ENERGY ESTIMATES FOR WEAKLY HYPERBOLIC SYSTEMS OF THE FIRST ORDER

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ABSTRACT. For a class of weakly hyperbolic system of the form $D_t - A(t, x, D_x)$, where $A(t, x, D_x)$ is a first-order pseudodifferential operator whose principal part degenerates like $t^{ls}$ at time $t = 0$, for some integer $l_s \geq 1$, well-posedness of the Cauchy problem is proved in an adapted scale of Sobolev spaces. In addition, an upper bound for the loss of regularity that occurs when passing from the Cauchy data to the solutions is established. In examples, this upper bound turns out to be sharp.

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1. INTRODUCTION

In this paper, we study the Cauchy problem for weakly hyperbolic systems of the form

\[
\begin{cases}
D_t U(t, x) = A(t, x, D_x)U(t, x) + F(t, x), & (t, x) \in (0, T) \times \mathbb{R}^n, \\
U(0, x) = U_0(x),
\end{cases}
\]

(1.1)

where $A(t, x, D_x)$ is an $N \times N$ first-order pseudodifferential operator. The precise assumptions on the symbol $A(t, x, \xi)$ are stated in (1.7) below.

In order to motivate these assumptions, let us discuss an example. Systems of the form (1.1) arise, e.g., in converting $m$th-order partial differential operators $P$ with principal symbol

\[
\sigma^m(P)(t, x, \tau, \xi) = \prod_{h=1}^m (\tau - t^{ls} \mu_h(t, x, \xi)), \quad l_s \geq 1,
\]

(1.2)

where $\mu_h \in C^\infty([0, T], S^{(1)})$ for $1 \leq h \leq m$, into first-order systems.

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Assuming strict hyperbolicity for $t > 0$, i.e., the $\mu_\ell$ are real-valued and mutually distinct, it is well-known, see, e.g., Ivrii–Petkov [10], that the Cauchy problem for the operator $P$ is well-posed in $C^\infty$ if and only if the lower-order terms satisfy so-called Levi conditions. In case of (1.2), Levi conditions are expressed as

$$P = \sum_{j+|\alpha| \leq m} a_{j\alpha}(t, x) t^{j+|\alpha|+1} |\alpha|-m+1 D_t^j D_x^\alpha,$$

(1.3)

with the coefficients $a_{j\alpha}(t, x)$ being smooth up to $t = 0$.

Operators of the form (1.3) satisfying (1.2) are particularly interesting because of two phenomena, both occurring when passing from the Cauchy data posed at $t = 0$ to the solutions in the region $t > 0$: One is loss of regularity and the other one is that the singularities may propagate in a non-standard fashion. These phenomena depend on the lower-order terms of $P$ in a sensitive way.

One of the first examples in this direction was given by Qī [14],

$$\begin{cases}
u_{tt}(t, x) - t^2 u_{txx}(t, x) - (4k + 1)u_x(t, x) = 0, \quad (t, x) \in (0, T) \times \mathbb{R}, \\
u(0, x) = \varphi(x), \quad \nu_t(0, x) = 0,
\end{cases}$$

(1.4)

where $k \in \mathbb{N}$. The solution to (1.4) is

$$u(t, x) = \sum_{j=0}^{k} c_{jk} t^{2j} \varphi^{(j)}(x + t^2/2)$$

for certain coefficients $c_{jk} \neq 0$. We see that $u(t, \cdot)$ for $t > 0$ has $k$ derivatives lost compared to $\varphi$. One actually loses $k$ derivatives for any real number $k \geq -1/4$, as can be shown by an explicit representation of the solution using special functions, see Taniguchi–Tozaki [16]. The parameter $k$ can even be a function $k(t, x)$ with $k(0, x) \geq -1/4$ leading to a loss of regularity of $k(0, x)$, see Dreher [3]. Further results concerning representation formulae for the solutions and the propagation of singularities can be found in Amano–Nakamura [1], Dreher–Reissig [4], Hanges [8], Nakamura–Uryu [13], Yagdian [19], Yoshikawa [20]. For the case of systems, see Kumano–Go [12].

The first line of (1.4) will be converted into a first-order system by setting

$$U(t, x) = \begin{pmatrix} g(t, D_x)u(t, x) \\ D_t u(t, x) \end{pmatrix},$$

where

$$g(t, \xi) = \left(1 - \chi \left(t^2(t^2/2)\right) \right) \xi^{1/2} + \chi \left(t^2(t^2/2)\right) t\xi,$$

and $\chi \in C^\infty(\mathbb{R}_+; \mathbb{R})$ fulfills $\chi(t) = 0$ if $t \leq 1/2$ and $\chi(t) = 1$ if $t \geq 1$. The symbol $g(t, \xi)$ will play an important role later on. We then obtain

$$D_t U(t, x) = A(t, x, D_x) U(t, x), \quad (t, x) \in (0, T) \times \mathbb{R},$$

(1.5)

where

$$A(t, x, \xi) = \chi \left(t^2(t^2/2)\right) \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + i t^{-1} \begin{pmatrix} 1 \\ b(t, x, \xi) \end{pmatrix} A_2(t, x, \xi),$$

(1.6)

$b(t, x, \xi) := (4k(t, x) + 1) \text{sgn} \xi$, and $A_2(t, x, \xi)$ comprises several terms of order zero, and other terms supported in the region $t^2 \xi \leq 2$.

Generalizing (1.6), we are going to consider the Cauchy problem (1.1) with operators $A(t, x, D_x)$ whose symbols are of the form

$$A(t, x, \xi) = \chi(\Lambda(t) \xi) \left(\Lambda(t) |\xi| A_0(t, x, \xi) - i l_k t^{-1} A_1(t, x, \xi) \right) + A_2(t, x, \xi),$$

(1.7)

where $A_0, A_1 \in C^\infty([0, T], S(0)), A_2 \in S^{-1, 1; \lambda} + S^{0, 0; \lambda}$ are $N \times N$ matrix-valued pseudodifferential symbols, the function $\Lambda(t) = t^l$ for the fixed integer $l \geq 1$ characterizes the kind of degeneracy at $t = 0$, $\Lambda(t) := \int_0^t \lambda(t') dt'$ is its primitive, and $\beta_\star := 1/(l_\star + 1)$. The symbol classes $S^{m, \eta; \lambda}$ for
m, η ∈ ℜ that are closely related to the kind of degeneracy under consideration will be introduced in Section 2.1. In fact, these symbol classes are characterized by two weight functions

\[ g(t, \xi) := (1 - \chi(A(t)\xi))\beta_\xi + \chi(A(t)\xi)\lambda(t)\xi \]

\[ h(t, \xi) := (1 - \chi(A(t)\xi))\beta_\xi + \chi(A(t)\xi)t^{-1}, \]

where \( m \) is the exponent of \( g(t, \xi) \) and \( \eta - m \) is the exponent of \( h(t, \xi) \). Note that \( A(t, x, \xi) \) in (1.7) belongs to the class \( S^{1,1:λ}. \)

We will present a symbolic calculus for matrices \( A(t, x, \xi) \) of the form (1.7) that for many purposes allows to argue on a purely algebraic level, in this way leading to short and compact proofs.

We also introduce function spaces \( H^{s,δ(x);λ}((0, T) \times ℜ^n) \) to which the solutions \( U(t, x) \) to (1.1) belong. Here, \( s \in ℜ \) is the Sobolev regularity with respect to \( (t, x) \) for \( t > 0 \), while \( δ = δ(x) \) is related to the loss of regularity at the point \( x \in ℜ^n. \) For instance, for \( s \in ℤ \), \( δ(x) = δ \) being a constant, the space \( H^{s,δ;λ}((0, T) \times ℜ^n) \) consist of all functions \( U(t, x) \) satisfying \( k_{m}\mathcal{A}_m \in L^2((0, T) \times ℜ^n) \) for \( 0 \leq j \leq s \) and arbitrary \( k_{mn} \in S^{m,m+η;λ}. \) The case of variable \( δ(x) \) will be discussed in detail in Section 3.

Our main result is the following:

**Theorem 1.1.** (a) Assume the symbol \( A(t, x, \xi) \) in (1.7) is symmetrizable-hyperbolic in the sense that there is a matrix \( M_0 \in C^∞([0, T], S^{(0)}) \) such that \( \det M_0(t, x, \xi) \geq c \) for some \( c > 0 \) and the matrix \( (M_0A_1M_0^{-1}(t, x, \xi)) \) is symmetric for all \( (t, x, \xi) \in [0, T] \times ℜ^n \times (ℜ^n \setminus 0) \). Then there is a function \( δ \in B^∞(ℜ^n; ℜ) \) such that, for all \( s \geq 0 \), \( U_0 \in H^{s+δ;λ}(0, T) \times ℜ^n \), and \( F \in H^{s,δ;λ}((0, T) \times ℜ^n) \), system (1.1) possesses a unique solution \( U \in H^{s,δ;λ}((0, T) \times ℜ^n) \). Moreover, we have the estimate

\[ ||U||_{H^{s,δ;λ}} \leq C (∥U_0∥_{H^{s+δ;λ}} + ∥F∥_{H^{s,δ;λ}}) \]

for a suitable constant \( C = C(s, δ, T) > 0. \) In particular, the loss of regularity that is independent of \( s \geq 0 \) does not exceed \( δ(δ(x) + m-1)l_s \).

(b) In (a), we can choose any function \( δ \in B^∞(ℜ^n; ℜ) \) for which there is matrix \( M_1 \in S^{(0)} \) such that the inequality

\[ \text{Re} \left( M_0A_1M_0^{-1} + [M_1M_0^{-1}, M_0A_0M_0^{-1}] \right)(0, x, \xi) \leq δ(x)1_N \]

holds for all \( (x, ξ) \in ℜ^n \times (ℜ^n \setminus 0). \) Here \([\cdot, \cdot]\) denotes the commutator and \( \text{Re} Q := (Q + Q^*)/2. \)

**Remark 2.** (a) Part (a) of Theorem 1.1 continues to hold if one solely assumes that \( A \in \mathfrak{O}p \mathfrak{S}^{1,1:λ} \) and there is an invertible \( M \in \mathfrak{O}p \mathfrak{S}^{0,0:λ} \) such that \( \text{Im}(MAM^{-1}) \in \mathfrak{O}p \mathfrak{S}^{0,1:λ} \), cf. Lemma 4.2. In this situation, however, we have no simple formula for \( δ \in B^∞(ℜ^n; ℜ). \)

(b) The loss of regularity for the weakly hyperbolic operator \( P \) from (1.3) equals \( β_s(δ(x) + m-1)l_s \), where \( δ \in B^∞(ℜ^n; ℜ) \) is the function satisfying (1.9) for the first-order systems that arises by converting \( P \).

It is among the aims of this paper to establish precise upper bounds on the loss of regularity upon an appropriate choice of the matrices \( M_0, M_1 \) in Theorem 1.1. For examples, see Section 5.

The paper is organized as follows: In Section 2, we introduce the symbol classes \( S^{m;η;λ} \) and certain sub-classes \( \tilde{S}^{m;η;λ} \) thereof, where the latter contains symbols \( A(t, x, \xi) \) that possess “one and a half” principal symbols

\[ \sigma^m(A) \in i^{m(λ+1)-η} C^∞([0, T]; S^{(m)}), \quad \tilde{σ}^{m-1,η}(A) \in S^{(m-1)}. \]

A similar calculus, but differentiation with respect to \( t \) is included in the pseudodifferential action, was established by Witt [18]. In case \( l_s = 1 \), there is related work by Boutet de Monvel [2], Joshi [11], Yosihkawa [20], and others. Eq. (1.7) actually defines the class \( \tilde{S}^{1,1;λ} \), where \( σ^1(A)(t, x, \xi) = λ(t)\xi A_0(t, x, \xi), \tilde{σ}^{0,1}(A)(x, \xi) = -il_s A_1(0, x, \xi) \) for \( A(t, x, \xi) \) as given there. According to Theorem 1.1, \( σ^1(A)(t, x, \xi), \tilde{σ}^{0,1}(A)(x, \xi) \) are
exactly the symbols which are needed to symmetrize system (1.1) and to read off the loss of regularity, respectively. In particular, for $Q$’s example (1.5), we have

$$\sigma^1(A)(t, x, \xi) = t|\xi| \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma^{0,1}(A)(x, \xi) = -i \begin{pmatrix} 1 \\ b(0, x, \xi) \\ 0 \end{pmatrix}. $$

We choose $M_0(t, x, \xi) = \frac{1}{2} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$, $(M_1 M_0^{-1})(x, \xi) = \frac{1}{4} \begin{pmatrix} 0 & b^{-1} \\ b+1 & 0 \end{pmatrix}$ $(0, x, \xi)$ to obtain

$$\text{Re} \left( M_0 A_1 M_0^{-1} + [M_1 M_0^{-1}, M_0 A_0 M_0^{-1}] \right) (0, x, \xi) = \frac{1}{2} \begin{pmatrix} 1 - Re b & 0 \\ 0 & 1 + Re b \end{pmatrix} (0, x, \xi).$$

This leads to a loss of regularity of $|\text{Re} k(0, x) + \frac{1}{4}| - \frac{1}{4}$ for system (1.4), see Remark 1.2 (b). Moreover, this result is sharp. The reason that we decided to introduce $\delta \in B^{\infty}((\mathbb{R}^n; \mathbb{R})$ in (1.9) via an estimate (rather than an equality) is that the factual loss of regularity is Lipschitz as function of $x$, but may fail to be of class $C^1$, as this example shows.

Section 3 is concerned with properties of the function spaces $H^{s,\delta}(x; \lambda)((0, T) \times \mathbb{R}^n)$. We extend results of Dreher–Witt [6] from the case of constant $\delta$ to the case of variable $\delta(x)$. Our main result Theorem 1.1 is then proved in Section 4. In Section 5, some special cases in which the a priori estimate (1.8) is employed are considered: differential systems, systems with characteristic roots of constant multiplicity for $t > 0$, and higher-order equations. Choosing the matrix $M_1$ suitably, we will find that the upper bound for the loss of regularity, as predicted by inequality (1.9), coincides with the actual loss of regularity, as known in special cases, see, e.g., Nakamura–Uryu [13]. In a forthcoming paper, we will provide lower bounds for the loss of regularity for system (1.1), and we will show that for a wide class of operators the a priori estimate given in the present paper is sharp.

Finally, in an appendix we provide an estimate that is useful to bring the remainder term $A_2(t, x, D_x) \in \text{Op} S^{0,0;\lambda} + \text{Op} S^{-1,1;\lambda} \subset L^\infty((0, T), \text{Op} S^{\beta_0}) \cap t^{-1} L^\infty((0, T), \text{Op} S^{0,0})$ under control.

2. Symbol classes

2.1. The symbol classes $S^{m, \eta; \lambda}$. In this section, we introduce the fundamental symbol classes $S^{m, \eta; \lambda}$ for $m, \eta \in \mathbb{R}$. For an $m$th-order symbol $a(t, x, \xi)$, the belonging of $a$ to $S^{m, \eta; \lambda}$ in case $\eta = m$ expresses the fact that $\sigma^m(a)$ degenerates like $\lambda^m(t)$ at time $t = 0$, and it expresses sharp Levi conditions on the lower order terms as well. Note that corresponding symbol estimates (involving the functions $g, h$ from (2.1)) are predicted by the definition of the function spaces $H^{s, \delta; \lambda}$ in Section 3. To be able to deal with operators that arise in reducing (1.1) with the help of the operator $\Theta$ from Lemma 3.3, where the latter is zeroth-order for $t > 0$, but of variable order $\beta, \delta(x)\lambda$, when restricted to time $t = 0$, we further introduce the symbol classes $S^{m, \eta; \lambda}_+$ as slightly enlarged versions of $S^{m, \eta; \lambda}$, but for $m \in \mathbb{R}, \eta \in B^{\infty}(\mathbb{R}^n; \mathbb{R})$.

In the sequel, all symbols $a(t, x, \xi)$ will take values in $N \times N$-matrices, for some $N \in \mathbb{N}$.

Let

$$g(t, \xi) := \lambda(t) \langle \xi \rangle + \langle \xi \rangle^{\beta_+}, \quad h(t, \xi) := (t + \langle \xi \rangle^{-\beta_+})^{-1}. \quad (2.1)$$

Definition 2.1. (a) For $m, \eta \in \mathbb{R}$, the symbol class $S^{m, \eta; \lambda}$ consists of all $a \in C^\infty([0, T] \times \mathbb{R}^n; M_{N \times N}(\mathbb{C}))$ such that, for each $(j, \alpha, \beta) \in \mathbb{N}^{1+2n}$, there is a constant $C_{j,\alpha, \beta} > 0$ with the property that

$$|\partial_x^j \partial_\xi^\alpha \bar{\partial}_\xi^\beta a(t, x, \xi)| \leq C_{j,\alpha, \beta} g(t, \xi) m h(t, \xi)^{m+j} \langle \xi \rangle^{-|\beta|} \quad (2.2)$$

for all $(t, x, \xi) \in [0, T] \times \mathbb{R}^n$.

(b) For $m \in \mathbb{R}, \eta \in B^{\infty}(\mathbb{R}^n; \mathbb{R})$, and $b \in \mathbb{N}$, the symbol class $S^{m, \eta; \lambda}_b$ consists of all $a \in C^\infty([0, T] \times \mathbb{R}^n; M_{N \times N}(\mathbb{C}))$ such that, for each $(j, \alpha, \beta) \in \mathbb{N}^{1+2n}$, there is a constant $C_{j,\alpha, \beta} > 0$ with the property that

$$|\partial_x^j \partial_\xi^\alpha \bar{\partial}_\xi^\beta a(t, x, \xi)| \leq C_{j,\alpha, \beta} g(t, \xi) m h(t, \xi)^{m+j} (1 + |\log h(t, \xi)|)^{b+|\alpha|} \langle \xi \rangle^{-|\beta|} \quad (2.3)$$
for all \((t, x, \xi) \in [0, T] \times \mathbb{R}^{2n}\). Moreover, we set
\[
S_{m, \eta; \lambda}^+ = \bigcup_{b \in \mathbb{N}} S_{(b)}^{m, \eta; \lambda}.
\]

As usual, we set
\[
S_{-\infty, \eta; \lambda}^- = \bigcap_{m \in \mathbb{R}} S_{m, \eta; \lambda},
\]
see Proposition 2.4 (a) and also (b). Similarly for \(S_{+}^{-\infty, \eta; \lambda}, S_{(b)}^{-\infty, \eta; \lambda}\).

**Remark 2.2.** In view of \(\tilde{g} \tilde{h}^t \sim \langle \xi \rangle\) and \(\tilde{g} \tilde{h}^{-1} \sim 1 + \Lambda(t) \langle \xi \rangle\), estimate (2.2) is equivalent to
\[
|\partial_t^j \partial_x^\alpha \partial_\xi^\beta a(t, x, \xi)| \leq C_{j, \alpha, \beta} \tilde{g}(t, \xi) m^{[\beta]} \tilde{h}(t, \xi) \eta^{-m-|\beta|+j}
\]
and
\[
|\partial_t^j \partial_x^\alpha \partial_\xi^\beta a(t, x, \xi)| \leq C_{j, \alpha, \beta} (1 + \Lambda(t) \langle \xi \rangle)^m \tilde{h}(t, \xi) \eta^{j+|\beta|} \langle \xi \rangle^{-|\beta|},
\]
respectively. A similar remark applies to (2.3).

We discuss some examples of use further on:

**Lemma 2.3.** Let \(m, \eta \in \mathbb{R}\). Then:

(a) \(\tilde{g}^m \tilde{h}^{\eta-m} \in S_{m, \eta; \lambda}^+\).

(b) For \(a \in C^\infty([0, T]; S^m)\) and \(l \in \mathbb{N}\), \(a \in S_{m; m(l+1)-l; \lambda}\) if and only if
\[
\partial_t^j a |_{t=0} \in S_{m-l_j}^{m-l_j}, \quad 0 \leq j \leq l - 1.
\]

(c) Let \(\chi \in C^\infty(\mathbb{R}_+; \mathbb{R})\), \(\chi(t) = 0\) if \(t \leq 1/2\), \(\chi(t) = 1\) if \(t \geq 1\). Then
\[
\chi^+(t, \xi) := \chi(\Lambda(t) \langle \xi \rangle) \in S_{0; \lambda}^{0, \lambda},
\]
while \(\chi^-(t, \xi) := 1 - \chi^+(t, \xi) \in S_{-\infty; \lambda}^{0, \lambda}\).

In particular, from (a), (b) we infer
\[
\lambda(t) \langle \xi \rangle \in S^{1, 1; \lambda}, \quad (t + \langle \xi \rangle^{-\beta})^{-1} \in S_{0; \lambda}^{0, \lambda}, \quad \Lambda(t) \langle \xi \rangle \in S^{1, 0; \lambda}.
\]

In the next proposition, we list properties of the symbol classes \(S_{m, \eta; \lambda}^m\) for \(m, \eta \in \mathbb{R}\) (with proofs which are standard omitted):

**Proposition 2.4.**

(a) \(S_{m, \eta; \lambda}^m \subseteq S_{m', \eta'; \lambda}^{m'} \iff m \leq m', \eta \leq \eta'\).

(b) Let \(a \in S_{m, \eta; \lambda}^m\). Then \(\chi^+(t, \xi) a \in S_{m', \eta; \lambda}^{m'}\) for some \(m' < m\) implies \(a \in S_{m', \eta; \lambda}^{m'}\). In particular, if \(a(t, x, \xi) = 0\) for \(\Lambda(t) \langle \xi \rangle \geq C\) and certain \(C > 0\), then \(a \in S_{-\infty; \lambda}^{-\infty, \eta; \lambda}\).

(c) If \(a \in S_{m, \eta; \lambda}^m\), then \(\partial_t^j \partial_x^\alpha \partial_\xi^\beta a \in S_{m-|\beta|, \eta+j-|\beta|(l+1); \lambda}^{m-|\beta|, \eta+j-|\beta|(l+1); \lambda}\).

(d) If \(a \in S_{m, \eta; \lambda}^m\), \(a' \in S_{m', \eta'; \lambda}^{m'}\), then \(a \circ a' \in S_{m+m'-1, \eta+\eta'-l(1+1); \lambda}^m\) and
\[
a \circ a' = aa' \mod S_{m+m'-1, \eta+\eta'-l(1+1); \lambda},
\]
where \(\circ\) denotes the Leibniz product with respect to \(x\).

(e) If \(a \in S_{m, \eta; \lambda}^m\), then \(a^* \in S_{m, \eta; \lambda}^m\) and
\[
a^*(t, x, \xi) = a(t, x, \xi)^* \mod S_{m-1, \eta-l(1+1); \lambda},
\]
where \(a^*\) is the (complete) symbol of the formal adjoint to \(a(t, x, D_x)\) with respect to \(L^2\).
(f) If \( a \in S^{m,\eta}(\mathbb{R}^n;\mathbb{R}^n) \) is elliptic in the sense that

\[
|\det a(t, x, \xi)| \geq c_1 (g^m(t, \xi) h^m(t, \xi))^N, \quad (t, x, \xi) \in [0, T] \times \mathbb{R}^n, \quad |\xi| \geq c_2
\]

for some \( c_1, c_2 > 0 \), then there is a symbol \( a' \in S^{-m, -\eta, \lambda} \) with the property that

\[ a \circ a' - 1, a' \circ a - 1 \in C^\infty([0, T]; S^{-\infty}). \]

Moreover,

\[ a' = a^{-1} \mod S^{-m-1, -\eta, -(l_\ast+1); \lambda}. \]

(g) \( \bigcap_{m, \eta} S^{m, \eta, \lambda} = C^\infty([0, T]; S^{-\infty}). \)

Similar results hold for the classes \( S^{m, \eta, \lambda}_+ \) for \( m \in \mathbb{R}, \eta \in B^\infty(\mathbb{R}^n; \mathbb{R}) \):

**Proposition 2.5.** (a) \( S^{m, \eta, \lambda}(b) \subseteq S^{m', \eta', \lambda}(b') \iff m \leq m', \eta \leq \eta', \text{ and } b \leq b' \text{ if } \eta = \eta'. \)

(b) \( S^{m, \eta, \lambda} \subseteq S^{m, \eta, \lambda}_+ \subseteq \bigcap_{c > 0} S^{m, \eta + c; \lambda}. \)

(c) If \( a \in S^{m, \eta, \lambda}(b) \), then \( \partial_x^j \partial_t^j \partial_\xi^j a \in S^{m-|j|, \eta-|j|(l_\ast+1)+j; \lambda}. \)

(d) If \( a \in S^{m, \eta, \lambda}(b), a' \in S^{m', \eta', \lambda}(b') \), then \( a \circ a' \in S^{m+m', \eta+\eta', \lambda} \) and

\[ a \circ a' = aa' \mod S^{m+m-1, \eta+\eta'-l_\ast; \lambda}(b+b'). \]

(e) If \( a \in S^{m, \eta, \lambda}(b) \), then \( a^* \in S^{m, \eta, \lambda}(b) \) and

\[ a^*(t, x, \xi) = a(t, x, \xi)^* \mod S^{m-1, \eta; \lambda}(b). \]

(f) \( S^{0,0; \lambda}_{(0)} \subset L^\infty((0, T); S^{0, \lambda}_{1, \delta}) \) for any \( 0 < \delta < 1 \).

From Proposition 2.5 (f) we conclude:

**Corollary 2.6.** \( \text{Op } S^{0,0; \lambda}_{(0)} \subset \text{Op } S^{0,0; \lambda}_{(0)} \subset \mathcal{L}(L^2). \)

### 2.2. The symbol classes \( \tilde{S}^{m, \eta, \lambda} \)

To establish precise upper bounds on the loss of regularity in Theorem 1.1 (b), we now refine the fundamental symbol classes \( S^{m, \eta, \lambda} \) to \( \tilde{S}^{m, \eta, \lambda} \), where symbols \( a(t, x, \xi) \) in the latter class admit “one and a half” principal symbols \( \sigma^m(a), \tilde{\sigma}^{m-1, \eta}(a) \). These principal symbols enable us to read off the loss of regularity.

**Definition 2.7.** For \( m, \eta \in \mathbb{R} \), the class \( \tilde{S}^{m, \eta, \lambda} \) consists of all \( a \in S^{m, \eta, \lambda} \) that can be written in the form

\[ a(t, x, \xi) = \chi^+(t, \xi) t^{-\eta} (a_0(t, x, t^{l_\ast+1} \xi) + a_1(t, x, t^{l_\ast+1} \xi)) + a_2(t, x, \xi), \quad (2.4) \]

where

\[ a_0 \in C^\infty([0, T]; S^{m}), \quad a_1 \in C^\infty([0, T]; S^{m-1}), \]

and \( a_2 \in S^{m-2, \eta, \lambda} + S^{m-1, -\eta-1; \lambda} \). With \( a(t, x, \xi) \) as in (2.4) we associate the two symbols

\[ \sigma^m(a)(t, x, \xi) := t^{-\eta} a_0(t, x, t^{l_\ast+1} \xi), \quad \tilde{\sigma}^{m-1, \eta}(a)(t, x, \xi) := a_1(0, x, \xi). \quad (2.5) \]

**Remark 2.8.** The symbol components \( \chi^+(t, \xi) t^{-\eta} a_j(t, x, t^{l_\ast+1} \xi) \) in (2.4) for \( j = 0, 1 \) belong to \( S^{m-j, \eta, \lambda} \), while \( a_2(t, x, \xi) \) is regarded as remainder term.
Lemma 2.10.

Note that this symbol is directly derived from $\sigma^m(a)$.

In the sequel, we shall employ the symbols

$$g(t, \xi) := \chi^{-}(t, \xi) \langle \xi \rangle^{\beta^*} + \chi^{+}(t, \xi) \lambda(t) \langle \xi \rangle,$$

$$h(t, \xi) := \chi^{-}(t, \xi) \langle \xi \rangle^{\beta^*} + \chi^{+}(t, \xi) t^{-1}.$$

Note that $g \sim \tilde{g}$, $h \sim \tilde{h}$ so that the symbol estimates (2.2) are not affected by this change.

Example 2.9. (a) Let $m, \eta \in \mathbb{R}$. Then $g^m h^{n-m} \in \tilde{S}^{m,\eta\lambda}$,

$$\sigma^m(g^m h^{n-m}) = t^{-\eta}(t^{\lambda+1} |\xi| \langle \xi \rangle)^{m}, \quad \tilde{\sigma}^{m-1,\eta}(g^m h^{n-m}) = 0. \tag{2.6}$$

(b) Let $a(t, x, \xi) := \sum_{|\alpha| \leq m} a_{\alpha}(t, x) t^{(|\alpha|\lambda+1)-m} \xi^\alpha$, where $a_{\alpha}(t, x) \in \mathcal{B}^\infty([0, T] \times \mathbb{R}^n)$ for $|\alpha| \leq m$. Then $a \in \tilde{S}^{m,\eta\lambda}$,

$$\sigma^m(a) = \sum_{|\alpha| = m} a_{\alpha}(t, x) (t^{\lambda+1})^\alpha,$$

$$\tilde{\sigma}^{m-1,\eta}(a) = \begin{cases} \sum_{|\alpha| = m-1} a_{\alpha}(0, x) \xi^\alpha & \text{if } m > 1, \\ 0 & \text{if } m = 0, 1. \end{cases}$$

The introduction of the principal symbols $\sigma^m(a)$, $\tilde{\sigma}^{m-1,\eta}(a)$ is justified by the next lemma:

**Lemma 2.10.** (a) The symbols $\sigma^m(a)$, $\tilde{\sigma}^{m-1,\eta}(a)$ are well-defined.

(b) The short sequence

$$0 \longrightarrow S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda} \longrightarrow \tilde{S}^{m,\eta\lambda} \longrightarrow \Sigma S^{m,\eta\lambda} \longrightarrow 0 \tag{2.7}$$

is exact, where $\Sigma S^{m,\eta\lambda} := \lambda^m(t) t^{-\eta+m} C^\infty([0, T]; S^{(m)}) \times S^{(m-1)}$ is the principal symbol space.

**Proof.** For $a \in \tilde{S}^{m,\eta\lambda}$ represented as in (2.4), we show that

$$a \in S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda} \iff a_0 = 0, a_1 \big|_{t=0} = 0.$$

This gives (a) and also the exactness of the short sequence (2.7) in the middle. Since the surjectivity of the map $(\sigma^m, \tilde{\sigma}^{m-1,\eta})$ is obvious, the proof will then be finished.

So, let us assume that $a_0 \neq 0$ or $a_1 \big|_{t=0} \neq 0$. If $a_0 \neq 0$, then $|\alpha| \geq C^{-1} g^m h^{n-m}$ for $A(t) \langle \xi \rangle \geq C$ in some conic set, and $C > 0$ sufficiently large. Hence, $a \notin S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda}$. If $a_0 = 0$, but $a_1 \big|_{t=0} \neq 0$, then we write

$$a_1(t, x, \xi) = b_0(x, \xi) + t b_1(t, x, \xi),$$

where $b_0 \in S^{(m-1)}$, $b_1 \in C^\infty([0, T], S^{(m-1)}).$ But $\chi^+(t, \xi) t^{-\eta+1} b_1(t, x, t^{\lambda+1} \xi) \notin S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda}$, while $\chi^+(t, \xi) t^{-\eta} b_0(x, t^{\lambda+1} \xi) \notin S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda}$ in view of $b_0 \neq 0$. Hence, again, $a \notin S^{m-2,\eta\lambda} + S^{m-1,\eta-1;\lambda}$.

Now, assume $a_0 = 0$ and $a_1 \big|_{t=0} = 0$. Write $a_1(t, x, \xi) = t b_1(t, x, \xi)$, where $b_1 \in C^\infty([0, T], S^{(m-1)}).$ Then

$$a(t, x, \xi) = \chi^+(t, \xi) t^{-\eta+1} b_1(t, x, t^{\lambda+1} \xi) + a_2(t, x, \xi).$$

But $\chi^+(t, \xi) t^{-\eta+1} b_1(t, x, t^{\lambda+1} \xi) \in S^{m-1,\eta-1;\lambda}$, hence the claim. \qed

Finally, the next two results partially sharpen Proposition 2.4:
Proposition 2.11. (a) If \( a \in \tilde{S}^{m,\eta;\lambda} \), \( a' \in \tilde{S}^{m',\eta';\lambda} \), then \( a \circ a' \in \tilde{S}^{m+m',\eta+\eta';\lambda} \) and
\[
\sigma^{m+m'}(a \circ a') = \sigma^{m}(a) \sigma^{m'}(a'),
\]
\[
\tilde{\sigma}^{m+m'-1,\eta+\eta'}(a \circ a') = \tilde{\sigma}^{m-1,\eta}(a) \tilde{\sigma}^{m'-1,\eta'}(a') + \tilde{\sigma}^{m-1,\eta}(a) \tilde{\sigma}^{m',\eta'}(a').
\]
(b) If \( a \in \tilde{S}^{m,\eta;\lambda} \), then \( a^* \in \tilde{S}^{m,\eta;\lambda} \) and
\[
\sigma^{m}(a^*) = \sigma^{m}(a)^*, \quad \tilde{\sigma}^{m-1,\eta}(a^*) = \tilde{\sigma}^{m-1,\eta}(a)^*.
\]
(c) If \( a \in \tilde{S}^{m,\eta;\lambda}([0, T] \times \mathbb{R}^{2n}; M_{N \times N}(\mathbb{C})) \) is elliptic, then \( |\det \sigma^m(a)| \geq c (t^{(d+1)m-\eta} |\xi|^m)^N \) for some \( c > 0 \) and the symbol \( a' \) from Proposition 2.4 (f) belongs to \( \tilde{S}^{-m,\eta;\lambda} \). Moreover,
\[
\sigma^{-m}(a') = \tilde{\sigma}^m(a)^{-1}, \quad \tilde{\sigma}^{-m-1,\eta}(a') = -\tilde{\sigma}^m(a)^{-1} \tilde{\sigma}^{-m,\eta}(a) \tilde{\sigma}^m(a) -1.
\]

Proof. A straightforward computation.

Lemma 2.12. Let \( a \in \tilde{S}^{m,\eta;\lambda} \) and \( \eta = (l_+ + 1)m \). Then
\[
\partial t a \in S^{m-1,\eta+1;\lambda} + S^{m,\eta;\lambda}.
\]

Proof. We have \( \partial_t a \in \tilde{S}^{m,\eta+1;\lambda} \) and, in general,
\[
\tilde{\sigma}^{m,\eta+1;\lambda}(\partial_t a) = (m(l_+ + 1) - \eta) \tilde{\sigma}^{m,\eta;\lambda}(a)
\]
Therefore, \( \tilde{\sigma}^{m,\eta+1;\lambda}(\partial_t a) = 0 \) in case \( \eta = (l_+ + 1)m \). The latter implies that \( \partial_t a \in S^{m-1,\eta+1;\lambda} + S^{m,\eta;\lambda} \).

Remark 2.13. (a) For the reader’s convenience, we summarize what vanishing of the single symbolic components for \( a \in \tilde{S}^{m,\eta;\lambda} \) means:
\[
\begin{align*}
\bullet \quad \sigma^m(a) = 0, & \quad \tilde{\sigma}^{m-1,\eta}(a) = 0 \iff a \in S^{m-2,\eta;\lambda} + S^{m-1,\eta;\lambda}, \\
\bullet \quad \sigma^m(a) = 0 \iff a \in S^{m-1,\eta;\lambda}, \\
\bullet \quad \tilde{\sigma}^{m,\eta}(a) = 0 \iff a \in S^{m-1,\eta;\lambda} + S^{m,\eta;\lambda}.
\end{align*}
\]
(b) Using the fact that asymptotic summation in the class \( S^{m,\eta;\lambda} \) is possible one can introduce the class \( \tilde{S}^{m,\eta;\lambda} \) of symbols \( a \in S^{m,\eta;\lambda} \) obeying asymptotic expansions into double homogeneous components, and then it turns out that
\[
\tilde{S}^{m,\eta;\lambda} = S^{m,\eta;\lambda} + S^{m-2,\eta;\lambda} + S^{m-1,\eta;\lambda}.
\]
The latter relation means that in \( S^{m,\eta;\lambda} \) precisely the two symbolic components from (2.5) survive. (Details on the class \( S^{m,\eta;\lambda} \) will be published in a forthcoming paper [5].)

3. Function spaces

In this section, we introduce the function spaces \( H^{s,\delta;\lambda} \) for \( s \in \mathbb{R}, \delta \in B^\infty(\mathbb{R}^n; \mathbb{R}) \) and investigate their basic properties. In case \( s, \delta \in \mathbb{R} \), these function spaces were introduced by Dreher–Witt [6] as abstract edge Sobolev spaces. Here, we shall assume that the case of constant \( \delta \) is known. Then the case of variable \( \delta \) is traced back to the case of constant \( \delta \). The key is the invertibility of the operator \( \Theta \), as stated in Lemma 3.3.

Definition 3.1. For \( s \in \mathbb{N}, \delta \in B^\infty(\mathbb{R}^n; \mathbb{R}) \), the space \( H^{s,\delta;\lambda} \) consists of all functions \( u = u(t, x) \) on \( (0, T) \times \mathbb{R}^n \) satisfying
\[
(g^{s-j}h^{(s+j)\delta})(t, x, D_x) D^j_t u \in L^2((0, T) \times \mathbb{R}^n), \quad 0 \leq j \leq s.
\]
For general \( s \in \mathbb{R}, \delta \in B^\infty(\mathbb{R}^n; \mathbb{R}) \), the space \( H^{s,\delta;\lambda} \) is then defined by interpolation and duality.

In particular, in case \( s \geq 0 \), we have \( (g^s h^{(s+\delta)\delta})(t, x, D_x) u \in L^2((0, T) \times \mathbb{R}^n) \) for any \( u \in H^{s,\delta;\lambda} \).
Lemma 3.3. Firstly defined for $C$ and Proposition 3.4 in their full strength.

Proof. We prove (3.2) in case $R = 1$, and also the fact that $\Theta(t, x, D_x)$ for large $K > 0$, and also the fact that $\Theta(t, x, D_x) \in \text{Op} S_{(0)}^{0,\delta(x)\nu;\lambda}$. The proof is then completed with the help of the next proposition.

The symbol $\Theta_{K,\delta}(t, x, \xi)$ belongs to the symbol class $S_{(0)}^{0,\delta(x)\nu;\lambda}$, but with parameter $K \geq K_0 > 0$. Similarly for $\Theta_{K,\delta}(t, x, \xi)$. If $R'_K := \Theta_{K,\delta} \circ \Theta_{K,-\delta} - \Theta_{K,\delta} \Theta_{K,-\delta}$, then, for all $\alpha, \beta \in \mathbb{N}^n$ and certain constants $C_{\alpha\beta} > 0$,\n\[
|\partial_x^\alpha \partial_\xi^\beta R'_K(t, x, \xi)| \leq C_{\alpha\beta} ((\xi)_K^{\beta} + \lambda(t)\xi K)^{-1} (t + (\xi)_K^{-\beta} x)^{-1} \times (1 + |\log(t + (\xi)_K^{-\beta})|)^{1 + |\alpha|}\xi K^{-|\beta|}, \quad (t, x, \xi) \in [0, T] \times \mathbb{R}^2, K \geq K_0 > 0
\]

(i.e., we have estimates (2.2), but with $\langle \xi \rangle$ replaced by $\langle \xi \rangle_K$). From the latter relation, it is seen that $R'_K(t, x, \xi) \to 0$ in $L^\infty((0, T); S(0))$ as $K \to \infty$, i.e., $R'_K(t, x, D_x) \to 0$ in $\mathcal{L}(L^2)$ as $K \to \infty$. Now, let $R_K := \Theta_{K,\delta} \circ \Theta_{K,-\delta} - 1$, i.e., $R_K = R'_K + \Theta_{K,\delta} \Theta_{K,-\delta} - 1$. Since $\Theta_{K,\delta} \Theta_{K,-\delta}(t, x, D_x) \to 1$ in $\mathcal{L}(L^2)$ as $K \to \infty$, it follows that $R_K(t, x, D_x) \to 0$ in $\mathcal{L}(L^2)$ as $K \to \infty$. Thus, $\Theta_{K,\delta} \circ (1 + R_K)^{-1}$ is a right inverse to $\Theta_{K,\delta}$, for large $K > 0$. In a similar fashion, a left inverse to $\Theta_{K,\delta}$ is constructed.

Moreover, $\Theta^{-1} = \Theta_{K,-\delta}$ mod $\text{Op} S_{(0)}^{\infty,-\delta(x)\nu;-(\nu+1)\lambda}$, as is seen from the constructions.

Proposition 3.4. For $m, s \in \mathbb{R}, \eta, \delta \in \mathcal{B}^{\infty}([\mathbb{R}^n; \mathbb{R}])$, we have\n\[
\text{Op} S_{(0)}^{m,\eta,\lambda} \subset \begin{cases} \mathcal{L}(H^{s,\eta+\delta,\lambda}, H^{s-m,\delta+2m,\lambda}) & \text{if } m \geq 0, \\ \mathcal{L}(H^{s,\eta+\delta,\lambda}, H^{s,\delta+\frac{m}{\nu},\lambda}) & \text{if } m < 0. \end{cases}
\] (3.2)

Proof. We prove (3.2) in case $m \geq 0$; the proof in case $m < 0$ is similar.

By interpolation and duality, we may assume that $s - m \in \mathbb{N}$. Then we have to show that, for $0 \leq k \leq j \leq s - m$,\n\[
h^{s+\delta}k u + m - g^{s-m-j}(D_i^j-k A)D_i^k u \in L^2
\]

provided $u \in H^{s,\delta,\lambda}$. We have\n\[
h^{s+\delta}k u + m - g^{s-m-j}(D_i^j-k A)D_i^k u = h^{m-\eta}g^{m-j+k}(D_i^j-k A)h^{s+\delta}k g^{s-k}D_i^k u + R D_i^k u \quad (3.3)
with \( h^{m-n}g^{m-j+k} (D_l^j A) \in \mathrm{Op} S^{-j+k,0;\lambda} \) and a remainder \( R \in \mathrm{Op} S^{s-j-1,(l+1)+\delta l+1-k;\lambda} \). Now, \( \mathrm{Op} S_{(j-k)}^{-j+k,0;\lambda} \subset \mathrm{Op} S^{0,0;\lambda} \) and \( h^{(s+\delta)l} g^{s-k} D_l^k u \in L^2 \) by assumption, i.e., the first summand on the right-hand-side of (3.3) belongs to \( L^2 \) by virtue of Corollary 2.6. The second summand is rewritten as

\[
RD_l^k u = Rg^{-s+k} (\Theta_{K,s+\delta})^{-1} \Theta_{K,s+\delta} g^{s-k} D_l^k u
\]

for some large \( K > 0 \), where \( Rg^{-s+k} (\Theta_{K,s+\delta})^{-1} \in \mathrm{Op} S_{(j-k)}^{-j+k-1,(l+1)+\delta l+1-k;\lambda} \subset \mathrm{Op} S^{0,0;\lambda} \) and again \( \Theta_{K,s+\delta} g^{s-k} D_l^k u \in L^2 \), i.e., also the second summand on the right-hand-side of (3.3) belongs to \( L^2 \). \( \square \)

In the following result, we summarize properties of the spaces \( H^{s,\delta;\lambda} \).

**Proposition 3.5.** Let \( s \in \mathbb{R} \), \( \delta \in \mathcal{B}^\infty(\mathbb{R}^n;\mathbb{R}) \). Then:

(a) \( \{H^{s,\delta;\lambda}; s \in \mathbb{R}\} \) forms an interpolation scale of Hilbert spaces (with the obvious Hilbert norms) with respect to the complex interpolation method.

(b) \( H^s_{\text{comp}}(\mathbb{R}^+ \times \mathbb{R}^n)|_{(0,T) \times \mathbb{R}^n} \subset H^{s,\delta;\lambda} \subset H^s_{\text{loc}}(\mathbb{R}^+ \times \mathbb{R}^n)|_{(0,T) \times \mathbb{R}^n} \).

(c) The space \( C^\infty(\mathbb{R}^n) \) is dense in \( H^{s,\delta;\lambda} \).

(d) For \( s > 1/2 \), the map

\[
H^{s,\delta;\lambda} \rightarrow \prod_{j=0}^{[s-1/2]} H^{s+\beta_j \delta l(x)l_+ - \beta_j^{-1} - \beta_j^{-1}}(\mathbb{R}^n), \quad u \mapsto (D_l^j u|_{t=0})_{0 \leq j \leq [s-1/2]}, \quad (3.4)
\]

where \([s-1/2]^{-} \) is the largest integer strictly less than \( s - 1/2 \), is surjective.

(e) \( H^{s,\delta;\lambda} \subset H^{s',\delta;\lambda} \) if and only if \( s \geq s', s + \beta_s \delta l_s \geq s' + \beta_{s'} \delta' l_{s'} \). Moreover, the embedding \( \{u \in H^{s,\delta;\lambda}; \text{supp} u \subset K\} \subset H^{s',\delta;\lambda} \) for some \( K \in [0,T) \times \mathbb{R}^n \) is compact if and only if \( s > s' \) and \( s + \beta_s \delta(x)l_s > s' + \beta_{s'} \delta'(x)l_{s'} \) for all \( x \) satisfying \( (0,x) \in K \).

**Proof.** For \( s, \delta \in \mathbb{R} \), it is readily seen that Definition 3.1 coincides with that one given in Dreher–Witt [6]. In this case, proofs may be found there. For variable \( \delta = \delta(x) \), we exemplarily verify (a), (d): To this end, we write \( H^{s,\delta;\lambda} = \Theta^{-1} H^{s,0;\lambda} \) for \( s \in \mathbb{R} \), with \( \Theta \) being the operator from Lemma 3.3.

(a) Since \( \{H^{s,0;\lambda}; s \in \mathbb{R}\} \) is an interpolation scale, \( \{H^{s,\delta;\lambda}; s \in \mathbb{R}\} \) is also an interpolation scale with respect to the complex interpolation method.

(d) Let \( \gamma_j u := D_l^j u|_{t=0} \). Then \( \gamma_j \Theta u \in H^{s-\beta_j - \beta_j^{-1}/2}(\mathbb{R}^n) \) for \( 0 \leq j \leq [s - 1/2]^{-} \), since (3.4) holds if \( \delta = 0 \).

Now, \( H^{s,\delta;\lambda} \rightarrow \prod_{j=0}^{[s-1/2]} H^{s+\beta_j \delta l(x)l_+ - \beta_j^{-1} - \beta_j^{-1}}(\mathbb{R}^n), \quad u \mapsto (\gamma_j u)_{0 \leq j \leq [s-1/2]} \) follows from

\[
\gamma_j u = (D_l^j)^{\beta_j \delta l(x)l_+} \gamma_j \Theta u,
\]

while the surjectivity of this map is implied by the reverse relation

\[
\gamma_j \Theta u = (D_l^j)^{\beta_j \delta l(x)l_+} \gamma_j u
\]

and the surjectivity of (3.4) in case \( \delta = 0 \). \( \square \)

We also need the following results:
Proposition 3.6. (a) If \( q(t, x, D_x) \in \text{Op}\, S^{0,0;\lambda}_{(0)} \) is invertible on \( H^{s,\delta;\lambda} \) for some \( s \in \mathbb{R}, \delta \in \mathcal{B}^\infty(\mathbb{R}^n;\mathbb{R}) \), then \( q(t, x, D_x) \) is invertible on \( H^{s,\delta;\lambda} \) for all \( s \in \mathbb{R}, \delta \in \mathcal{B}^\infty(\mathbb{R}^n;\mathbb{R}) \) and
\[
q(t, x, D_x)^{-1} \in \text{Op}\, S^{0,0;\lambda}_{(0)}.
\]
(b) Conversely, if \( q_0 \in C^\infty([0, T]; S^{(0)}) \) and \( q_1 \in S^{-1} \) are given, where \( |\det q_0(t, x, \xi)| \geq c \) for all \( (t, x, \xi) \in [0, T] \times \mathbb{R}^{2n} \) and a certain \( c > 0 \), then there is an invertible operator \( q(t, x, D_x) \in \text{Op}\, S^{0,0;\lambda}_{(0)} \) in the sense of (a) such that
\[
\sigma^0(q) = q_0, \quad \tilde{\sigma}^{-1,0}(q) = q_1.
\]

Proof. (a) By conjugating the operator \( q(t, x, D_x) \) with the inverse of \( (g^* h^* \Theta)(t, x, D_x) \), where \( \Theta(t, x, \xi) \) is as in Lemma 3.3, we may suppose that \( s = 0, \delta = 0 \). From the invertibility of \( q(t, x, D_x) \) on \( H^{0,0;\lambda} \), we then conclude the ellipticity of the symbol \( q(t, x, \xi) \) in the standard fashion, i.e., we have \( |\det q(t, x, \xi)| \geq c_1 \) for all \( (t, x, \xi) \in [0, T] \times \mathbb{R}^{2n}, |\xi| \geq c_2, \) and some constants \( c_1, c_2 > 0 \). By the analogue of Proposition 2.4 (f) for the class \( S^{0,0;\lambda}_{(0)} \), there is a symbol \( q_1(t, x, \xi) \in S^{0,0;\lambda}_{(0)} \) such that
\[
q \circ q_1 - 1 \in C^\infty([0, T]; S^{-\infty}).
\]
It follows that
\[
q(t, x, D_x) q(t, x, D_x) q(t, x, D_x)^{-1} = q(t, x, D_x) q_1(t, x, D_x) \quad \text{mod } C^\infty([0, T]; \text{Op } S^{-\infty}),
\]
i.e., by multiplying both sides from the left by \( q(t, x, D_x)^{-1} \in \text{Op}\, S^{-0,0;\lambda}_{1,\beta_1}, \) \( q(t, x, D_x)^{-1} = q_1(t, x, D_x) \mod C^\infty([0, T]; \text{Op } S^{-\infty}) \)
and \( q(t, x, D_x)^{-1} \in \text{Op}\, S^{0,0;\lambda}_{(0)} \).

(b) The rather long proof is deferred to Appendix A.2. \( \Box \)

4. Symmetrizable-hyperbolic systems

In this section we prove our main result Theorem 1.1.

4.1. Reduction of the problem. For \( A \in \text{Op}\, \tilde{S}^{1,1;\lambda} \), throughout we shall adopt the notation
\[
\sigma^1(A)(t, x, \xi) = \lambda(t)|\xi| A_0(t, x, \xi), \quad \tilde{\sigma}^{0,1}(A)(x, \xi) = -i \xi A_1(x, \xi),
\]
where \( A_0 \in \mathcal{B}^\infty([0, T]; S^{(0)}), A_1 \in S^{(0)} \). Likewise, for the symmetrizer \( M \in \text{Op}\, \tilde{S}^{0,0;\lambda} \), we shall write
\[
\sigma^0(M)(t, x, \xi) = M_0(t, x, \xi), \quad \tilde{\sigma}^{-1,0}(M)(x, \xi) = -i \xi |\xi|^{-1} M_1(x, \xi),
\]
where \( M_0 \in \mathcal{B}^\infty([0, T]; S^{(0)}), M_1 \in S^{(0)} \). Condition (1.9) is
\[
\text{Re} \left( M_0 M_1^{-1} + [M_1 M_0^{-1}, M_0 A_0 M_0^{-1}] \right) \leq \delta(x)1_N. \tag{4.1}
\]

Remark 4.1. Because \( M_0 A_0 M_0^{-1} \) is symmetric,
\[
\text{Re} [M_1 M_0^{-1}, M_0 A_0 M_0^{-1}] = i \left[ \text{Im}(M_1 M_0^{-1}), M_0 A_0 M_0^{-1} \right],
\]
i.e., (4.1) amounts to choose \( \text{Im}(M_1 M_0^{-1}) \) appropriately.

Lemma 4.2. For system (1.1) with \( A(t, x, \xi) \in \tilde{S}^{1,1;\lambda} \), the following conditions are equivalent:
(a) There is an \( M_0 \in C^\infty([0, T]; S^{(0)}) \) such that \( |\det M_0(t, x, \xi)| \geq c \) for some \( c > 0 \) and the matrix
\[
(M_0 A_0 M_0^{-1})(t, x, \xi)
\]
is symmetric for all \( (t, x, \xi) \in [0, T] \times \mathbb{R}^n \times (\mathbb{R}^n \setminus 0) \).
(b) There is an operator \( M(t, x, D_x) \in \text{Op}\, \tilde{S}^{0,0;\lambda} \) that is invertible on \( L^2 \) such that
\[
\text{Im}(M A M^{-1}) \in \text{Op}\, S^{0,1;\lambda},
\]
i.e., \( \text{Im} \sigma^1(M A M^{-1}) = 0 \).
Proof. If (a) is fulfilled, let $M(t, x, D_x) \in \text{Op} \tilde{S}^{0,0;\lambda}$ be invertible such that $\sigma^0(M)(t, x, \xi) = M_0(t, x, \xi)$. Such an operator $M$ exists according to Proposition 3.6 (b). Then we have that the matrix

$$\sigma^1(\text{AM}^{-1})(t, x, \xi) = \lambda(t)|\xi| (M_0 A_0 M_0^{-1})(t, x, \xi)$$

is symmetric for all $(t, x, \xi)$, i.e., $\sigma^1(\text{Im}(\text{AM}^{-1}))(t, x, \xi) = 0$ and $\text{Im}(\text{AM}^{-1}) \in \text{Op} S^{0,1;\lambda}$.

Vice versa, if (b) is satisfied, then we can take $\sigma^0(M)(t, x, \xi)$ for $M_0(t, x, \xi)$ in (a). □

Definition 4.3. System (1.1) is called symmetrizable-hyperbolic if the conditions of Lemma 4.2 are fulfilled. It is called symmetric-hyperbolic if $A_0(t, x, \xi)$ is already symmetric, i.e., $\text{Im} A \in \text{Op} S^{0,1;\lambda}$.

Proposition 4.4. In the proof of Theorem 1.1, we can assume that

$$A(t, x, \xi) = \chi^+(t, \xi) \left( \lambda(t)|\xi| A_0(t, x, \xi) - i\alpha t^{-1} A_1(x, \xi) \right) + A_2(t, x, \xi),$$

where $A_0 \in C^\infty([0, T]; S^{(0)})$, $A_0 = A_0$, $A_1 \in S^{(0)}$,

$$\Re A_1(x, \xi) \leq 0,$$

and $A_2 \in S^{-1,1;\lambda} + S^{0,0;\lambda}$; and $\delta = 0$.

Proof. Note that (4.2) means $\sigma^1(A)(t, x, \xi)$ is symmetric, while $\text{Im} \tilde{\sigma}^{0,1}(A)(x, \xi) \geq 0$.

Let the assumptions of Theorem 1.1 be satisfied. In particular, let $\delta \in B^\infty(\mathbb{R}^n; \mathbb{R})$ satisfy (1.9). We reduce (1.1) in two steps.

(a) Using the symmetrizer $M \in \text{Op} \tilde{S}^{0,0;\lambda}$, that is an isomorphism from $H^{s,\delta;\lambda}$ onto $H^{s,\delta;\lambda}$ for all $s \in \mathbb{R}$ by Proposition 3.4, while $M(0, x, D_x)$ is an isomorphism from $H^s(\mathbb{R}^n)$ onto $H^s(\mathbb{R}^n)$, instead of (1.1) we consider the equivalent system satisfied by $V := MU$:

$$\begin{aligned}
& D_t V(t, x) = B(t, x, D_x) V(t, x) + G(t, x), \\
& V(0, x) = V_0(x),
\end{aligned}$$

where $B = \text{AM}^{-1} + (D_t M) M^{-1}$, $V_0 = M(0, x, D_x) U_0$, $G = MF$.

We have $B \in \text{Op} \tilde{S}^{1,1;\lambda}$, $\sigma^1(B) = \lambda(t)|\xi| (M_0 A_0 M_0^{-1})(t, x, \xi)$,

$$\tilde{\sigma}^{0,1}(B) = \tilde{\sigma}^{0,1}(\text{AM}^{-1}) = -i\alpha \left( M_0 A_1 M_0^{-1} + [M_1 M_0^{-1}, M_0 A_0 M_0^{-1}] \right)$$

according to the composition rules in Proposition 2.11. In the last line, it was employed that $(D_t M) M^{-1} \in \text{Op} S^{0,1;\lambda}, \tilde{\sigma}^{0,1((D_t M) M^{-1})} = 0$ by virtue of Lemma 2.12.

Thus, we can assume that $A_0(t, x, \xi)$ is symmetric, $M_0(t, x, \xi) = 1_N$, and $M_1(t, x, \xi) = 0$ in Theorem 1.1. In this first reduction, $\delta$ has not been changed.

(b) Now assume $A_0(t, x, \xi)$ is symmetric, $M_0(t, x, \xi) = 1_N$, and $M_1(t, x, \xi) = 0$. Then using the operator $\Theta$ from Lemma 3.3, that is an isomorphism from $H^{s,\delta;\lambda}$ onto $H^{s,0;\lambda}$ for all $s \in \mathbb{R}$, while $\Theta(0, x, D_x) = \left(D_x\right) K_{\delta(x)}$ is an isomorphism from $H^{s+\beta,\delta(x)}(\mathbb{R}^n)$ onto $H^s(\mathbb{R}^n)$, instead of (1.1) we consider the equivalent system satisfied by $V := \Theta U$:

$$\begin{aligned}
& D_t V(t, x) = B(t, x, D_x) V(t, x) + G(t, x), \\
& V(0, x) = V_0(x),
\end{aligned}$$

where this time $B = \Theta A\Theta^{-1} + (D_t \Theta) \Theta^{-1}$, $V_0 = \Theta(0, x, D_x) U_0$, $G = \Theta F$.

By Lemma 4.5 below, $\Theta A\Theta^{-1} + (D_t \Theta) \Theta^{-1} \in \text{Op} \tilde{S}^{1,1;\lambda}$, $\sigma^1(\Theta A\Theta^{-1} + (D_t \Theta) \Theta^{-1}) = \lambda(t)|\xi| A_0$,

$$\tilde{\sigma}^{0,1}(\Theta A\Theta^{-1} + (D_t \Theta) \Theta^{-1})(x, \xi) = -i\alpha (A_1(x, \xi) - \delta(x)) 1_N.$$

Thus we can, in addition, assume that $\Re A_1 \leq 0$. This second reduction changes $\delta$ to zero. □
Lemma 4.5. Let $\Theta$ be as in Lemma 3.3. Then $\Theta A \Theta^{-1} + (D_t \Theta) \Theta^{-1} \in \text{Op} \hat{S}^{1,1;\lambda}$ and
\[ \sigma^1(\Theta A \Theta^{-1} + (D_t \Theta) \Theta^{-1}) = \sigma^1(A), \]
\[ \tilde{\sigma}^{0,1}(\Theta A \Theta^{-1} + (D_t \Theta) \Theta^{-1}) = \tilde{\sigma}^{0,1}(A) + i\delta(x)l_* 1_N. \]

Proof. We have $\Theta A \Theta^{-1} \in \text{Op} \hat{S}^{1,1;\lambda}$ and $\sigma^1(\Theta A \Theta^{-1}) = \sigma^1(A)$, $\tilde{\sigma}^{0,1}(\Theta A \Theta^{-1}) = \tilde{\sigma}^{0,1}(A)$ because of $\Theta \circ A \Theta^{-1} = \Theta_{K,\delta} A \Theta_{K,-\delta} = A \mod S^{1,-1;\lambda}$. Furthermore,
\[ (D_t \Theta) \circ \Theta^{-1} = (D_t \Theta_{K,\delta}) \Theta_{K,-\delta} \mod S^{1,-1;\lambda}, \]
so we consider the product $(D_t \Theta_{K,\delta}) \Theta_{K,-\delta}$:
\[ (D_t \Theta_{K,\delta}) \Theta_{K,-\delta} = \left( \lambda(t) \langle \xi \rangle_K \chi' (\Lambda(t) \langle \xi \rangle_K) (t^{-\delta(x)}l_* - \langle \xi \rangle_K^{\beta, \delta(x)}l_*) - \delta(x)l_* \chi_K^+(t, \xi) t^{-\delta(x)}l_* - 1 \right) \left( \chi_K^+(t, \xi) t^{\delta(x)}l_* + \chi_K^-(t, \xi) t^{\delta(x)}l_* \right) = \lambda(t) \langle \xi \rangle_K \chi' (\Lambda(t) \langle \xi \rangle_K) \chi_K^+(t, \xi) \left( 1 - \langle c_1 \Lambda(t) \langle \xi \rangle_K \rangle^{\beta, \delta(x)}l_* - 1 \right) + \lambda(t) \langle \xi \rangle_K \chi' (\Lambda(t) \langle \xi \rangle_K) \chi_K^+(t, \xi) \left( 1 - \langle c_1 \Lambda(t) \langle \xi \rangle_K \rangle^{\beta, \delta(x)}l_* - 1 \right) - \delta(x)l_* \chi_K^+(t, \xi) \chi_K^+(t, \xi) \chi(K) \langle \xi \rangle_K \langle \xi \rangle_K - \beta, \delta(x)l_* - 1 - \delta(x)l_* \chi_K^+(t, \xi) \chi_K^+(t, \xi) t^{-1} \]
with $c_1 = l_* + 1$. The first three summands on the right-hand side belong to $S^{1,-1;\lambda}$, since we have, e.g.,
\[ \chi'(t) (1 - \chi(t)) \in C^\infty_t (\mathbb{R}_+); \text{thus, } d_1 \leq \Lambda(t) \langle \xi \rangle_K \leq d_2 \text{ for certain constants } 0 < d_1 < d_2 \text{ on the support of the first summand and the derivatives of } (c_1 \Lambda(t) \langle \xi \rangle_K)^{-\beta, \delta(x)}l_* \text{ with respect to } x \text{ do not produce logarithmic terms in the estimates.} \]
Thus, we obtain
\[ (D_t \Theta) \circ \Theta^{-1} = i\delta(x)l_* \chi_K^+(t, \xi) t^{-1} \mod S^{1,-1;\lambda}, \]
i.e., $(D_t \Theta) \Theta^{-1} \in \text{Op} \hat{S}^{1,1;\lambda}$ and $\sigma^1((D_t \Theta) \Theta^{-1}) = 0$, $\tilde{\sigma}^{0,1}((D_t \Theta) \Theta^{-1}) = i\delta(x)l_* 1_N$, as required. \qed

4.2. Proof of Theorem 1.1. We now come to the proof of the main theorem. We divide this proof into three steps. Thereby, we always assume the reductions made in Proposition 4.4.

First step (Basic a priori estimate). Each solution $U$ to system (1.1) satisfies the a priori estimate (1.8) in case $s = 0$, i.e.,
\[ \|U\|_{H^{0,0;\lambda}}(0, T) \leq C \left( \|U_0\|_{L^2(\mathbb{R}^n)} + \|F\|_{H^{0,0;\lambda}}(0, T) \right), \tag{4.5} \]
where $C = C(T) > 0$.

Proof. First recall that $H^{0,0;\lambda}(0, T) \times \mathbb{R}^n) = L^2((0, T) \times \mathbb{R}^n)$.
Rewrite (1.1) in the form $(D_t - B)U = iF$, where
\[ B(t, x, \xi) = iA(t, x, \xi) = B_1(t, x, \xi) + B_2(t, x, \xi), \]
\[ B_1(t, x, \xi) - i\chi^+(t, \xi) \left( \lambda(t) \langle \xi \rangle_0 A_0(t, x, \xi) - il_* t^{-1} A_1(x, \xi) \right) \in S^{1,-1;\lambda}, \]
and $B_2 \in S^{0;\lambda}$. By construction,
\[ (B_1 + B_1^*) (t, x, \xi) \leq 2q(t, \xi) 1_N, \]
where $q(t, \xi) = Cg(t, \xi)^{-1} h(t, \xi)^2$ and $\int_0^t q(t', \xi) \, dt' \in L^\infty((0, T), S_{0,0})$. From Lemma A.1, we infer
\[ \|U(t, \cdot)\|_{L^2(\mathbb{R}^n)}^2 \leq C \left( \|U_0\|_{L^2(\mathbb{R}^n)}^2 + \int_0^t \|F(t', \cdot)\|_{L^2(\mathbb{R}^n)}^2 \, dt' \right). \tag{4.6} \]
Integrating this inequality over the time interval $(0, T)$ yields the desired estimate (4.5). \qed
Second step (**a priori** estimate of higher-order derivatives). Each solution $U$ to system (1.1) satisfies the **a priori** estimate (1.8) in case $s > 0$, i.e.,

$$
\|U\|_{H^{s,0,\lambda}((0,T) \times \mathbb{R}^n)} \leq C \left( \|U_0\|_{H^{s}((\mathbb{R}^n)} + \|F\|_{H^{s,0,\lambda}((0,T) \times \mathbb{R}^n)} \right),
$$

where $C = C(s, T) > 0$.

**Proof.** For any $s \in \mathbb{R}$, we have $U \in H^{s+1,0,\lambda}$ if and only if $g(t, D_x)h^{l_s}(t, D_x)U, h^{l_s}(t, D_x)D_t U \in H^{s,0,\lambda}$. Moreover, the vector $(g(t, D_x)h^{l_s}(t, D_x)U, h^{l_s}(t, D_x)D_t U)^T$ is a solution to the Cauchy problem

$$
\begin{cases}
D_t \left( g h^{l_s} U \right) + \left( A_{00} 0 \right) \left( g h^{l_s} U \right) + \left( A_{10} A_{11} \right) \left( h^{l_s} D_t U \right) = \left( \langle D_x \rangle U_0(x) \right),

\left( h^{l_s} U \right)(0,x) = \left( \langle D_x \rangle^{1-\beta_s} \left( A(0,x, D_x)U_0(x) + F(0,x) \right) \right),
\end{cases}
$$

where

$$
A_{00} = g h^{l_s} A(g h^{l_s})^{-1} + (D_t g)g^{-1} + l_s(D_t h)h^{-1},
$$

$$
A_{10} = \left[ h^{l_s}(D_t A) + l_s(D_t h)h^{-1-1} A \right] (g h^{l_s})^{-1},
$$

$$
A_{11} = h^{l_s} A h^{-l_s}.
$$

By Lemma 4.6 below, induction on $s \in \mathbb{N}$, and interpolation in $s \geq 0$, we then deduce the second step from the first one. \hfill \square

**Lemma 4.6.** We have $\begin{pmatrix} A_{00} & 0 \\ A_{10} & A_{11} \end{pmatrix} \in \text{Op} \tilde{S}^{1,1,\lambda}$ and

$$
\sigma^1 \left( \begin{pmatrix} A_{00} & 0 \\ A_{10} & A_{11} \end{pmatrix} \right) = \begin{pmatrix} \sigma^1(A) & 0 \\ 0 & \sigma^1(A) \end{pmatrix},
$$

$$
\sigma^{0,1} \left( \begin{pmatrix} A_{00} & 0 \\ A_{10} & A_{11} \end{pmatrix} \right) = \begin{pmatrix} \sigma^{0,1}(A) & 0 \\ 0 & \sigma^{0,1}(A) \end{pmatrix}.
$$

In particular, $\begin{pmatrix} A_{00} & 0 \\ A_{10} & A_{11} \end{pmatrix}$ fulfills the same assumptions as $A \in \text{Op} \tilde{S}^{1,1,\lambda}$ does, but for $(2N) \times (2N)$ matrices. Furthermore,

$$
\begin{pmatrix} \langle D_x \rangle U_0 \\ \langle D_x \rangle^{1-\beta_s} \left( A(0)U_0 + F(0) \right) \end{pmatrix} \in H^s(\mathbb{R}^n),
$$

$$
\begin{pmatrix} g h^{l_s} F \\ D_t h^{l_s} F \end{pmatrix} \in H^{s,0,\lambda}
$$

provided that $U_0 \in H^{s+1}(\mathbb{R}^n), F \in H^{s+1,0,\lambda}$.

**Proof.** A straightforward calculation using Proposition 2.11 and (2.6) gives $g h^{l_s} A(g h^{l_s})^{-1} \in \text{Op} \tilde{S}^{1,1,\lambda}$,

$$
\sigma^1(g h^{l_s} A(g h^{l_s})^{-1}) = \sigma^1(A), \quad \sigma^{0,1}(g h^{l_s} A(g h^{l_s})^{-1}) = \sigma^{0,1}(A),
$$

$$(D_t g)g^{-1}, (D_t h)h^{-1} \in \text{Op} \tilde{S}^{0,1,\lambda},
$$

$$
\sigma^{0,1}((D_t g)g^{-1}) = -i\xi_s, \quad \sigma^{0,1}((D_t h)h^{-1}) = i,
$$

$h^{l_s}(D_t A)(g h^{l_s})^{-1}, (D_t h)h^{-1-1} A(g h^{l_s})^{-1} \in \text{Op} \tilde{S}^{0,1,\lambda}$,

$$
\sigma^{0,1}(h^{l_s}(D_t A)(g h^{l_s})^{-1}) = -i\xi_s \sigma^{1}(A), \quad \sigma^{0,1}((D_t h)h^{-1-1} A(g h^{l_s})^{-1}) = i\xi \sigma^{1}(A),
$$

and $h^{l_s} A h^{-l_s} \in \text{Op} \tilde{S}^{1,1,\lambda}$,

$$
\sigma^1(h^{l_s} A h^{-l_s}) = \sigma^1(A), \quad \sigma^{0,1}(h^{l_s} A h^{-l_s}) = \sigma^{0,1}(A).
$$

Thus, (4.9), (4.10) hold. Moreover, (4.11) is obvious. \hfill \square

**Third step (Existence and uniqueness).** For all $U_0 \in H^s(\mathbb{R}^n), F \in H^{s,0,\lambda}((0,T) \times \mathbb{R}^n)$, where $s \geq 0$, system (1.1) possesses a unique solution $U \in H^{s,0,\lambda}((0,T) \times \mathbb{R}^n)$ satisfying the **a priori** estimate (4.7).
**Proposition 5.1.** Suppose that possesses a solution

Proof. Let \( s \geq 1 \), the general case then follows by density arguments. By Proposition 3.5 (c), we may suppose that \( U_0 \in C_{\text{comp}}^{\infty}(\mathbb{R}^n) \), \( F \in C_{\text{comp}}^{\infty}([0, T] \times \mathbb{R}^n) \).

We replace the operator \( A(t, x, D_x) \) by \( A_\varepsilon(t, x, D_x) \) for \( 0 < \varepsilon \leq 1 \), where

\[
A_\varepsilon(t, x, \xi) = \chi^+(t, \xi) \left( \Lambda(t) \xi | A_0(t, x, \xi) - i\lambda(t + \varepsilon)^{-1} A_1(t, x, \xi) \right) + A_{2\varepsilon}(t, x, \xi),
\]

\[
A_{2\varepsilon}(t, x, \xi) = \frac{t + \langle \xi \rangle^{-\beta_s}}{t + \langle \xi \rangle^{-\beta_s} + \varepsilon} A_2(t, x, \xi).
\]

The system \( D_t - A_\varepsilon(t, x, D_x) \) is symmetrizable-hyperbolic with the lower-order term belonging to the space \( L^\infty((0, T), S^{0}_{1,0}) \). Therefore, the Cauchy problem

\[
\begin{aligned}
D_t U_\varepsilon(t, x) &= A_\varepsilon(t, x, D_x)U_\varepsilon(t, x) + F(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}^n, \\
U_\varepsilon(0, x) &= U_0(x),
\end{aligned}
\]

possesses a unique solution \( U_\varepsilon \in C^\infty([0, T], H^\infty(\mathbb{R}^n)) \), see TAYLOR [17].

The set \( \{ A_\varepsilon : 0 < \varepsilon \leq 1 \} \) is bounded in \( S^{1,1,\lambda} \). Hence, the second step provides an estimate

\[
\| U_\varepsilon \|_{H^{s,0,\lambda}(0, T) \times \mathbb{R}^n} \leq C \left( \| U_0 \|_{H^s(\mathbb{R}^n)} + \| F \|_{H^{s,0,\lambda}((0, T) \times \mathbb{R}^n)} \right).
\]

that holds uniformly in \( 0 < \varepsilon \leq 1 \). Furthermore, the set \( \{ (A_\varepsilon - A_\varepsilon')/(\varepsilon - \varepsilon') : 0 < \varepsilon' < \varepsilon \leq 1 \} \) is bounded in \( S^{0,2,\lambda} \). From the first step as well as Propositions 3.4, 3.5 (e), we deduce that

\[
\| U_\varepsilon - U_\varepsilon' \|_{H^{0,0,0}} \leq C \| (A_\varepsilon - A_\varepsilon') U_\varepsilon \|_{H^{0,0,0}} \leq C(\varepsilon - \varepsilon') \| U_\varepsilon \|_{H^{1,0,0}}
\]

for \( 0 < \varepsilon' < \varepsilon \leq 1 \). Since \( s \geq 1 \), this implies that \( U_\varepsilon \) converges to some limit \( U \) in the space \( H^{0,0;\lambda} \) as \( \varepsilon \to +0 \).

The rest of the proof is standard. \( \square \)

5. Applications

We discuss three examples demonstrating the value of Theorem 1.1.

5.1. Differential systems. Differential systems of the form (1.1) with \( A(t, x, \xi) \) from (1.7) are of restricted interest, because a lower-order term as described by the term \( \chi^+(t, \xi) t^{-1} A_1(t, x, \xi) \) cannot occur. Hence, the loss of regularity is always zero.

Consider the operator

\[
\begin{aligned}
L &= D_t + \sum_{j=1}^{n} t^s a_j(t, x)D_{x_j} + a_0(t, x),
\end{aligned}
\]

where \( a_j \in \mathcal{B}^\infty([0, T] \times \mathbb{R}^n; M_{N \times N}(\mathbb{C})) \) for \( 0 \leq j \leq n \). With \( A(t, x, \xi) := -\sum_{j=1}^{n} t^s a_j(t, x)\xi_j - a_0(t, x), \)

\[
\sigma^1(A)(t, x, \xi) = -\lambda(t) |\xi| \sum_{j=1}^{n} a_j(t, x) \xi_j / |\xi|, \quad \delta^{0,1}(A)(t, x, \xi) = 0.
\]

**Proposition 5.1.** Let the differential system (5.1) be symmetrizable-hyperbolic. Then, for all \( s \geq 0 \), \( U_0 \in H^s(\mathbb{R}^n) \), and \( F \in H^{s,0,\lambda}((0, T) \times \mathbb{R}^n) \), the Cauchy problem

\[
\begin{aligned}
LU(t, x) &= F(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}^n, \\
U(0, x) &= U_0(x),
\end{aligned}
\]

possesses a solution \( U \in H^{s,0,\lambda}((0, T) \times \mathbb{R}^n) \). This solution \( U \) is unique in \( L^2 \).

Proof. We have \( A_1 = 0 \). Let \( M_0 \) be a symmetrizer for \( A_0 \), and \( M_1 = 0 \). Then (1.9) is satisfied with \( \delta = 0 \). The assertion follows immediately from Theorem 1.1. \( \square \)
5.2. Characteristic roots of constant multiplicity. An interesting class of systems to which Theorem 1.1 applies is that of systems having characteristic roots of constant multiplicity.

Definition 5.2. System (1.1) is said to have characteristic roots of constant multiplicity if it is symmetrically-hyperbolic in the sense of Definition 4.3 and if

\[
\det (\tau \mathbf{1}_N - \sigma^1(A)(t, x, \xi)) = \prod_{h=1}^{r} (\tau - t^{\mu_h(t, x, \xi)})^{N_h},
\]

where \(\mu_h \in C^\infty([0, T], S^{(1)})\) for \(1 \leq h \leq r\) are real-valued, \(N_1 + \cdots + N_r = N\), and

\[
|\mu_h(t, x, \xi) - \mu_{h'}(t, x, \xi)| \geq c, \quad 1 \leq h < h' \leq r,
\]

for some \(c > 0\).

Remark 5.3. In case \(r = N\), we have \(N_1 = \cdots = N_r = 1\) and the operator \(D_t - A(t, x, D_x)\) is strictly hyperbolic for \(t > 0\).

If \(D_t - A(t, x, D_x)\) has characteristic roots of constant multiplicity, then there exists a matrix \(M_0 \in C^\infty([0, T], S^{(0)})\) with \(|\det M_0(t, x, \xi)| \geq c > 0\) such that

\[
B_0(t, x, \xi) := (M_0A_0M_0^{-1})(t, x, \xi) = \text{diag}(\mu_1 \mathbf{1}_{N_1}, \ldots, \mu_r \mathbf{1}_{N_r})(t, x, \xi)
\]

is a diagonal matrix. With \(A_1(x, \xi) = i l^{-1}_s \delta^{0,1}(\lambda)(x, \xi)\) as before, we put

\[
B_1(x, \xi) := M_0(0, x, \xi)A_1(x, \xi)M_0(0, x, \xi)^{-1} = \begin{pmatrix}
B_{1,11} & B_{1,12} & \cdots & B_{1,1r} \\
B_{1,21} & B_{1,22} & \cdots & B_{1,2r} \\
\vdots & \vdots & \ddots & \vdots \\
B_{1,r1} & B_{1,r2} & \cdots & B_{1,rr}
\end{pmatrix}
\]

(5.3)

where \(B_{1,jk} \in C^\infty([0, T], S^{(0)})\) is an \(N_j \times N_k\) matrix.

Proposition 5.4. Assume system (1.1) has characteristic roots of constant multiplicity, and define \(B_0, B_1\) as above. Let \(\delta \in \mathcal{B}(\mathbb{R}^n; \mathbb{R})\) be so that

\[
\Re B_{1,jj}(x, \xi) \leq \delta(x) \chi_{N_j}, \quad (x, \xi) \in \mathbb{R}^n \times (\mathbb{R}^n \setminus 0), \quad 1 \leq j \leq r.
\]

Then, for all \(s \geq 0\), \(U_0 \in H^{s+\beta, \delta(x)k}\), and \(F \in H^{s, \delta(x)\lambda}\), the Cauchy problem (1.1) possesses a unique solution \(U \in H^{s, \delta(x)\lambda}\).

Proof. Assuming (5.4), we are looking for a matrix \(M_1 \in S^{(0)}\) such that

\[
\Re(B_1 + [M_1M_0^{-1}, B_0])(0, x, \xi) \leq \delta(x) \chi_{N}, \quad (x, \xi) \in \mathbb{R}^n \times (\mathbb{R}^n \setminus 0).
\]

We are done if we can find a matrix \(P_1 = M_1M_0^{-1}\) in such a way that

\[
B_1 + [P_1, B_0] = \begin{pmatrix}
B_{1,11} & 0 & \cdots & 0 \\
0 & B_{1,22} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & B_{1,rr}
\end{pmatrix}
\]

(5.5)

is block-diagonal.

Such a matrix \(P_1\) can be constructed using the fact that \(B_0\) is diagonal with distinct eigenvalues for the different blocks, and employing the following result, see TAYLOR [17, Chap. IX, Lemma 1.1]:

For \(E \in M_{M \times M}(\mathbb{C}), F \in M_{N \times N}(\mathbb{C})\), the map

\[
M_{M \times N}(\mathbb{C}) \rightarrow M_{M \times N}(\mathbb{C}), \quad T \mapsto TF - ET,
\]

is bijective if and only if \(E\) and \(F\) have disjoint spectra.
We choose $P_1$ so that $P_{1, jj} = 0$ for $1 \leq j \leq r$, where the meaning of $P_{1, jj}$ is the same as in (5.3). Then $[P_1, B_0]_{jk} = P_{1, jk}B_{0, kk} - B_{0, jj}P_{1, jk}$ for $j \neq k$, while $[P_1, B_0]_{jj} = 0$ for $1 \leq j \leq r$. According to the result just quoted, we can choose $P_{1, jk}$ for $j \neq k$ so that

$$B_{1, jk} + [P_1, B_0]_{jk} = 0, \quad j \neq k.$$  

That is, by this choice of $P_1$ we kill all off-diagonal entries of $B_1$, while the diagonal entries of $B_1$ remain unchanged. Thus, we end up with (5.5).

Example 5.5. There are two extreme cases exemplified by (a), (b) below:

(a) Let $r = N$, see Remark 5.3. Then we can choose any $\delta \in B^\infty(\mathbb{R}^n; \mathbb{R})$ satisfying

$$\text{Re}(M_0 A_1 M_0^{-1})_{jj}(0, x, \xi) \leq \delta(x), \quad (x, \xi) \in \mathbb{R}^n \times (\mathbb{R}^n \setminus 0), \quad 1 \leq j \leq N.$$  

In a forthcoming paper, we will show that this bound on $\delta$ is sharp.

(b) Consider the Cauchy problem

$$\begin{cases} D_t U(t, x) + i\alpha a(t, x) h(t, D_x) U(t, x) = F(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}^n, \\ U(0, x) = U_0(x), \end{cases} \tag{5.6}$$

where $a \in B^\infty([0, T] \times \mathbb{R}^n; M_{N \times N}(\mathbb{C}))$. Then $A(t, x, \xi) = -i\alpha a(t, x) h(t, \xi)$, $A_0(t, x, \xi) = 0$, and $A_1(t, x, \xi) = a(t, x)$. By choosing $M_0(t, x, \xi) = M_0(0, x, \xi)$ so that $M_0(0, x, \xi)$ is unitary and diagonalizes $\text{Re} a(0, x)$, we see that we can choose any $\delta \in B^\infty(\mathbb{R}^n; \mathbb{R})$ satisfying

$$\delta(x) \geq \max_{1 \leq j \leq N} \nu_j(x),$$

where $\nu_1(x), \ldots, \nu_N(x)$ are the eigenvalues of $\text{Re} a(0, x)$ (not necessarily distinct).

5.3. Higher-order scalar equations. Let $L$ be the operator

$$L = D_t^m + \sum_{j + |\alpha| \leq m, \ j < m} a_{j\alpha}(t, x) i^{j+(l+1)|\alpha|-m} D_t^j D_x^\alpha, \quad (t, x) \in (0, T) \times \mathbb{R}^n,$$

where $a_{j\alpha} \in B^\infty([0, T] \times \mathbb{R}^n)$ for $j + |\alpha| \leq m, j < m$. We assume $L$ to be strictly hyperbolic in the sense that

$$\sigma^m = \prod_{h=1}^{m} (\tau - \lambda_h(t, x, \xi)),$$

where $\lambda_h \in C^\infty([0, T], S^{(1)})$, $1 \leq h \leq m$, are real–valued, and

$$|\lambda_h(t, x, \xi) - \mu_h(t, x, \xi)| \geq c|\xi|, \quad 1 \leq h < h' \leq m, \quad c > 0.$$  

We define a reduced principal symbol of $L$,

$$p(\tau) := p(t, x, \tau, \xi) = \tau^m + p_{m-1} \tau^{m-1} + \cdots + p_1 \tau + p_0,$$

where

$$p_j(t, x, \xi) := \sum_{|\alpha| = m-j} a_{j\alpha}(t, x) \left( \frac{\xi}{|\xi|} \right)^\alpha,$$

and a reduced secondary symbol,

$$q(\tau) := q(t, x, \tau, \xi) = q_{m-2} \tau^{m-2} + q_{m-3} \tau^{m-3} + \cdots + q_1 \tau + q_0,$$

where

$$q_j(t, x, \xi) := i\lambda_j^{-1} \sum_{|\alpha| = m-j-1} a_{j\alpha}(0, x) \left( \frac{\xi}{|\xi|} \right)^\alpha.$$  

The loss of regularity is then determined as follows:
Proposition 5.6. Let $s \geq 0$, $\delta \in \mathcal{B}^\infty(\mathbb{R}^n; \mathbb{R})$ satisfy
\[
\delta(x) \geq \sup_{1 \leq h \leq m} \sup_{|\xi|=1} \left( -\frac{x}{x^2_{\xi h}} + \text{Re} q \right) (0, x, \mu_h(0, x, \xi), \xi). \tag{5.7}
\]
Then, for all $u_j \in H^{s+m-j, \beta_1, \ldots, \beta_s, \delta(x)\lambda}$, for $0 \leq j \leq m-1$, $f \in H^{s, \delta(x)+m-1, \lambda}$, the Cauchy problem
\[
\begin{aligned}
    L u(t, x) &= f(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}^n, \\
    D_t^j u(0, x) &= u_j(x), \quad 0 \leq j \leq m-1,
\end{aligned} \tag{5.8}
\]
possesses a solution $u \in H^{s+m-1, \delta(x)\lambda}$. This solution $u$ is unique in the space $H^{m-1, \delta(x)\lambda}$.

Proof. We convert problem (5.8) into an $m \times m$ system of the first order. Then it is equivalent to the Cauchy problem
\[
\begin{aligned}
    D_t U(t, x) &= A(t, x, D_x)U(t, x) + F(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}^n, \\
    U(0, x) &= U_0(x),
\end{aligned}
\]
where $U = \begin{pmatrix} g^{m-1} & g^{m-2} & \cdots & g \\ D_{m-1} & D_{m-2} & \cdots & D_0 \end{pmatrix} \in H^{s, \delta(x)+m-1, \lambda}$ (if and only if $u \in H^{s+m-1, \delta(x)\lambda}$, see Remark 3.2 (b) (i)),

\[
U_0 = \begin{pmatrix} \langle D_x \rangle_{a_{m-1}} & \langle D_x \rangle_{a_{m-2}} & \cdots & \langle D_x \rangle_{a_0} \\ \langle D_x \rangle_{a_{m-1}} & \langle D_x \rangle_{a_{m-2}} & \cdots & \langle D_x \rangle_{a_0} \end{pmatrix} \in H^{s, \delta(x)+m-1, \lambda},
\]

\[
A(t, x, \xi) = \begin{pmatrix} (m-1) \frac{D_g g}{g} & g & 0 & \ldots & 0 & 0 \\ 0 & (m-2) \frac{D_g g}{g} & g & \ldots & 0 & 0 \\ 0 & 0 & (m-3) \frac{D_g g}{g} & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & \frac{D_g g}{g} & \frac{D_g g}{g} \\ -\frac{a_0}{g^{a_{m-2}}} & -\frac{a_1}{g^{a_{m-1}}} & -\frac{a_2}{g^{a_{m-1}}} & \ldots & -\frac{a_{m-2}}{g} & -a_{m-1} \end{pmatrix},
\]

and $a_j(t, x, \xi) = \sum_{|\alpha|=m-j} a_{j\alpha}(t, x) t^{j+(i_s+1)|\alpha|-m+1} \xi^\alpha$.

From Example 2.9 (b), we infer that $A \in \tilde{S}^{1,1, \lambda}$, $\sigma^1(A)(t, x, \xi) = \lambda(t) |\xi| A_0(t, x, \xi)$, where

\[
A_0(t, x, \xi) = \begin{pmatrix} 0 & 1 & 0 & \ldots & 0 & 0 \\ 0 & 0 & 1 & \ldots & 0 & 0 \\ 0 & 0 & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & 0 & 1 \\ -p_0 & -p_1 & -p_2 & \ldots & -p_{m-2} & -p_{m-1} \end{pmatrix},
\]

and $\sigma^{0,1}(A)(x, \xi) = -il_s A_1(x, \xi)$, where

\[
A_1(x, \xi) = \begin{pmatrix} m-1 & 0 & 0 & \ldots & 0 & 0 \\ 0 & m-2 & 0 & \ldots & 0 & 0 \\ 0 & 0 & m-3 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & 1 & 0 \\ -q_0 & -q_1 & -q_2 & \ldots & -q_{m-2} & 0 \end{pmatrix}.
\]
Now, it is easy to provide a symmetrizer $M_0$ for $A_0$, namely

$$M_0(t, x, \xi)^{-1} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ \mu_1 & \mu_2 & \cdots & \mu_m \\ \vdots & \vdots & \ddots & \vdots \\ \mu_1^{m-1} & \mu_2^{m-1} & \cdots & \mu_m^{m-1} \end{pmatrix}.$$  

Note that $\det M_0^{-1} = \prod_{h<h'} (\mu_h - \mu_{h'})$ and, for $1 \leq h, j \leq m$,

$$(M_0(t, x, \xi))_{hj} = \frac{\mu_h^{m-j} + p_{m-1} \mu_h^{m-j-1} + \cdots + p_{j+1} \mu_h + p_j}{\partial \mu_h}.$$  \hspace{1cm} (5.9)

According to our general scheme, see Example 5.5 (a), to read off the loss of regularity we have to calculate

$$(M_0 A_1 M_0^{-1})_{hh} = \sum_{j, k} (M_0)_{hj} (A_1)_{jk} (M_0^{-1})_{kh}$$

$$= \sum_{j=1}^{m-1} (m - j) (M_0)_{hj} (M_0^{-1})_{jh} + \sum_{j=1}^{m-1} q_{j-1} (M_0)_{hm} (M_0^{-1})_{jh}$$

$$= m - \sum_{j=1}^{m} (M_0)_{hj} (M_0^{-1})_{jh} - \sum_{j=1}^{m-1} q_{j-1} (M_0)_{hm} (M_0^{-1})_{jh}.$$ 

By virtue of (5.9),

$$\sum_{j=1}^{m} j (M_0)_{hj} (M_0^{-1})_{jh} = \sum_{j=1}^{m} j \left( \mu_h^{m-j} + p_{m-1} \mu_h^{m-j-1} + \cdots + p_{j+1} \mu_h + p_j \right) \mu_h^{j-1}$$

$$= \sum_{j=1}^{m} j^{j+1} p_j \mu_h^{j-1} \left( \frac{\partial \mu_h}{\partial \mu} + \frac{\partial \theta}{\partial \mu} \right) (0, x, \mu_h, \xi)$$

and

$$\sum_{j=1}^{m-1} q_{j-1} (M_0)_{hm} (M_0^{-1})_{jh} = \sum_{j=1}^{m-1} q_{j-1} \mu_h^{j-1} \frac{\partial q}{\partial \mu} (0, x, \mu_h, \xi).$$

Hence, the assertion follows. \hspace{1cm} $\square$

**Remark 5.7.** The expression

$$l_\star \sup_{x \in \mathbb{R}^n, |\xi| = 1} \left( - \frac{\partial^2 q}{\partial \mu^2} + \Re q \right) (0, x, \mu_h, 0, x, \xi)$$

is the connecting coefficient $m_h^\star$ from AMANO–NAKAMURA [1].

A. **APPENDICES**

A.1. **A useful estimate.** We consider a matrix pseudodifferential operator $\partial_t - B(t, x, \xi)$ and its forward fundamental solution $X(t, t')$ which is defined by the relations

$$(\partial_t - B(t, x, D_x)) \circ X(t, t') = 0, \quad 0 \leq t' \leq t \leq T,$$

$$X(t', t) = I, \quad 0 \leq t' \leq T.$$ 

We suppose that this forward fundamental solution operator exists and maps $\mathcal{S}(\mathbb{R}^n)$ onto itself. Our assumptions on $B(t, x, D_x)$ are as follows:

- $B(t, x, \xi) = B_1(t, x, \xi) + B_\delta(t, x, \xi)$ with $B_1 \in L^\infty((0, T), S^1_{1,0})$, $B_\delta \in L^\infty((0, T), S^0_{\phi, \delta})$, where $0 \leq \delta \leq \phi \leq 1$, $\delta < 1$. 


Lemma A.1. Under these assumptions, the forward fundamental solution operator can be extended such as acting boundedly from $L^2(\mathbb{R}^n)$ onto itself,

$$X \in L^\infty(\triangle_+, \mathcal{L}(L^2(\mathbb{R}^n))), \quad \triangle_+ = \{(t, t') : 0 \leq t' \leq t \leq T\}.$$ 

**Proof.** For $(t, t') \in \triangle_+$, we define a mapping $Y(t, t') : \mathcal{S}(\mathbb{R}^n) \to \mathcal{S}(\mathbb{R}^n)$ by

$$Y(t, t') = \exp(-p(t, x, D_x)) \circ \exp(p(t', x, D_x)) \circ X(t, t').$$

Obviously, $Y(t', t') = I$. Since the symbol $p(t, x, \xi)$ does not depend on $x$ and $\xi$ simultaneously, we have

$$\partial_t \circ Y(t, t') = -q(t, x, D_x) \circ Y(t, t')$$

$$+ \exp(-p(t, x, D_x)) \circ \exp(p(t', x, D_x)) \circ B(t, x, D_x) \circ X(t, t')$$

$$= (B - q1_N + \left[ e^{-p(t, x, D_x)} e^{p(t', x, D_x)} 1_N, B \right] e^{p(t', x, D_x)} e^{-p(t, x, D_x)}) \circ Y(t, t')$$

$$= (B_1 - q1_N + B_0) \circ Y(t, t')$$

for some $B_0 \in L^\infty(\triangle_+, \mathcal{S}^{(0)}_{\mathcal{E}_0})$ because of $\exp(\pm p(t, x, \xi)) \in L^\infty((0, T), \mathcal{S}^{(0)}_{\mathcal{E}_0})$.

For fixed $t' \in [0, T]$, $U_0 \in \mathcal{S}(\mathbb{R}^n)$, we define a function $U(t, x) = Y(t, t') U_0(x)$ which solves

$$\partial_t U = (B_1 - q1_N + B_0) U, \quad (t, x) \in (t', T) \times \mathbb{R}^n,$$

$$U(t', x) = U_0(x).$$

Employing the sharp Gårding inequality and Calderón-Vaillancourt’s theorem, we obtain

$$\partial_t (U(t, \cdot), U(t, \cdot)) = 2 \mathrm{Re} (\partial_t U(t, \cdot), U(t, \cdot)) = 2 \mathrm{Re} ((B_1 - q1_N + B_0) U(t, \cdot), U(t, \cdot))$$

$$\leq ((B_1 + B_1^* - 2q1_N) U(t, \cdot), U(t, \cdot)) + 2 \| (B_0 U)(t, \cdot) \|_{L^2} \| U(t, \cdot) \|_{L^2} \leq C \| U(t, \cdot) \|_{L^2}^2.$$ 

Then Gronwall’s lemma implies $\| U(t, \cdot) \|_{L^2} \leq C \| U(t', \cdot) \|_{L^2}$, i.e.,

$$Y \in L^\infty(\triangle_+, \mathcal{L}(L^2(\mathbb{R}^n))).$$

The operators $\exp(\pm p(t, x, D_x))$ map $L^2(\mathbb{R}^n)$ continuously and bijectively onto itself which completes the proof. \hfill \square

A.2. **Proof of Proposition 3.6 (b).** We need the following result:

**Lemma A.2.** For each $N \times N$ matrix function $q_0 \in \mathcal{S}^{(0)}$ satisfying $| \det q_0(x, \xi) | \geq c$ for all $(x, \xi) \in \mathbb{R}^n \times (\mathbb{R}^n \setminus 0)$ and some $c > 0$, there is an invertible operator $Q \in \mathcal{S}^{(0)}_{\mathcal{E}_0}(\mathbb{R}^n)$ such that $\sigma^0(Q)(x, \xi) = q_0(x, \xi)$.

**Proof.** We construct two invertible operators $Q_1, Q_2 \in \mathcal{S}^{(0)}_{\mathcal{E}_0}(\mathbb{R}^n)$ such that

$$\sigma^0(Q_1)(x, \xi) = q_0(x, \xi) q_0(x^0, \xi)^{-1}, \quad \sigma^0(Q_2)(x, \xi) = q_0(x^0, \xi)$$

for some $x^0 \in \mathbb{R}^n$. Then the composition $Q_1 Q_2$ has the desired properties.

**Construction of $Q_1$.** We employ the parameter-dependent calculus of GRUBB [7].
Rename \(q_0^0(x, \xi)\) to \(q_0(x, \xi)\). Then \(q_0(x, \xi) = 1_N\) for all \(\xi \in \mathbb{R}^n \setminus 0\). Therefore, there is an invertible \(N \times N\) matrix function \(p_0 \in S^{(0)}(\mathbb{R}^n \times ((\mathbb{R}^n \times \mathbb{R}_+^e) \setminus 0))\) such that \(|\det p_0(x, \xi, \mu)| \geq c/2\) for \((x, \xi, \mu) \in \mathbb{R}^n \times ((\mathbb{R}^n \times \mathbb{R}_+^e) \setminus 0)\) and
\[
p_0(x, \xi, 0) = q_0(x, \xi), \quad (x, \xi) \in \mathbb{R}^n \times (\mathbb{R}^n \setminus 0).
\]
We now set
\[
p(x, \xi, \mu) := \chi(|\xi, \mu|) \left(p_1(x, \xi, \mu) + \chi(|\xi|) \left(p_0(x, \xi, \mu) - p_1(x, \xi, \mu)\right)\right),
\]
where \(p_1(x, \xi, \mu) := \sum_{|a| < k} \frac{\partial^a p_0(x, \xi, \mu)}{a!}\) for some integer \(k > 0\), see [7, Remark 2.1.13]. According to [7, Theorem 3.2.11], there is a \(\mu_0 \geq 0\) such that, for all \(\mu \geq \mu_0\), the operator \(p(x, D_x, \mu) : L^2(\mathbb{R}^n) \to L^2(\mathbb{R}^n)\) is invertible. It sufﬁces to set \(Q_1 := p(x, D_x, \mu)\), where \(\mu \geq \mu_0\).

**Construction of \(Q_2\).** Rename \(q_0(x, \xi)\) to \(q_0(\xi)\). The task to construct \(q \in S^0_{cl}\) such that \(\sigma^0(q)(x, \xi) = q_0(\xi)\) and \(q(x, D_x) \in \text{Op} S^0_{cl}\) is invertible can be fulﬁlled within the framework of \(SG\)-calculus, where one has symbols which have asymptotic expansions into components which are homogeneous in both the \(x\)- and the \(\xi\)-variables. In particular, we have a symbol \(\sigma_e^0(q)(x, \xi) \in S^{(0)}(\mathbb{R}^n_+ \times 0) \widehat{\otimes}_{x} S^0_{cl}(\mathbb{R}^n_+\xi)\), having the status of a second principal symbol, subject only to the restriction \(\sigma^0(\sigma_e^0(q)(x, \xi)) = q_0(\xi)\). Choosing \(\sigma_e^0(q)(x, \xi)\) as an elliptic symbol in \(x \neq 0\) uniformly with respect to \(\xi\), we get that \(q(x, D_x) : L^2(\mathbb{R}^n) \to L^2(\mathbb{R}^n)\) is a Fredholm operator. Moreover, upon an appropriate choice of \(\sigma_e^0(q)(x, \xi)\) we can achieve each integer as index of this operator. We choose \(\sigma_e^0(q)(x, \xi)\) in such a way that \(q(x, D_x) : L^2(\mathbb{R}^n) \to L^2(\mathbb{R}^n)\) has index 0. Then, by adding a contribution from \(\text{Op} S^{-\infty}(\mathbb{R}^n_+ \times \mathbb{R}^n_+\xi)\) if necessary, we ﬁnally arrive at an operator \(q(x, D_x)\) that is invertible as operator on \(L^2(\mathbb{R}^n)\). We leave the details of this construction to the reader. For more on \(SG\)-calculus we refer, e.g., to Schulze [15].

**Proof of Proposition 3.6 (b).** There is a generalization of Lemma A.2 to the case \(q_0 \in C^\infty([0, T]; S^{(0)}_\lambda)\). Therefore, we ﬁnd an invertible operator \(Q_1 \in C^\infty([0, T]; \text{Op} S^{(0)}_\lambda)\) such that \(\sigma^0(Q_1(t, x, \xi) = q_0(t, x, \xi)\) for \((t, x, \xi) \in [0, T] \times \mathbb{R}^n \times (\mathbb{R}^n \setminus 0)\). Since \(q \in C^\infty([0, T]; S^0_{cl} + S^{-1})\) implies \(q \in S^{(0), \lambda}_{cl}\), where \(\sigma^{-1, 0}(q) = 0\), it remains to construct an operator \(Q_2 \in \text{Op} \tilde{S}^{0, 0, \lambda}_\lambda\) such that
\[
\sigma^0(Q_2)(t, x, \xi) = 1_N, \quad \sigma^{-1, 0}(Q_2)(x, \xi) = q_0(0, x, \xi)^{-1} q_1(x, \xi),
\]
and the composition \(Q_1 Q_2\) has the desired properties.

Rename \((q_0^{-1} q_1)(0, x, \xi)\) to \(q_1(x, \xi)\) and set \(Q_2 = q(t, x, D_x)\), where
\[
q(t, x, \xi) = 1_N + \chi(\Lambda(t) \xi/d) t^{-((l+1)/2)} q_1(x, \xi)
\]
for some large \(d > 0\) to be chosen. We have
\[
\left| \chi(\Lambda(t) \xi/d) t^{-(l+1)/2} q_1(x, \xi) \right| \leq C d^{-1}, \quad (t, x, \xi) \in [0, T] \times \mathbb{R}^{2n},
\]
for some \(C > 0\) and \(d > 0\) is large enough. From Hörmander [9, Theorem 18.1.15], we conclude that
\[
\left\| \chi(\Lambda(t) D_x/d) t^{-(l+1)/2} q_1(x, D_x) \right\|_{L(L^2(\mathbb{R}^n))} \leq \frac{1}{3} + C' \left( \frac{\Lambda(t)}{d} \right)^{1/2}, \quad t \in [0, T],
\]
for some \(C' > 0\) and \(d \geq C/3\) is large enough. Choosing additionally \(d \geq 9C'^2 \Lambda(T)\), we find that, for each \(t \in [0, T]\), the operator \(q(t, x, D_x)\) is invertible on \(L^2(\mathbb{R}^n)\) with
\[
\|q(t, x, D_x)^{-1}\|_{L(L^2(\mathbb{R}^n))} \leq 3.
\]
This completes the proof. \(\square\)
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