xi) \quad \text{for any } \lambda > 0. \]

We take as \( \psi(y, \omega, s) \) the solution of (2.15) for the initial condition \( \psi(0, \omega, s) = \psi_\alpha(\omega, \xi) \). Remark that \( \psi(y, \omega, s) \) is determined for all \( (y, \omega, s) \in \mathbb{R} \times \mathbb{R} \times C^+ \).
and $C^\omega(R \times R \times C_+)$. To show (2.16) and (2.17), we make use of the bicharacteristic curve of the equation (2.15). Consider a curve in $(y, \omega)$-space with a parameter $s$ defined by

$$\frac{dy(l)}{dl} = \frac{\partial \kappa_2}{\partial \omega}(y(l), \omega(l), s)$$

$$\frac{d\omega(l)}{dl} = -\frac{\partial \kappa_2}{\partial y}(y(l), \omega(l), s)$$

$y(0)=0$ $\omega(0)=\omega$

$(-\infty < l < \infty)$.

Let $\omega \in \Delta^{(3)}$ and suppose that $\omega(l) \in \Delta^{(1)}$ for $l \in [-l_0, l_0]$, then (2.9) shows that $\left\lvert \frac{dy(l)}{dl} \right\rvert \geq \gamma_2$. Let $\frac{dy(l)}{dl} \geq \gamma_2$ then we have $y(l) - y(l') \geq \gamma_2(l - l')$ for $-l_0 \leq l' < l \leq l_0$. On the other hand, $(\partial_\omega \kappa_2)(y(l), \omega(l), s) \neq 0$ only when $|y(l)| \leq d$. Therefore we may assume that $\frac{d\omega(l)}{dl}(l) = 0$ if $l \in [l_1, l_2]$, where $[l_1, l_2]$ is an interval such that $l_2 - l_1 \leq \frac{2d}{\gamma_2}$. From this it follows that an estimate

$$|\omega(l) - \omega(l')| \leq \frac{2d}{\gamma_2} \sup |\partial_\omega \kappa_2|$$

$$\leq C \frac{2d}{\gamma_2} |l|$$

holds for any $l, l' \in [-l_0, l_0]$. Therefore when $d$ is so small as

$$2d \leq \frac{\gamma_2}{C} \inf (d_4 - d_2, d_3 - d_1),$$

$\omega(0) \in \Delta^{(4)}$ leads $\omega(l) \in \Delta^{(1)}$ for all $l \in R$ and if $\omega(0) \in \Delta^{(5)}$ we get $\omega(l) \in \Delta^{(3)}$ for all $l \in R$. Thus (2.16) and (2.17) follow immediately from the above fact with the aid of

$$\psi(y(l), \omega(l), s) = \psi(\omega(0), \xi)$$

for all $l$.

The relation (2.22) shows that $\psi(y, \omega, s) = \psi(d, \omega, s)$ for all $y > d$ or $\psi(y, \omega, s) = \psi(-d, \omega, s)$ for all $y < -d$. Evidently $\psi(y, \lambda \omega, \lambda s) = \lambda \psi(y, \omega, s)$ for $\lambda > 0$. Then by taking account of (2.16) and (2.17), $\psi(y, \omega, s) \in S_2^\omega$ is derived. Q.E.D.

Next consider a neighborhood of $(\omega_0, s_0)$ such that $\omega_0^2 + |s_0|^2 = 1$ and $L_{\alpha}(0, \kappa, \omega_0, s_0) = 0$ has a purely imaginary double root, which occurs when $(i\omega + \varphi(0))s = s^2$. Assumption I leads that $s_0 = i\xi_1$. Remark that

$$\Gamma(0, \omega_0, s_0) = ib\omega_0 \neq 0.$$

We construct $2 \times 2$ matrix-valued $C^\omega$-function $\mathcal{D}(y, \omega', s')$, defined for
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\((y, \omega', s') \in R \times \{(\omega, \eta + i \xi); \omega^2 + \xi^2 = 1, 0 \leq \eta \leq \eta_2 \text{ and } |\omega - \omega_1| + |\xi - \xi_1| \leq d_6\) = \(R \times U\) where \(d_6\) is some positive constant, with the following properties:

(i) \(D(y, \omega', s')\) is symmetric
(ii) \(2 \text{Re} \ D(y, \omega', s').M(y, \omega', s') \geq \eta' = \text{Re} \ s'\)
(iii) \(D(y, \omega', s')V = q\) implies that \(D(y, \omega', s')V \cdot V \geq |V|^2 - C|q|^2\).

This method is completely due to Kreiss [9]. When \(D(y, \omega', s')\) with the above properties is constructed we can prove the following

**Proposition 2.8.** There exist positive constants \(\eta_2\) and \(C\) such that

\[(2.24) \eta \|X(D_y, \xi) V(x, y, s)\|^2 + \langle X(D_y, \xi) V(0, y, s) \rangle^2 \leq C \{\|p\|^2 + \|X, [M, V] + \|q\|^2 + \langle X, D \rangle V \}^2\]

holds for all \(s = \eta + i \xi\) such that \(\eta \leq \eta_2\), \(\xi\), where \(X(\omega, \xi)\) is a \(C^\infty\)-function such that \(X(\lambda \omega, \lambda \xi) = X(\omega, \xi)\) for \(\lambda > 0\) and

\[X(\omega, \xi) = \begin{cases} 1 & \text{when } |\omega' - \omega_1| + |\xi' - \xi_1| \leq d_6 - \varepsilon \\ 0 & \text{when } |\omega' - \omega_1| + |\xi' - \xi_1| > d_6 \end{cases}\]

where \(\varepsilon > 0\).

Proof. Take \(D_i(y, \omega, s) \in S^0_{C_+}\) such that \(D_i(y, \omega, s) = D(y, \omega', s')\) when \((\omega', s') \in U\), and symmetric in \(R^2 \times C_+\). Operate \(X(D_y, s)\) to the both sides of (i) of (2.7) and we have

\[\frac{\partial}{\partial x} X_i V = \mathcal{M} X_i V + [X_i, \mathcal{M}] V + X_i P\]

Put \(V_i(x, y, s) = X_i(D_y, s) V(x, y, s)\), then

\[2 \text{Re} \left(D_i(y, D_y, s) V_i, -P_1\right) = 2 \text{Re} \left(D_i(y, D_y, s) V_i, -\frac{\partial}{\partial x} V_i\right) + 2 \text{Re} \left(D_i V_i, \mathcal{M} V\right) = I + II.\]

\[I = 2 \text{Re} \langle D_i(y, D_y, s) V_i(0, y, s), V_i(0, y, s) \rangle + 2 \text{Re} \left(\left(D_i(y, D_y, s) - D_i(y, D_y, s)^\dagger \right)\frac{\partial V_i}{\partial x}, V\right)\]

\[\geq 2 \text{Re} \langle D_i(y, D_y, s) V_i(0, y, s), V_i(0, y, s) \rangle - C \|V_i\| \left\|V_i\right\| + \frac{1}{|s|} \|P_1\|,\]

here we used \(D_i(y, \omega, s) - D_i(y, \omega, s) \in S^{-1}_{C_+}\) since \(D_i(y, \omega, s)\) is symmetric.
\[ II = ((D^*_1 H + M^* D_1) V_1, V_1) \]

from Lemma 2.2
\[ = ((2 \Re D_1 M_0)(y, D_y, s)V_1, V_1) + (R_0 V_1, V_1) \]

where \( R_0(y, \omega, s) \in S^0_{c+} \), then
\[ \geq \eta ||V_1||^2 - C ||V_1||^2. \]

Thus we get
\[(2.25) \quad \eta ||V_1||^2 + 2 \Re \langle D_1(y, D_y, s)V_1(0, y, s), V_1(0, y, s) \rangle \]
\[ - C ||V_1||^2 - C ||P_1||^2 \]
\[ \leq C(||V_1||^2 + ||P_1||^2). \]

On the other hand \( BV_1 = \chi_q + [\mathcal{B}, \chi] V \), and from the property (iii) we have
\[ 2 \Re \langle D_1(y, D_y, s)V_1(0, y, s), V_1(0, y, s) \rangle \]
\[ \geq \langle V_1(0, y, s) \rangle^2 \left( \frac{C}{|s|} \langle V_1(0, y, s) \rangle^2 \right) \]
\[ - C \langle \chi_q \rangle^2 + \langle [\mathcal{B}, \chi] V \rangle^2 \right). \]

Inserting this estimate into (2.25) we have (2.24). Q.E.D.

Now let us construct \( D(y, \omega', s') \) with the properties (i)~(iii). Put
\[ \kappa_0 = \kappa_0(0, \omega_1, i\xi_1) \]
\[ Q_0 = \begin{bmatrix} 2i\kappa_0 + 1 & 2 \\ i\kappa_0 & 1 \end{bmatrix} \]

and
\[ \tilde{M}(y, \omega, s) = Q_0 \mathcal{M}(y, \omega, s) Q_0^{-1}. \]

Then
\[ \tilde{M}_0(0, \omega_1, i\xi_1) = Q_0 \mathcal{M}_0(0, \omega_1, i\xi_1) Q_0^{-1} = \begin{bmatrix} \kappa_0 & i \\ 0 & \kappa_0 \end{bmatrix}. \]

Let
\[ \lim_{\eta \to 0} \frac{\partial \tilde{M}_0}{\partial \eta}(y, \omega, \eta + i\xi) = \mathcal{M}(y, \omega, \xi) = [h_{ij}(y, \omega, \xi)]_{i,j=1,2}. \]

It is easily seen that
\[ a_{ii}(0) h_{2i}(0, \omega_1, \xi_1) = \left( \frac{\partial L_0}{\partial s} \right)(0, \kappa_0, i\omega_1, i\xi_1). \]

Remark that the regularly hyperbolicity of \( L \) with respect to \( t \) assures
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\[ |L_0(y, \kappa, i\omega, s)| \geq c_0 \Re s \]

for all \( \kappa \) purely imaginary. Then from

\[ L_0(0, \kappa, i\omega, \eta + i\xi) = L_0(0, \kappa, i\omega, i\xi) + \eta \frac{\partial L_0}{\partial s}(0, \kappa, i\omega, i\xi) + O(\eta^2) \]

it follows

\[ \left| \frac{\partial L_0}{\partial s}(0, \kappa, i\omega, i\xi) \right| \geq c_0, \]

which shows

\[ |h_\Delta(0, \omega_1, \xi)| \geq 2c . \]

Now we pose

**Assumption IV.** \( |h_\Delta(y, \omega, \xi)| \geq c \) for all \( y \in \mathbb{R}, (\omega, \xi) \in \{(\omega, \xi) ; |\omega - \omega_1| + |\xi - \xi_1| \leq d, \omega^2 + \xi^2 = 1 \} \) where \( c \) and \( d \) are positive constants.

(2.26) \[
\begin{align*}
\tilde{M}_0(y, \omega', \eta' + i\xi') &= \tilde{M}_0(0, \omega, i\xi) + \tilde{M}_0(y, \omega', \eta' + i\xi') \\
- \tilde{M}_0(y, \omega', i\xi') &= \tilde{M}_0(0, \omega, i\xi) - \tilde{M}_0(0, \omega, i\xi)
\end{align*}
\]

where

\[ \mathcal{E}(y, \omega', \xi') = \frac{1}{i} \{ \tilde{M}_0(y, \omega', \xi') - \tilde{M}_0(0, \omega, i\xi) \} . \]

Notice that all the entries of \( \mathcal{E}(y, \omega', \xi') \) are real-valued and

(2.27) \[ |\mathcal{E}(y, \omega', \xi')| \leq C \{|\omega' - \omega_1| + |\xi' - \xi_1| + \text{variation of coefficients of } L_0\} . \]

**Lemma 2.9.** The matrix

\[
\begin{bmatrix}
0 & k_1 \\
k_1 & k_2
\end{bmatrix}
+ \begin{bmatrix}
a & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
0 & 1 \\
0 & 0
\end{bmatrix}
+ \begin{bmatrix}
e_1 & e_2 \\
e_3 & e_4
\end{bmatrix}
= (\mathcal{D}_0 + \mathcal{A})(C_0 + \mathcal{E})
\]

is symmetric if all entries are real, \( 1 + e_2 \neq 0 \) and

\[ a = \frac{k_1 e_1 + k_2 e_2 - k_1 e_4}{1 + e_2} . \]

Of course \( a = 0(\sum |e_i|) \) when \( \sum |e_i| \to 0 \).

Let us put
\[ \tilde{\mathcal{D}}(y, \omega', s') = \begin{bmatrix} 0 & k_1 \\ k_1 & k_2 \end{bmatrix} + \begin{bmatrix} a(y, \omega', s') & 0 \\ 0 & 0 \end{bmatrix} - iv' \begin{bmatrix} 0 & -f \\ f & 0 \end{bmatrix} = \mathcal{D}_0 + \mathcal{A}(y, \omega', s') - iv' \mathcal{F} \]

where \( a(y, \omega', s') \) is determined by Lemma 2.9 from \( \mathcal{E}(y, \omega', s') \) and \( k_i (i=1, 2) \) and \( f \) are constants which will be determined later.

\[ 2 \, \text{Re} \tilde{\mathcal{D}}(y, \omega', s') \mathcal{M}_0(y, \omega', s') = \gamma' \{ 2 \, \text{Re} (\mathcal{F}_0 + \mathcal{D}_0 \mathcal{M}) + 0(\gamma' + |\mathcal{E}|) \} . \]

Since

\[ \mathcal{F}_0 + \mathcal{D}_0 \mathcal{M} = \begin{bmatrix} \mathcal{K}_h \mathcal{S} & \mathcal{S}_h \mathcal{K} \\ \mathcal{K}_h \mathcal{S}_h & \mathcal{S}_h \mathcal{K}_h + \mathcal{K}_h \mathcal{S}_h + f \end{bmatrix} \]

we can make \( \text{Re}(\mathcal{F}_0 + \mathcal{D}_0 \mathcal{M}) \geq 1 \) by choosing as \( k_h \mathcal{S} \geq 2 \) (from Assumption IV) and \( f \) sufficiently large. Then when \( |\mathcal{E}| \) is not so large we get

\[ 2 \, \text{Re} \tilde{\mathcal{D}}(y, \omega', s') \mathcal{M}_0(y, \omega', s') \geq \gamma' \]

for \( 0 \leq \gamma' \leq \gamma_0 \). \( |\mathcal{E}| \) becomes small according to \( d_\alpha \) and the variation of coefficients. Put

\[ \mathcal{D}(y, \omega', s') = \mathcal{U}_0 \tilde{\mathcal{D}}(y, \omega', s') \mathcal{U}_0 \]

then it satisfies (i) and (ii).

\[ (\mathcal{D}(y, \omega', s') V, V) = (\tilde{\mathcal{D}}(y, \omega', s') \tilde{V}, \tilde{V}) \geq 2 \, \text{Re} (k_1 \tilde{\vartheta}_1 + k_2 \tilde{\vartheta}_2 + \mathcal{K}_h \mathcal{S}_h \tilde{\vartheta}_1 + \mathcal{S}_h \mathcal{K}_h + f) - 0(\gamma' \mathcal{E}^2) \tilde{V}^2 \]

where \( \tilde{V} = (\tilde{\vartheta}_1, \tilde{\vartheta}_2) = \mathcal{U}_0 V \),

\[ \geq -2k_1 |\tilde{\vartheta}_1|^2 - \frac{k_2}{2} |\tilde{\vartheta}_2|^2 . \]

\[ \mathcal{D}(y, \omega', s') = b_1(y, \omega', s') \tilde{\vartheta}_1 + b_2(y, \omega', s') \tilde{\vartheta}_2 \]

then \( b_1(0, \omega', s') = \Gamma(0, \omega', s') \). From (2.23) when \( d_\alpha \) and the variation of the coefficients are not so large \( |\Gamma(y, \omega', s')| \geq \epsilon \), this implies that

\[ |\tilde{\vartheta}_1|^2 \leq C |\tilde{\vartheta}_2|^2 + \epsilon \]

Inserting this into (2.28) we have

\[ (\mathcal{D}(y, \omega', s') V, V) \geq |\tilde{V}|^2 - C |\gamma|^2 \]

by choosing \( k_\epsilon \) large. Thus (iii) is proved.
Now, remark that Assumption IV is satisfied when the variation of the coefficients and \( d' \) are sufficiently small.

The number of the points \((\omega_0, \xi_0)\) considered in Proposition 2.6 are two and the number of the points \((\omega_i, \xi_i)\) considered in Proposition 2.8 are four. Let us denote by \( X(\omega_0, \xi_0) \) the sum of \( X_0(\omega, \xi) \) and \( X_0(\omega, \xi) \) of all the points \((\omega_0, \xi_0)\) and \((\omega_i, \xi_i)\). Then it is easy to get the estimate of the type of (2.24) for \( X(D_\gamma, \xi)V(x, y, s) = (1 - X(D_\gamma, \xi))V(x, y, s) \). Indeed, we can use the method of Proposition 2.6 by taking

\[
\mathcal{N}(y, \omega, s) = \begin{bmatrix} \kappa_-(y, \omega', s') & -i \\ \kappa_+(y, \omega', s') & -i \end{bmatrix}
\]

and

\[
\mathcal{D}(y, \omega, s) = \begin{bmatrix} \beta & 0 \\ 0 & -1 \end{bmatrix}
\]

Remark that it holds that

\[
|s|^2 \sum_{i=0}^{2} \| [\mathcal{H}, X_\gamma]V \|^2 \leq C \left\{ \| (\psi(D_\gamma, \xi) + \alpha)X_\gamma V \|^2 + |s|^2 \sum_{i=1}^{2} \| X_i V \|^2 + \| V \|^2 \right\}
\]

and

\[
|s|^2 \sum_{i=0}^{2} \langle [\mathcal{B}, X_\gamma]V \rangle^2 \leq C \left\{ \langle (\psi(D_\gamma, \xi) + \alpha)X_\gamma \rangle + |s|^2 \sum_{i=1}^{2} \langle X_i V \rangle + \langle V \rangle^2 \right\}.
\]

Then we have

**Theorem 2.10.** When the variation of the coefficients and \( d \) are sufficiently small, there exist positive constants \( C_0 \) and \( \eta_0 \) such that for any solution \( v(x, y) \) of (2.5) in \( H^3(R^4) \), the estimate

\[
(2.29) \quad \eta \left( \| v(x, y) \|^2 + \| v(x, y) \|^2 \right) + \langle v(0, y) \rangle^2 + \langle v(0, y) \rangle^2 + \langle \partial_v(0, y) \rangle^2 \\
\leq C_0 \left\{ \| \varphi(x, y) \|^2 + \langle q(y) \rangle^2 \right\}
\]

holds when \( \text{Re} \ s = \eta \geq \eta_0 \).

Proof. (2.29) is derived for \( s \) such that \( \eta_0 \leq \eta \leq c_0 |\xi| \) by combining Propositions 2.6 and 2.8 and the above remarks. On the other hand when \( \eta > c_0 |\xi| \), (2.29) is already known in the general theory of boundary value problems for elliptic equations. Q.E.D.

**Corollary of Theorem 2.10.**
holds when $\text{Re } s \geq \eta_0$.

Proof. Recall an apriori estimate concerning an elliptic boundary value problem

$$a_2(y, \partial_x, \partial_y)u(x, y) = (a_{11}\partial_x + 2a_{12}\partial_x \partial_y + a_{22}\partial_y^2)u(x, y)$$

$$= f(x, y) \text{ in } \mathbb{R}^x$$

$$u(x, y) \mid_{x=0} = g(y),$$

for some positive constant $C$

(2.31) \[ ||u(x, y)||_2^2 \leq C (||f||^2 + ||g||^2 + ||u||^2). \]

Apply it for

$$a_2v = p-sa_1v + s^2v$$

$$= g + s\rho(a_{12} + b)v$$

and we have

$$||v||_2^2 \leq C \{ ||p||^2 + ||sv||^2 + ||sv||^2 + ||sv||^2 + ||sv||^2 + ||sv||^2 \}. $$

From (2.29) we have

$$\eta[||sv||^2 + ||sv||^2 + ||sv||^2] \leq C \{ ||sv||^2 + ||sv||^2 \},$$

insert this into the above, (2.30) follows. Q.E.D.

Let us denote by $L\varphi(s)$ the operator from $H^2(\mathbb{R}^2)$ into $L^2(\mathbb{R}^2) \times H^{1/2}(\mathbb{R})$ defined by

$$L\varphi(s)u = \{L\varphi(s)u, B\varphi(s)u \mid_{x=0}\}. $$

**Theorem 2.11.** $L\varphi(s)$ is a bijective mapping when $\text{Re } s \geq \eta_0$ and $L\varphi(s)^{-1}\{f(x, y, s), g(y, s)\}$ is $H^2(\mathbb{R}^2)$ valued holomorphic function when $f$ and $g$ are vector valued holomorphic function in $L^2(\mathbb{R}^2)$ and $H^{1/2}(\mathbb{R})$ respectively.

Proof. $L\varphi(s)$ the formal adjoint of $L\varphi(s)$ has the principal part

$$L\varphi(y, -\partial_x, -\partial_y, s).$$

Then for a boundary operator $B$ with the principal part

$$B(y, -\partial_x, -\partial_y, s)$$

we have for all $u, v \in H^2(\mathbb{R}^2)$
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\[(L \phi(s)u, v) - (u, L^* \phi(s)v) = \int (B(s)u \bar{v} + u \bar{B}(s)v) dy.\]

Since the apriori estimate for \(L^* \phi(s), B(s)\) of the type (2.30) holds for \(Re s \geq \gamma_0^s\), we see that \(\mathcal{L}_\phi(s)\) is a bijective mapping. The last part of Theorem is easily proved with the aid of (2.30).

2.3. Energy estimate

Hereafter, in this section, we assume that the operators (2.1) and (2.2) satisfy Assumptions I~IV posed in the previous paragraph.

**Proposition 2.12.** For a solution \(u(x, y, t) \in L^2(H^3(R^2_+)) \cap L^2(H^2(R^2_+)) \cap L^2(H^1(R^2_+)) \cap L^2(L^2(R^2_+))\) of (2.4), the energy estimate holds:

\[(2.32) \quad \int_0^T \left\{ ||u(x, y, t)||^2 + ||u'(x, y, t)||^2 + \langle u(0, y, t), u'(0, y, t) \rangle \right\} dt \leq C_T \left\{ ||u(x, y, 0)||^2 + ||u'(x, y, 0)||^2 + ||f(x, y, 0)||^2 + \int_0^T (||f'(x, y, t)||^2 + \langle g'(y, t), \phi \rangle) dt \right\} \quad \text{for } t \in [0, T]

where \(C_T\) depends on \(L \phi, B \phi\) and \(T\) and is independent of \(u\).

Proof. At first assume that \(u(x, y, 0) = u'(x, y, 0) = 0, f(x, y, 0) = 0\) and \(g(y, 0) = 0\). Take a function \(\chi(t) \in C^\infty(R)\) such that

\[\chi(t) = \begin{cases} 1 & t < T \\ 0 & t > T + \delta \ (\delta > 0) \end{cases}

Then

\[(2.33) \quad L \phi \chi(t)u(x, y, t) = \chi(t)f(x, y, t) - [L \phi, \chi]u
\]

\[(2.34) \quad B \phi \chi(t)u(x, y, t) = \chi(t)g(y, t) - [B \phi, \chi]u.

Put \(\chi(t)u(x, y, t) = v(x, y, t)\) and the right-hand side of (2.33) and (2.34) as \(f_o\) and \(g_o\) respectively. Evidently \(v\) and \(f_o\) are in \(L^2(R_+, L^2(R^2_+))\) and \(g_o\) is in \(L^2(R_+, L^2(R))\). Define \(f_i(x, y, t)\) \((i = 1, 2)\) by

\[f_i(x, y, t) = \begin{cases} \frac{\partial f_o(x, y, t)}{\partial t} & \text{for } t \leq t_o \\ 0 & \text{for } t > t_o \end{cases}
\]

\[f_3(x, y, t) = \frac{\partial f_2(x, y, t)}{\partial t} - f_1(x, t, y),\]
and \( g_i \) \((i=1, 2)\) by the same way. Laplace transformation with respect to \( t \) gives

\[
L_\psi(y, \partial_x, \partial_y, s)\vartheta(x, y, s) = \tilde{f}_i(x, y, s)
\]

\[
B_\psi(y, \partial_x, \partial_y, s)\vartheta(x, y, s) \big|_{x=0} = \tilde{g}_i(y, s)
\]

where \( \vartheta, \tilde{f}_i \) and \( \tilde{g}_i \) are the Laplace image of \( \psi, f_i \) and \( g_i \) respectively. Then for all \( \Re s \geq \eta_0 \)

\[
\vartheta(x, y, s) = L_\psi(s)^{-1}(\tilde{f}_i(x, y, s), \tilde{g}_i(y, s))
\]

and

\[
\tilde{f}_i(x, y, s) = \frac{1}{s}(\tilde{f}_i(x, y, s) + \tilde{f}_i(x, y, s))
\]

\[
\tilde{g}_i(y, s) = \frac{1}{s}(\tilde{g}_i(y, s) + \tilde{g}_i(y, s)).
\]

Put

\[
\vartheta_i(x, y, s) = \frac{1}{s}L_\psi(s)^{-1}(\tilde{f}_i(x, y, s), \tilde{g}_i(y, s))
\]

and they are holomorphic in \( \Re s \geq \eta_0 \), moreover

\[
||\vartheta_i(x, y, s)|| \leq Ce^{-t_0 \Re s}
\]

holds since \( ||\tilde{f}_i(x, y, s)|| \leq Ce^{-t_0 \Re s} \) and \( \langle \tilde{g}_i(y, s) \rangle \leq Ce^{-t_0 \Re s} \). Therefore \( \vartheta_i(x, y, t) \) the inverse image of \( \vartheta_i(x, y, s) \) has the support in \([t_0, \infty)\), then \( u(x, y, t) = \vartheta_i(x, y, t) \) for \( t \in [0, t_0) \). The Parseval's equality shows

\[
\int_0^\infty e^{-2\pi t}(|v_i(x, y, t)|^2 + |v_i(x, y, t)|^2)dt
\]

\[
= \int_{-\infty}^\infty (||\vartheta_i(x, y, \eta + i\xi)||^2 + ||\vartheta_i(x, y, \eta + i\xi)||^2)d\xi
\]

\[
\leq \frac{C}{\eta} \int_{-\infty}^\infty (||\tilde{f}_i(x, y, \eta + i\xi)||^2 + \langle \tilde{g}_i(y, \eta + i\xi) \rangle^2)d\xi
\]

\[
= \frac{C}{\eta} \int_0^{t_0} e^{-2\pi \xi}||\tilde{f}_i(x, y, t)||^2 + \langle \tilde{g}_i(y, t) \rangle^2 dt,
\]

thus (2.32) holds by taking \( C_T = Ce^{2\pi T} \).

Next let us prove the general case. Take \( w(x, y, t) \in \mathcal{C}_0^\infty(H^3(R^4_1)) \cap \mathcal{C}_0^\infty(H^1(R^4_1)) \cap \mathcal{C}_0^\infty(L^2(R^4_1)) \) as

\[
\begin{cases}
L_\psi w = f(x, y, 0) & \text{in } R^2 \times (0, T) \\
w(x, y, 0) = u(x, y, 0) & \text{in } R^2_+ \\
\frac{\partial w}{\partial t}(x, y, 0) = u'(x, y, 0) & \text{in } R^2_+
\end{cases}
\]
then \( v(x, y, t) = u(x, y, t) - w(x, y, t) \) satisfies the condition assumed in the first. Applying the just obtained result we have

\[
\int_0^t \left( ||u(x, y, t) - w(x, y, t)||^2 + ||u'(x, y, t) - w'(x, y, t)||^2 \right) dt 
\leq C_T \int_0^t \left( ||f(x, y, t)||^2 + g'(y, t) + (Bw)'(0, y, t) \right) dt.
\]

Remark that

\[
||w(x, y, t)||^2 + ||w'(x, y, t)||^2 
\leq C_T \left( ||u(x, y, 0)||^2 + ||u'(x, y, 0)||^2 + ||f(x, y, 0)||^2 \right),
\]

and

\[
\langle Bw'(y, t) \rangle \leq C_T \left( ||u(x, y, 0)||^2 + ||u'(x, y, 0)||^2 + ||f(x, y, 0)||^2 \right),
\]

which inserting into the above, (2.32) follows. Q.E.D.

Define \( ||u(x, y, t)||_{k,R^2_x} \) and \( \langle g(y, t) \rangle_{k,R} \) \((k=1, 2, \ldots)\) by

\[
||u(x, y, t)||^2_{k,R^2_x} = \sum_{i=0}^k \left( \frac{\partial}{\partial t} \right)^i u(x, y, t)_{k-i,L^2(R^2_x)},
\]

\[
\langle g(y, t) \rangle^2_{k,R} = \sum_{i=0}^k \left( \frac{\partial}{\partial t} \right)^i g(y, t)_{k-i,L^2(R)}.
\]

respectively.

**Theorem 2.13.** For a solution \( u(x, y, t) \in C^0_t(H^{m+2}(R^2_x)) \cap C^1_t(H^{m+1}(R^2_x)) \)

\( \cap \cdots \cap C^m_t((L^2(R^2_x)) \) the energy estimate

\[
(2.35) \quad \int_0^t ||u(x, y, t)||^2_{m,R^2_x} dt 
\leq C_{T,m} \left\{ ||u(x, y, 0)||^2_{m,2} + ||u'(x, y, 0)||^2_{m,1} + ||f(0)||^2_{m,R^2_x} + \int_0^t (||f'(x, y, t)||^2_{m,R^2_x} + \langle g'(y, t) \rangle^2_{m,R}) dt \right\}
\]

for all \( t \in [0, T] \)

holds for \( m=1, 2, 3, \ldots \).

Proof. The \((m-1)\)-times differentiation in \( t \) the both sides of (2.4) gives

\[
L_q(u^{(m-1)}(x, y, t)) = f^{(m-1)}(x, y, t)
\]

\[
B_q(u^{(m-1)}(x, y, t))|_{x=0} = g^{(m-1)}(y, t).
\]

It follows from Proposition 2.12 that
With the aid of (2.31) we get an estimate

\[
\|u(x, y, t)\|_{m-1}^2 + \|u(y, 0)\|_{m-2}^2 + \int_0^t \|f(x, y, t)\|_{m-2}^2 + \langle g^*(y, t) \rangle dt
\]

from \(L\phi u = f, B\psi u |_{x=0} = g\). Then (2.35) is derived by inserting the above estimate and by using

\[
\|u^{(m-1)}(x, y, 0)\|_{m-1}^2 + \|u^m(y, 0)\|_{m-2}^2 + \int_0^t \|f(x, y, t)\|_{m-1}^2 + \langle g^*(y, t) \rangle dt
\]

Q.E.D.

2.4. Existence and regularity of the solution

**Theorem 2.14.** For given data \(u_0, u_1, f\) and \(g\), if they satisfy the compatibility condition of order \(m+2\), there exists a solution \(u(x, y, t)\) of (2.3) uniquely in \(H^{m+2}(R_+ \times (0, T))\).

**Proof.** Consider at first the case of \(m=0\). Assume that \(u_0(x, y) = u_1(x, y) = 0, f(x, y, 0) = f'(x, y, 0) = 0\) and \(g(y, 0) = g'(y, 0) = 0\). Put

\[
\tilde{u}(x, y, s) = \frac{1}{s} \mathcal{L}^{-1}_\psi(s)(\tilde{f}'(x, y, s), \tilde{g}''(y, s)).
\]

Then Corollary of Theorem 2.10 shows

\[
\|\tilde{u}(x, y, s)\|_{m}^2 + \|\tilde{s}\tilde{u}(x, y, s)\|_{m-2}^2 + \|s^2\tilde{u}(x, y, s)\|_{m-2}^2 \leq \frac{C}{\gamma} (\|\tilde{f}'(x, y, s)\|_{m}^2 + \|g''(y, s)\|_{m}^2).
\]

Of course \(\tilde{u}(x, y, s)\) is holomorphic in \(\text{Re } s \geq \eta_0\). The inverse Laplace image \(u(x, y, t)\) of \(\tilde{u}(x, y, s)\) exists as \(L^2(R_+)^-\)-valued distribution and from the above estimate \(e^{-rt}u(x, y, t) \in H^2(R_+ \times R)\) and \(u(x, y, t) = 0\) for \(t < 0\). Evidently

\[
L\phi u = f \quad \text{in } R_+^2 \times (0, \infty)
\]

\[
B\psi u |_{x=0} = g(y, t) \quad \text{in } R \times (0, \infty).
\]

This means that \(u(x, y, t) \in H^2(R_+^2 \times (0, T))\) is the desired solution of (2.4). Next let us consider the case of non zero initial data. Take a function
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\[ v(x, y, t) = u_o(x, y) + tu_1(x, y) + \frac{t^2}{2} u_2(x, y), \]

then

\[ (f - L_\varphi v)(x, y, 0) = \frac{\partial}{\partial t} (f - L_\varphi v)(x, y, 0) = 0 \]

\[ (g - B_\varphi v)(y, 0) = \frac{\partial}{\partial t} (g - L_\varphi v)(y, 0) = 0 \]

follow from the compatibility condition of order 2. The just obtained result shows the existence of \( w(x, y, t) \in H^2(R^2 \times (0, T)) \) satisfying

\[ L_\varphi[w] = f - L_\varphi[v] \]

\[ B_\varphi[w] = g - B_\varphi[v] \]

\[ w(x, y, 0) = w'(x, y, 0) = 0. \]

Then \( u(x, y, t) = w(x, y, t) + v(x, y, t) \) is the required solution.

Now we prove Theorem for \( m \geq 1 \). Set

\[
u(x, y, t) = u_o(x, y) + tu_1(x, y) + \sum_{k=2}^{m-1} \frac{t^k}{(m-1)!} u_{m-k}(x, y) + \int_0^t \frac{(t-\tau)^{m-1}}{(m-1)!} w_m(x, y, \tau) d\tau
\]

where \( w_m(x, y, t) \in H^2(R^2 \times (0, T)) \) is the solution of

\[ L_\varphi[w_m] = f^{(m)}(x, y, t) \]

\[ B_\varphi[w_m] = g^{(m)}(y, t) \]

\[ w_m(x, y, 0) = u_m(x, y) \]

\[ w'_m(x, y, 0) = u_{m+1}(x, y), \]

whose existence is assured by the result for \( m=0 \) since \( u_m(x, y) \), \( u_{m+1}(x, y) \), \( f^{(m)}(x, y, t) \) and \( g^{(m)}(y, t) \) satisfy the compatibility condition of order 2. It is easy to see that \( u(x, y, t) \) is a solution of (2.3) for \( u_o, u_1, f \) and \( g \). Now we get \( u(x, y, t) \in H^{m+2}(R^2 \times (0, T)) \) from \( u^{(m)}(x, y, t) = w_m(x, y, t) \in H^2(R^2 \times (0, T)) \) with the aid of (2.36). Q.E.D.

2.5. Finiteness of the propagation speed

Lemma 2.15. Let \( u(x, y, t) \in C_0^0(H^2(R^2)) \cap C_0^0(H^1(R^2)) \cap C_0^0(L^2(R^2)) \) be a solution of (2.4). If

\[
f(x, y, t) = 0 \quad \text{for} \quad x + v_q t \leq \delta, \quad x, t \geq 0
\]

\[
g(y, t) = 0 \quad \text{for} \quad v_q t \leq \delta, \quad t \geq 0
\]

\[
u_o(x, y) = u_1(x, y) = 0 \quad \text{for} \quad 0 \leq x \leq \delta,
\]

then...
then \( u(x, y, t) = 0 \) for \( x + v_\phi t \leq \delta \), where \( v_\phi \) denotes the maximam propagation speed of the Cauchy problem for the hyperbolic operator \( L_\phi \).

Proof. Let \( v(x, y, t) \) be the solution of the Cauchy problem \( L_\phi u = f \) for the initial data \( \{ u_0(x, y), u_1(x, y) \} \), where \( u_0(x, y) \) is extend to \( x < 0 \) by 0. The finiteness of propagation speed shows that \( v(x, y, t) = 0 \) when \( x + v_\phi t \leq \delta \), \( t \geq 0 \), therefore \( v(x, y, t) \) satisfies (2.4) when \( v_\phi t \leq \delta \). By applying (2.32) for \( u(x, u, t) = v(x, y, t) \) we have \( u(x, y, t) = v(x, y, t) \) for \( 0 \leq v_\phi t \leq \delta \), this proves Lemma. Q.E.D.

Lemma 2.16. Let \( u(x, y, t) \in \mathcal{E}^\phi_0(H^2(R^2)) \cap \mathcal{E}^\phi_0(H^1(R^2)) \cap \mathcal{E}^\phi_0(L^2(R^2)) \) be a solution of (2.4) and \( U \) be a neighborhood of \( t = y = 0 \) in \( \{(y, t): y \in R, t > 0\} \). If

\[
\begin{align*}
  f(x, y, t) &= 0 & \text{for } (x, y, t) & \in R_+ \times U \\
  g(y, t) &= 0 & \text{for } (y, t) & \in U \\
  u_0(x, y) &= u_1(x, y) = 0 & \text{for } (x, y) & \in R_+ \times \{U \cap (t = 0)\},
\end{align*}
\]

then there exists a neighborhood \( U_0 \) of \( y = t = 0 \) in \( \{(y, t): y \in R, t > 0\} \) such that \( u(x, y, t) = 0 \) in \( R_+ \times U_0 \).

Proof. Consider the Flomgren transformation in \((y, t)\) space

\[
\begin{align*}
  t' &= t + y^2 \\
  y' &= y.
\end{align*}
\]

Define \( \bar{u}(x, y', t') \) by \( \bar{u}(x, y, t + y^2) = u(x, y, t) \) for \( t' - y'^2 > 0 \) and equals zero for \( t' - y'^2 \leq 0 \). \( \bar{f} \) and \( \bar{g} \) are defined by the same way. From the condition posed on \( u_0, u_1 \) we have \( \bar{u}(x, y', t') \in \mathcal{E}^\phi_0(H^1(R^2)) \cap \mathcal{E}^\phi_0(H^1(R^2)) \cap \mathcal{E}^\phi_0(L^2(R^2)) \) when \( t' \leq \delta_0 \) for some constant \( \delta_0 > 0 \) and \( \bar{u}(x, y', 0) = \bar{u}(x, y', 0) = 0 \). Evidently \( \bar{f}(x, y', t') = 0 \) and \( \bar{g}(y', t') = 0 \) when \( t' \leq \delta_0 \). And it holds that

\[
\begin{align*}
  \bar{L}_\phi \bar{u} &= \bar{f} & \text{in } R^2_+ \times (0, \delta_0) \\
  \bar{B}_\phi \bar{u} \big|_{x=0} &= \bar{g} & \text{in } R \times (0, \delta_0),
\end{align*}
\]

where

\[
\begin{align*}
  \bar{L}_\phi &= (1 - a_{12}p^2) \frac{\partial^2}{\partial t^2} - 2a_{12}p \frac{\partial^2}{\partial x \partial t'} - 2a_{12}p \left( \frac{\partial}{\partial t'} + 2y' \frac{\partial}{\partial y'} \right) \frac{\partial}{\partial t'} \\
  &\quad - \left\{ a_{11} \frac{\partial^2}{\partial x^2} + 2a_{12} \left( \frac{\partial}{\partial t'} + 2y' \frac{\partial}{\partial y'} \right) \frac{\partial}{\partial x} + a_{21} \left( \frac{\partial}{\partial t'} + 2y' \frac{\partial}{\partial y'} \right) \right\} \frac{\partial}{\partial t'} \\
  \bar{B}_\phi &= a_{11}(y') \frac{\partial}{\partial x} + (a_{12}(y') + b(y')) \left\{ \frac{\partial}{\partial y'} + \varphi \left( \frac{\partial}{\partial t'} + 2y' \frac{\partial}{\partial y'} \right) \right\} \frac{\partial}{\partial y'}.
\end{align*}
\]

5) \( \bar{L}_\phi \) and \( \bar{B}_\phi \) are not of the form (2.1) and (2.1), but Theorem 2.10 (therefore Theorem 2.13) holds for any operators which are of the form (2.1) and (2.1) at \( y = 0 \) and whose variation of the coefficients and \( d \) are so small.
By changing the values of coefficients of $L_\varphi$ and $B_\varphi$ in \{y'; | y'| \geq \delta_i\} and by taking $\delta_i$ sufficiently small, we can assume $L_\varphi$ and $B_\varphi$ satisfy Assumptions I~IV. And we see that $L_\varphi \tilde{u} = 0$ and $B_\varphi \tilde{u} = 0$ for $0 \leq t' \leq \delta_i$ by taking account of the fact $u(x, y', t') = 0$ when $y'^2 - t' > 0$. Apply the energy estimate (2.32) for (2.37) and we get $\tilde{u}(x, y', t') = 0$ for $t' \leq \delta_i$. This shows that $u(x, y, t) = 0$ when $y'^2 + t \leq \delta_i$.

Q.E.D.

The above lemma derives that the propagation speed of the tangential direction of (2.3) for $\varphi = 0$ is majorated by

$$\sup_{x \in \mathbb{R}} \sqrt{\frac{a_{11}(y)a_{22}(y) - a_{12}(y)^2 + b(y)^2}{a_{11}(y)}}$$

with the aid of the sweeping out method of F. John. Thus we get

**Proposition 2.17.** The propagation speed of (2.4) for $\varphi = 0$ is majorated by

$$\sup_{x \in \mathbb{R}} \sqrt{\frac{a_{11}(y)a_{22}(y) - a_{12}(y)^2}{a_{11}(y)}}$$
in the tangential direction and

$$\sup_{x \in \mathbb{R}} \sqrt{\frac{a_{11}(y)a_{22}(y) - a_{12}(y)^2}{a_{11}(y)}}$$
in the normal direction.

**3. Proof of main theorem**

Let $s_o = (x_o, y_o) \in S$ and the outer unit normal of $S$ at $s_o$ be $(-1, 0)$. Consider a transformation $M$

$$\begin{cases} x' = x - \mu(y) \\ y' = y - y_o. \end{cases}$$

where $x = \mu(y)$ represents an equation of $S$ near $s_o$. $M$ maps a neighborhood of $s_o$ in $\Omega$ into $\mathbb{R}^2$. Then (1.1) is transformed by $M$ into the equations

$$\begin{cases} L^{(\varphi)}[\tilde{u}] = \tilde{f} \\ B^{(\varphi)}[\tilde{u}] = \tilde{g} \\ \tilde{u}(x', y', 0) = \tilde{u}_0(x', y') \\ \tilde{u}'(x', y', 0) = \tilde{u}_1(x', y'), \end{cases}$$

where

$$L^{(\varphi)} = \frac{\partial^2}{\partial t^2} - \left((1 + \mu'(y')) \frac{\partial^2}{\partial x'^2} - 2\mu'(y') \frac{\partial^2}{\partial x' \partial y'} - \frac{\partial^2}{\partial y'^2} \right) + \text{(first order)}$$

$$B^{(\varphi)} = (1 - \mu'(y)) \frac{\partial}{\partial x'} + b(y') \frac{\partial}{\partial y'}.$$
Since \( \mu'(0)=0 \) by defining suitably the coefficients in \( \{y'; |y'|>\delta\} \) and by choosing \( \delta \) sufficiently small we can assume that \( L^{(m)} \) and \( B^{(m)} \) satisfy Assumptions I-IV of the previous section. The finiteness of the propagation speed of (2.4) derives the finiteness of the propagation speed of (1.1) in a neighborhood of \( s_0 \in \Omega \times R_+ \). This fact holds for arbitrary \( s_0 \in S \). On the other hand the finiteness of the propagation speed in the interior of \( \Omega \times R_+ \) is already known. Thus the finiteness of the propagation speed of (1.1) is proved. And by taking account of Proposition 2.17 we see that the propagation speed of (1.1) is majorated by \( v_{\text{max}}=\sup_{y \in R} \sqrt{1+\frac{(b_1 n_1 - b_2 n_2)^2}{b_1^2 + b_2^2}} \).

Put
\[
C(x_0, y_0, t_0) = \{(x, y, t) ; |x-x_0| + |y-y_0| \leq v_{\text{max}}(t-t_0)\}.
\]
then for \( (x, y, t) \in C(x_0, y_0, t_0) \cap (\Omega \times (0, \infty)) \), if
\[
f(x, y, t) = 0 \quad \text{in } C(x_0, y_0, t_0) \cap (\Omega \times (0, \infty))
\]
\[
g(x, y, t) = 0 \quad \text{in } C(x_0, y_0, t_0) \cap (S \times (0, \infty))
\]
\[
u_0(x, y) = u_1(x, y) = 0 \quad \text{in } C(x_0, y_0, t_0) \cap (\Omega \times \{t=0\}),
\]
then \( u(x, y, t)=0 \) in \( C(x_0, y_0, t_0) \cap (\Omega \times (0, \infty)) \).

Remark that when the given data \( \{u_0, u_1, f, g\} \) satisfy the compatibility condition for (1.1) of order \( m \), \( \{\tilde{u}_0, \tilde{u}_1, \tilde{f}, \tilde{g}\} \) satisfy the compatibility condition or order \( m \) for (2.4) by changing the values in \( \{y'; |y'|>\delta\} \).

Let \( d \) be a positive constant such that any \( s_0 \in S \), if a solution \( \tilde{u}(x', y', t) \) satisfy (3.2) in \( R_0 \times (0, T) \), \( u(x, y, t) \) satisfy (1.1) in \( (\Omega \cap (x, y) - s_0 < d) \times (0, T) \). Set \( \Omega_d = \Omega \cap (x, y) - s_0 < d \). Define \( \tilde{u}(x, y, t) \) for \( (x, y, t) \) such that \( C(x, y, t) \cap \{t=0\} \subset \Omega_d \) by \( u(x, y, t) = \tilde{u}(x', y', t) \), and for \( (x, y, t) \) such that \( C(x, y, t) \cap (S \times (0, T)) = \phi \) \( u(x, y, t) \) equals the solution of the Cauchy problem \( Lu=f \), \( u(x, y, 0) = \delta(x, y) \) and \( u'(x, y, 0) = u_1(x, y) \). We see that, by taking account of the above remarks, by this definition \( u(x, y, t) \) is well defined and satisfies (1.1) for \( 0 \leq t \leq \frac{d}{v_{\text{max}}} = t_0 \).

If the given data satisfy the compatibility condition of order \( m+2 \), it follows that \( u(x, y, t) \in H^{m+2}(\Omega \times (0, t_0)) \) from Theorem 2.14. Then we have

**Proposition 3.1.** When the data \( \{u_0, u_1, f, g\} \) satisfy the compatibility condition of order \( m+3 \), there exists a solution \( u(x, y, t) \in E^0(\Omega \times (0, t_0)) \cap E^1(\Omega \times (0, t_0)) \cap \cdots \cap E^{m+1}(\Omega \times (0, t_0)) \) of (1.1) for \( t \in [0, t_0] \).

By applying this proposition step by step we see for any \( T \), when the given data satisfy the compatibility condition of order \( 3\left(\left\lceil \frac{T}{t_0} \right\rceil + 1\right)+m \), there exists
a solution of (1.1) in $E^m_t(H^{m+2}(\Omega)) \cap E^\frac{1}{2}_t(H^{m+1}(\Omega)) \cap \cdots \cap E_\frac{m+2}{2}(L^2(\Omega))$ for $t \in [0, T]$. This proves our Theorem 1.

**Appendix**

Consider a mixed problem

$$
\begin{align*}
\Box u &= f(x, y, t) \quad \text{in } R^2 \times (0, T) \\
Bu &= \left( -\frac{\partial}{\partial x} + b \frac{\partial}{\partial y} \right) u(x, y, t) \big|_{x=0} = g(y, t) \\
u(x, y, 0) &= u_0(x, y) \\
\frac{\partial u}{\partial t}(x, y, 0) &= u_1(x, y),
\end{align*}
$$

(A.1)

where $b$ is a positive constant.

**Theorem A.** (A.1) has a propagation speed $\sqrt{1+b^2}$.

This theorem shows that when $b \neq 0$, (A.1) has a propagation speed larger than Cauchy problem since that of Cauchy problem is 1.

Let us denote by $E^m(\Box, B)$ the set of data $\Psi = (u_0, u_1, f, g) \in H^{m+2}(R^2) \times H^{m+1}(R^2 \times (0, T)) \times H^{m+1}(R \times (0, T))$ satisfying the compatibility condition of order $m$ for $\Box$ and $B$, for which we equip the following norm

$$
|\Psi|^m = ||u_0(x, y)||_{m+2, L^2(R^2)} + ||u_1(x, y)||_{m+1, L^2(R^2)} + ||f(x, y, t)||_{m+1, L^2(R^2 \times (0, T))} + ||g(y, t)||_{m+1, L^2(R \times (0, T))}.
$$

Theorem 2.14 shows that the mapping from $E^m(\Box, B)$ to $H^m(R^2 \times (0, T))$ defined by

$$
\Psi \rightarrow u(x, y, t)
$$

is continuous. Therefore for any fixed point $(x_0, y_0, t_0)$, the mapping from $E^m(\Box, B)$ to $C$ defined by

$$
\Psi \rightarrow u(x_0, y_0, t_0)
$$

also continuous, namely for any $\Psi = (u_0, u_1, f, g) \in E^m(\Box, B)$ it holds

$$
|u(x_0, y_0, t_0)| \leq C|\Psi|.
$$

(A.2)

where $C$ does not depend on $(x_0, y_0, t_0)$.

Assume that the maximum propagation speed of (A.1) is $v_0$, and set

$$
C_0(x_0, y_0, t_0) = \{(x, y, t) \mid |x-x_0| + |y-y_0| \leq v_0(t_0-t)\}.
$$

Remark that $u(x_0, y_0, t_0)$ is invariant with any change of values of data in the outside of $C_0(x_0, y_0, t_0)$. 
Put
\[ u_n(x, y, t) = \exp \left\{ n(-bx + \sqrt{1+b^2} t - y) \right\} \]
\[ u_n(x, y, t) = u_n(x, y, 0) h(ny) \]
\[ u_m(x, y) = u_m(x, y, 0) h(ny) \]
\[ f_n(x, y, t) = k(nt) \square \{ u_n(x, y, t) h(ny) \} \]
\[ g_n(y, t) = Bu_n(x, y, t) h(ny) k(nt) \]
where \( h(y) \) is a \( C^\infty \)-function such that \( h(y) = 0 \) for \( y < 0 \), \( h(y) = 1 \) for \( y > 1 \) and \( k(t) \) is a \( C^\infty \)-function such that \( k(t) = 1 \) for \( t < 1 \), \( k(t) = 0 \) for \( t \geq 2 \). Evidently
\[ \Psi_n = (u_{n_0}, u_{n_1}, f_n, g_n) \in \bigcap_{m=1}^\infty E^m(\square, B) \] and
\[ \|\Psi_n\|_2 \leq \text{const} n^4. \]

Let us denote by \( \tilde{u}_n(x, y, t) \) the solution of (A.1) for the data \( \Psi_n \), then by taking account of the definition of \( v_0 \) we have
\[ \tilde{u}_n(x, y, t) = \tilde{u}_n(x, y, t) \quad \text{in} \quad \left\{ (x, y, t); x \geq 0, y - v_0 t \geq \frac{1}{n} \text{ and } t \geq 0 \right\} \]

since \( \square u_n(x, y, t) = 0 \) in \( R^2 \times [0, \infty) \), \( Bu_n(0, y, t) = 0 \) in \( R \times [0, \infty) \) and \( u_{n_0}(x, y) = u_n(x, y, 0), u_m(x, y) = u_m(x, y, 0), f_n(x, y, t) = 0, g_n(y, t) = 0 \) hold if \( y > \frac{1}{n} \).

Now we prove Theorem A. Assume that \( v_0 < \sqrt{1+b^2} \). Take a point such \( (y_0, t_0) \) that \( t_0 > 0, y_0 - v_0 t_0 > 0 \) and \( y_0 - \sqrt{1+b^2} t_0 < 0 \). From (A.4) we have
\[ \tilde{u}_n(0, y_0, t_0) = \exp \left\{ n(\sqrt{1+b^2} t_0 - y_0) \right\} \]
for sufficiently large \( n \). On the other hand from (A.2) and (A.3) it holds
\[ |\tilde{u}_n(0, y_0, t_0)| \leq \text{const} n^4. \]

Then (A.5) and (A.6) shows that
\[ \exp \left\{ n(\sqrt{1+b^2} t_0 - y_0) \right\} \leq \text{const} n^4 \]
holds for any sufficiently large \( n \), this is a contradiction since \( \sqrt{1+b^2} t_0 - y_0 > 0 \). Thus we have
\[ v_0 \geq \sqrt{1+b^2} \]

By combining the just obtained result and Proposition 2.17, Theorem A is proved.

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References


